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Research article

Dissolved oxygen, stream temperature, and fish habitat response to environmental water purchases

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ABSTRACT

Environmental water purchases are increasingly used for ecological protection. In Nevada's Walker Basin (western USA), environmental water purchases augment streamflow in the Walker River and increase lake elevation of terminal Walker Lake. However, water quality impairments like elevated stream temperatures and low dissolved oxygen concentrations also limit ecosystems and species, including federally-threatened Lahontan cutthroat trout. In this paper, we prioritize water volumes and locations that most enhance water quality for riverine habitat from potential environmental water rights purchases. We monitored and modeled streamflows, stream temperatures, and dissolved oxygen concentrations using River Modeling System, an hourly, physically-based hydrodynamic and water quality model. Modeled environmental water purchases ranged from average daily increases of 0.11–1.41 cubic meters per second (m^3/s) during 2014 and 2015, two critically dry years. Results suggest that water purchases consistently cooled maximum daily stream temperatures and warmed nightly minimum temperatures. This prevented extremely low dissolved oxygen concentrations below 5.0 mg/L, but increased the duration of moderate conditions between 5.5 and 6.0 mg/L. Small water purchases less than approximately 0.71 m^3/s per day had little benefit for Walker River habitat. Dissolved oxygen concentrations were affected by upstream environmental conditions, where suitable upstream water quality improved downstream conditions and vice versa. Overall, this study showed that critically dry water years degrade environmental water quality and habitat, but environmental water purchases of at least 0.71 m^3/s were promising for river restoration.

1. Introduction

Water regulation and diversions from Nevada's Walker River cause low streamflows, high stream temperatures and low dissolved oxygen (DO) concentrations, which fragment aquatic habitats and limit native fish species, like Lahontan cutthroat trout (LCT) (*Oncorhynchus clarki henshawi*) (USFWS, 2003). LCT are a federally threatened species (USFWS, 1975) that have been reduced to headwater streams in the Walker Basin and occupy approximately 3% of their historical habitat in the western Great Basin (Dunham et al., 1999). Cumulative effects of water diversions have also impacted terminal Walker Lake, causing lake elevation to fall and salinity to increase, and extirpating LCT from the lake (Beutel et al., 2001; Sharpe et al., 2007). The problems in the Walker Basin are common in arid, semi-arid, and Mediterranean climates, where streamflow regulation, water diversions, and water quality impairments degrade and fragment cold water fisheries and habitats (Baron et al., 2002). Examples are widespread, including rivers in Spain (Bae et al., 2016) South America (Grantham et al., 2013), and throughout the American West (Goniea et al., 2006; Nehlsen et al., 1991; Moyle et al., 2011).

One Walker Basin restoration strategy is to increase streamflow and Walker Lake elevation through environmental water purchases (Collopy and Thomas, 2009; Ise and Sunding, 1998). Congress enacted the Energy and Water Development Appropriations Act (H.R. 2419) in 2006 to acquire environmental water from willing sellers (Collopy and Thomas, 2009). Purchased or leased water may be available as farmers upgrade to more efficient irrigation infrastructure (Sunding et al., 2002) or switch to less water-intensive crops (Bishop et al., 2010). To date, nearly 25 million cubic meters (Mm^3) (20,000 acre feet) of water have been purchased for instream uses and to restore Walker Lake, approximately one third of the goal (NFWF, 2016). Environmental water purchases (also

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called water transfers or markets) are increasingly applied to maintain or enhance aquatic ecosystems in the western US, Australia, Chile, Mexico, China, and South Africa (Grafton et al., 2011; Debaere et al., 2014).

Instream flow dedications and management are a major thrust of national and international stream restoration research (Richter and Thomas, 2007). However, water quality impairments like warm stream temperatures and low DO concentrations also limit ecosystems and habitats (USFWS, 2003). Stream temperatures drive biological, physical, and chemical properties of rivers, including metabolic rates and life histories of aquatic organisms, productivity, chemical reactions, nutrient cycling, and DO concentrations (Poole and Berman, 2001). DO concentrations also affect metabolic rates of aquatic organisms, predation risk, and influence organism behavior and fish community structure (Magoulick and Kobza, 2003). Agricultural diversions reduce streamflow volume which raises stream temperatures by reducing thermal mass and slowing water travel time (Poole and Berman, 2001). DO saturation concentrations have an inverse relationship with stream temperatures, so that as temperatures increase, less DO is contained in water (Chapra, 2008). DO concentrations have been reduced from warm stream temperatures and are exacerbated by warm, nutrient-rich agriculture returns flows (Jalali and Kolahchi, 2009). Nutrients promote biological activity, creating dead and decaying biomass which consumes DO as respiration (Odum, 1956).

