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Effects of Environmental Water Rights Purchases on Dissolved Oxygen, Stream Temperature, and Fish Habitat

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EFFECTS OF ENVIRONMENTAL WATER RIGHTS PURCHASES ON DISSOLVED

OXYGEN, STREAM TEMPERATURE, AND FISH HABITAT

by

Nathaniel R. Mouzon

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ABSTRACT

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by

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Utah State University, 2016

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Human impacts from land and water development have degraded water quality and altered the physical, chemical, and biological integrity of Nevada's Walker River. Reduced instream flows and increased nutrient concentrations affect native fish populations through warm daily stream temperatures and low nightly dissolved oxygen concentrations. Environmental water purchases are being considered to maintain instream flows, improve water quality, and enhance habitat for native fish species, such as Lahontan cutthroat trout. This study uses the River Modeling System (RMSv4), an hourly, physically-based hydrodynamic and water quality model, to estimate streamflows, temperatures, and dissolved oxygen concentrations in the Walker River. Stream temperature and dissolved oxygen changes were simulated from potential environmental water purchases to prioritize the time periods and locations that water purchases most enhance stream temperatures and dissolved oxygen concentrations for aquatic habitat. Environmental water purchases ranged from 0.03 cms to 1.41 cms average daily increases. Modeling results indicate that increased water purchases generally affect dissolved oxygen in two ways. First, environmental water purchases increase the thermal mass of the river, cooling daily stream temperatures and warming nightly temperatures. This prevents conditions that cause the lowest nightly dissolved oxygen concentrations (moderate production impairment thresholds are <5.0 mg/L and acute mortality thresholds are <3.0 mg/L) but increases the duration of nightly chronic conditions (<6.0 mg/L) due to the inverse relationship between dissolved oxygen saturation concentration and stream temperature. Second, dissolved oxygen concentrations are affected by upstream environmental conditions. High water quality upstream improves degraded downstream water quality conditions, but the reverse is also true wherein poor upstream water quality degrades water quality downstream.

(112 Pages)

PUBLIC ABSTRACT

Effects of Environmental Water Rights Purchases on Dissolved Oxygen, Stream Temperature, and Fish Habitat

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Degraded water quality has reduced aquatic species abundance and survivability in Nevada's Walker River. Low instream flows and increased nutrients affect native fish populations through high daily stream temperatures and low nightly dissolved oxygen concentrations. Increasing streamflow, through environmental water purchases, may improve water quality and enhance habitat for native fish species, such as Lahontan cutthroat trout. This study uses River Modeling System, a computer model, to estimate streamflows, stream temperatures, and dissolved oxygen concentrations in the Walker River. Streamflow increases are simulated to determine potential improvements to high water temperatures and low dissolved oxygen concentrations, enabling the prioritization of time periods and locations that water purchases most improve habitat for native species. Environmental water purchases ranged from 0.03 cms to 1.41 cms average daily increases. Modeling results show that increased streamflow generally affects dissolved oxygen concentrations in two ways. First, more streamflow keeps stream temperatures cooler during the day but also allows temperatures to stay warmer at night. This prevents conditions that cause the lowest nightly dissolved oxygen concentrations but increases the overall length of time that dissolved oxygen concentrations remain under preferred levels. This effect is due to the inverse relationship between dissolved oxygen concentrations and stream temperature. Second, dissolved oxygen concentrations are

affected by upstream environmental conditions. High water quality upstream improves poor downstream water quality conditions, but the reverse is also true wherein poor upstream water quality can worsen water quality downstream.

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Nate Mouzon

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CHAPTER 1

INTRODUCTION

The physical and biological integrity of Nevada's Walker River is highly altered from land and water development. This has caused low instream flows, water quality degradation, habitat fragmentation, geomorphic instability, and declining native fish populations, especially for Lahontan cutthroat trout (LCT) (*Oncorhynchus clarki henshawi*) (Walker Basin Restoration Program, 2011). It is estimated that LCT occupy less than three percent of their historical habitat, resulting in LCT being listed as a federally threatened species under the Endangered Species Act (Coffin and Cowan, 1995; Dunham et al., 1999; USFWS, 1975). The problems in the Walker Basin are common throughout much of the American West, where streamflow alterations, diversions, and water quality impairments have generally degraded cold-water fisheries and the extent of cold-water habitats is a fraction of what it once was (Baron et al., 2002).

Efforts to restore ecosystems to improve LCT health and abundance are receiving considerable attention and funding (Vander Zanden et al., 2003). In 2002, Congress enacted Public Law 107-171, allocating $375 million to the Desert Terminal Lakes Program (USBR, 2015). This program aims to improve ecological conditions related to LCT decline by improving habitat within the Walker Basin and other desert terminal lakes. Water quality impacts of water development in the Walker River include both physical and chemical degradation, specifically low streamflows, high stream temperatures and low dissolved oxygen (DO) concentrations (USFWS, 2003). Agricultural diversions have decreased flow and depth, and increased water residence time, causing critically warm stream temperatures and fragmentation of suitable fish habitats (Sharpe et al., 2008). Warm stream temperatures are created by a decrease of thermal mass and a reduction in the assimilative heat capacity of the water (Poole and Berman, 2001; Cassie, 2006; Olden and Naimen, 2010). DO concentrations have been reduced in conjunction with warm stream temperatures and are exacerbated by warm, nutrient-rich agriculture returns flows, resulting in eutrophication (Jalali and Kolahchi, 2009). DO saturation concentrations have an inverse relationship with temperature meaning, as temperatures increase less DO is contained in the water (Chapra, 1997). Nutrients promote biological activity, creating large amounts of dead and decaying biomass which consumes DO from respiration during breakdown (Odum, 1956). The cumulative effects of agricultural diversions also impact Walker Lake. Water use has greatly reduced freshwater inflow into Walker Lake, resulting in a decline of lake elevation and wildlife habitat, and an increase in lake salinity (Beutel et al., 2001; Sharpe et al., 2008).

One strategy for reducing stream temperatures and increasing DO is to increase instream flow by purchasing water rights. Termed “Environmental Water Transfers,” reallocating water back to streams shows promise to improve stream temperatures by increasing the thermal capacity of the river (Elmore et al., 2015) and dilute nutrient concentrations downstream of water treatment facilities (Sunding et al., 2002; Landry, 1998; Isé and Sunding, 1998). In the Walker basin, purchased or leased water rights may be available from willing sellers as farmers reduce water use by upgrading to more efficient irrigation infrastructure or temporarily switch to less water-intensive crops

(Walker Basin Project, 2015). Congress enacted the Energy and Water Development Appropriations Act (H.R. 2419) in 2006, creating a program to acquire environmental water rights from willing sellers in the Walker Basin to increase streamflow into Walker Lake and restore aquatic and riparian habitat in Walker River (Collopy and Thomas, 2009).

Mechanistic-based hydrologic and water quality models are powerful tools that aid our understanding of hydrodynamics, water quality, and habitat effects of increased flows in water scarce regions. Models test varying hydrologic flows, subjecting them to the same physical conditions and therefore, isolating the effects that flow alone will have on water quality. Some modeling efforts have described general relationships between increased flows and river temperatures. Gu and Li (2002) found that river temperatures cool by 80% with only a 20% flow increase, providing evidence to support the utility of EWTs as well as the benefit of modeling the effects of purchases before transactions take place. Instream flows and stream temperatures on California's Shasta River were modeled by Null et al. (2010) to quantify the amount of water needed to maintain flows and stream temperatures for coho salmon (*O. kisutch*), and compare restoration alternatives. Models also suggest that reducing water temperature or diluting nutrient concentrations may improve DO (Magoulick and Kobza, 2003; van Vliet and Zwolsman, 2008; Geisler, 2005).

No research has specifically examined the effects of environmental water transfers or timing of purchases on DO concentrations in streams. To improve understanding of environmental water purchase effects on stream temperatures and DO concentrations, an hourly, 1-dimensional water quality model was developed to simulate increased flows. Hypothetical flow volumes are added to a calibrated, mechanistic simulation model, estimating stream temperature and DO concentrations. Model results provide quantitative estimates of water purchase quantity, timing, and locations that most improve Walker River temperature and DO concentrations, quantifying uncertainty and aiding management decisions. The unique and novel approach of this research will improve understanding of how increased streamflow from water purchases changes DO concentrations and stream temperature, improving habitat management for native fishes. Objectives for this research are to: 1) measure the extent and seasonality of high stream temperatures and low DO concentrations that limit cold water habitat in the Walker River and its tributaries and, 2) simulate thermal and DO changes from increased streamflow to prioritize the timing and locations that water purchases most enhance water quality and cold water habitat. Objectives one and two will be addressed by analyzing measured data and simulation modeling, respectively.

CHAPTER 2

BACKGROUND

2.1 Study Site

The Walker Basin encompasses 10,500 km^2 and is located in western Nevada and eastern California (Fig. 1). Headwaters are split between two tributaries, the East Walker and West Walker Rivers. Both tributaries drain California's east-slope Sierra Nevada Mountains (Sharpe et al., 2008). Geographically, the Walker River transitions from conifer woodland vegetation in the Sierra Nevada to sagebrush scrub in the Great Basin desert valley (Jones, 1992). The primary water source for the Walker River is snowmelt from the Sierra Nevada (Yuan et al., 2004). The river's terminus is Walker Lake, one of only six freshwater terminal lakes in the world and one of only three desert terminal lakes in North America that historically supported a freshwater fishery (Collopy and Thomas, 2009).

Three reservoirs have been built in the Walker basin to provide irrigation for agriculture. On the East Walker River, Bridgeport Reservoir has storage capacity of approximately 52 million cubic meters (mm^3) and is located at an elevation of 1950 m above sea level. West Walker River streamflow is diverted to Topaz Reservoir, an off-stream reservoir, straddling the California-Nevada state line (Yardas, 2007). Topaz Reservoir has storage capacity of approximately 73 mm^3 and sits at an elevation of 1525 m above sea level. Both tributary reservoirs are bottom release reservoirs and are physical barriers to fish passage (Jones, 1992). The East and West Walker tributaries converge south of Yerington, Nevada, to become the mainstem Walker River. The mainstem Walker River is impounded midway to Walker Lake by Weber Reservoir, with storage capacity of approximately 15 mm^3 and an elevation of 1285 m above sea level. Weber Reservoir is a bottom release reservoir but allows for fish passage using a roughened channel fishway.

Water withdrawal effects on the river and lake began in 1852 when Walker River water was diverted to irrigate agricultural lands (Horton, 1996). Agriculture is the dominant land use in the basin and is the main consumer of water. Within the basin, water is over-allocated and full water demands can only be met in wet years (Yardas, 2007). For an average snowpack year (when snowpack equals 100% of normal), 84% of agricultural water rights are satisfied. A wet year with at least 130% of normal snowpack is required to supply enough water to fulfill the entire allocation of water rights to farmers in the basin (Sharpe et al., 2008).

To meet water demands during dry years, supplemental groundwater rights were approved by the State of Nevada beginning in the 1960s. Subsequently, groundwater pumping in Smith and Mason Valleys (Fig. 1) has decreased the water table, resulting in a net increase in recharge from the Walker River to the aquifer, and created a net decrease in streamflow passing the heavily developed Wabuska area on the mainstem of the Walker River (Carroll et al., 2010). The cumulative effects of agriculture diversions and water table depression have reduced streamflow and degraded water quality in the river (e.g., high water temperatures and low DO) and Walker Lake (high total dissolved solids and reduced habitat; Fig. 2) (WRIT, 2003). Degradation to both Walker Lake and River has decreased the extent of suitable riverine habitat for LCT by 97% and eliminated LCT from Walker Lake (Coffin and Cowan, 1995; Dunham, 1999) (Fig. 3).

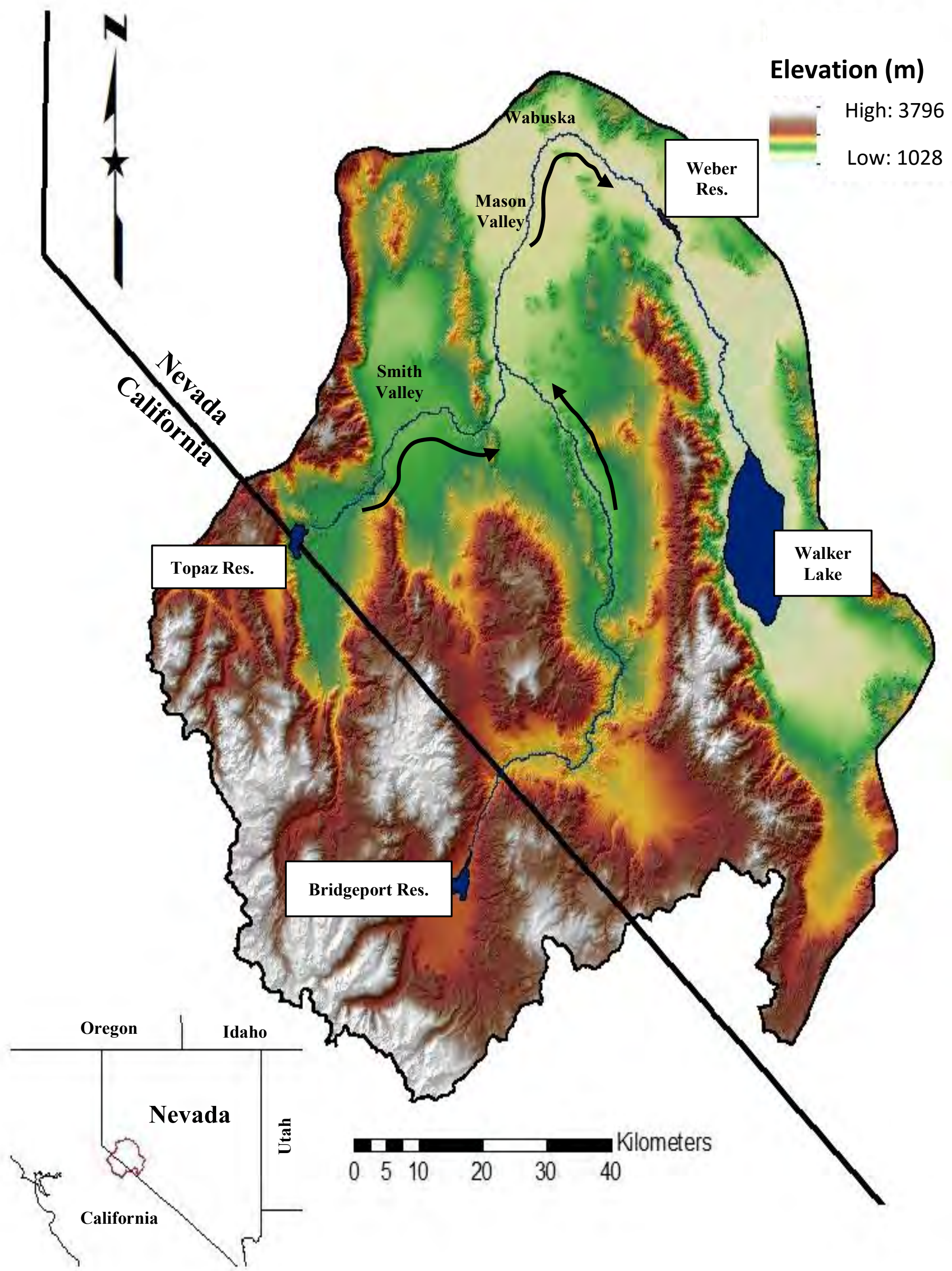

Fig. 1. Walker River Basin showing East, West, and mainstem Walker River. Arrows indicate streamflow direction.

