Sensitivity of a Semi-Arid Riparian Ecosystem to Climatic Variability in the Southwestern United States

Mark D. Dixon

Department of Biology, University of South Dakota
414 E. Clark Street
Vermillion, SD 57069 USA

Juliet C. Stromberg

School of Life Sciences, Arizona State University
PO Box 874501
Tempe, AZ 85287 USA

Thomas Meixner

Department of Hydrology and Water Resources, University of Arizona
Harshbarger Building
Tucson, AZ 85721 USA

James F. Hogan

Monitoring and Assessment Section, New Mexico Environment Department
1190 St. Francis Drive, Room N2110
Santa Fe, NM 87505 USA

David C. Goodrich
Agricultural Research Service, United States Department of Agriculture
2000 East Allen Road
Tucson, AZ 85719 USA

Abstract: Climatic change will have strong impacts on riverine ecosystems and their associated riparian zones, particularly in arid and semi-arid regions around the world. In the southwestern United States, conservation and restoration of riparian habitats has become a priority for resource management agencies and conservation groups, and these areas are biodiversity hot spots within the arid/semi-arid landscape. Given the dependence of human societies on water, these areas are impacted by water resource development, both of ground and surface waters, with the potential for conflict heightened under an increasingly arid climate and a growing human population. Although changes in temperature will directly affect riparian vegetation, riparian landscapes are likely to be most strongly influenced by climate-linked changes in surface and groundwater hydrology. Using the San Pedro River (Arizona, USA) as our primary case study, we review findings from two decades of research on the relationships between riparian vegetation dynamics, climate, geomorphic change, and both surface and subsurface hydrologic processes. The distribution, composition, and productivity of riparian vegetation are dependent on both surface flows and groundwater dynamics. Floods, both as a source of water and as an agent of ecological disturbance, are important for driving riparian vegetation dynamics. In the Desert Southwest, the magnitude and seasonality (summer vs. winter) of floods, which are influenced by large scale climatic teleconnections, impact recruitment of riparian tree species, productivity of herbaceous vegetation, and other ecosystem processes. Spatial and temporal patterns in groundwater discharge in riparian ecosystems control low flows and influence vegetation composition, growth and productivity. Flood-driven recharge of the alluvial aquifer may be important for sustaining low flows and shallow groundwater levels through subsequent drier periods. While influenced by both floods and groundwater dynamics, riparian vegetation also exerts important feedbacks on these processes, and on entire system response, via evapotranspiration and influences on bank stability and channel dynamics. Cumulative effects of past water management and local geologic conditions may also influence sensitivity of riparian vegetation to climatic change. Over the length of the river, vegetation response will vary spatially depending on a site's history of

groundwater pumping as well as on geologically-controlled rates of groundwater discharge; stream reaches that are presently approaching critical hydrobiotic thresholds will be the most sensitive to climate-linked changes in stream hydrology. Regionally (and globally), water resource management decisions will greatly influence the sensitivity of riparian ecosystems to climatic change, affecting the ability of these systems to maintain biological diversity and provide other services of value to humans.

Keywords: riparian vegetation, *Populus*, *Tamarix,* groundwater, surface water, San Pedro River

Introduction

Climatic change will have strong impacts on rivers and their associated riparian zones, particularly in arid and semi-arid regions around the world (Arnell 2003, Palmer et al. 2008). Riparian ecosystems in the southwestern United States are sustained within an otherwise arid landscape by the availability of surface water and groundwater associated with drainages. Most General Circulation Models (GCMs) project that this region, and indeed, most other desert regions of the world, will become increasingly arid under a changing climate (Seager et al. 2007, IPCC 2007). In addition to projected increases in temperatures, climatic change may influence precipitation seasonality, amount, and storm intensity. These precipitation changes, in tandem with changes in temperature and evaporative demand, will influence the hydrologic processes that control the structure and function of riparian areas.