No research has specifically examined the effects of environmental water purchases on DO concentrations in streams, although Elmore et al. (2016) showed that environmental water purchases in the Walker Basin may reduce maximum daily stream temperatures by up to 3 °C while increasing minimum daily stream temperatures by approximately 1 °C. This confirms previous research showing increasing streamflow may decrease stream temperature by increasing the thermal capacity of rivers (Null et al., 2010; Gu and Li, 2002). Existing research also suggests that cooler stream temperatures could reduce DO concentrations by increasing the amount of oxygen that may be dissolved in water (Magoulick and Kobza, 2003; Ficklin et al., 2013), and which supports the hypothesis that environmental water purchases may improve river DO concentrations.

We build on modeling research completed by Elmore et al. (2016) by simulating the effects of environmental water purchases on DO concentrations and stream temperatures in the Walker River using River Modeling System, an hourly, 1-dimensional hydrodynamic and water quality model. Objectives for this research are to: 1) measure the extent and seasonality of high stream temperatures and low DO concentrations that limit aquatic habitat in the Walker River, and 2) simulate stream temperature and DO concentration change from environmental water purchases. Improving understanding of the locations and volumes that environmental water purchases affect DO concentrations and stream temperatures will allow for coordinated management of streamflow and environmental water quality for better river restoration decision-making.

2. Background

2.1. Study site

The Walker Basin is 10,500 km^2 and is located in western Nevada and eastern California (Fig. 1). Headwaters are split between two major tributaries, the East Walker and West Walker Rivers. Both tributaries drain California's east-slope Sierra Nevada Mountains (Sharpe et al., 2007). Mountain snowmelt is the primary water source (Yuan et al., 2004). The Walker Basin transitions from conifer woodland vegetation in the Sierra Nevada Mountains to sagebrush scrub in the Great Basin Desert (Jones, 1992). The river's terminus is Walker Lake, one of only three terminal lakes in North America that historically supported a freshwater fishery (Collopy and Thomas, 2009).

Three reservoirs have been built to provide reliable water for agriculture. On the East Walker River, Bridgeport Reservoir has storage capacity of approximately 52 Mm^3. West Walker River streamflow is diverted to Topaz Reservoir, a 73 Mm^3 off-stream reservoir, straddling the California-Nevada state line. Both tributary reservoirs are bottom release reservoirs and are physical barriers to fish passage (Jones, 1992). The mainstem Walker River is impounded by Weber Reservoir, with storage capacity of approximately 15 Mm^3. Weber Reservoir has a bottom release with a roughened channel fishway. The dam does not have outletworks that can be managed for downstream temperatures (Rheinheimer et al. 2014).

Irrigated agriculture began in the basin in 1852 (Horton, 1996). Agriculture is the dominant land use and the main consumer of water. Principal crops include irrigated pasture, alfalfa, root crops, and grains. Within the basin, water is over-allocated and full water demands are met only in wet years (Yardas, 2007). For an average snowpack year, 84% of agricultural water rights are satisfied. A wet year with at least 130% of normal snowpack is required to fulfill all water rights in the basin (Sharpe et al., 2007). During dry years, supplemental groundwater rights provide additional water. Groundwater pumping in agricultural valleys has lowered the water table, increasing recharge from the Walker River to the aquifer (Carroll et al., 2010).

2.2. Hydrologic conditions

The Sierra Nevada Range and the Walker Basin have experienced a prolonged and ongoing drought since 2012. Water year (October 1 through September 30) 2014 and 2015 had the lowest recorded snowpack, as a percentage of April 1 average, of the last 14 years of available data. Of the four sites to measure snowpack in the Walker Basin, only two had measureable snowpack on April 1, 2015 (CDEC, 2016). The river was dewatered downstream of Wabuska (Fig. 1) from September 9 through November 7, 2014 and again from August 28 through December 15, 2015. This was unprecedented in the Walker River.

2.3. Water quality and stream ecology

Stream temperatures largely determine the overall health of aquatic ecosystems (Poole and Berman, 2001). Effects on aquatic organisms are typically defined in relation to chronic 7-day temperature stress. In laboratory studies, 60% of adult LCT died when stream temperatures exceeded 26 °C for a week and complete mortality occurred within two days when temperatures exceeded 28 °C (Dickerson and Vinyard, 1999). Optimal temperatures for spawning cutthroat trout (all subspecies) range from 6 °C to 17 °C. Embryos and juveniles prefer temperatures of 10 °C and 15 °C, respectively (Hickman and Raleigh, 1982). In trout streams, LCT avoid water temperatures exceeding 26 °C and fish are limited by maximum rather than mean daily temperatures (Dunham et al., 1999). Here, we assume a lethal threshold of 28 °C for LCT.

Low DO concentrations in milligrams per liter (mg/L) creates hypoxic conditions for fish species and other aquatic organisms. While fish may tolerate short-term exposure to hypoxia, few persist in low oxygen conditions (Magoulick and Kobza, 2003). Trout growth rates are impaired at DO concentrations below 8 mg/L, growth rate is reduced up to 22% when concentrations are below 6 mg/L, and mortality occurs at 3 mg/L (WDOE, 2002; Carter, 2005). Thresholds for this paper assume moderate impairment begins at 6 mg/L and