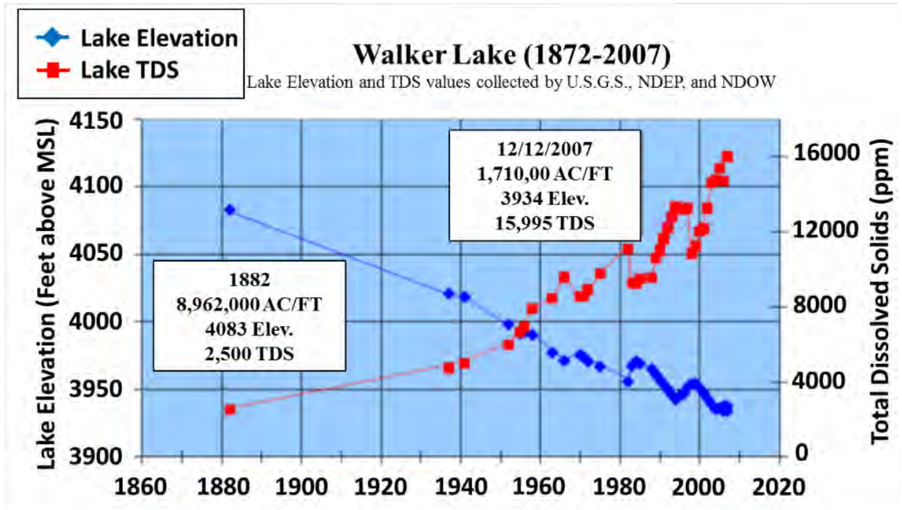

Fig. 2. Walker Lake historical elevation and corresponding total dissolved solids (adapted from Sharpe et al., 2008).

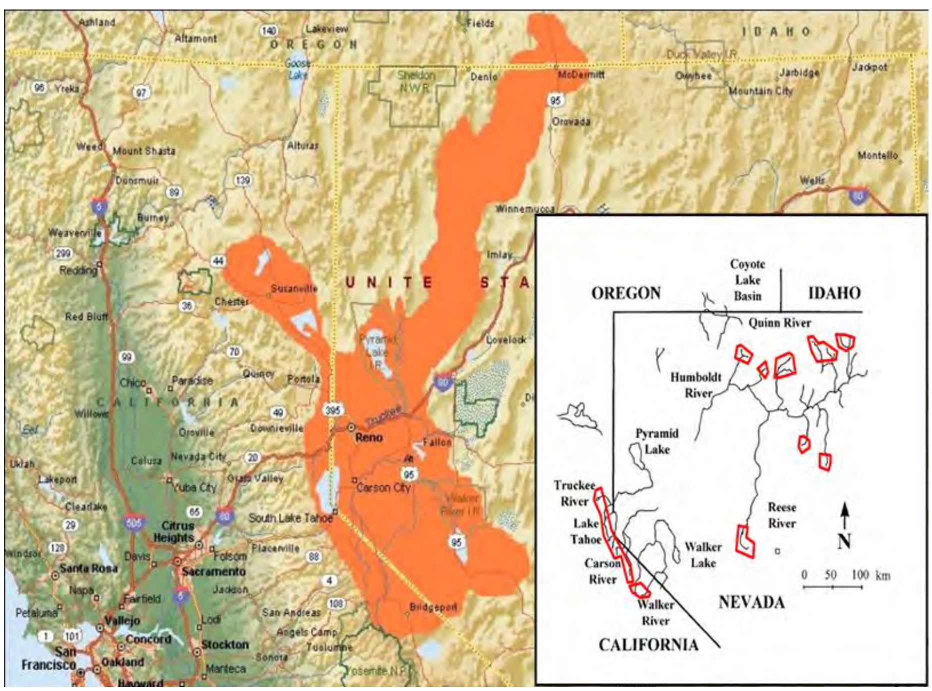

Fig. 3. Historical distribution of Lahontan cutthroat trout (orange) and current distribution (insert; red boxes) (adapted from Behnke, 2002; Dunham et al., 1999).

2.2 Walker River Hydrologic Conditions

A prolonged drought persisted for the duration of this study. Following a very wet water year (WY) in 2011, the following four years were increasingly dry (Table 1). A water year extends from October 1 through September 30. Water year 2014 (WY2014) and water year 2015 (WY2015) recorded the lowest snowpack, as a percentage of April 1st 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 (Table 2) (CDEC, 2016). At the Wabuska Drain area of the Walker River (rkm 77.52), water ceased to flow and the river became dry from September 9, 2014 until November 7, 2014, and again on August 28, 2015 until December 15, 2015 (Fig. 4). This was unprecedented in the Walker River and model results are necessarily omitted for these time periods.

2.3 Water Temperature and Stream Ecology

One parameter that determines the overall health of aquatic ecosystems in stream ecology is water temperature (Coutant, 1999). Ectothermic animal species are adapted to

Table 1
Walker Basin snowpack as percent of normal measured on April 1 of each year

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Percent	89	66	78	135	132	47	87	81	92	162	50	53	40	5

Table 2
Walker Basin snow water equivalent (SWE) in centimeters measured on April 1 of each year

Year	2010	2011	2012	2013	2014	2015
SWE (cm)	203.2	290.3	36.8	57.4	33.0	3.8

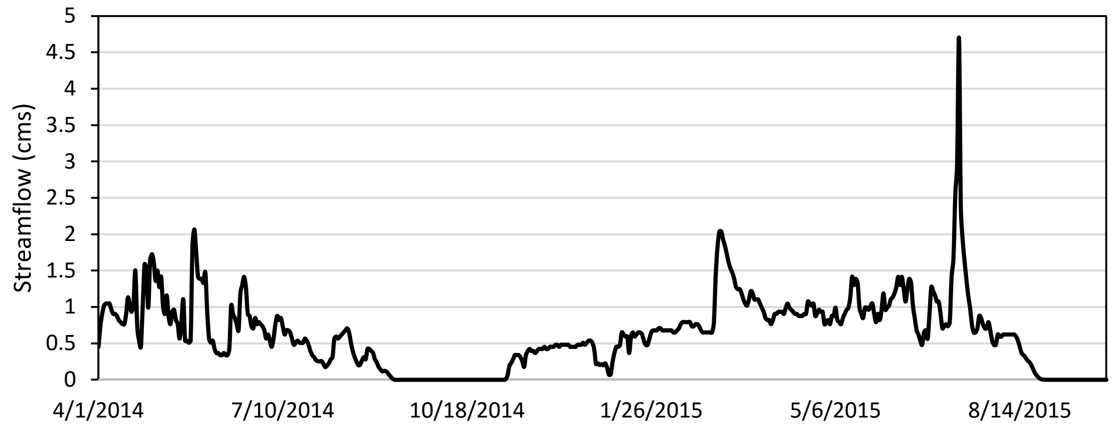

Fig. 4. Walker River streamflow at the Wabuska Drain (river kilometer 77.52) for WY2014 through WY2015.

and depend upon a characteristic temperature window of their natural environment (Pörtner, 2001). Effects on aquatic organisms are most often defined in relation to chronic (7 day) temperature stress. Laboratory tests of chronic temperature tolerance have shown that the 7 day upper thermal limit of survival and growth for LCT is between 22°C and 24°C (Dickerson and Vinyard, 1999) (Table 3). Dickerson and Vinyard (1999) found mortality was approximately 60% over seven days at temperatures exceeding 26°C and complete mortality within two days when temperatures exceeded 28°C. LCT withstood acute (< 2 hrs) water temperatures above 28°C in laboratory settings. Field studies, such as those performed in Coyote Lake, Quinn River, and the Humbolt River, suggest that LCT abundance is greatly reduced at temperatures exceeding 28°C, although emigration to cooler sites or mortality due directly or indirectly to temperature was postulated (Dunham et al., 2003). Dunham (1999) concluded that LCT avoid maximum daily water temperatures exceeding 26°C and that daily average temperatures were less consistent for determining occupied versus avoided habitat, implying that fish respond strongly to maximum, rather than mean temperatures. This finding shows promise for improving LCT survival. Elmore et al. (2015) concluded that increased streamflow in the Walker River did little to decrease mean daily stream temperatures but reduced maximum daily temperatures by up to 3°C during low flow conditions. Access to thermal refugia, where increased flows, groundwater discharge, and even irrigation canals with diurnal temperature patterns that deviate from streams, may connect habitat and provide relief from daily temperature highs, improving summer survival.

Seasonal and daily variations of water temperature are essential determinants for the distribution of aquatic organisms. River temperature controls are grouped into four main categories: (i) atmospheric conditions, (ii) shading, (iii) stream discharge, and (iv) hyporheic streambed interactions. Atmospheric conditions, including incoming shortwave radiation, longwave radiation, air temperature, relative humidity, precipitation, evaporation, and wind speed, are principally responsible for the heat exchange processes occurring at the water surface (Caissie, 2006). Comparisons of air and water temperature show air temperature is a strong driver for water temperature for the Walker River (Fig. 5), likely driven by incoming shortwave radiation (Caissie, 2006). Riparian

Table 3
Level of water temperature impairment to adult Lahontan cutthroat trout (Dickerson and Vinyard, 1999)

Level of Impairment	**Water Temperature (°C)**
Limit to avoid acute mortality	28
Severe production impairment	27
Moderate production impairment	26
Slight production impairment	25
No production impairment	24

vegetation and topography, including stream banks and hillslopes, provide shade, typically reducing atmospheric influence on water temperature. The degree of shading from banks and hillslopes depends not only on height, but also on the elevation angle of the sun and the orientation of the stream channel (Rutherford et al., 1997). Riparian vegetation also provides shade and affects stream temperature in three main ways; 1) reducing the maximum daily water temperature on cloudless, sunny days, 2) increasing the daily minimum water temperature through the partial offset of outgoing radiation emitted by the water on cloudless nights, and 3) affecting the stream micro-climate (e.g., air temperature, humidity, and wind speed), which in turn affects evaporation, conduction, ground temperature, and water temperature (Rutherford et al., 1997).

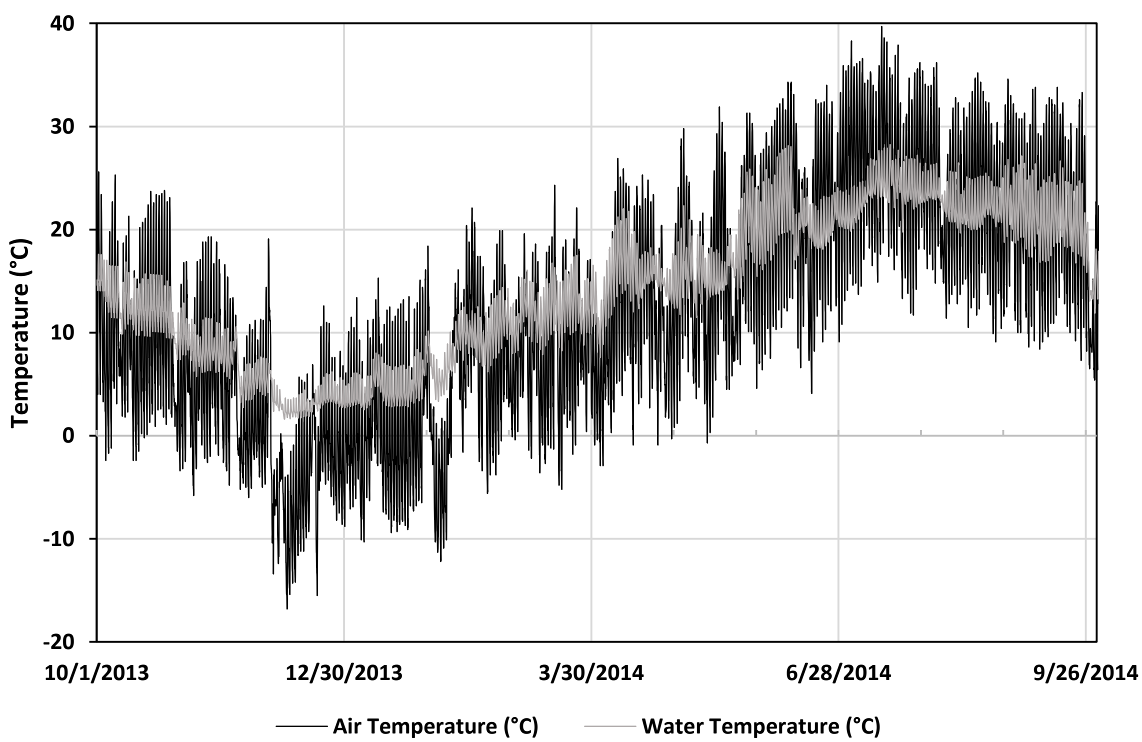

Fig. 5. Walker River hourly air and stream temperature in Mason Valley for WY2014.