Conservation and restoration of riparian areas is a priority for natural resource management in the American Southwest, as these habitats are biodiversity hot spots within the semi-arid landscape. These habitats are impacted by water resource development, both of groundwater and surface waters, with the potential for conflict heightened under an increasingly arid climate and a growing human population. Although changes in temperature will directly affect plant growth, climate-linked changes in surface and groundwater hydrology will have the strongest influence on riparian landscapes. Using the San Pedro River (Arizona, USA) as our primary case study, we review findings from two decades of research (Goodrich et al. 2000, Stromberg and Tellman 2009a, Brookshire et al. 2010) on interactions among riparian vegetation, climate, geomorphic change, and both surface and subsurface hydrologic processes, and examine the potential implications of climatic change for riparian ecosystems in the semi-arid southwestern United States.

Study Area

The San Pedro River begins in northeastern Mexico and flows north until its confluence with the Gila River, near Winkelman, Arizona (USA). The upper (southern) 50 km of the river in the United States is protected as the San Pedro Riparian National Conservation Area (SPRNCA) by the U.S. Bureau of Land Management (BLM). The San Pedro is one of the few low-elevation rivers in the region that contains significant reaches of perennial flow and is not regulated by dams. The upper San Pedro is recognized as one of the "Last Great Places" by The Nature Conservancy, with exceptionally high biodiversity of plants, birds, reptiles, mammals, and other taxa (Stromberg and Tellman 2009). Accordingly, the San Pedro is sometimes considered a reference site for understanding the processes and patterns that sustain healthy riparian ecosystems in semi-arid regions. Vegetation along the San Pedro is composed of desert grassland and shrub-scrub in the uplands, with woodlands of velvet mesquite (*Prosopis velutina*), a leguminous shrub-tree species, and grasslands of big sacaton (*Sporobolus wrightii*) on the riparian terraces. Forests of Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*), with perennial wetland plants bordering the channel, dominate the floodplain on reaches with perennial flow. With increasing depth to groundwater and decreasing surface flow frequency, woody floodplain vegetation shifts to dominance by shrublands of tamarisk (*Tamarix ramosissima*), a Eurasian shrub-tree species; mesquite; and other more drought tolerant species (Stromberg et al. 1996, 2006, 2009a).

Current management issues focus on the present and potential future effects of municipal and domestic groundwater pumping on the state of the riparian ecosystem and river base flows. Over the last two decades, concerns have arisen that groundwater pumping, in particular by the municipality of Sierra Vista and the Fort Huachuca military base, has led to cones of depression in the regional water table, potentially altering flow paths that support the alluvial aquifer, dry season base flows in the San Pedro, and the riparian ecosystem (Mac Nish et al. 2009). These concerns have been fueled, in part, by significant declines in summer base flows since the late 1930s (Pool and Coes 1999) and significant annual overdrafts in the groundwater budget of the Sierra Vista subbasin (Mac Nish et al. 2009).

Southwestern Climate and Hydrology

General Circulation Models (GCMs) generally project more arid conditions for the American Southwest, with higher temperatures and lower precipitation (Seager et al. 2007, Serrat-Capdevila et al. 2007), although some have suggested that current models significantly underestimate potential increases in precipitation (Wentz et al. 2007). Earlier projections for the region, down-scaled from several climate models, showed mixed results in terms of precipitation change, with some models suggesting increased winter precipitation, and others projecting precipitation declines (SRAG 2000).

The borders of the three major "hot" deserts (Mojave, Sonoran, Chihuahuan) in North America converge in Arizona and form a west to east gradient in rainfall amount and seasonality, with greater aridity and dominance by frontal winter rainfall in the west, and higher precipitation amounts with greater dominance by summer convective rainfall in the east (Sheppard et al. 2002). The upper (southern) San Pedro basin is influenced by a "Chihuahuan" climatic regime, with 65% of average annual rainfall occurring in the summer and 35% in the winter, while the lower (northern) portion of the basin has a "Sonoran" climate, with a nearly even mix of summer and winter precipitation (Stromberg and Tellman 2009). On the upper San Pedro, these temporal patterns in rainfall divide the year into roughly four hydrologic seasons: summer wet (monsoon) season (July – September), fall dry season (October – November), winter wet season (December – March), and spring (or pre-monsoon) dry season (April – June).

