# Chapter 1. Development of the Science of Riparian Ecology in the Semi-Arid Western United States

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## Introduction

The science of riparian ecology in the West developed over several decades, especially in the Southwest and California, as the importance of this ecosystem, its components, productivity, functions, and relationship to system hydrology became better understood. While it seems incredible today, it was only 50 years ago that streamside vegetation in the arid Southwest and portions of California were the subject of much concern as most flood control and water agencies wanted the permanent removal of riparian habitat. The early research within riparian habitats in the 1950s and 1960s focused primarily on methods of removal and reasons for its destruction (Gatewood et al. 1950; Fox 1977; Horton et al. 1964; Robinson 1952). Most studies of western rivers in the 1960s addressed the "fact" that riparian vegetation, referred to mostly as phreatophytes (i.e., plants tapping groundwater), was utilizing a large portion of the shallow groundwater moving through watersheds. At that time, most water managers believed that this water could be better allocated to human activities and needs, primarily agricultural, municipal, and industrial uses. In the semi-arid West, water lost to evapotranspiration by watersheds and phreatophytic plants was considered to be water unavailable for human use, and thus "wasted." Consequently, several studies beginning in the early 1950s were designed to demonstrate water consumption by watersheds (Gottfried et al. 1999) as well as riparian/phreatophytic plant communities with little or no concern or focus for other values such as the unique riparian habitat (Decker et al. 1962; Robinson 1952). In fact, at the time, a U.S. Department of Agriculture scientist and leading water expert wrote: "Phreatophyte vegetation seriously affects water supplies in arid and semi-arid regions. Knowledge of the extent and nature of the vegetation cover is needed as a basis for planning treatments of the vegetation and estimating the potential water savings and other effects" (Horton et al. 1964: 34).

The Horton et al. 1964 paper was typical of phreatophyte-focused papers and reports of the time. During these early days, most riparian research focused on water use by individual plants, while other research projects attempted to determine water saving through modification of large tracts of land by removing riparian vegetation. Some of these habitat modification projects began as early as 1950 when woody riparian plants in general (native and nonnative) were targeted for removal (Gatewood et al. 1950) and continued well into the 1960s when the focus had mostly shifted to removing the exotic or invasive shrub/tree tamarisk (saltcedar; *Tamarix* spp.) (Chew 2013; Culler et al. 1982). Anticipated results of these studies prompted governmental and private agencies to invest significant financial resources in attempting to reduce or rid drainage ways of riparian vegetation. Studies of water use by riparian plant communities, especially non-native communities, continued from the 1950s and 1960s into the 1980s and 1990s (e.g., Sala et al. 1996; Smith et al. 1998). The practice of removing phreatophytes, especially large tracts of tamarisk, continues to today. Indeed, controversy over the relative costs/values of tamarisk vs. native riparian species is greatly debated today. For example, efforts to control tamarisk by introducing several species of beetle (*Diorhabda* spp.) from Asia continue to remind us that threats to riparian ecosystems still persist (see below and chapters 4 and 5).

During the late 1960s in Arizona, phreatophyte issues were mostly focused on native streamside vegetation. At that time, the Salt River Project and Army Corps of Engineers either removed or planned removal of extensive stands of cottonwoods (*Populus fremontii*) and other riparian plants along watercourses, including the Verde and Gila Rivers, in Arizona, to "salvage" water and "enhance" river flow. The Verde project resulted not only in loss of terrestrial wildlife habitat but also aquatic impacts including "siltation of the river gravels and spawning beds" (Tellman et al. 1997). Under pressure from avian experts (see below) and in consideration of alteration of spawning gravels, the practice, at least within native stands of riparian habitat, was "found to have little long-term impact on water supplies downstream, so it was discontinued after more than a decade of effort" (Tellman et al. 1997). However, as detailed below, efforts at *Tamarix* removal have persisted into the early 21st century.

U.S. Department of Agriculture scientists were joined by scientists from other agencies in developing comprehensive literature on water salvage. From 1958 (Robinson 1958) into the 2000s, and even as early as 1927 (Meinzer 1927), the U.S. Geological Survey (USGS) issued a series of Professional Papers that addressed both surface water and groundwater issues (e.g., Culler et al. 1982). In addition, USGS issued numerous publications as Water Supply Papers suggesting, as the title implies, that the importance of water was primarily viewed in the context of human usage. Earlier in that era Horton compiled and abstracted 691 publications on the general subject of phreatophyte control (Horton 1973). In general, the publications Horton cited assigned little to no value to the ecological importance of streamside vegetation. As Water Supply project results accumulated, however, it became increasingly clear that the projected water savings from most phreatophyte control projects were ephemeral to non-existent (Barz et al. 2009; Graf et al. 1984).

In the early 1970s, the scientific community was awakening to the ecological uniqueness and high biotic productivity of streamside habitats (see Appendix A for early riparian scientists), and it was after several of these ecological studies, primarily on birds, that the disproportionate productivity of riparian habitats compared to upland habitats was being documented (Carothers et al. 1974; Hubbard 1971, 1977a,b; Hynes 1975; Johnson 1971; Johnson et al. 1977, 1987; Wauer 1977; Zimmerman 1970). In addition, between the late 1960s and early 1980s, a series of events occurred that ushered out the era of phreatophyte control targeted on native riparian species and initiated the establishment of the science of riparian ecology and the riparian habitat conservation movement. Academic and management conferences in Arizona, California, and Colorado were held documenting the importance of the relationship of the riparian ecosystems to the natural riverine community (see Appendix B for a list of conferences).