Stream discharge, is a function of inflows, outflows, and with channel geometry, determines stream volume and surface area, which influences travel time and heating capacity (Caissie, 2006). Low flows decrease the assimilative heat capacity of the river, requiring less energy to increase water temperature and slow stream velocity, exposing water to atmospheric conditions longer (Poole and Berman, 2001). When low flows coincide with warm summer air temperatures, the decreased assimilative heating capacity enables atmospheric conditions to drive stream temperatures, affecting aquatic organisms negatively in some climates (Conner et al., 2003). In the Walker River, measured data indicate that high summer water temperatures coincide with high air temperatures and low streamflows (Elmore et al., 2015) (Fig. 6). Low flows also increase the degree of influence that inflows and hyporheic streambed temperatures have on the stream. In summer in agriculturally-intensive basins utilizing flood irrigation, surface return flows may be warmer than when originally diverted (Yardas, 2007). Thus, agricultural withdrawals reduce thermal mass in streams and return flow contributions may be warmer than stream temperatures, resulting in unnaturally warm downstream temperatures. In the Walker River, flow reductions and warm return flows generally warm stream temperatures longitudinally during summer (Fig. 7), although Weber Reservoir moderates stream temperatures somewhat, demonstrating temperature regulation from increased thermal capacity.

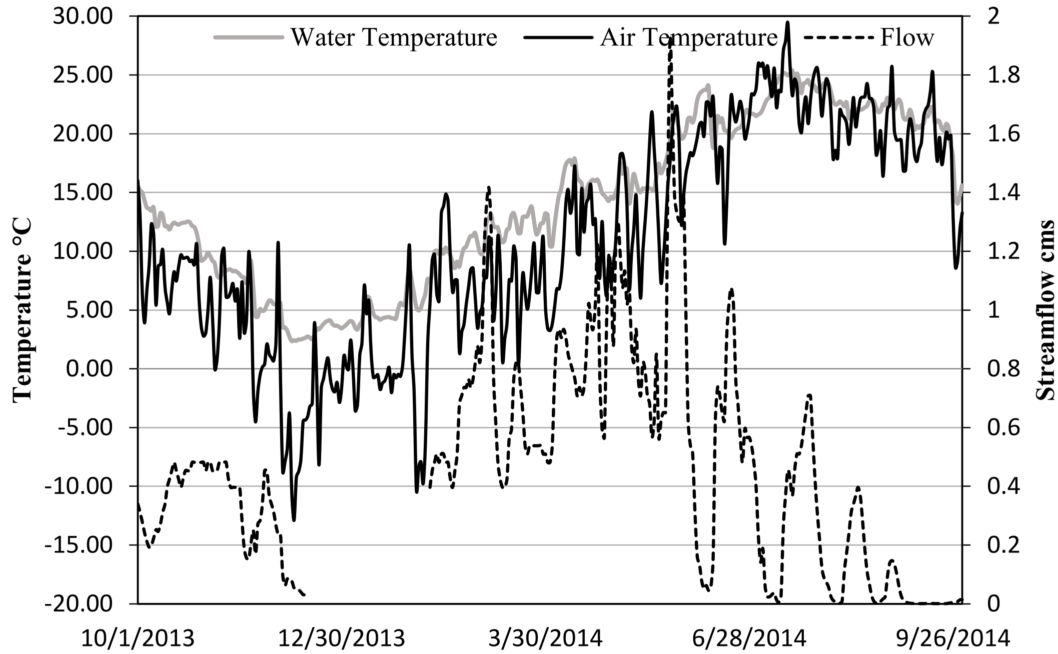

Fig. 6. Measured daily average Walker River stream temperature, air temperature, and streamflow for WY2014.

2.4 Dissolved Oxygen and Stream Ecology

DO drivers in streams can be grouped into two main categories 1) geophysical characteristics of the drainage basin, and 2) the biogeochemical and physical environment of the stream itself (O'Connor, 1967) (Fig. 8). The geophysical characteristics include air temperature of the region, drainage area and inflow, and the geographic features of the stream, such as elevation. Temperature is a function of both climate and season as well as the solar radiation that directly affects stream temperatures. Freshwater inflow determines a stream's total dissolved solids, a measure of salinity. Elevation is merely an estimation of atmospheric pressure. Geophysical characteristics (temperature, freshwater inflow, and atmospheric pressure) determine the maximum amount of DO, in milligrams

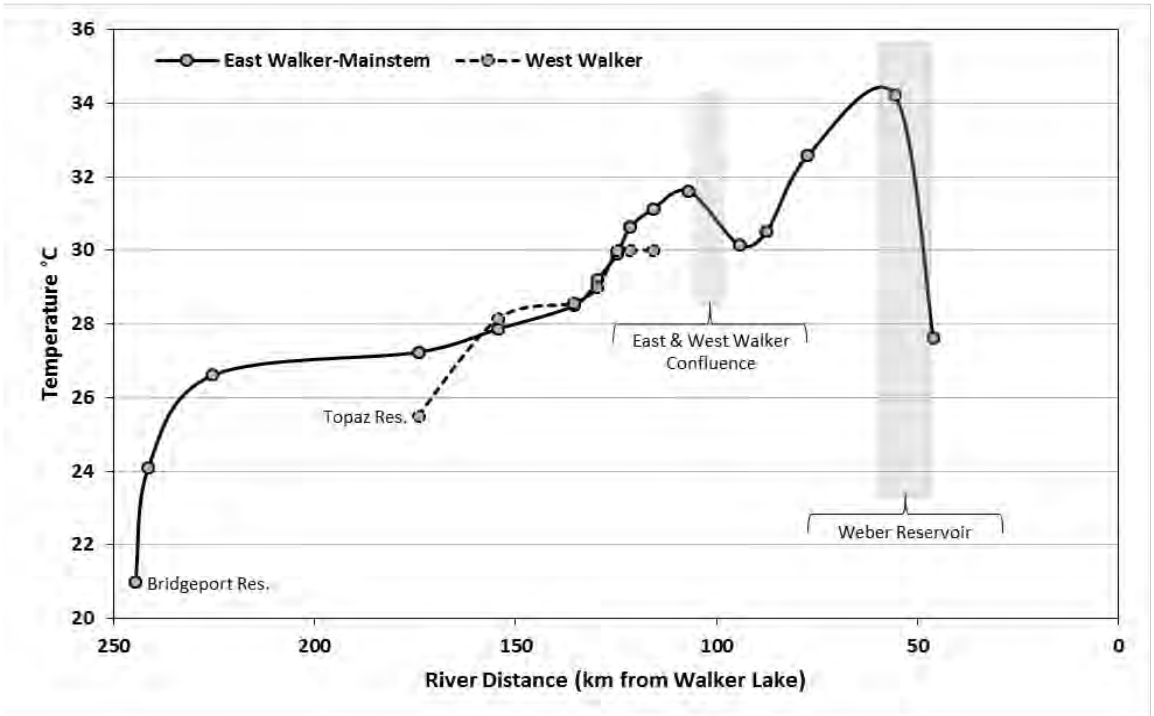

Fig. 7. Measured Walker River longitudinal stream temperature on July 13, 2014, at 17:00. Data below rkm 46.2 has been eliminated due to no streamflow between rkm 41.7 and Walker Lake.

per liter (mg/L), that water may contain in equilibrium (100% saturation) (Chapra, 1997). DO saturation concentration has an inverse relationship with each of the geophysical factors, meaning as any of these factors increase, DO saturation concentration decreases. The second category, the biogeochemical and physical environment, determines the sources and sinks of DO from either natural or manmade origins (O'Connor, 1967). DO sources are primary production and reaeration. Primary production from submerged aquatic vegetation, benthic algae (periphyton), and free floating phytoplankton all contribute to DO as a byproduct of photosynthesis (Odum, 1956). When water is undersaturated reaeration moves oxygen from the atmosphere into the water to achieve an equilibrium state of DO saturation (Chapra, 1997). In systems with low reaeration, DO

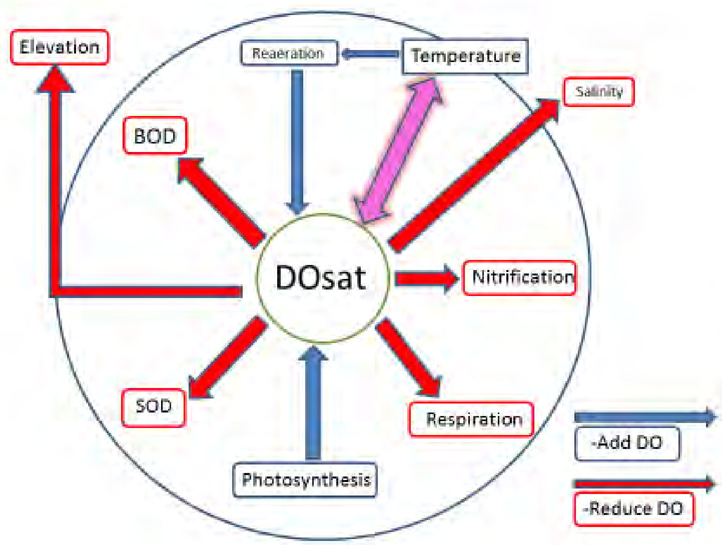

Fig. 8. Stream factors affecting dissolved oxygen in streams. Factors inside of blue circle are temperature dependent. BOD is biochemical oxygen demand, SOD is sediment oxygen demand, and DOsat is the DO saturation concentration of the water.

production is solely dependent on photosynthesis. DO sinks are respiration, nitrification, and biochemical (BOD) and sediment (SOD) oxygen demand (Chapra, 1997). The combination of sources and sinks create a diel pattern of DO concentration wherein peaks occur in the afternoon and minimums occur in the early morning before sunrise. The magnitude of the diel pattern is an indicator of biological activity and, consequently, nutrient concentrations in water (Fig. 9).

High stream temperatures reduce DO saturation concentrations and high nutrient concentrations increase biological activity. Temperature is also important to biological activity. Algal production increases exponentially as temperature increases (Khangaonkar et al., 2012). As a rule of thumb, biogeochemical reactions double for every 10°C increase (Odum, 1956). With increased biological activity comes an increase in dead and

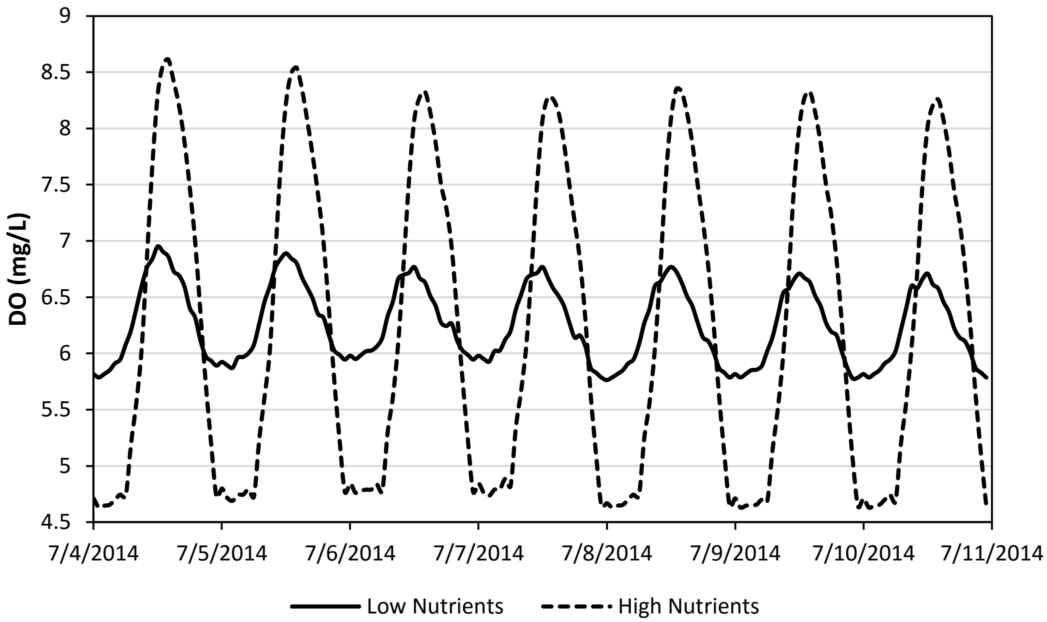

Fig. 9. Diel DO concentrations patterns due to low and high nutrients.

decomposing organic matter, reducing DO through respiration. In sum, increased temperature and high nutrients decrease DO by reducing water saturation concentration level and increasing DO consumption from respiration (Whitehead et al., 2009). Periods of low DO can cause fish death, especially in cold-water fishes such as salmonids (salmon and trout).

Salmonids are highly susceptible to low DO concentrations. Like temperature thresholds, DO must be maintained above specific levels for trout and salmon to survive and grow. Salmonid growth rates are impaired at DO concentrations below 8 mg/L, with growth rate reductions of up to 22% when concentrations drop below 6 mg/L (WDOE, 2002). Moderate production impairment begins at 5 mg/L and acute mortality begins at 3 mg/L (Carter, 2005) (Table 4).