Three basic storm types that differ in their extent, intensity, and frequency influence precipitation and flooding patterns in the region (Hirschboeck 2009). First, local convective storms occur during the summer months (July – September) as a function of the North American monsoon, which brings moist, warm air up from the Gulf of Mexico, the eastern Pacific, and the Gulf of California (Sheppard et al. 2002). These storms drive intense, short-duration floods that occur annually on the San Pedro. Second, frontal storm systems off of the eastern Pacific Ocean, particularly in the winter and early spring (e.g., December – March) produce lower intensity, longer duration precipitation events that may be regional in extent. Floods are typically moderate-sized, but may be of longer duration and larger extent, sometimes producing large, geomorphically effective floods on larger rivers (Huckleberry 1994). Third, inland incursions of dissipating tropical storms occasionally occur in the fall (September - October). These events are highly sporadic in occurrence, but have been associated with some of the largest floods on the San Pedro and other Arizona rivers in the last 75 years (Webb and Betancourt 1992, Hirschboeck 2009).

Temporal variation in the relative frequencies and magnitudes of these storm events and the floods that they generate may be influenced by large-scale atmospheric-ocean connections, such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (Webb and Betancourt 1992, Sheppard et al. 2002, McCabe et al. 2007, 2008). Higher winter rainfall and flooding from frontal systems has often been associated with El Niño years (warm phase of ENSO), and with a higher frequency of El Niño events occurring during positive (warm) phases of the PDO. Years with higher rates of groundwater recharge in ephemeral stream channels have also been associated with positive ENSO and PDO conditions (Pool 2005). In addition, seven of nine large floods associated with dissipating tropical storms on the San Pedro occurred during positive phases of the PDO (Hirschboeck 2009). Although most (90%) of the annual maximum flood peaks over 1950-2005 on the San Pedro were from summer convective storms, the magnitudes of floods generated from frontal and tropical storms have generally exceeded the magnitude of summer convective floods since 1965.

Climatic change may interact with, or accentuate these large-scale drivers of precipitation patterns. For instance, there is some evidence that warming of Pacific sea surface temperatures could lead to more frequent or enhanced El Niño dynamics, which could in turn lead to increased frequency and magnitude of Pacific frontal precipitation and winter floods (Garfin and Lenart 2007). Global warming may intensify the hydrologic cycle, leading to an increase in extreme storms and intense rainfall events (IPCC 2007). Conceivably, climatic change could lead to increased aridity and an overall decline in precipitation and in the frequency of small to moderate floods, but produce an increased frequency of extreme flood events. Such changes could increase the potential for episodic large runoff events that lead to channel avulsion or extreme incision and widening, as occurred on rivers across the region in the late 19th and early 20th centuries as part of the "arroyo" phenomenon (Turner et al. 2003, Hereford and Betancourt 2009).

The potential effects of climatic change on groundwater recharge and base flow have only recently received attention. Using a three dimensional groundwater model, Serrat-Capdevila et al. (2007) examined projections from a suite of 17 climate change models and four climate change scenarios on groundwater recharge for 2000-2100. Their results suggest that climatic change is likely to result in lower basin recharge, resulting in lower base flows or more frequent seasonal loss of surface flow. These results may even apply to scenarios with modest increases in precipitation, as increases in evapotranspiration (ET) from higher temperatures may exceed precipitation increases, leading to declines in recharge. Although not examined specifically in their paper, the seasonality of precipitation and temperature changes would likely have a strong influence on whether recharge would increase, decrease, or remain unchanged with future climatic change. Increases in winter precipitation, in particular, have the greatest potential to increase recharge due to lower winter time ET rates, although increases in winter temperature and concurrent increases in ET may decrease recharge (Ajami et al. submitted).