One of the early studies, a 5-year riparian breeding bird study, documented the highest population densities of nesting birds ever recorded in any habitat in North America (Carothers and Johnson 1970; Carothers et al. 1974). The study was initially funded by the Forest Service, U.S. Department of Agriculture and later by the Arizona Game and Fish Department in direct response to the request by the Salt River Project in Phoenix, Arizona, to the Forest Service to remove the cottonwood and willow habitat on public land along the Verde River in central Arizona. One of the more pragmatic results of this study was that the ecological damage of indiscriminate phreatophyte control was exposed, and the practice, especially with native riparian habitats, began to decline significantly. During this same time, the series of riparian conferences continued to highlight and strengthen the data on the importance of the riparian corridor and its significance to wildlife and general riverine ecology.

## The River Continuum Concept and Riparian Habitat Values Recognized

The recognition of both high species diversity and high density of obligate wildlife and plant species within riparian ecosystems was coincident with the introduction of another important ecological concept, the River Continuum Concept (RCC) (Vannote et al. 1980). The RCC emphasized the interrelatedness of riparian and aquatic riverine ecosystems. In addition, it recognized and fully valued the synergism of the interdependency of biological and physical interactions in a river system, both longitudinally and laterally, which included the stream side community. Before then, riverine studies tended to focus on individual elements of aquatic systems, e.g., fisheries or limnology, or else components of riparian system, e.g., birds, mammals and plants. Other important riparian-related activities during the 1980s included classification of riparian plant communities (e. g., Brown 1982; Szaro 1989), a systematic evaluation of the state of riparian ecology, and an assessment of needs for further, especially quantified, information about riparian ecosystems (Johnson et al. 1985; Knopf et al. 1988).

About this time, some investigators began to recognize the value of the invasive *Tamarix* as functional wildlife habitat and considered hundreds of miles of streamside habitats on some rivers dominated by *Tamarix* as productive and “naturalized” components of riparian ecosystems (Johnson 1977; Johnson and Carothers 1982, 1987; see also Chew 2009, 2013). Studies thereafter and into the 1990s focused on the need for maintaining a natural hydrograph for the recruitment of native vegetation and proper functioning of the riverine system (e.g., Junk et al. 1989; Poff et al. 1997). Finally, in the late 1990s and continuing to the present, widespread concern developed for the protection of existing native riparian habitats as well as restoration of previously degraded habitats where possible (Rieger et al. 2014; Zeedyk and Clothier 2012).

Development of riparian ecology and the riparian environmental movement were mostly western undertakings with much of the research located in West Coast States of California, Oregon, and Washington, and semi-arid States of Utah, Nevada, Arizona, New Mexico, and Texas. Other studies were going on in Colorado and the northern Rockies as well. Johnson and Lowe (1985) described development of riparian ecology in the Southwest, attributing its late appearance to a lack of interest in the transition zone from water to upland as well as “the complexity of riparian ecosystems [forming] the ecotone [and] a textbook example of the edge effect.” The term riparian was found mostly in “western” publications while terms such as “bottomland hardwoods,” “floodplain forests,” and similar terms were used mostly in the East. The U.S. Fish and Wildlife Service (USFWS) “wetlands manual,” written by three eastern and one midwestern scientists, did not even use the term “riparian” (Cowardin et al. 1979). A search of the Library of Congress catalog by a committee of the National Research Council of the National Academy of Science (NRC 2002) using the term “riparian” disclosed an increasing number of entries from 1960 to 1990, mostly from western United States. A search using Google Scholar for the first 20 riparian publications also showed, for the United States, very few when the terms “riparian” and “eastern U.S.” were used together.

## Anthropogenic Changes to Western Rivers

By the 1960s, both surface water and groundwater resources in the vicinity of large metropolitan and high-intensity agricultural areas had been severely impacted by human activity. Instream flow levels in stream reaches above ground, as well as levels of water tables below ground, had been greatly reduced throughout much of the region (Zektser et al. 2005). Large rivers in which flow levels were measurably reduced or modified by large dams, diversions for urban and agricultural use, and other water projects included most lower reaches and tributaries of the Colorado, Gila, Salt, and Verde Rivers in Arizona; Rio Grande and Pecos Rivers in New Mexico and western Texas; and Sacramento, San Joaquin, and Owens Rivers in California. In most of these river systems the natural hydrograph had been irrevocably modified in all but relatively short reaches of their headwaters.

In addition to large dams and water diversion projects, many smaller dams along major tributaries further reduced normal flows interrupting the natural hydrograph along thousands of miles of rivers, drowning riparian habitat in reservoirs above dams and desiccating downstream riparian ecosystems through dewatering. Even rivers in lands set aside as “natural areas,” such as Big Bend and Grand Canyon National Parks, have been impacted by large dams, upstream and downstream of the Park’s boundaries, such as Glen Canyon Dam and Hoover Dam on the Colorado River in Arizona (Carothers and Brown 1991; Johnson 1991; Johnson and Carothers 1987;) and Elephant Butte, Caballo, and Amistad Dams on the Rio Grande in New Mexico and Texas (Chew 2006, 2013; Wikipedia 2016).

Rivers such as the Santa Cruz, Rillito, and Gila Rivers in southern Arizona were perennial streams at time of settlement by Euro-Americans but had been largely reduced to intermittent or ephemeral streams by excessive groundwater and irrigation withdrawals by the mid-1950s (Webb and Leake 2006; Webb et al. 2014). Indeed, by the first few decades of the 20th century it was the rare western river system where any semblance of the natural hydrograph was preserved for any distance below its headwaters. The exception to this is the Yellowstone River, which is the longest undammed, naturally flowing river in the West although 2016 plans for a dam on its lower reaches may change this.