Table 4
Dissolved oxygen concentration impairment to adult salmonids (Carter, 2005)

Level of Impairment	DO concentration (mg/L)
No production impairment	8
Slight production impairment	6
Moderate production impairment	5
Severe production impairment	4
Limit to avoid acute mortality	3

CHAPTER 3

METHODS

3.1 Model Description and Development

This study uses Tennessee Valley Authority's River Modeling System version 4 (RMS) (Hauser and Schohl, 2002). This model was chosen because it is open source, has riparian shading logic, is process-based, and is supported by Tennessee Valley Authority. RMS simulates flow, stream temperature, and dissolved oxygen for WY2014 and WY2015, both modeled on an hourly time step. Model extent is 305 km with a spatial resolution of 0.3 km. RMS is a one-dimensional, longitudinal numerical model composed of a hydrodynamic module (ADYN) and a water quality module (RQUAL) (Hauser and Schohl, 2002). The two modules are written in Fortran and are run consecutively.

ADYN, the hydrodynamic module, simulates time-varying velocity, depth, flow, and water surface elevation (Hauser and Schohl, 2002). ADYN solves one-dimensional equations for conservation of mass and momentum (St. Venant equations) using a four point implicit finite difference scheme with weighted spatial derivatives (Hauser and Schohl, 2002). Model input for this module are channel geometry, streambed roughness coefficients, upstream and lateral inflows, and initial water surface elevations and discharges.

Successful simulation by ADYN passes velocities and depths to RQUAL, the water quality module. Using the same geometric input as ADYN, RQUAL solves the mass transport equation using a Holly-Priessman numerical scheme (Hauser and Schohl, 2002). RQUAL simulates water temperature, nitrogenous (NBOD) and carbonaceous (CBOD) biochemical oxygen demand, and dissolved oxygen in rivers and advection-dominated reservoirs where the one-dimensional longitudinal flow assumption is appropriate (Hauser and Schohl, 2002). This study only focuses on results of stream temperature and DO concentrations. Model input includes meteorological data (air temperature, dew point temperature, wind speed, cloud cover, barometric pressure, solar radiation), boundary condition water quality, and initial water quality throughout the modeled stream reach. Model inputs and data sources are provided in Table 5.

Table 5
Input data types, sources, collection duration, and locations

Data Type	**Source**	**Collection Period**	**Location**
Channel Geometry	LiDAR-USFWS	2011	East, West, and mainstem Walker River
River Center-Point	Measured (Elmore et al. 2015)	2012	20 Sites along the East, West, and mainstem Walker River
Streamflow	USGS	Oct. 2014-Sept. 2015	18 USGS gaging throughout the basin
Canopy Cover	LiDAR-USFWS, Measured (Elmore et al. 2015)	2011 and 2012	East, West, and mainstem Walker River
Meteorology	UNR-DRI, MesoWEST	Oct. 2014-Sept. 2015	Smith Valley, NV
Stream Temperature	Measured	Oct. 2014-Sept. 2015	20 locations using iButtons and 10 using MiniDOTs througout the East, West, and mainstem Walker River
Dissolved Oxygen	Measured	Nov. 2014-Sept. 2015	10 locations using MiniDOTS throughout East, West , and mainstem Walker River

3.2 Channel Geometry

Walker River geometry is described by five-point river cross sections represented at 999 nodes from the outlets of Bridgeport and Topaz Reservoirs to the mouth of Walker Lake (Fig. 10). Each node was spaced evenly for the entire length of the East, West, and mainstem Walker River, a distance of 305 km. Light Detection and Ranging (LiDAR) digital terrain model data were collected in 2011 and estimate lateral elevations at 5m and 25m from the river centerline (Fig. 11) (Elmore et al., 2015). For center point depth, 20 river cross sections were measured and elevations between cross sections were interpolated, resulting in an estimated average depth of 0.94 m (Elmore et al., 2015). The stream bed roughness coefficient (Manning's n) was set to a uniform 0.05, representing a natural stream channel with weeds and pools (Chapra, 1997).

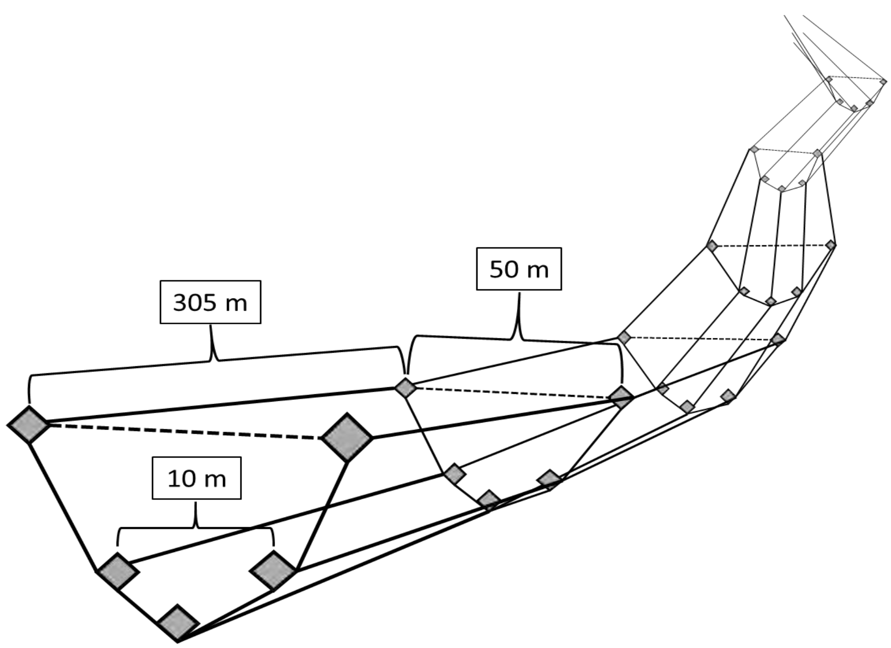

Fig. 10. Five-point river geometry schematic.

Fig. 11. LiDAR image showing five-point cross section geometry (Elmore et al., 2015).

Weber Reservoir is modeled as a spill-top weir with an internal boundary condition at rkm 46.9. For this reach, cross sectional data were unavailable. Channel geometry was therefore estimated by gradually decreasing water depth from a maximum of 9.1 m at the base of the Weber Reservoir to the closest upstream point that reservoir effects were no longer observed – a distance of approximately 6 km (Elmore et al., 2015).

3.3 Walker River Input Data and Model Development

3.3.1 Streamflow

RMS requires daily streamflow data for boundary and initial conditions. It also requires stream gains and losses, termed accretions and depletions, to account for natural streamflow volume changes, small manmade diversions, and return flows. Streamflow differences between eighteen USGS gages estimate total accretions and depletions. Accretions and depletions during non-irrigation season (November 1 – March 31) are attributed to natural seeps or losses to groundwater. The change in accretions and depletions between irrigation season (April 1-October 31) and non-irrigation season estimate agricultural diversions. Diversion records are not available and are estimated from comparisons of irrigated and non-irrigated time periods.

Diversion estimates were made based on water budgets described in the previous paragraph and previous studies conducted using Walker Basin irrigation documents (Elmore et al., 2015; Pahl, 2000; WRIT, 2003; Yardas, 2007; Sharpe et al., 2008). Approximately 80% more streamflow depletions occur during the irrigation season (April 1-October 31) between USGS gages than occur the rest of the year, which was attributed to irrigation diversions. For river reaches containing multiple diversion canals, each was assigned a percentage of the 80% depletion according to relative diversion size. Final diversion percentages are presented in Table 6. In the event of an accretion during the irrigation season, the diversion was assumed to be zero (Elmore et al., 2015). Accretions sources could be from springs, ephemeral drainages, and agricultural return, among others. Twelve major accretion/depletion reaches were determined for the Walker River (Fig. 12).

3.3.2 Measured Dissolved Oxygen and Temperature

Ten dissolved oxygen sensors were deployed from November 2013 through November 2015. The sensor selected for this extended deployment was the MiniDOT by Precision Measurement Engineering, Inc. (PME) because it is low cost, easy to use, and accurate. The MiniDOT senses and stores temperature and dissolved oxygen measurements. The dissolved oxygen sensor is an optode that measures lifetime-based

Table 6
Diversion percentages and locations (Elmore et al., 2015)

Location	***River Km***	***Diversion Name***	***Percent depletion assigned to diversion***	***Total depletion diverted between gages***
WW Reach 1	27.71	Saroni Canal (SARONI)	11%	70%
	26.01	Colony-Plymouth Canal (COLONY)	39%	
	24.68	Gage-Petersen Canal (GAGE)	20%	
WW Reach 3	8.16	Tunnel Ditch (TUNNEL)	88%	88%
EW Reach 2	77.40	Baker-SnyderNelson Greenwood Hall Hilburn Ditches (BNGHH)	25%	80%
	76.26	Fox-Mickey Ditches (FOX)	55%	
WR Reach 1	63.54	Mcleod-Campbell Ditches (MCCAMP)	33%	80%
	61.27	SAB Sciariani West-Hyland Joggles Dairy Ditches (SSWJD)	47%	

luminescence quenching of fluorescence of a thin membrane. The oxygen logger collects measurements of dissolved oxygen with an accuracy of ± 5% in the 0 to 150% oxygen saturation range and temperature with an accuracy of ± 0.1°C in the 0 °C to 30 °C temperature range (PME, 2012). The logger comes pre-calibrated by the manufacturer and requires no field calibration.

Varying elevations, streamflow volumes, water sources, nutrient concentrations, atmospheric conditions, etc. exist along the 305 km of the modeled river length. To capture this variability for model boundary conditions and calibration, dissolved oxygen loggers were deployed throughout the Walker Basin. Logger locations were determined based on river access and to capture the water quality conditions of key areas of interest. For the extended deployment, sensor housings were constructed to protect sensors and allow technicians to access them for service and data download. Two types of protective

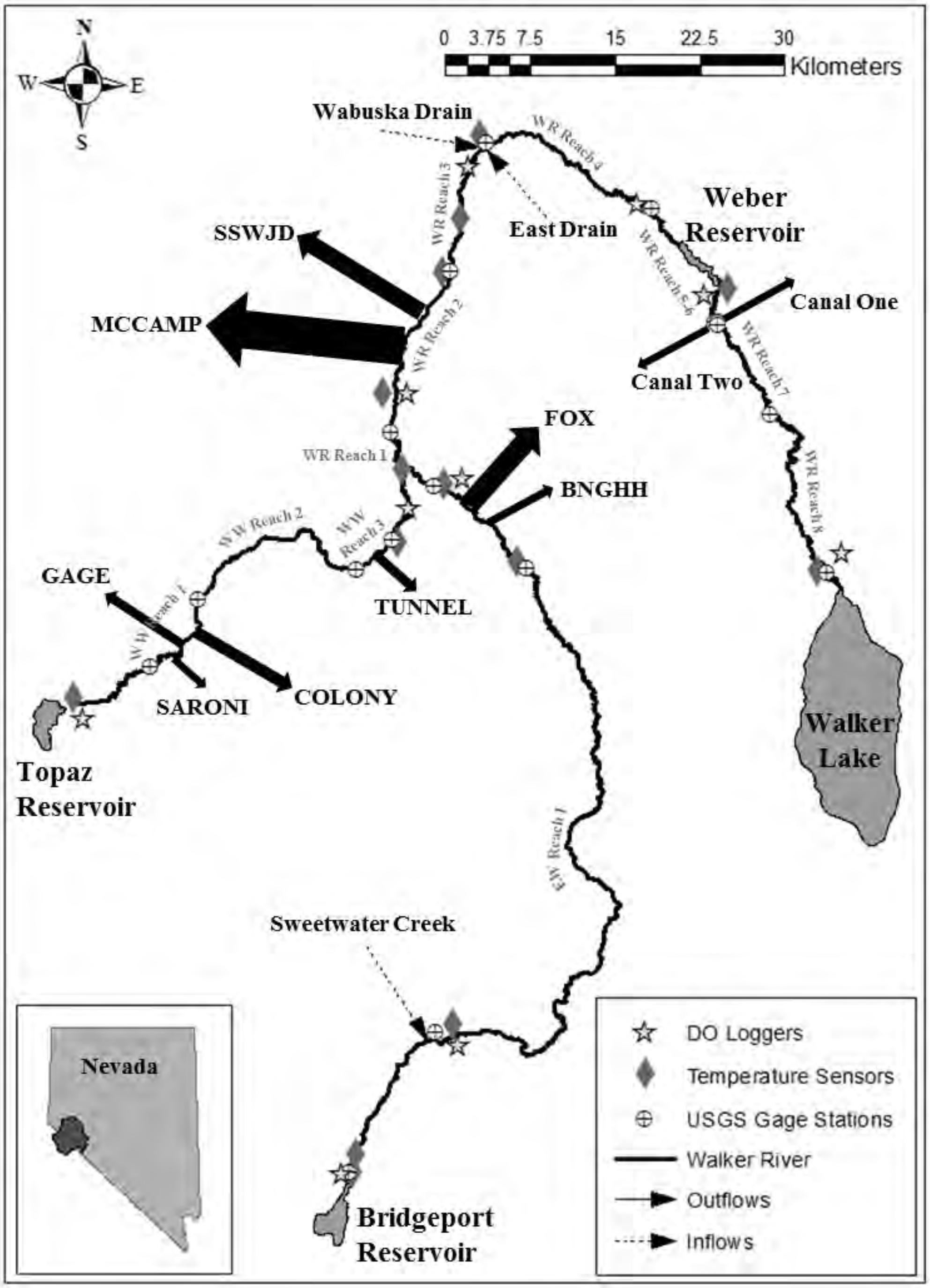

Fig. 12. Major inflows, outflows, and accretion/depletion reaches for the Walker River and its tributaries. Outflow arrow thickness is relative to average annual diversion rate (m^3/year) (Yardas, 2007); inflow arrows are not scaled with inflow rate. Diversion acronyms are provided in Table 6. EW stands for East Walker, WW stands for West Walker, and WR stands for the mainstem Walker River.

housings were designed for the PME MiniDOT's deployment (Fig. 13). The first type has PVC tubing with drilled end caps, connected to vinyl coated wires with stainless steel cable clamps, and attached using drive clamps to angled iron rebar. The second design incorporated the same PVC tubing and vinyl wire construct but was attached using 6" U-bolts inside of an 8"x8"x8" concrete half block. The second design was needed for sensor submersion in very low flows and to protect the logger from trampling by cows. Data was downloaded monthly, or bimonthly during summer, and sensor membranes and copper mesh screens covering sensors to discourage bio-growth were removed and cleaned.