Influences of Hydrology on Riparian Ecosystem

Floods

Summer floods, typically generated by intense convective storms during the “monsoon” season, stimulate primary production on the San Pedro, including growth by perennial plants and reproduction and growth of annuals (Stromberg et al. 2009a). These floods may also be important for dispersing and scarifying seeds (e.g., for mesquite), transporting sediment and driving channel dynamics, stimulating decomposition of organic material in the floodplain, and temporarily recharging floodplain aquifers, which may help sustain base flows during and following the summer monsoon season (Baillie et al. 2007).

Winter and spring floods are particularly important for recruitment of dominant riparian tree species. Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) are dominant native tree species that occur along perennially flowing rivers in the southwestern United States. Tamarisk or salt cedar (*Tamarix ramosissima*) is a Eurasian tree-shrub species that has become naturalized on many rivers in the region. All three are “pioneer” species that rarely recruit within established stands and require floods to scour or deposit open mineral substrates for seedling recruitment. Seed dispersal by *Populus* and *Salix* is concentrated during the spring and early summer, putting it out of phase with summer monsoonal floods (Stromberg et al. 1991). Optimal conditions for recruitment occur following moderate to large winter or spring floods that drive geomorphic dynamics and form bare, moist sediment surfaces. Subsequent slowly receding flows moisten sediment surfaces, deposit water borne seeds, and then sustain early seedling growth and survival by maintaining elevated base flows or groundwater levels (Mahoney and Rood 1998, Shafroth et al. 1998). Conditions for large-scale *Populus* and *Salix* recruitment are episodic and are associated with large, relatively long duration floods generated from fall and winter frontal precipitation or from very large fall storms generated by dissipating tropical storms (Stromberg 1998, Stromberg et al. 2010). While also associated historically with winter floods on the San Pedro, recruitment by *Tamarix* may be better able to respond to floods later in the season than the native species, given its extended period of seed dispersal and greater tolerance of dry conditions (Stromberg 1997, Beauchamp and Stromberg 2007). Under perennial flow conditions with shallow groundwater, *Populus* and *Salix* seedlings outcompete *Tamarix* seedlings (Sher and Marshall 2003), although the converse may be true under drier conditions.

Groundwater and Base Flows

Spatial and temporal variability in groundwater levels and stream flows strongly influence vegetation composition and structure. Alluvial groundwater depth and its dynamics influence the distribution, condition, and composition of woody phreatophytes (plants that use groundwater) in the floodplain, while the duration of base flow (or conversely, of dry conditions) directly influences herbaceous vegetation composition and productivity along the low-flow channel (Stromberg et al. 2007). Obligate phreatophytic tree species (e.g., *Populus* and *Salix*) require nearly constant access to saturated soils just above the water table in order to survive in arid environments. Facultative phreatophytes, such as *Tamarix* and *Prosopis*, use groundwater, but also can access other water sources (e.g., unsaturated soil moisture) and tolerate periods where groundwater is unavailable. Lite and Stromberg (2005) defined hydrologic thresholds under which dominance shifted from *Populus* to *Tamarix* along the San Pedro. *Populus* dominated at sites with maximum groundwater depths shallower than 2.6 m, annual fluctuations of less than 0.5 m in monthly groundwater levels, and surface flows present 76% of the year or greater; with *Tamarix* dominant on sites with deeper, more highly fluctuating groundwater and a lower frequency of base flow.