## Early Ecological Studies

By the early- and mid-1970s, numerous ecological studies, especially on birds, were underway along rivers of the Southwest and California (Carothers and Johnson 1975; Carothers et al. 1974; Gaines 1974, 1980; Gavin and Sowls 1975; Hubbard

1971, 1977a,b; Johnson and Simpson 1971; Ohmart and Anderson 1977; Wauer 1977; Zimmerman 1970). We found only one much earlier study comparable to these studies conducted in 1949 along Dry Creek in the San Joaquin Valley, California (Ingles 1950). In addition to data on avian population densities and species richness, most of the early studies also contained information on vegetation associated with birds.

The studies conducted throughout the Southwest and California in the 1970s were undertaken, in part, due to increasing losses of riparian and related riverine habitat, losses that had started with the settlement of the West by Euro-Americans (Carothers 1977; Dobyns 1981; Knopf et al. 1988). Conservation and loss of these ecosystems were not of much general environmental concern until the 1970s and 1980s when several riparian conferences addressed these issues. To counter loss or removal of riparian plant communities, studies were designed to demonstrate that these communities were, in reality, complex ecosystems supporting a broad range of other species. Some of these studies were cooperative ventures among several individuals and agencies.

For example, the project to demonstrate the avian impacts of cutting down cottonwood trees along the Verde River was a joint effort of the Forest Service, U.S. Department of Agriculture, Arizona Game and Fish Department, U.S. Fish and Wildlife Service, Museum of Northern Arizona, and Prescott College. These earliest avian studies were of great scientific interest, demonstrating the critical habitat characteristics of the riparian plant community. Simultaneously, studies of riparian forests in the Gila River Valley of New Mexico documented the remarkable density and diversity of riparian birds (Hubbard 1971, 1977a,b; Zimmerman 1970). Shortly thereafter similar information was developed for the birds of the lower Rio Grande (Wauer 1977) and in the Lower Colorado River Valley (Anderson and Ohmart 1977; Rosenberg et al. 1991).

To our knowledge, the aforementioned studies provide the earliest quantified documentation of the importance of riparian vegetation as avian habitat in the Southwest. This also triggered a demand to better understand the importance of riparian ecosystems not only as habitat for birds and other wildlife and invertebrates (e.g., Patton 1977), but also as an ecological system that offers other important functions and services, including water quality, flood control, groundwater recharge, nutrient cycling, seed dispersal, migratory corridors, and recreation.

Even today, studies focused on other riparian vertebrates, i.e., amphibians, reptiles, and mammals, as well as invertebrates, have not received the same amount of attention as birds. Birds are generally more visible and more easily studied than other vertebrates because they are mostly diurnal, arboreal, and call attention through song. To determine factors such as species richness and population densities of the other three vertebrate groups, trapping and other special equipment and techniques are generally required. We have shown that riparian avian studies were widespread in the West by the mid to late 1970s. However, a 1988 publication by the Forest Service (Szaro et al. 1988) entitled Management of Amphibians, Reptiles and Small Mammals in North America, containing 54 papers, had only one paper on riparian amphibians and reptiles and three on riparian mammals. Not surprisingly, only one of these papers compares species richness in upland habitat types to riparian types in Arizona, finding much higher species diversity of amphibians and reptiles in riparian habitat compared to upland habitat (Jones 1988).

## Focus on Riparian Habitats

During the 1970s and continuing through the 1990s, with increasing interest in riparian systems, mapping and classification of vegetation in the Southwest became the focus of some researchers (Brown 1982; Lowe and Brown 1973). Different riparian communities were recognized based on elevation differences with lower elevation communities along river systems ranging from ephemeral to perennial, while higher elevation riparian systems where available water was more certain tended to include a mix of riverine and upland species (Szaro 1990). Lowe (1961, 1964) illustrated these communities in his "The Vertebrates of Arizona", and more recently, Patten (1998) recognized the importance of the interaction of elevation and water availability gradients. Brown et al. (1977) published a drainage map for Arizona and in 1993–1994 the Arizona Game and Fish Department developed a dataset that identified and mapped riparian vegetation associated with perennial waters in response to the requirements of the 1992 Riparian Area Act (this act amended Arizona Revised Statute CARS 45-101; Kubly et al. 1997). Maps were created using two major sources of imagery: Landsat Thematic Mapper digital satellite data and Multiple Resolution Aerial Videography. The data were created to serve as base information for use in GIS systems for a variety of planning and analysis purposes. These data also demonstrated how much perennial vegetation had been lost along streams and rivers since the early 1900s, with nearly all losses associated with dams, groundwater pumping, agricultural clearing, and phreatophyte control.

Other impacts of human land use such as ranching (i.e., livestock grazing) and other forms of agriculture, especially when linked to irrigation, also were documented as causing major changes and loss of riparian areas (Belsky et al. 1999; Ohmart 1996). William Platts was a pioneer in many studies of livestock impacts on riparian systems (Platts 1979, 1981). Also, many of his studies dealt with grazing effects on fisheries and thus indirectly on riparian systems (Platts 1981). Platts' articles, although not all necessarily from the Southwest, greatly influenced thinking about impacts of grazing in the Southwest as did articles by Wayne Elmore who headed Bureau of Land Management's riparian program for many years (e.g., Elmore 1992; Elmore and Beschta 1987). In the late 1960s, the USFS Southwest Region realized that many riparian forests did not include multiple age classes but only mature trees. This apparent lack of recruitment led to greater control of grazing along rivers and reduction of removal of riparian plant communities.