In addition to the ten MiniDOT sensors, fourteen iButton temperature sensors were deployed in the basin, show in Fig. 12. At some places, where the sensor was placed at the same location as the MiniDOT, the iButton served to confirm water

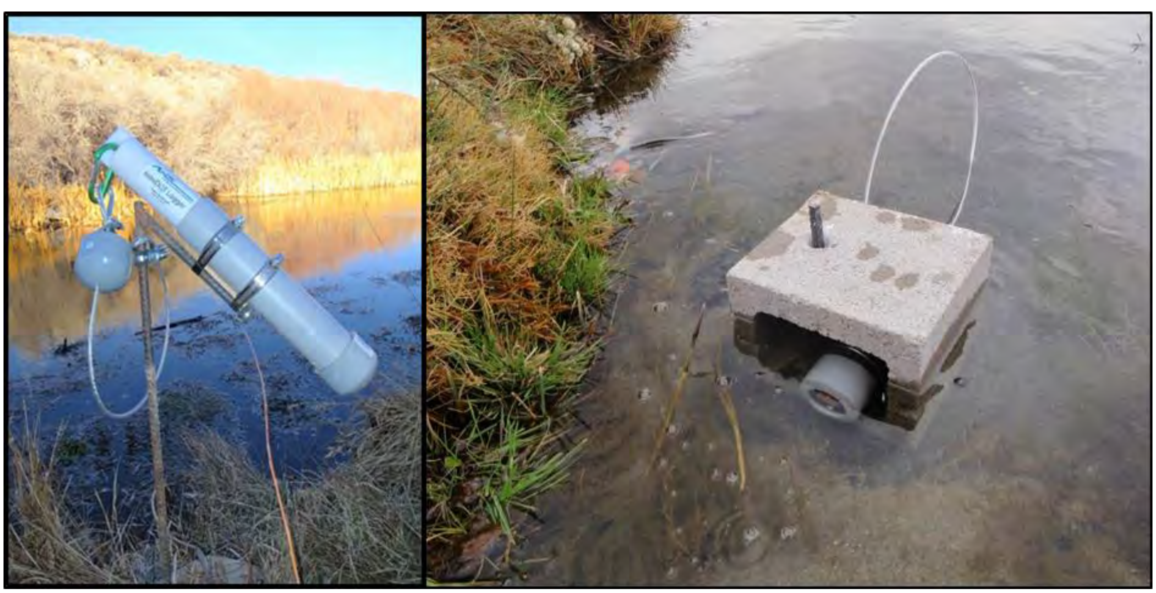

Fig. 13. MiniDOT sensor deployment housings.

temperatures. In others, iButtons provided additional data for model calibration. The iButton Model DS1921G sensors have a temperature range of -40°C to +85°C, accuracy of ±1°C, and a resolution of 0.5°C (iButton Link Technology, 2015).

3.3.3 Meteorological Data

The Smith Valley, NV, meteorological station provided input meteorological data and is managed by the Desert Research Institute (DRI) and accessed through the MesoWest website (DRI, 2014; MesoWest, 2014). Meteorological data included cloud cover, air temperature, dew point temperature, air pressure, wind speed, and solar radiation. All variables were direct downloads from the MesoWest website except for cloud cover. Cloud cover data was unavailable but known to be important for riverine modeling (Bureau of Reclamation, 2010).

Cloud cover is typically estimated from incoming solar radiation data, although specific guidelines for estimating cloud cover could not be found in the literature. For other studies, cloud cover estimates were assumed to be zero, based on the typical atmospheric conditions during modeling, or cloud cover was estimated using measured shortwave radiation (Giesler, 2005). No discussion was given pertaining to ratios or percentages of incoming solar radiation changes for assigning cloud cover fraction. I estimated cloud cover by grouping incoming solar radiation into seven day (weekly) periods, where the highest daily total was assumed to be a cloud free day and all other days in the seven day periods were reduced as a percentage of this maximum. I also tested five alternative methods for estimating cloud cover from solar radiation data (Appendix B) and found the seven day solar radiation method to be reliable. This is the same method that was used for the first application of the Walker River RMS model, years 2011 and 2012 (Elmore et al., 2015).

3.3.4 Riparian Vegetation Shading

RMS riparian shading logic estimates solar radiation transmitted through riparian vegetation. Vegetation height and type determine the amount of solar radiation transmittance. Riparian vegetation type and height was estimated by Elmore et al. (2015). Solar radiation transmittance for major vegetation types along the Walker River is: 1) 100% solar radiation transmittance for no significant vegetation (0 - 4.57 m tall), 2) 9% solar radiation transmittance for medium-height mixed shrub vegetation (5.57 - 9.14 m), and 3) 14% solar radiation transmittance for tall vegetation consisting primarily of large cottonwoods (> 9.14 m) (Elmore et al., 2015). Riparian conditions have not changed measurably since 2012.

3.3.5 Model Fit Statistics

Modeled WY2014 and WY2015 streamflow, temperature, and DO were compared to measured data to test and calibrate models. Root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE), ratio of root mean square error to standard deviation of measured data (RSR) and percent bias (PBIAS) were calculated for streamflow, stream temperature, and DO concentrations to quantify model fit (Moriasi et al., 2007). RMSE measures the difference between a measured value and a modeled value by calculating the square root of the mean of the square of all the error. Values close to zero indicate good model performance. NSE is a statistic that indicates how well the measured versus modeled data fit a 1:1 line. NSE is defined as one minus the sum of the absolute squared differences between the modeled and measured values normalized by the variance of the measured values (Krause et al., 2005). The range of NSE is between 1 and -∞, with 1 being a perfect fit. Values below zero indicate that the mean value of the measured data would be a better predictor than the model. RSR standardizes RMSE using the standard deviation of the measured data. The resulting statistic and reported values can apply to various constituents because it incorporates the benefits of error index statistics and includes a normalization factor. RSR varies from 0, indicating zero RMSE and therefore perfect model fit, to a large positive value. PBIAS measures the average tendency of the modeled data to be larger or smaller than measured counterparts. Optimal values are 0%, where positive or negative values indicate model over or underestimation. Over or underestimation in different seasons or months can average to 0%, which is misleading if this statistic is alone presented (without NSE, RSR, or RMSE). A breakdown of statistical values into model performance categories is shown in Table 7. Together all of these statistics combine to provide a robust statistical description for assessing hydrologic model fit (Moraisi et al., 2007).

Table 7
Model statistics and corresponding performance ratings (Moriasi et al., 2007)

Performance Rating	**NSE**	**RSR**	**PBIAS**	**RMSE (cms)**	**RMSE (^{o}C)**	**RMSE (mg/L)**
Very Good	0.75 < NSE ≤ 1.00	0.00 ≤RSR≤0.50	PBIAS < ±10	RMSE < 0.14	RMSE < 1.0	RMSE < 1.0
Good	0.65<NSE ≤0.75	0.50 <RSR≤0.60	±10 ≤PBIAS < ±15	0.14≤RMSE<0.28	1.0≤RMSE<1.75	1.0≤RMSE<1.75
Satisfactory	0.50<NSE ≤0.65	0.60 <RSR≤0.70	±15≤ PBIAS <±25	0.28≤RMSE<0.71	1.5≤RMSE<2.25	1.5≤RMSE<2.25
Poor	NSE ≤0.50	RSR>0.70	PBIAS ≥ ±25	RMSE > 0.71	RMSE >2.25	RMSE >2.25

The model was calibrated by adjusting daily flow volumes and diversion percentages for streamflow, heat exchange coefficients for stream temperature, and DO coefficients for DO concentrations to improve model fit. Streamflows and diversion percentages were adjusted to maintain enough streamflow during the extremely dry study years (~ 0.06 - 0.14 cms) so that models did not crash. Added water was subtracted downstream (at the next node) to maintain conservation of water mass. Twelve USGS streamflow gages, 10 iButton temperature loggers, and five MiniDOT DO sensors were used for streamflow, temperature, and DO calibration, respectively. Table 8 lists parameters that were adjusted to calibrate stream temperature while Tables 9 and 10 list parameters that were adjusted to calibrate DO.

Water temperature coefficients were unchanged from WY2011 and WY2012 RMS models (Elmore et al., 2015) (Table 8). Recalibrating temperature coefficients provided a slightly better model fit for WY2014 and WY2015, although WY2011 and WY2012 coefficients maintained a good fit (discussed further in results). I used the WY2011 and WY2012 heat exchange coefficient values to facilitate model comparison for all years and to not skew model calibration for the extremely dry conditions observed in WY2014 and WY2015.

Coefficients that control the production and reduction of DO were determined based on typical values suggested in the literature and by adjusting coefficients to values that provided best fit of measured to modeled DO concentrations (Table 10). Photosynthesis rate (PMAX20, $gO_2/m^2/hr$), macrophyte respiration rate (RESP20, $gO_2/m^2/hr$) and sediment oxygen demand (SOD) rate (SK20, $gO_2/m^2/day$) coefficients were estimated based on statistical fit. PMAX20 values were adjusted in an effort to match daily peaks of measured DO concentrations. Walker River PMAX20 values remained within the ranges of previous studies (high of 1.48 gO2/m2/hr, low of 0.29 gO2/m2/hr) (Geisler 2005; Westphal and Lefkowitz 2011). Literature on water quality models state that RESP20 values commonly fall between 10%-30% of PMAX20 (Chapra, 1997; Hauser and Schohl, 2002). For my model, efforts were made to assign RESP20 values at 20% PMAX20, although one reach required a RESP20 value at 23% of PMAX20 to maintain diurnal timing. These values are similar to estimated RESP20 for a study using RMSv4 in California's Shasta River (Geisler 2005; Appendix C). Remaining differences between modeled and measured DO were attributed to SOD (SK20) and coefficients adjusted accordingly. SOD values were similar to or slightly higher than published maximum SOD rates of 2.0 to 2.3 gO2/m2/day range (Geisler 2005; Westphal and Lefkowitz 2011). See Appendix C for additional detail. Due to changing environmental conditions, such as accumulation or reduction in macrophyte or periphyton cover and SOD, site specific coefficient values for PMAX20, RESP20, and SK20 were calibrated to different values between WY2014 and WY2015.

Different calibrated photosynthesis, respiration, and SOD rates in WY2014 and WY2015 represented environmental conditions that varied during the two irrigation seasons. First, flows were lower overall in WY2015 than WY2014, cooling nighttime temperatures. Cooler temperatures allowed nightly DO saturation concentrations to remain higher, preventing DO concentrations from decreasing to values that occurred

Table 8
Heat exchange coefficients calibrated in RQUAL (Hauser and Schohl, 2002)

Parameter	Parameter Description	Final Value	Suggested range or value
AA	Wind speed coefficient in wind-driven evaporative cooling	1.8e-09	0.5e-9 to 4e-9
BB	Wind exponent in wind-driven evaporative cooling	1.0e-9	1e-9 to 3e-9
XL	Upper layer bed thickness (cm)	21	5 to 50
XL2	Deep layer bed thickness (cm)	200	10 to 200
DIF	Thermal diffusivity of bed material (cm^2/hr)	50	25-50
CV	Bed heat storage capacity (cal/cm^3 °C)	0.68	0.4-0.7
BETW	Fraction of solar radiation absorbed in water surface	0.4	0.4
BEDALB	Albedo of bed material	0.1	0.1 to 0.5
SHSOL	Fraction of solar radiation absorbed by shaded water	0.4	0.0 to 1.0
SHDBT	Fraction of drybulb/dewpoint temperatures depression by which drybulb temperature is cooler over shaded water	0.5	0.0 to 1.0

during WY2014. Second, in WY2015 the Walker Basin experienced a wetter spring and summer than WY2014 (NWS, 2016). Rain events are not represented in snowpack or snow water equivalent measurements from winter precipitation detailed in Tables 1 and 2. Rain events rapidly changed streamflow well above volumes released by Bridgeport and Topaz Reservoirs. One such event occurred during the second week of July, 2015, when releases from neither Bridgeport Reservoir nor Topaz Reservoir accounted for the increased streamflow (Fig. 14). Streamflow increased 6-fold from 0.79 cms on July 7 to 4.70 cms on July 12, 2015. This event flushed the river, potentially reducing SOD and allowing higher DO concentrations for the remainder of the irrigation season. Large suspended sediment loads from the sudden runoff could have scoured benthic algae, removing oxygen consuming biota (Butts and Evans, 1978; Francoeur and Biggs, 2006).

For these reasons, I calibrated lower SOD rates for the entire irrigation season in WY2015 versus WY2014.