A range of hydrologic conditions occurs longitudinally along the San Pedro, with reaches with perennial flow and stable, shallow groundwater interspersed with reaches with intermittent flow and more variable groundwater. An assessment model has been developed that classifies riparian condition at the site or reach scale based on a suite of bio-indicators (Stromberg et al. 2006) or hydrologic thresholds (Brand et al. in press). The model describes three riparian condition classes for the San Pedro, with a suite of accompanying vegetation and hydrologic conditions. Condition class 3 (wet) reaches have perennial stream flow and shallow, relatively stable groundwater that supports tall riparian forests and woodlands dominated by hydric pioneer species (*Populus fremontii* and *Salix gooddingii*), along with high cover of herbaceous wetland plants along the stream. Condition class 2 (intermediate) reaches have seasonally intermittent stream flow (e.g., may be dry in April-June), more highly fluctuating groundwater levels, and a mix of cottonwood/willow riparian woodland and tamarisk shrubland, with lower cover of wetland herbaceous species along the channel. Condition class 1 (dry) reaches have highly intermittent stream flow, deeper, more variable alluvial groundwater levels, and riparian vegetation dominated by tamarisk shrubland, with herbaceous wetland plants absent except after large winter or spring floods that temporarily sustain base flow during the April-June dry season (Bagstad et al. 2005).

Boundaries of these condition classes, or of reaches characterized by specific hydrologic conditions, may change between years due to variation in climate and management. Currently, 40% of the upper San Pedro within the SPRNCA is in condition class 1 (wet), 55% in condition class 2 (intermediate), and 6% in condition class 1 (dry) (Stromberg et al. 2006). Many perennial (condition class 3) reaches are defined by shallow bedrock that forces groundwater to the surface. Adjacent downstream reaches may also be perennial because of the influence of this net input of groundwater to base flow. Such "gaining" reaches are characterized by a higher proportion of surface flow supported by regional groundwater sources (Baillie et al. 2007). Other, typically "losing" (influent) reaches may vary between perennial and intermittent depending on climatic conditions of that or the previous year and are more dependent on flood-driven alluvial recharge processes. In many cases, reaches in condition class 2 (intermediate) have intermittent flow because surface flow ceases during the spring (April-June) dry season. Following years with large or frequent fall, winter, or spring floods, however, surface flow may be sustained through the spring dry season, resulting in perennial flow through the entire year. Water from these large floods is temporarily stored via recharge of the alluvial aquifer, and then progressively released as base flow. Years with enhanced base flow can result in increased productivity of herbaceous wetland plants along the channel (Bagstad et al. 2005) and may facilitate episodic recruitment by riparian woody vegetation.

The sensitivity of these sites and the river as a whole to climatic variability depends on subsurface geology (e.g., depth to bedrock), the local history of groundwater pumping, flood-driven alluvial recharge, and the degree to which the alluvial water table is linked to regional groundwater flow. Groundwater pumping may induce somewhat drier river conditions that impact riparian vegetation. In turn, the relatively drier groundwater conditions induce increased flood-driven recharge of the near stream-alluvial aquifer. In this way, past and continued groundwater pumping may make the river itself more susceptible to changes in climate that affect flood frequency, seasonality, and magnitude. Over the length of the river, vegetation response will vary spatially depending on a site's history of groundwater pumping as well as on geologically-controlled rates of groundwater discharge; stream reaches that are presently approaching critical hydro-biotic thresholds will be the most sensitive to climate-linked changes in stream hydrology. These thresholds are, in part, a function of how much the groundwater that supports base flow is from slow regional sources vs. storm flow supported recharge of the alluvial aquifer (Baillie et al. 2007). Reaches that are more dependent on flood-driven recharge are generally those classified as dry and intermediate condition classes (classes 1 and 2). Thus, the reaches most likely to experience change are those that currently lose surface flow conditions for at least part of the year. Relatively small declines in average groundwater depth (e.g., 0.5 m) would convert most intermediate (class 2) reaches to the dry condition (class 1), with accompanying cascading influences on the riparian ecosystem (Stromberg et al. 2009b, Brand et al. in press).