From the 1970s well into the 21st century, riparian research continued to expand from descriptive studies of riparian plant and animal communities, to ecophysiological studies, to ecosystem studies, with emergence of new journals such as Ecohydrology in 2008. Many of these studies addressed functional relationships, such as between environmental drivers, e.g., water table and streamflow changes and vegetation response (Busch et al. 1992; Fenner et al. 1985; Shafroth et al. 1998, 2000; Stromberg et al. 2005, 2010), or canopy changes including avian community responses (e.g., Anderson and Ohmart 1977; Anderson et al. 1983; Johnson and Haight 1985; Stromberg et al. 1993). As riparian communities declined or were altered, ecologists attempted to explain those factors that were causing this decline, many being associated with water management (Busch and Smith 1995). As more water was removed from rivers of the West, studies were developed to demonstrate the range of instream flow requirements of riparian ecosystems (Arthington et al. 2006; Shafroth et al. 2010). These eventually were called environmental flows as they were flows that supported all components of the riverine system and often mimicked natural flow requirements, flows necessary for a healthy riverine system (Poff et al. 1997; Poff and Zimmerman 2010).

Riparian research in semi-arid regions during the 1980s and into the 1990s and later was being conducted not only in the Southwest but also along the eastern Sierras of California. Unlike the more mesic west slopes of the Sierras, the eastern slopes support riparian ecosystems similar to those along rivers in the Southwest. Most of the research in this region related to water relations of the riparian system, or components of it, since many of the eastern Sierra streams were being controlled and/or diverted to move water into the Los Angeles aqueduct or for hydropower production. Examples of this research included studies by Stromberg and Patten (1990, 1992) and Smith et al. (1991). Also, in the late 1970s and 1980s, a group of students from California studied the flows into and dropping levels of Mono Lake, a closed basin lake in the eastern Sierra. This group, led by David Gaines (1974), an environmental activist and ornithologist, helped form the Mono Lake Committee which today works toward protection of the lake. In 1987 a committee of the National Research Council/National Academy of Sciences studied dropping lake levels of Mono Lake, its causes, reduced stream inflows, and consequences (NRC 1987).

## Hydrology, Instream Flows, and the Natural Hydrograph

Further concern for appropriate flows for riparian and riverine processes was based on, and stimulated research on, the hydrological processes that triggered responses of the riparian ecosystem. Flooding was shown to be an essential disturbance process for the long-term maintenance of riparian systems because most characteristic riparian woody species were successional species recruited during and after flood (Brady et al. 1985; Stromberg 2001). For example, the importance of uncontrolled flood flows and their timing and magnitude was found to be critical to establishment and maintenance of riparian systems (Brown et al. 1977). The “recruitment box” model developed by Mahoney and Rood (1998) documented how these processes interacted to enhance seedling establishment of riparian plant species. Other disturbance processes that were found to be important to riparian dynamics included fire that results in a change in population size structure with more mature cottonwoods, smaller willows, and fewer *Tamarix* (Stromberg and Rychener 2010).

A significant change in the long-term pattern of annual flows can substantially reduce the vigor and productivity of riparian ecosystems or the basic characteristics of a stream’s natural hydrograph (Annear et al. 2004; Merritt and Poff 2010; Poff et al. 1997). Those elements of the “natural hydrograph” currently recognized as necessary to protect and nurture aquatic and terrestrial ecosystems consist of seasonally variable flows that include relatively stable flows as well as flood flows from winter storm events and summer monsoon rains (Annear et al. 2004). The annual pattern, and the multi-year variability, in these flows set the stage for the aquatic and terrestrial biological resources that can survive and evolve in the system. Each stream, unless it is dam regulated or otherwise significantly altered by anthropogenic influences, or natural causes such as earthquakes, has a pattern of flow that is generally dictated by climate, topography, geology, depth to groundwater, and other factors (Annear et al. 2004).

A fundamental understanding of what is needed to maintain aquatic and terrestrial riverine ecosystems includes four elements of the important instream flow principle of connectivity: longitudinal flows (flows that extend over the length of a stream course); lateral flows (flows that cover the width of the channel and floodplain); vertical flows (flows that provide sufficient stream depth and connect to the hyporheic corridor); and flow duration (the amount of time a flow is at a particular level) (see Annear et al. 2004). Moderate to high floods reshape the riparian habitats by scouring and depositing sediments onto substrates above the active stream channel and redistributing organic material that can benefit healthy riparian vegetation (Annear et al. 2004; Bunn and Arthington 2002; Leenhouts et al. 2006; Poff et al. 1997; Shafroth et al. 2000; Smith et al. 1991). These same flows also can benefit aquatic habitats by redistributing gravel and fine substrates that are important for fish spawning and rearing. Extreme flooding events can uproot riparian vegetation and scour instream aquatic food upon which fish species rely (Meffe and Minckley 1987). Large floods preferentially impair nonnative fishes over flood-adapted natives (Gido et al. 2013; Propst et al. 2008). This "re-setting" of the fish community can give the native fishes at least a temporary window in time to rebound from the negative (competitive and predatory) interactions with nonnatives.

During the later decades of the 1900s, several river systems were studied as integrated ecosystems along elevation and river volume or flow gradients. Some were small, such as Aravaipa Creek (e.g., Barber and Minckley 1966; Lowe 1964; Minckley 1981), some intermediate in size, such as San Pedro River (e.g., Stromberg and Tellman 2009), and some large, such as the Colorado River (e.g., Carothers and Brown 1991; Johnson and Carothers 1987) and studies by the Bureau of Reclamation's Glen Canyon Environmental Studies and other Federal and State agencies in the 1980s and early 1990s (NRC 1991).

## Rise and Fall of *Tamarix*

One of the more interesting issues in telling the history of our understanding aridland riparian ecosystem concerns the role of introduced species, especially *Tamarix* species. Although Russian olive (*Elaeagnus angustifolia*) has also been introduced and spread throughout western North America, it does not occupy as dominant a role as tamarisk in the riparian ecosystems of the arid Southwest where understanding the role of tamarisk and methods for its eradication dominate discussions about nonnative riparian species (Nagler et al. 2011).