Table 9
Dissolved oxygen coefficients for photosynthesis and respiration calibrated in RQUAL (Hauser and Schohl, 2002)

Parameter	**Parameter Description**	**Final Value**	**Suggested range or value**
THR	Temperature correction coefficient for reaeration	1.024	1.024
THB	Temperature correction coefficient for CBOD decay	1.047	1.047
BK20	Deoxygenation rate at 20°C for CBOD (1/day)	0.2	0.2
THN	Temperature correction coefficient for NBOD decay	1.09	1.09
NK20	Deoxygenation rate at 20°C for NBOD (1/day)	0.2	0.2
THS	Temperature correction coefficient for SOD	1.065	1.065
EXCO	Light extinction coefficient	0.1	0.05-0.3: 0.05 clean water, 0.3 turbid water
HMAC	Average macrophyte height from bottom of channel (ft)	1.0	1-3 ft
THPR	Temperature correction coefficient for macrophyte photosynthesis and respiration	1.08	1.08
BS20	CBOD settling rate (1/day)	0.656	Calculated: K_s=v_s/depth, assume v_s=0.3 m/d, depth=Avg. depth of river (ft)
WFAC	Weir aeration equation multiplication factor	1.0	-1.0 – 1.0
EQV	Weir aeration efficiency at 15°C (E15)	0.5	0 - 1.0
SFAC	Factor to multiply all SK20 in reach to test sensitivity	1.0	1.0
SK20	SOD rate (gO_2/m^2/day)	See Table 10	Reach specific
PFAC	Factor to multiply all PMAX20 in reach to test sensitivity	1.0	1.0
PMAX20	Photosynthetic rate for attached algae (gO_2/m^2/hour)	See Table 10	Reach specific
RFAC	Factor multiplying all RESP20 in reach to test sensitivity	1.0	1.0
RESP20	Attached algae respiration rate (gO_2/m^2/hour)	See Table 10	Reach specific: 0.1 to 0.3 times PMAX20

Table 10
Photosynthesis rate (PMAX20), respiration rate (RESP20) and SOD rate (SK20) calibrated for WY2014 and WY2015. PMAX20 & RESP20 = $gO_2/m^2/hr$; SK20 = $gO_2/m^2/day$

		WY2014			WY2015		
	River Kilometer	PMAX20	RESP20	SK20	PMAX20	RESP20	SK20
Reach 1	225.37	1.48	0.296	3.72	1.35	0.270	3.52
	121.51	0.39	0.078	3.75	0.39	0.090	5.65
	111.74	0.34	0.068	1.98	0.42	0.084	1.05
	87.60	0.36	0.072	4.85	-	-	-
	77.52	-	-	-	0.50	0.100	0.95
Reach 2	0.92	0.82	0.164	3.20	0.37	0.074	0.57

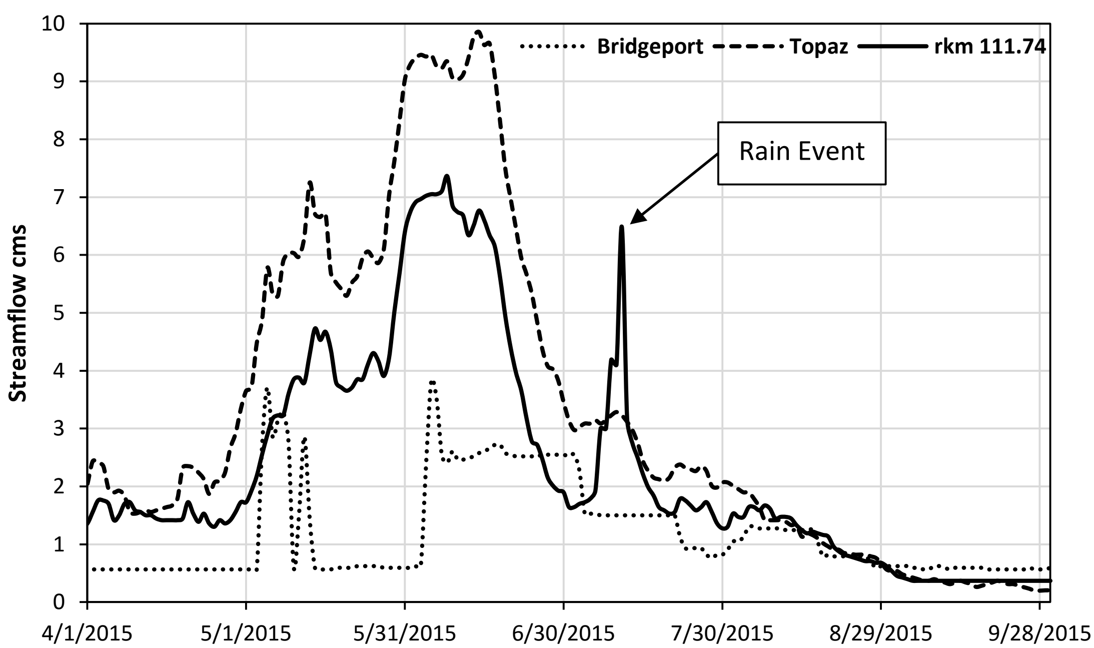

Fig. 14. Streamflow from Bridgeport Reservoir, Topaz Reservoir, and USGS gage 10300600 at rkm 111.74 (just below confluence on mainstem Walker River).

3.3.6 Model Runs

Environmental water transfers were represented as reduced diversions or increased reservoir outflow (stored water rights) during the irrigation season. Additional model runs representing reduced oxygen consuming processes or sediment oxygen demand were also completed. Model runs completed for WY2014 and WY2015 are described below.

Seventeen model runs each were completed for WY2014 and WY2015, one "Historical Condition" run and 16 alternative condition runs (Table 11). The Historical condition run was based on the current conditions of flow, stream temperature, and DO concentrations. This run was the calibrated condition and to which all other run performances were measured. The first alternative run represented existing environmental water transfers throughout the irrigation season. Existing water purchase rates are based on water year type. Both WY2014 and WY2015 were critically dry years. Daily existing transfers are not uniform. Each day has a different streamflow rate assigned based on the seniority of the right. For simplicity, all model run rates in Table 11 are given as the average for the entire irrigation season.

"Diversion Off" model runs depict alternatives with no diversions at specific locations, leaving the water as streamflow. Large water transfer alternatives of 0.71 cms and 1.41 cms were completed only for locations where this quantity of water had been diverted with current conditions (Bridgeport, Topaz, McCamp, and SSWJD). (Note: 0.71 cms equals 25 cfs and 1.41 cms equals 50 cfs.) Instream flows from "Diversions Off" could equal, but not exceed, the largest amount of water that had been diverted on any specific day with the current conditions model run. For example, for the 0.71 cms model run at the SSWJD diversion, if the current conditions daily canal diversion was greater than 0.71 cms then 0.71 cms was left as instream flow each day and the excess diverted to SSWJD. If less than 0.71 cms had been diverted with current conditions, then all water was left as instream flow from that location. In this way, no water was added to the system during environmental water transfer alternative model runs, except for four model runs representing increased outflow from the two reservoirs (Bridgeport and Topaz) that serve as the boundary condition inputs. One model run, No Diversions, diverted no water from any canal, allowing all water released at Bridgeport and Topaz Reservoirs to flow to Walker Lake and represents an upper bound of environmental water transfer effects on instream flow and quality.

Sensitivity analyses of respiration and sediment oxygen demand on DO were also performed. Nine model runs for each year represented a reduction in nutrient concentrations in the surface water. Reductions of 10, 20, and 30% of oxygen consuming factors (RESP20 and SK20) were tested to determine their sensitivity to lowering daily DO.

Finally, only irrigation season flow, temperature, and DO are analyzed and reported. Modeled winter stream temperatures under-predicted measured temperatures by up to 10 ^{o}C. This is caused by model code that ignores the heat of condensation for warmer river systems such as those found in the U.S. Southeast (Elmore et al., 2015). Rather than modify model code, results focus on irrigation season from April 1-September 30, the pertinent time period for environmental water transfers.

Table 11
Model runs for WY2014 and WY2015

		Bridgeport	Topaz	SARON	COLONY	GAGE	TUNNEL	BNGHH	FOX	MCCAMP	SSWJD
Historical Conditions		-	-	-	-	-	-	-	-	-	-
Existing	WY2014	0.11			0.11	0.11		0.11			0.11
Transfers	WY2015	0.11			0.11	0.11		0.11			0.11
Daily Additions (0.71 cms)		0.71	0.71								0.71
Daily Additions (1.41 cms)		1.41	1.41								1.41
SARON Off	WY2014			0.08							
	WY2015			0.03							
COLONY Off	WY2014				0.27						
	WY2015				0.11						
GAGE Off	WY2014					0.14					
	WY2015					0.06					
TUNNEL Off	WY2014						0.28				
	WY2015						0.16				
BNGHH Off	WY2014							0.12			
	WY2015							0.28			
FOX Off	WY2014								0.25		
	WY2015								0.13		
MCCAMP Off	WY2014									0.73	
	WY2015									0.71	
SSWJD Off	WY2014										0.51
	WY2015										0.58
No Diversions	WY2014	-	-	0.08	0.27	0.14	0.28	0.12	0.25	0.73	0.51
	WY2015	-	-	0.03	0.11	0.06	0.16	0.28	0.13	0.71	0.58

CHAPTER 4

RESULTS

4.1 Measured Data

Measured stream temperatures indicate that acute (>28 °C) temperature thresholds are exceeded for the Walker River during the irrigation season. Exceedances occur more often and to a greater extant in the lower reaches (rkm 121.51 of EW to rkm 77.52 mainstem WR and rkm 10.09 to the confluence on WW) of both the East and West Walker tributaries and the mainstem Walker River during summer months (Fig. 15; Fig. 16). Higher stream temperatures were measured during WY2014 than WY2015, despite greater flow in WY2014. High temperatures persist in WY2014 from approximately early June to mid-August. WY2015 develops the same temperature profile in early June but a substantial decrease in stream temperature occurs in early July and persists for the duration of the irrigation season. Temperature logger burial and dry river conditions reduced the measured temperature timeframe in some reaches of mainstem Walker River for WY2015.

Measured DO indicates that concentrations fell below chronic production impairment thresholds (<6.0 mg/L) at all measured locations on the Walker River during the irrigation season in both WY2014 and WY2015 (Fig. 17; Fig. 18). In WY2014, acute (<3.0 mg/L) limits were exceeded periodically in all but the most upper reach of the East Walker River at rkm 225.37. Measured data indicates that DO concentrations generally worsen downstream in the Walker River (Fig. 19). During WY2015, the

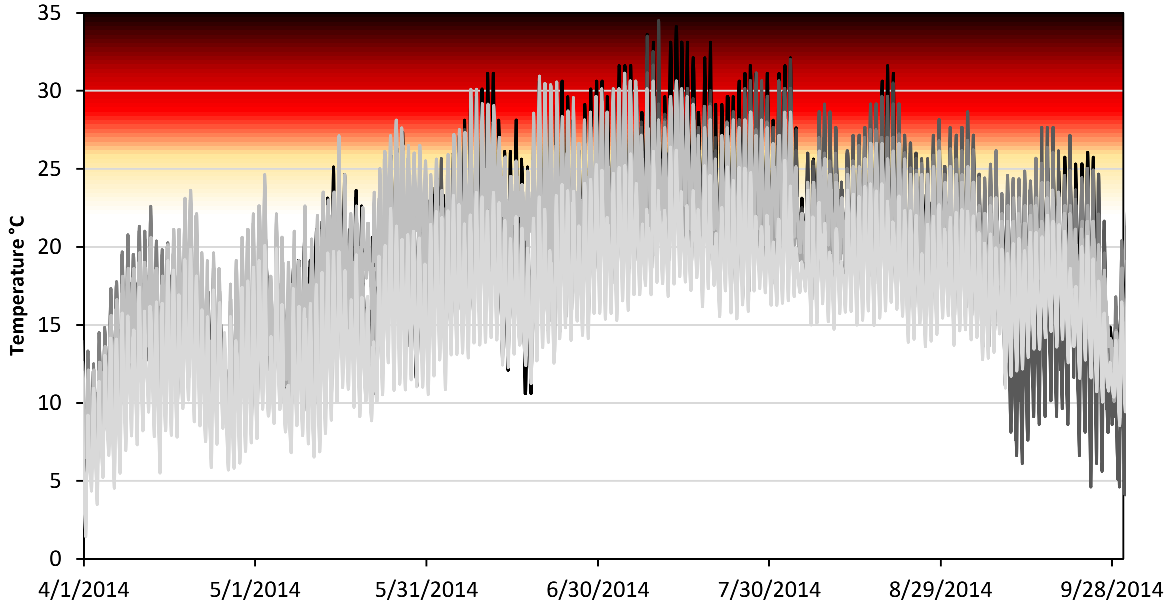

Fig. 15. Measured stream temperatures from Bridgeport and Topaz Reservoirs to rkm 77.83 for WY2014. Lighter hues are towards headwaters, hues darken downstream. Figure gradient represents LCT acute (28°C) upper thermal temperature limit (Dickerson and Vinyard 1999).