Biotic Feedbacks

While influenced by both floods and groundwater dynamics, riparian vegetation also exerts important feedbacks on these processes, and on entire system response, via transpiration and effects on bank stability and channel dynamics. Woody phreatophytic species, both native and non-native, are important components of the hydrologic budget on the San Pedro, with demonstrable effects on daily and seasonal alluvial groundwater levels and stream base flow (Leenhouts et al. 2006). A three-fold increase in the area of woody phreatophytes (e.g., *Populus*, *Prosopis*) along the river over the last 55 years (Stromberg et al. 2010) may be a contributing factor to historic declines in base flows (Thomas and Pool 2006), although the relative effects of climate, groundwater pumping, and water use by vegetation are difficult to disentangle. Current estimates suggest that transpiration by woody riparian vegetation may comprise half of the total groundwater usage in the Sierra Vista subbasin (Stromberg et al. 2009b), with perhaps 60% of groundwater use by vegetation along the upper San Pedro attributable to transpiration by riparian mesquite (*Prosopis velutina*) woodlands (Leenhouts et al. 2006). Current vegetation management within the SPRNCA includes clearing and prescribed burns to reduce cover of mesquite, and is in part aimed to reduce total groundwater use by the riparian ecosystem (Stromberg et al. 2009b).

Conclusions

Globally, water resource management decisions will greatly influence the sensitivity of riparian ecosystems to climatic change, affecting the ability of these systems to maintain biological diversity and provide other services of value to humans (Palmer et al. 2008). On the San Pedro, the future condition of the riparian ecosystem will be influenced by climatic change (Dixon et al. 2009, Stromberg et al. in press), by water resource decisions, and by the interaction between the two. A generally more arid future climate and unsustainable groundwater pumping could lead to significant changes in hydrology and riparian vegetation, with reductions in the length of perennial stream flow and declines in the area of forests of *Populus* and *Salix* (Serrat-Capdevila et al. 2007, Brand et al. in press). Given the dependence of many bird species on tall-canopied riparian forests with perennial stream flow, such changes could lead to significant declines in biodiversity and ecosystem services along the upper San Pedro (Brookshire et al. 2010, Brand et al. in press). Future changes in the frequency, duration and intensity of winter rainfall, which are uncertain under climate change projections, could also have important influences on the riparian ecosystem. If climatic change leads to an enhanced El Niño dynamic, then the frequency of large fall-winter floods could increase, partially ameliorating the effects of higher temperatures and increased aridity during the growing season, and driving patch dynamics of disturbance dependent tree species (Dixon et al. 2009). Changes in flood regime may be particularly important for affecting near stream alluvial recharge that helps sustain perennial flow in the river. Reaches in which regional groundwater inputs are minimal, and that have seasonally intermittent stream flow that is supported by flood-driven recharge of the alluvial aquifer, will be particularly sensitive to the effects of climate change on the seasonality, duration, magnitude, and frequency of flooding.

References

Ajami, H., T. Meixner, F. Dominguez, J. Hogan, T. Maddock III. Submitted. Seasonalizing mountain system recharge in semi-arid catchments: Implications for climate change impacts. *Water Resources Research*.

Arnell, N. W. 2003. Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. *Hydrology and Earth Systems Sciences* 7: 619-641.

Baillie, M. N., J. F. Hogan, B. Ekwurzel, A. K. Wahi, and C. J. Eastoe. 2007. Quantifying water sources to a semiarid riparian ecosystem, San Pedro River, Arizona using geochemical tracers. *Journal of Geophysical Research – Biogeosciences*. 112 G03S02.

Bagstad, K. J., J. C. Stromberg, and S. J. Lite. 2005. Response of herbaceous riparian plants to rain and flooding on the San Pedro River, Arizona, USA. *Wetlands* 25(1): 210-223.

Beauchamp, V. B. and J. C. Stromberg. 2007. Flow regulation of the Verde River, Arizona encourages Tamarix recruitment but has minimal effect on Populus and Salix stand density. *Wetlands* 27(2): 381-389.