Since *Tamarix* was introduced to the United States from Asia in the early 1800s, the complex of several species that we know today as saltcedar or tamarisk have garnered a significant amount of attention from erosion control specialists, horticulturalists, wildlife ecologists, and, of course, water managers whose responsibilities include providing water for the human environment. As discussed earlier, it was those water managers and the rapidly proliferating complex of *Tamarix* species that led to phreatophyte control in the mid-1900s. In the past several decades it has become apparent that *Tamarix* as wildlife habitat, while not as productive as native riparian woodlands, can have significant value (Bateman et al. 2013; Davis et al. 2011; Hunter et al. 1988;

Johnson and Carothers 1987; Paxton et al. 2011; Stromberg et al. 2009). High wildlife use and the "naturalization" of *Tamarix* is well documented for hundreds of miles of river downstream of dams where either pre-dam conditions precluded the establishment of extensive riparian woodlands, or alternatively where regulated floodplains were no longer suitable for native riparian species (Anderson et al. 1977; Carothers and Brown 1991; Carothers and Dolan 1982; Johnson and Carothers 1987).

Now, with the introduction of biological control of *Tamarix* and its apparent success in defoliating the plant throughout most of its range in western riparian habitats, another important riparian resource is well on its way to being lost (see Chapter 5). Interestingly, when the U.S. Department of Agriculture biologists of Animal and Plant Health Inspection Service (APHIS) developed their effective *Diorhabda* spp. beetle release program, they made several fundamental errors in judgment including inadequate experimental evidence concerning the effect of the beetles (APHIS 2005).

For example, while acknowledging that the post-beetle revegetation with native species would not be possible in some areas, they generally approached this biological control project with the expectation that removal of *Tamarix* alone was the goal. APHIS generally assumed that once *Tamarix* was disadvantaged, native species, especially cottonwoods and willows, would return to riparian systems. It is now apparent that without "strategic restoration approaches" the native riparian community is unlikely to recover (Shafroth et al. 2013). Observations of the Colorado River above, within, and below Grand Canyon include the unfortunate reality that once the beetles have done their work, nonnative perennials and annual non-woody weeds and shrubs sprout and spread under the dying *Tamarix*. Unfortunately, recolonization of native riparian species in the shadow of the declining *Tamarix* has proven to be unlikely without significant restoration of soils and other biotic and abiotic environmental elements (see references in Chapter 5; Paxton et al. 2011; Shafroth et al. 2008).

APHIS also significantly underestimated the rate at which the beetles would spread. They predicted decades for the beetle to eventually occupy much of the western range of *Tamarix* (DeLoach et al. 2000); however, the reality is that within less than a decade the beetles swept like a plague through the western range of the species and occupied and defoliated a large part of the *Tamarix* range (see Tamarisk Coalition information online, http://www.tamariskcoalition.org). The beetles have neither invaded central or eastern Arizona below the Mogollon Rim nor occupied the Lower Gila and Salt Rivers or the Lower Colorado River below Bill Williams River, but it is only a matter of time before it will be difficult to find stands of *Tamarix* that have not been infested with the beetles. Perhaps the greatest oversight made by APHIS was their apparent assumption that *Tamarix* was of little wildlife value. They ignored a large body of knowledge regarding the value of *Tamarix* to wildlife, including studies documenting the significant use and carrying capacity for birds, mammals, reptiles, amphibians, and invertebrates (see references in Sher and Quigley 2013).

Attitudes toward *Tamarix* have changed since it was first introduced. Chew (2013) has recognized three phases of scientific and management attitudes toward the species. Clearly, we are now entering the fourth stage of the focus on *Tamarix* as a significant riparian species (Stromberg et al. 2009). In this fourth phase we are entering the unknown. What replaces *Tamarix* and the rate at which recolonization occurs are not predictable at this time. In Chew's first phase from introduction to the early

1900s, the species were celebrated and widely propagated for their role in erosion control, wind breaks, ornamental landscaping, and shade, especially in dryland situations where available water was limited and the species could thrive. By the second phase in the mid-1900s, when *Tamarix* was beginning to be reviled for its heavy water consumption and rapid proliferation throughout aridland watersheds, the word phreatophyte or "well plant" was first used (Meinzer 1923). This is when the phreatophyte control concept was born.

Unfortunately, while the focus was on *Tamarix*, other native riparian woodland species were also targeted (Carothers et al. 1974). It was firmly believed during the mid-1900s to the late 1960s that if *Tamarix* and, secondarily, native riparian species were eliminated or controlled, the water used in evapotranspiration by these "water wasters" would be more available for beneficial uses (see above and Gatewood et al. 1950). It was during Chew's second phase when limited local and regional attempts were made, including mechanical removal, burning, poisoning and drowning, to remove *Tamarix*, albeit ineffectively. This focus on *Tamarix* and other riparian woodland species occurred decades before the disproportionately high value to wildlife of riparian habitats compared to upland habitats was fully recognized (see Carothers 1977).

Additionally, later studies demonstrated that projected savings in "water salvage" had been greatly exaggerated and, in some cases, seemed to be non-existent. This was the case for a USGS *Tamarix* removal study area of about 5,500 acres (2,225 ha) upstream of the Coolidge Dam and its reservoir, San Carlos Reservoir, on the Gila River in Arizona (Culler et al. 1982, Graf et al. 1984). Not only did removal of *Tamarix* not improve water savings, *Tamarix* rapidly recovered and the floodplain is now densely covered with the plant.