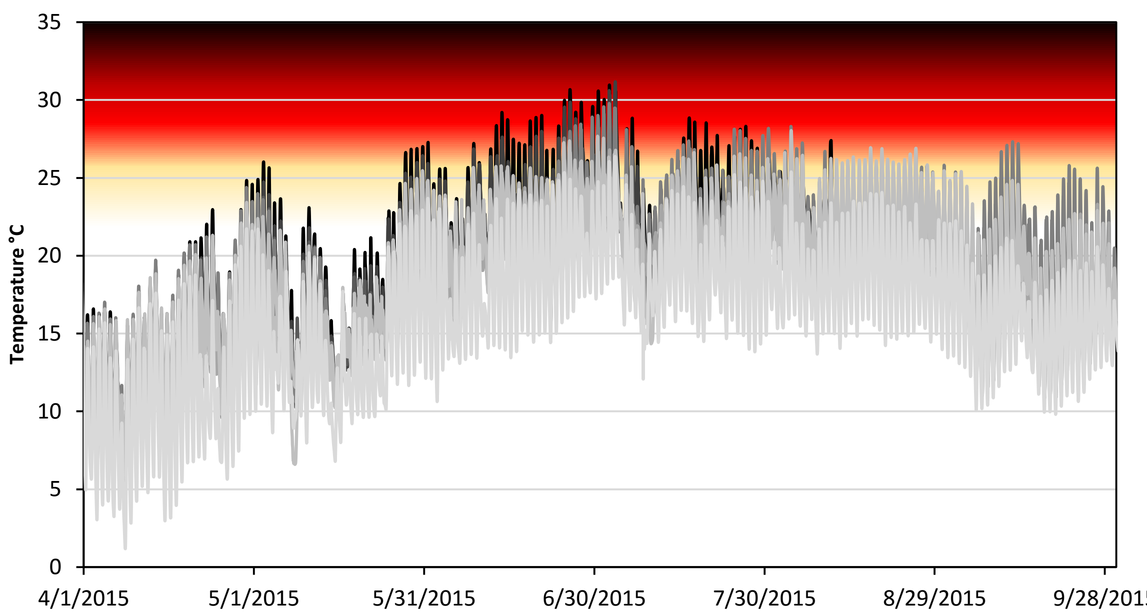

Fig. 16. Measured stream temperatures from Bridgeport and Topaz Reservoirs to rkm 77.83 for WY2015. Lighter hues are towards headwaters, hues darken downstream. Figure gradient represents LCT acute (28°C) upper thermal temperature limit (Dickerson and Vinyard 1999).

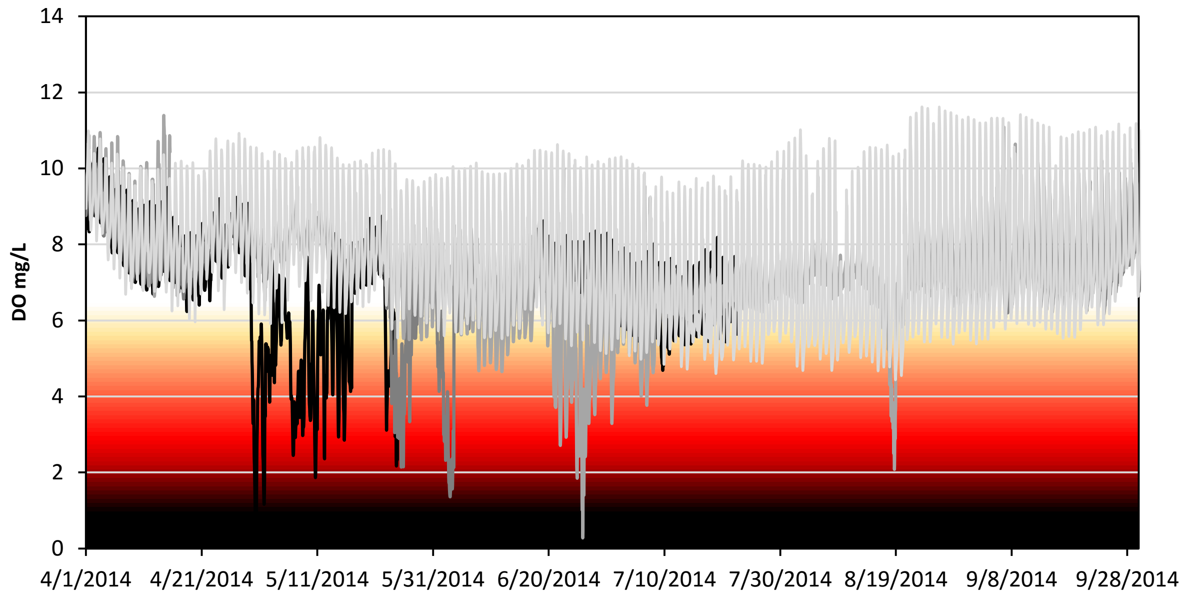

Fig. 17. Measured DO concentrations for WY2014. Lighter hues are towards headwaters, hues darken downstream. Figure gradient represents salmonid production impairment concentrations from slight impairment (<6.0 mg/L) to acute mortality (3.0 mg/L) (Carter 2005).

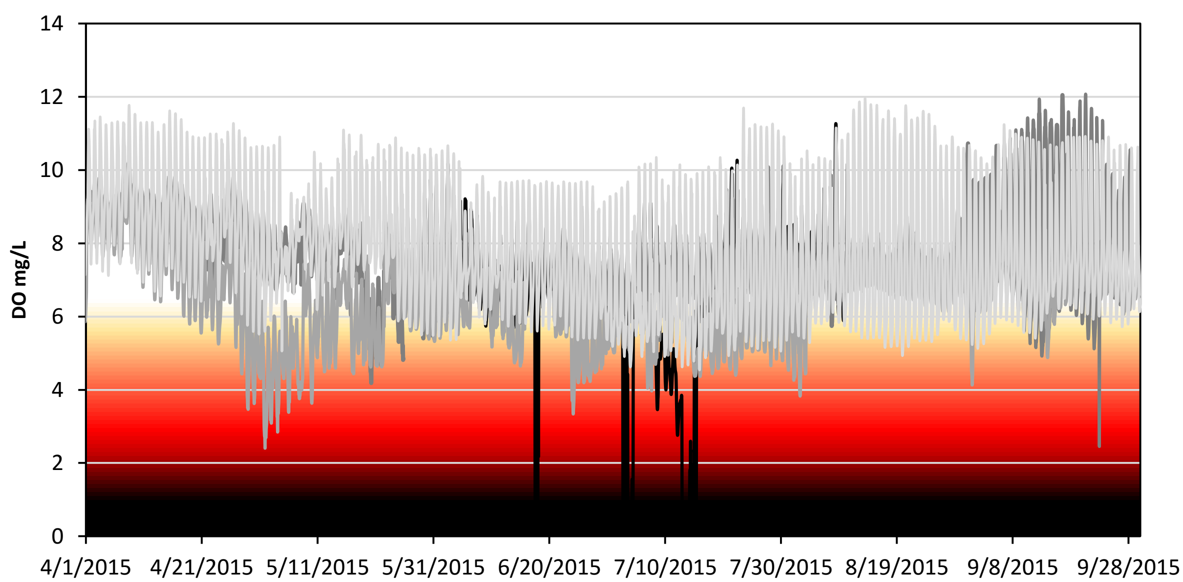

Fig. 18. Measured DO concentrations for WY2015. Lighter hues are towards headwaters, hues darken downstream. Figure gradient represents salmonid production impairment concentrations from slight impairment (<6.0 mg/L) to acute mortality (3.0 mg/L) (Carter 2005).

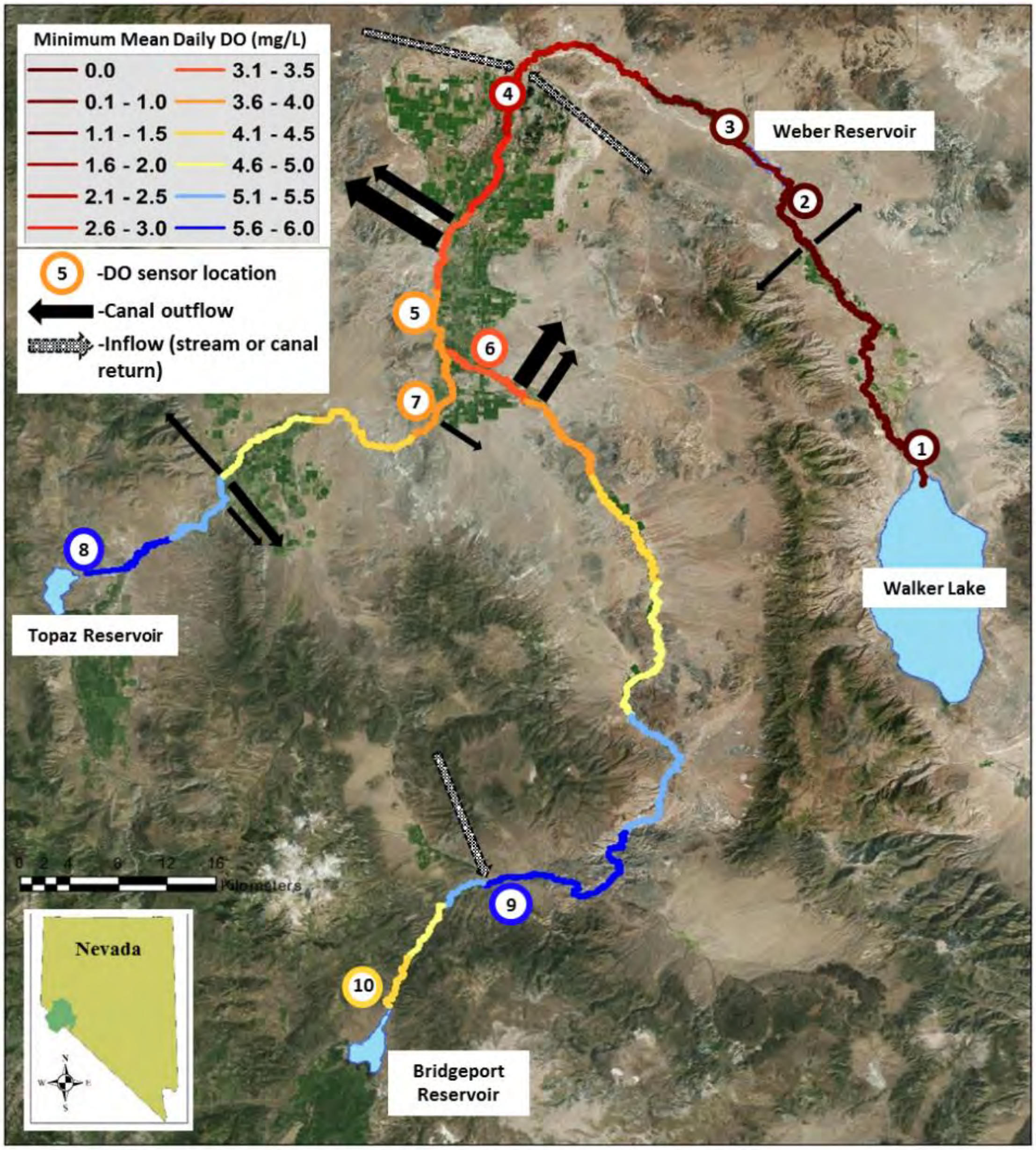

Fig. 19. Walker River Basin showing stream colors indicating lowest measured mean daily DO concentrations, in mg/L, for WY2014. Black arrows indicate agricultural canal outflows scaled to average canal flow volume. Spotted arrows represent inflows (either natural streams or agriculture return canals).

entire West Walker tributary and upper East Walker tributary remained above acute limits but occasionally dropped to concentrations below moderate (<5.0 mg/L) impairment. Below rkm 121.51 in the lower East Walker River and the Walker River to the Wabuska Drain area (rkm 77.52) recorded DO concentrations below acute thresholds limit for salmonid habitat at some point during irrigation season.

4.2 Calibration Results

Due to prolonged drought, model results exclude flow and water quality data from rkm 47.28 to 0 (outflow of Weber Reservoir to mouth of Walker Lake). Periods of no flow were frequently measured between rkm 47.28 and rkm 42.51. Zero flow was measured downstream of rkm 41.77 from November 25, 2013 through the end of the study. At those times, all flow released from Weber Reservoir was diverted resulting in a dry and disconnected river from Weber Reservoir at rkm 41.77 to Walker Lake at rkm 0. Measured temperature and DO downstream of Weber Reservoir are not representative of a flowing stream but rather of ponded water or low flow spring seeps. For this reason, model results for DO are reported to the most downstream monitoring site with measurable flow located at rkm 77.83.

4.2.1 Streamflow

Overall, both modeled years fit measured irrigation season data well (Fig. 20; Fig. 21). Average annual WY2014 irrigation season streamflow has an RMSE of 0.12 cms, NSE of 0.96, RSR of 0.17, and PBIAS of 3.48%, and WY2015 irrigation season streamflow has an RMSE of 0.14 cms, NSE of 0.97, RSR of 0.14, and a PBIAS of 3.62% (Table 12). Very good model fit reflects low instream flow conditions.

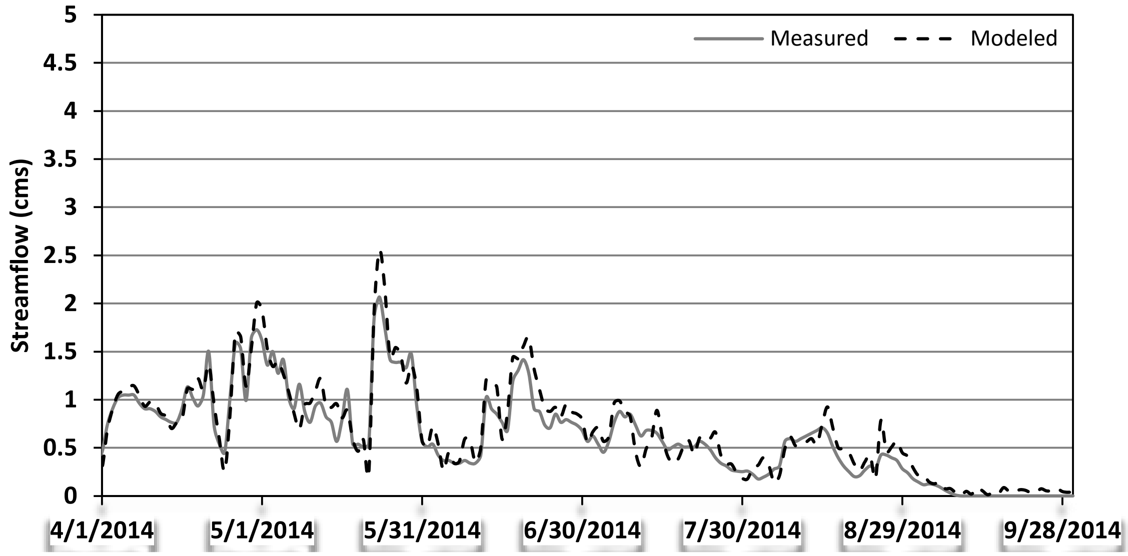

Fig. 20. Measured versus modeled daily streamflow for WY2014 at rkm 77.83.