Brand, L. A., J. C. Stromberg, D. C. Goodrich, M. D. Dixon, K. Lansey, D. Kang, D. S. Brookshire, and D. J. Cerasale. In press. Projecting avian responses to linked changes in groundwater and riparian floodplain vegetation along a dryland river: a scenario analysis. *Ecohydrology*.

Brookshire, D. S., D. Goodrich, M. D. Dixon, L. A. Brand, K. Benedict, K. Lansey, J. Thacher, C. D. Broadbent, S. Stewart, M. McIntosh, and D. Kang. 2010. Ecosystem services and reallocation choices: a framework for preserving semi-arid regions in the Southwest. *Journal of Contemporary Water Research and Education* 144: 60-74.

Dixon, M. D., J. C. Stromberg, J. T. Price, H. Galbraith, A. K. Fremier, and E. W. Larsen. 2009. Potential effects of climate change on the upper San Pedro riparian ecosystem. In *Ecology and*

Conservation of the San Pedro River, 57-72. Tucson, Arizona, USA: The University of Arizona Press.

Garfin, G. and M. Lenart. 2007. Climate change. Effects of Southwest water resources. *Southwest Hydrology*, January/February 2007: 16-17, 34.

Goodrich, D. C., Chehbouni, A., Goff, B., et al., 2000. Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) program special issue. *J. Agricultural and Forest Meteorology* 105(1-3): 3-20.

Huckleberry, G. A. 1994. Contrasting channel response to flooding on the middle Gila River, Arizona. *Geology* 22: 1083-1086.

Hereford, R. and J. L. Betancourt. 2009. Historical geomorphology of the San Pedro River: archival and physical evidence. In *Ecology and Conservation of the San Pedro River*, 232-250. Tucson, Arizona, USA: The University of Arizona Press.

Hirschboeck, K. K. 2009. Flood flows of the San Pedro River. In *Ecology and Conservation of the San Pedro River*, 300-312. Tucson, Arizona, USA: The University of Arizona Press.

IPCC. 2007. Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK.

Leenhouts, J. M., J. C. Stromberg, and R. L. Scott. 2006. *Hydrologic requirements of and consumptive ground-water use by riparian vegetation along the San Pedro River, Arizona*. USGS Scientific Investigations Report 2005-5163.

Lite, S. J. and J. C. Stromberg. 2005. Surface water and groundwater thresholds for maintaining Populus-Salix forests, San Pedro River, Arizona. *Biological Conservation* 125: 153-167.

Mac Nish, R., K. J. Baird, and T. Maddock III. 2009. Groundwater hydrology of the San Pedro River basin. In *Ecology and Conservation of the San Pedro River*, 285-299. Tucson, Arizona, USA: The University of Arizona Press.

Mahoney, J. M. and S. B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment - an integrative model. *Wetlands* 18: 634-645.

McCabe, G., J. L. Betancourt, H. G. Hidalgo. 2007. Associations of decadal to multidecadal sea-surface temperature variability with Upper Colorado River flow. *Journal of the American Water Resources Association* 43(1): 183–192.

McCabe, G. J., J. L. Betancourt, S. T. Gray, M. A. Palecki, H. G.,Hidalgo. 2008. Associations of multi-decadal sea-surface temperature variability with U.S. drought. *Quaternary International* 188: 31-40.

Palmer, M. A., C. A. R. Liermann, C. Nilsson, M. Florke, J. Alcamo, P. S. Lake, and N. Bond. 2008. Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment* 6(2): 81-89.

Pool, D. R. 2005. Variations in climate and ephemeral channel recharge in southeastern Arizona, United States. *Water Resources Research* 41 W11403.

Pool, D., and A. Coes. 1999. *Hydrogeologic Investigations of the Sierra Vista Subwatershed of the Upper San Pedro Basin, Cochise County, Southeast Arizona*. Water-Resources Investigations Report 99-4197.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of a more arid climate in southwestern North America. *Science* 316: 1181-1184.