It was not until Chew's third phase (1960s to early 2000) that "*Tamarix* suppression" began in earnest (Chew 2013). Notwithstanding organized attempts at eradication in the 1960s and 1970s, little success on *Tamarix* control was ever realized. We know now that part of the reason for the success of the species is the fact that *Tamarix* easily proliferates, dispersing seed over many months. Compared to seed dispersal patterns of native species that disperse seed aligned with winter/spring high-water, *Tamarix* are especially successful and replaces the native species in areas where the natural hydrograph has been modified by dams, irrigation withdrawal, flood control structures, declining water tables, livestock overgrazing and other anthropogenic watershed and stream alterations (Culler et al. 1982; Johnson 2013; Merritt and Poff 2010; Stromberg et al. 2007; Turner 1974).

Indeed, along river systems within the Southwest where the natural hydrograph has not been significantly modified, *Tamarix* is often relatively rare and unable to gain a foothold. Examples can be found along the upper portions of the Verde River and tributaries (Beauchamp and Stromberg 2007) and the San Pedro River and tributaries (Stromberg and Tellman 2009) in Arizona, and portions of the Upper Gila and tributaries (Hubbard 1971, 1977b) in New Mexico where the native riparian community remains largely intact.

For sections of those rivers where anthropogenic perturbations to the stream occur, *Tamarix* has been found to dominate. Merritt and Poff (2010) have convincingly demonstrated that the decline of western riparian systems can be primarily traced to flow alterations and that, with or without the introduction of *Tamarix*, the native riparian gallery forests would have declined. However, *Tamarix* is sufficiently adaptive such that it may establish and sometimes proliferate even in areas where the natural hydrograph has not been modified (Merritt and Poff 2010; see also Johnson 2013).

Following Chew's chronological sequence, we now find ourselves in the fourth and what may prove to be the final phase of the rise and fall of *Tamarix* in the Southwest. This fourth phase began in earnest in about 2000 with the introduction of biological control. The release of exotic Asian beetles has to be considered the most aggressive and finally successful attempt at removing *Tamarix*. As documented in McLeod's excellent account of the history of the beetle release program (Chapter 5), the biological control of the *Tamarix* was far more effective than its designers could have ever hoped or imagined. The *Tamarix*-defoliating beetle is now invading the nesting areas of the endangered southwestern willow flycatcher (and 90-plus other avian species and countless other vertebrates and invertebrates) in Arizona, California, New Mexico, Nevada, Texas and Utah http://www.tamariskcoalition.org/events/tamarisk-beetle-maps). If the beetle spreads farther without mitigation, the flycatcher's survival is likely to be threatened—and perhaps that of several other species—and it may significantly change the wildlife carrying capacity of hundreds of thousands of acres of naturalized second-growth riparian habitat comprised of non-native tamarisk.

APHIS indicated that mitigation could be needed if the release of beetles resulted in defoliation of occupied habitat of the endangered flycatcher (APHIS 2005). Mitigation could include planting native willows and cottonwoods or appropriate riparian species to replace dying *Tamarix*—to help endangered birds. The Center for Biological Diversity and the Maricopa Audubon Society are currently suing APHIS in U.S. District Court for Arizona [Case 4:09-cv-00172-FRZ]. The Plaintiffs allege that APHIS violated its affirmative obligations under the Endangered Species Act section 7(a)(1) by failing to adopt a program to offset the harm caused by the beetle release, and by taking no action to mitigate the adverse effects of the beetle prior to and after suspending the program. (Note: As of June 2010 APHIS's beetle release program was formally suspended in 13 States: Colorado, Idaho, Iowa, Kansas, Missouri, Nebraska, Nevada, North Dakota, Oregon, South Dakota, Montana, Washington, and Wyoming. The Lower Colorado River States were not included because the southwestern willow flycatcher continues to use *Tamarix* for nesting in those States.)

APHIS is taking the position that the Plaintiffs are mistaken about the scope of an agency's duties under ESA section 7 by improperly assuming the agency has a duty to offset all adverse effects of their action. APHIS also argues that it did the best it could and took a variety of affirmative conservation actions to benefit numerous listed species, including the flycatcher, and that the mitigation the Plaintiffs seek is beyond APHIS' authority. While the legal case[1] is far from being resolved, one thing is certain: The introduced riparian species complex *Tamarix* is predicted to soon be a shadow of its former value to western riparian wildlife. With some luck, once *Tamarix* is further reduced (nobody really expects complete eradication), the beetles' appetite will not switch to native riparian species. Additionally, if appropriate hydrological conditions can be maintained in areas with *Tamarix* removal, cottonwood and willow can compete in the early growth stages and may prevent further invasion and enhance natural recovery (Stromberg 1997).

## Restoration of Riparian Habitat: Putting the Genie Back in the Bottle

During the developing period of riparian studies, the young science of restoration ecology, including efforts to restore denuded riparian habitat, was also gaining significant traction and attention (e.g., Goodwin et al. 1997; and Stanley et al., in prep.). The rapid expansion of this interest in riparian habitat restoration is documented by Koehler and Thomas' (2000) annotated bibliography Managing for Enhancement of Riparian and Wetland Areas of the Western United States, which lists approximately 250 documents focused primarily on riparian restoration along living streams. In a 2007 study of riparian and river restoration projects in the Southwest, approximately 33 percent were riparian management while others included, for example, flow modification and instream habitat recovery (Shah et al. 2007). Riparian management included intensive management of livestock allotments to protect or improve the conditions of riparian areas.

