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Effectiveness of environmental flows for riparian restoration in arid regions: A tale of four rivers

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ABSTRACT

Environmental flows have become important restoration tools on regulated rivers. However, environmental flows are often constrained by other demands within the river system and thus typically are comprised of smaller water volumes than the natural flows they are meant to replace, which can limit their functional efficacy. We review environmental flow programs aimed at restoring riparian vegetation on four arid zone rivers: the Tarim River in China; the Bill Williams River in Arizona, U.S.; the delta of the Colorado River in Mexico; and the Murrumbidgee River in southern Australia. Our goal is to determine what worked and what did not work to accomplish restoration goals. The lower Tarim River in China formerly formed a "green corridor" across the Taklamakan Desert. The riparian zone deteriorated due to diversion of surface and groundwater for irrigated agriculture. A massive restoration program began in 2000 with release of 1038 million cubic meters of water over the first three years. Groundwater levels rose but the ecological response was less than expected politically, socially and within the scientific community. However, releases continued and by 2015 portions of the original iconic *Populus euphratica* (Euphrates poplar) forest were reestablished. The natural flow regime of the Bill Williams River was disrupted by construction of a dam in 1968, dramatically reducing peak flows along with associated fluvial processes. As a result, the channel narrowed and riparian vegetation expanded and was comprised largely of an introduced shrub species (*Tamarix* spp.). Environmental flow releases including small, managed floods and sustained base flows have been implemented since the mid 1990's to promote establishment and maintenance of native riparian trees (cottonwoods and willows) and have been successful, although in a "downsized" portion of the valley bottom. Experience from the Bill Williams was used to help design the Minute 319 environmental flow in the delta of the Colorado River in 2014. Water was released as a short, one-time pulse during spring with the intent of starting new cohorts of cottonwood and willow. However, fluvial disturbance was limited by the relatively small magnitude pulse, low flows did not continue throughout the growing season in some reaches, native tree recruitment was low, and most of the new plants recruited were *Tamarix*. The inundated portion of the floodplain did respond with a temporary increase in greenness as measured by satellite vegetation indices, however. The Murrumbidgee River in Australia is a tributary in the Murray-Darling River Basin, which supports iconic red gum (*Eucalyptus camaldulensis*) forests that depend on near-yearly floods for maintenance. During the recent Millennial Drought (2000–2010) environmental flows were provided on an experimental basis to small portions of the Yanga National Forest to see how much water was needed. As with the Colorado River delta, gains in vegetation vigor as measured by satellite vegetation indices following the flows were temporary. Environmental flows in the Bill Williams were able to restore enough overbank flooding and fluvial disturbance to promote some establishment of new cohorts of trees, but on the Colorado and Murrumbidgee Rivers larger volumes of total flows released over longer periods and targeted restoration will be needed to restore the ecosystems. A measure of

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success in restoring the Euphrates poplar forest on the Tarim and germinating new chorts of willows on the Bill Williams has been achieved after 15–20 years of environmental flows, but the Colorado River delta and Murrumbidgee Rivers have only received one or two flows. Success in enhancing native trees in the Colorado delta has been achieved in restoration plots, but the Murrumbidgee will require large overbank flows on a continuing schedule to rejuvenate the red gum forest.

1. Introduction

Managing flow releases from dams for downstream environmental benefits ("environmental flows") was historically directed at maintaining fish habitat (Orth and Maughan, 1982), but since the 1990s environmental flows have been used as restoration tools for a variety of purposes (Nilsson and Berggren, 2000; Arthington, 2012; Konrad et al., 2011, 2012). Environmental flows sometimes target riparian vegetation, including objectives such as: to promote germination and establishment of native trees (Rood et al., 2003, 2007); to recharge the alluvial aquifer to support existing, desirable vegetation (Stromberg et al., 2007); to wash salts from the riverbank to favor mesic native trees over salt-tolerant invasives (Gross, 2003); and to scour the riverbed to remove invasive species and create new bars for establishment of native trees (Richardson et al., 2007; Wilcox and Shafroth 2013).

Environmental flows are typically designed to restore elements of the unregulated (natural) flow regime (Merritt et al., 2010; Poff et al., 1997), but planning and implementing such flows can be challenging (Olden et al., 2014; Konrad et al., 2011, 2012). One complication is that the amount of water allocated for environmental flows is often much less than was provided by natural flow events. Additionally, natural ecosystem dynamics are often a product of complex sequences of flows. For example, riparian ecosystems are typically not climax communities but are dynamic mosaics of habitats in different states of succession (Standford et al., 2005), and attempting to replicate the hydrological factors that lead to desirable restoration outcomes can be difficult. Therefore, success is not guaranteed, and strategies for environmental flows should be based on determining suitable magnitude, frequency, duration, timing, and rates of change of flows to meet specific objectives at specific sites (Richter et al., 2003).