Serrat-Capdevila, A., J. B. Valdes, J. Gonzales Perez, K. Baird, L. J. Mata, and T. Maddock III. 2007. Modeling climate change impacts – and uncertainty – on the hydrology of a riparian system: The San Pedro Basin (Arizona/Sonora). *Journal of Hydrology* 347: 48-66.

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: 577-590.

Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21: 219-238.

Sher, A. A. and D. L. Marshall. 2003. Seedling competition between native *Populus deltoides* (Salicaceae) and exotic *Tamarix ramosissima* (Tamaricaceae) across water regimes and substrate types. *American Journal of Botany* 90: 413-422.

SRAG (Southwest Regional Assessment Group). 2000. *Preparing for a changing climate: the potential consequences of climate variability and change.* http://www.ispe.arizona.edu/research/swassess/pdf/complete.pdf. Accessed August 2006.

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. 1998. Dynamics of Fremont cottonwood (*Populus fremontii*) and saltcedar (*Tamarix chinensis*) populations along the San Pedro River, *Arizona. Journal of Arid Environments* 40: 133-155.

Stromberg J. C. and B. Tellman (editors). 2009a. *Ecology and Conservation of the San Pedro River*. Tucson, Arizona, USA: The University of Arizona Press.

Stromberg, J. C. and B. Tellman. 2009b. Introduction. In *Ecology and Conservation of the San Pedro River*, 1-10. Tucson, Arizona, USA: The University of Arizona Press.

Stromberg, J. C., D. T. Patten, and B. D. Richter. 1991. Flood flows and dynamics of Sonoran riparian forests. Rivers 2(3): 221-235.

Stromberg, J. C., R. Tiller, and B. Richter. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro River, Arizona, USA. *Ecological Applications* 6: 113-131.

Stromberg, J. C., S. J. Lite, T. J. Rychener, L. R. Levick, M. D. Dixon, and J. M. Watts. 2006. Status of the riparian ecosystem in the upper San Pedro River, Arizona: application of an assessment model. *Environmental Monitoring and Assessment* 115: 145-173.

Stromberg, J. C., V. B. Beauchamp, M. D. Dixon, S. J. Lite, and C. Paradzick. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid southwestern United States. *Freshwater Biology* 52: 651-679.

Stromberg, J. C., S. J. Lite, M. D. Dixon, and R. L. Tiller. 2009a. Riparian vegetation. In *Ecology and Conservation of the San Pedro River*, 13-36. Tucson, Arizona, USA: The University of Arizona Press.

Stromberg, J. C., M. D. Dixon, R. L. Scott, T. Maddock III, K. J. Baird, and B. Tellman. 2009b. Status of the upper San Pedro River (USA) riparian ecosystem. In *Ecology and Conservation of the San Pedro River*, 371-387. Tucson, Arizona, USA: The University of Arizona Press.

Stromberg, J. C., M. G. F. Tluczek, A. F. Hazelton, and H. Ajami. 2010. A century of riparian forest expansion following extreme disturbance: Spatio-temporal change in Populus/Salix/Tamarix forests along the Upper San Pedro River, Arizona, USA. *Forest Ecology and Management* 259(6): 1181-1189.

Stromberg, J. C., S. J. Lite, and M. D. Dixon. In press. Effects of stream flow patterns on riparian vegetation of a semiarid river: Implications for a changing climate. *River Research and Applications*

Thomas, B. E. and D. R. Pool. 2006. *Trends in streamflow of the San Pedro River, southeastern Arizona, and regional trends in precipitation and streamflow in southeastern Arizona and southwestern New Mexico*. USGS Professional Paper 1712.

Turner, R. M., R. H. Webb, J. E. Bowers, and J. R. Hastings. 2003. *The Changing Mile Revisited.* Tucson, Arizona, USA: The University of Arizona Press.

Webb, R. H., and J. L. Betancourt. 1992. *Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona*. USGS Water-Supply Paper 2379, 40 p.

Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears. 2007. How much more rain will global warming bring? *Science* 317: 233-235.