In the past several years, riparian habitat studies have expanded beyond hydroriparian ecosystems (associated with perennial streams) and mesoriparian ecosystems (associated with intermittent streams) (Johnson et al. 1984). Now workers ranging from ecologists to city planners (Krausman et al. 1985; Steiner et al. 1999) conduct investigations on conservation, management, and restoration of xeroriparian ecosystems associated with the long-overlooked but spatially abundant and wildlife-rich ephemeral river systems along washes and arroyos (Cooke and Reeves 1976; Levick et al. 2008).

Most published studies available today indicate that while some restoration successes are impressive, complete restoration of riverine systems is often an elusive goal once they are damaged. This includes both the aquatic and terrestrial components. However, in some situations, riparian ecosystem resilience is remarkable in its ability to recover from direct destructive impacts like flooding, wildfire, and livestock overgrazing. In fact, ample evidence exists that once floods and fires have passed, it is not unusual for natural processes to return the damaged areas to their original vitality. For example, a massive 850 cms (30,000 cfs) flood in Arizona's Aravaipa Canyon in October 2008 scoured over 25 miles of the canyon bottom and destroyed approximately half of the cottonwood-willow gallery forest; however, within a decade the area was largely recovered to pre-flood conditions (Burtell 2013). Similarly, a human-caused wildfire in Grand Canyon's Deer Creek in 1972 completely denuded a mile of floodplain of mature cottonwoods; yet again, within a decade or so, the area was naturally revegetated to a closed gallery forest (Carothers and Brown 1991). The most remarkable example of the impact of overgrazing on riparian habitat and the resilience of the riparian system to recover is the Bureau of Land Management's San Pedro Riparian National Conservation Area in southern Arizona. Once livestock grazing was prohibited within the conservation area (approximately 50 miles), cottonwood-willow gallery forest tripled in size in a 30-year period (NRST 2012; Stromberg and Tellman 2009).

While many and varied techniques are available to reestablish riparian vegetation once it is damaged or removed, the constant onslaught of human activities that change fluvial processes and natural channel ecological functions, combined with the long history of exotic species introductions and our general inability to counteract these aliens, provides a constant frustration to river restoration attempts. Moreover, as Stanley et al. (in prep.) have documented for the State of California, most restoration projects are extremely small and of 276 separate restoration projects analyzed in the 1990s, 83 percent were less than 20 acres in size. Shah et al. (2007), when analyzing data from 576 riparian restoration projects in the Southwest, indicated that few were over 3 km in length thus allowing for a better chance of success.

What is important to emphasize in the above flooding, fire, and grazing examples of natural restoration of the riparian habitat is that in all three areas, the natural hydrograph and the ground-water recharge system were largely intact. In areas where the hydrologic regime can be restored to some semblance of the "natural hydrograph" and the deviation from normal surface and subsurface flow and storage cycle conditions can be understood, large-scale restoration is possible. An excellent example of riparian restoration success is the effort of The Nature Conservancy (TNC) in the Lower San Pedro River Basin to acquire and protect large tracts of land adjacent to riparian areas. Once the land is acquired and it is possible to remove ecosystem stresses, such as excessive groundwater pumping, removal of diversion structures, restoration of base flows, control of grazing, and off-road vehicle use, riparian habitat eventually comes back as watersheds restore in the uplands and groundwater recharge returns to some semblance of pre-depletion levels (Haney 2005, Stromberg and Tellman 2009).

However, there are locations where riparian restoration is almost impossible on a large scale and will rarely occur without the intervention of intense management. These include situations where impoundments, diversions, depletion of surface and groundwater supplies, and proliferation of exotic species are the reasons for native riparian habitat declines. While we can celebrate the recent efforts of TNC in the Lower San Pedro River and elsewhere throughout the arid Southwest, we have clearly reached a new level of crisis with the release of the tamarisk beetle and the destruction of thousands of acres of "second class" riparian habitat. This has clearly reduced wildlife-supporting riparian habitat throughout the arid Southwest.

The ravages of the tamarisk beetle have set this crisis stage and there does not seem to be a reasonable solution in the near future. Major dams and impoundments altered the natural hydrograph on most large streams and rivers and ushered in the first profoundly destructive phase of riparian habitat demise. Many of those impoundments, while clearly controlling most flood flows, precluded conditions necessary for the recruitment of cottonwoods and willows (Mahoney and Rood 1998) and allowed for the proliferation of the nonnative *Tamarix*. As detailed in earlier sections of this paper, *Tamarix* was largely reviled by water managers and conservationists alike. Nevertheless, the nonnative woody plant did proliferate over thousands of acres of hydrologically altered stream channels. Though a nonnative, *Tamarix* was better than no woody vegetation along the native-plant-denuded stream channels, and it did form suitable habitat for hundreds of native wildlife species as well as provide stream cover and nutrient input in the form of allochthonous organic material. Now, as the tamarisk beetle has proliferated virtually unchecked throughout the arid Southwest, there are hundreds of stream channels where dead and dying *Tamarix* are no longer even second-class riparian habitat. Areas under the dying *Tamarix* are mostly revegetating with non-woody shrubs and herbaceous species, many of which are nonnatives (Chapter 5).

It is important to point out that the Tamarisk Coalition, founded in 1999 in advance of the onslaught of the tamarisk beetle, is a non-profit dedicated to the advancement of the restoration of riparian lands through collaboration, education, and technical assistance (http://tamariskcoalition.org/about-us/accomlishments). They are actively pursuing restoration of habitat where the *Tamarix* has been defoliated, but their efforts to date are relatively small and include removing dead and dying vegetation and reestablishment of native grasses combined with planting some woody cottonwood and willow species. Large-scale efforts to restore more than a few acres of habitat are extremely costly and non-existent at this time.