Several papers have reviewed the effectiveness of large-scale environmental flows in a variety of biomes and results have been mixed (e.g., Olden et al., 2014; Davies et al., 2014; Konrad et al., 2011, 2012). Therefore, each flow event should be evaluated for successes, failures and lessons learned. Olden et al. (2014) recommended that environmental flows should be analyzed by asking three questions: why was the flow experiment conducted?; what knowledge was gained from the flow and its outcomes?; and what challenges remain in meeting restoration goals? Shafroth et al. (2010) advocated combining existing hydrologic and ecologic information and models with empirical relationships determined during flow events to produce predictive hydrology-ecology models, with particular attention paid to determining threshold levels of volume and duration of flows needed to produce desired outcomes. Davies et al. (2014) and Konrad et al. (2011, 2012) recommended treating each flow event as a manipulative experiment, and advocated using the term "large-scale flow experiments" rather than environmental flows.

This study reviews four cases in which environmental flows have been used to attempt restoration of riparian vegetation on four dryland rivers: the Tarim River in China (Hou et al., 2007); the Bill Williams River in Arizona (Shafroth et al., 1998, 2010; Wilcox and Shafroth 2013); the delta of the Colorado River in the U.S. and Mexico (Jarchow et al., 2017; Pitt and Kendy, 2017; Kendy et al., 2017); and the Murrumbidgee in New South Wales, Australia (Baldwin et al., 2013; Doody et al., 2015; Nagler et al., 2016). A discussion of the successes, failures and lessons learned is presented. A major theme running through the paper is the need to balance environmental versus societal demans as a constraint on many environmental flow programs, thereby limiting their ecological effectiveness.

2. Tarim River, China

Prior to development of large-scale irrigation projects starting in the 1950s, the lower Tarim River formed a 320 km "green corridor" of riparian and wetland vegetation as much as 5–10 km wide between the now-existing Daxihaizi Reservoir and Taitemar Lake in the Taklimakan Desert in northeastern China (Yongbo and Chen, 2007; UNESCO, 2010). Water in the river arises from snow melt in mountains outside the basin. The river supports iconic *Populus euphratica* (Euphrates poplar) forests. These trees have been called "living fossils", having originated 60 million years ago with the uplifting of the Tibetan Plateau. Individual trees can live as long as 1000 years (UNESCO, 2010). By 1972 flows were reduced to only 20% of former volumes due to upstream diversions for agriculture; portions of the river were seasonally dry; and the water table dropped below the tolerance limit of the *P. euphratica* trees that formed the base of the ecosystem (Chen et al., 2003; Yongo and Chen, 2007). Taitemar Lake was dry. By the 1990s the water table had dropped from 3 to 5 m to 8–12 m deep and 47% of the remaining *P. euphratica* trees were dead (Chen et al., 2003). The forested area had decreased from 5.4×10^4 ha to 0.5 10^4 ha over 50 years and was in danger of extinction (Ling et al., 2015).

In 2000 the Chinese government undertook a major effort to restore the ecosystem through the Ecological Water Development Project (Bao et al., 2017; Yongbo and Chen, 2007; Zhu et al., 2016). The Ministry of Water Resources allocated the equivalent of $2 billion US dollars for a massive restoration effort to raise the water table to support the existing *P. euphratica* trees and create a hydrologic regime to recruit new trees to the floodplain. Over the first three years several releases of water were made from upstream reservoirs, totaling 1038 mcm of water. The water table responded positively and water once again flowed into Taitemar Lake (Yongbo and Chen, 2007; Chen et al., 2009) but the rejuvenation of the *P. euphratica* forest that was desired was slow to develop, and at first the effort did not meet political and social expectations (Hou et al., 2007). However, releases have continued, averaging about 200 mcm yr^{-1} (Yan et al., 2014; Chen et al., 2014; Aishan et al., 2015; Zhu et al., 2016).

A restored forest has developed but it is much narrower than the original forested area. The floodplain forest has made an excellent recovery within 200 m of the riverbed with medium results extending up to 800 m from the riverbed (Aishan et al., 2015). Importantly, survival and recruitment of new cohorts of *P. euphratica* have been documented (Aishan et al., 2015). The restoration effort is now regarded as successful, although recovery of the riparian zone has been slower and over a narrower width than originally