Additionally, restoring non-salt-tolerant trees such as willows and cottonwood is initially difficult because *Tamarix* alters soil chemistry enough to reduce restoration success (Siemion and Stevens 2015). On the Rio Grande in the vicinity of Elephant Butte Reservoir, the Bureau of Reclamation has been initiating riparian restoration efforts as mitigation for listed species, but like most attempts to restore native species where *Tamarix* has dominated for years, the restoration areas are quite small (<20 acres) (BOR 2016). Reintroduction of beaver to restore local hydrology and stimulate recovery of a woody riparian community has been used along some smaller rivers in the semi-arid West with some success (Carrillo et al. 2009; Castro et al. 2015; Welch 1997). Unfortunately, beavers' preference for cottonwood and willow over the nonnative *Tamarix* slows recovery of a native riparian forest (see chapters 6 and 7 [beavers] and 4, and restoration chapters in Johnson et al., in prep.).

Climate change also poses significant problems for riparian habitat restoration. The conventional wisdom for the trajectory of climate change seems to tend toward understanding that the arid Southwest will become warmer and drier, thus piling on additional threats to existing riparian habitat. Some researchers are now advocating that the use of "local stocks" of riparian vegetation be replaced with more southerly stocks where the plants are already adapted to warmer and drier conditions. The belief is that climate change is happening so quickly that the local seed and cuttings that are currently sources for revegetation are maladapted.

Thus, if the objective is to revegetate cottonwood and willow stands along the Verde River in central Arizona, seed sources and cuttings should come from farther to the south, perhaps from the San Pedro River drainage (Carroll et al. 2014; T. Whitham, Northern Arizona University, personal communication; Whitham et al. 2006). Additionally, a warmer climate will change winter and spring runoffs from higher elevations where snow collects. This is expected to affect the phenology of riparian species and thus results of restoration activities. Genotypic elasticity of woody riparian species may be sufficient to overcome this, but use of more adapted genotypes may be required for successful restoration.

## Summary

A review of the history of riparian ecological science shows an evolution from attempting to solve anthropogenic issues relating to water supply to guiding broad programs of riverine management. In the early years of riparian ecology, river systems were primarily considered sources of water for urban systems, agriculture, and industry. Consequently, the more water made available for these uses, that is, the social ecological system, the more the economy and human welfare would be advanced. To improve delivery of water by riverine systems, science was expected to reduce competing uses of water along the delivery system. This included lining canals and removing, or challenging, the use of water by vegetation growing along the riverine floodplain, that is, riparian vegetation.

Scientists began to evaluate the amount of water used by riparian vegetation and suggested that removing this vegetation could salvage enough water to balance any negative aspects of removal. Consequently, "experiments" were untaken to remove riparian trees and shrubs from the edge of the rivers, or total removal of that plant community where it had overrun the extended floodplain. Success in improving water yield by these procedures was never proven as significant.

Concurrent studies in the 1970s and 1980s shed light on the ecological values of the riparian vegetation, not just as an aggregation of plants but as a complex ecosystem important to riverine functions and one that formed important habitat for many species. Other studies documented the ecological values and disproportionate diversity and density of some vertebrates using these systems. Most early studies along these lines were avian studies. Birds were found to use many strata of the riparian vegetation and thus these habitats were critical in survival and maintenance of most of the avian species of the Southwest lowlands. This information, along with evidence of little or no water savings with riparian vegetation removal, essentially put a stop to programs that removed or highly modified riparian vegetation.

Unfortunately, discovery of the importance of riparian vegetation followed on a lengthy period of dam building in the West. Some dams were constructed many years earlier but, again to improve water delivery to urban/industrial/agricultural centers, water needed to be "stored" and these social ecological systems also needed electrical power that the dams could supply. Dams were managed to control downstream flows along with inundating upstream riverine systems. Many important riparian systems went under water and the negative consequences of a highly modified downstream river flow was demonstrated by riparian research. The importance of the whole riverine system took on a new meaning with the development of the River Continuum Concept, and importance of natural flows (including the concept of environmental flows) was emphasized and supported through extensive riparian/riverine research.

Into the 1980s, more riparian research was initiated to address the response of different components of riparian ecosystems to alterations of the many drivers that influenced these systems. Changes in flows, alteration of groundwater levels, introduction of exotic species, and diversion of channel systems are all examples of modifications studied. Exotic species became of great importance with the expansion of *Tamarix* throughout the West. *Tamarix* impacted many functions of both modified and unmodified riparian ecosystems. Consequently, removing or destroying some riparian systems, those dominated by *Tamarix*, was back in vogue. The rise and fall of the *Tamarix* spp. in the western United States is a classic story of the unintended consequences of not just the introduction of an exotic species, but of ecosystem destruction. *Tamarix* changed the natural hydrograph of streams and rivers, followed later by largely unadvisable attempts to fight it, but it was found to be beneficial as wildlife habitat, with yet another introduced species, the tamarisk leaf beetle.

Today, basic research on riparian functions is still ongoing but more emphasis is being placed on understanding and restoring riparian systems that have been altered. This effort will reach new heights in the shadow of the *Tamarix* beetle's impacts as hundreds of thousands of acres of second-growth riparian habitats are becoming available for restoration efforts. Although costs for this restoration will be substantial, benefits to wildlife and stream ecology should more than adequately justify the expense and effort.

Riparian research in the West will continue to develop more refined data on function and how this information can guide management. These efforts must include continuing dialog among riparian specialists, users, and the public if we expect riparian systems to continue to be part of the western mosaic of ecosystems and habitat for those species for which this system is critical. The future of riparian ecology is not only better understanding of functional components of these important systems but better ways in which scientists, managers, decisionmakers, and the public can work together to use all forms of data to create a successful future for these critical western riverine systems.

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Note
This case was legally resolved in June 2018 (see McLeod, volume 1) as this publication was in press.

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