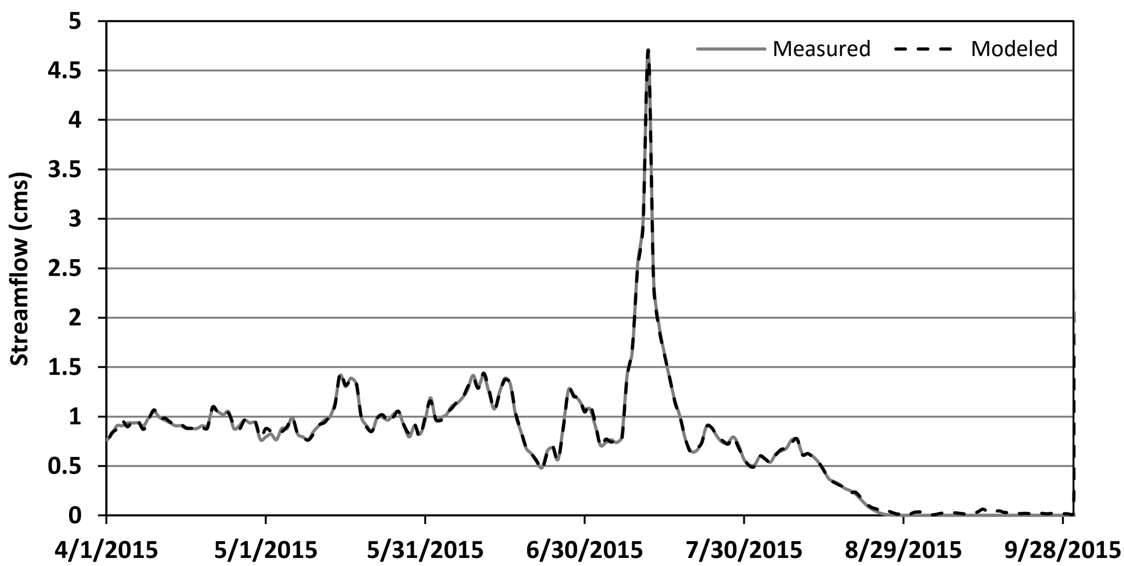

Fig. 21. Measured versus modeled daily streamflow for WY2015 at rkm 77.83.

Table 12
Measured versus modeled WY2014 and WY2015 streamflow statistics

WY2014 River	River Km	RMSE (cms)	NSE (unitless)	RSR (unitless)	PBIAS (%)	n (days)
East Walker	137.39	0.06	0.95	0.22	0.55	183
	121.51	0.06	0.94	0.24	4.49	183
Reach Statistics	-	**0.06**	**0.95**	**0.23**	**2.52**	**183**
Walker	112.81	0.27	0.97	0.17	5.43	183
	94.32	0.15	0.91	0.30	6.80	161
	77.83	0.16	0.96	0.19	8.59	161
	53.38	0.09	0.96	0.21	4.25	161
Reach Statistics	-	**0.17**	**0.95**	**0.22**	**6.27**	**166**
West Walker	37.27	0.06	1.00	0.02	0.04	183
	14.97	0.11	1.00	0.06	0.15	183
	10.39	0.15	0.99	0.08	1.03	183
Reach Statistics	-	**0.11**	**1.00**	**0.05**	**0.41**	**183**
	Average	**0.12**	**0.96**	**0.17**	**3.48**	**176**
WY2015 River						
East Walker	137.39	0.18	0.92	0.28	4.62	183
	121.51	0.12	0.87	0.35	17.48	183
Reach Statistics	-	**0.15**	**0.90**	**0.32**	**11.05**	**183**
Walker	112.81	0.45	0.94	0.23	11.32	183
	94.32	0.02	1.00	0.03	0.62	174
	77.83	0.02	1.00	0.02	0.28	150
	53.38	0.05	0.98	0.14	-0.68	149
Reach Statistics	-	**0.14**	**0.98**	**0.11**	**2.88**	**164**
West Walker	37.27	0.11	1.00	0.03	0.23	183
	14.97	0.11	1.00	0.05	0.55	183
	10.39	0.18	0.99	0.08	-1.81	183
Reach Statistics	-	**0.13**	**1.00**	**0.05**	**-0.34**	**183**
	Average	**0.14**	**0.97**	**0.14**	**3.62**	**175**

4.2.2 Stream Temperature

RMS stream temperature parameter calibration values from WY2011 (wet year) and WY2012 (dry year) stream temperature modeling efforts (Elmore et al., 2015) were maintained for WY2014 and WY2015 to further test model fit. Overall, the calibrated values still held well for both WY2014 and WY2015, although modeled daily highs and diurnal magnitude were somewhat muted in both years (Fig. 22; Fig. 23). This is unlikely to affect average temperature results, but may underestimate daily high temperatures and overestimate daily low temperature results. Modeled stream temperature results in the critically dry years may thus be conservative estimates. Average annual WY2014 irrigation season stream temperature has an RMSE of 2.3 °C, NSE of 0.92, RSR of 0.28, and a PBIAS of -6.55%, and WY2015 irrigation season stream temperature has an RMSE of 1.9 °C, NSE of 0.86, RSR of 0.37, and a PBIAS of 0.97% (Table 13).

4.2.3 Dissolved Oxygen

DO sonde burial, biological fouling, and mechanical malfunction created periods of questionable data that could not be analyzed with confidence. These measured data were eliminated from my analysis, resulting in analysis reported to the most downstream location at the Wabuska Drain, rkm 77.83 (Fig. 24). Of the measured data that passed quality control, the modeled results show a good to very good fit (Moriasi et al., 2007). The model captures the timing and magnitude of diurnal swings with reasonable accuracy for both WY2014 and WY2015 (Fig. 25; Fig. 26). Average annual WY2014 irrigation season DO has an RMSE of 0.6 mg/L, NSE of 0.91, RSR of 0.29, and a PBIAS of 0.51% and WY2015 has an RMSE of 0.6 mg/L, NSE of 0.68, RSR of 0.56, and a PBIAS of 0.81% (Table 14).

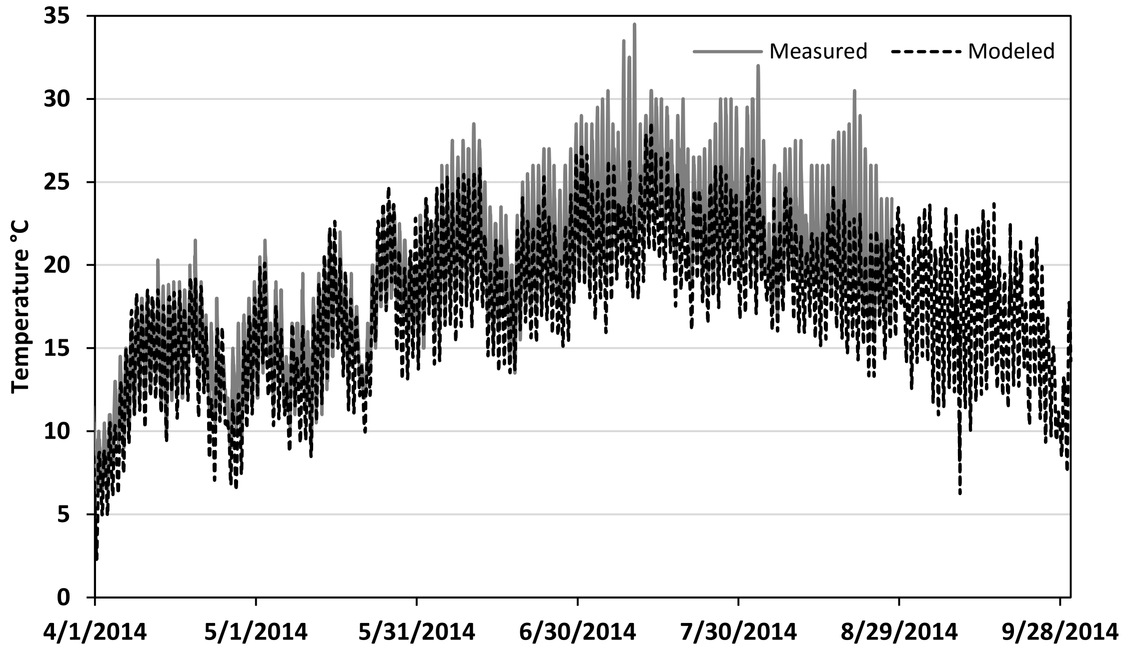

Fig. 22. Measured versus modeled hourly stream temperatures for WY2014 at rkm 87.69.

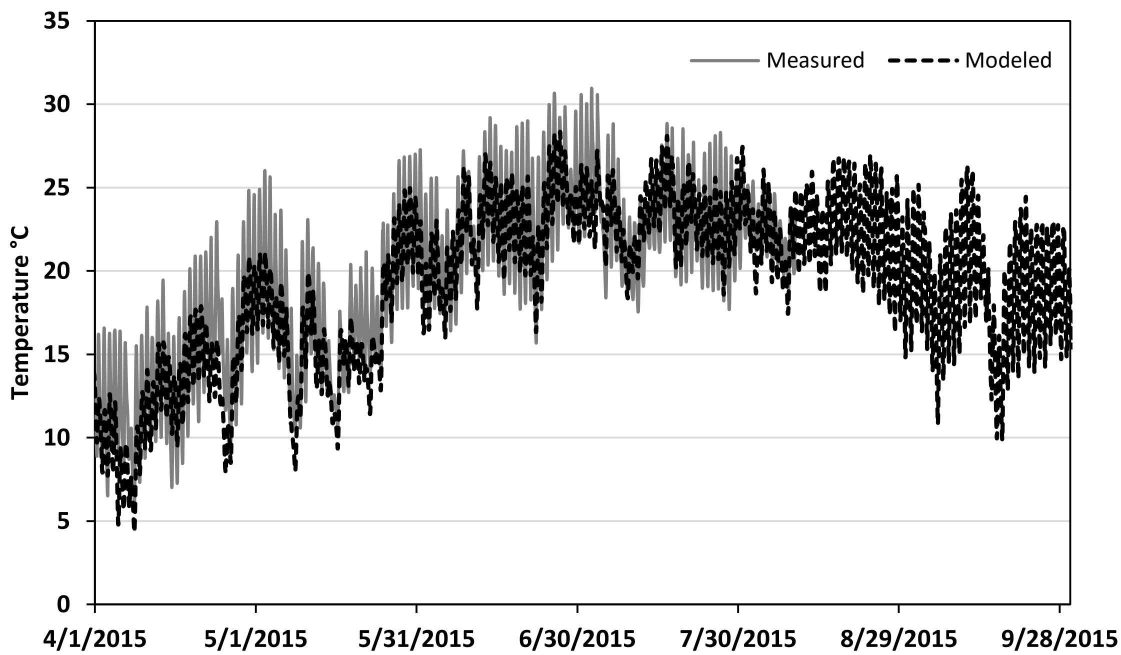

Fig. 23. Measured versus modeled hourly stream temperatures for WY2015 at rkm 87.69.

Table 13
Measured versus modeled WY2014 and WY2015 stream temperature statistics

<u>WY2014</u> ***River***	**River km**	**RMSE (°C)**	**NSE (unitless)**	**RSR (unitless)**	**PBIAS (%)**	**n (Hours)**
East Walker	225.37	1.5	0.96	0.20	5.75	4392
	135.56	3.2	0.83	0.42	-11.21	2861
	121.51	2.6	0.90	0.32	-10.07	4392
Reach Statistics	-	**2.4**	**0.90**	**0.31**	**-5.18**	**3882**
Walker	111.74	2.1	0.93	0.26	-7.87	3363
	94.32	2.6	0.92	0.28	-10.35	3312
	87.69	2.4	0.93	0.26	-8.73	3568
	77.83	3.1	0.89	0.34	-9.15	4392
Reach Statistics	-	**2.5**	**0.92**	**0.28**	**-9.03**	**3659**
West Walker	39.72	1.2	0.97	0.16	0.19	4040
	10.09	1.9	0.92	0.29	-7.52	4392
Reach Statistics	-	**1.6**	**0.95**	**0.22**	**-3.67**	**4216**
	Average	**2.3**	**0.92**	**0.28**	**-6.55**	**3857**
<u>WY2015</u> ***River***						
East Walker	225.37	2.3	0.76	0.49	12.28	4392
	135.56	1.7	0.87	0.36	0.73	3956
	121.51	2.4	0.76	0.49	3.50	4392
Reach Statistics	-	**2.1**	**0.79**	**0.45**	**5.50**	**4247**
Walker	111.74	1.8	0.90	0.31	-1.16	2859
	94.32	1.6	0.88	0.35	-5.10	843
	87.69	1.8	0.92	0.28	-4.17	2354
	77.83	2.1	0.83	0.41	-2.91	3600
Reach Statistics	-	**1.8**	**0.88**	**0.34**	**-3.34**	**2414**
West Walker	39.72	1.4	0.93	0.26	2.02	3886
	10.09	1.7	0.89	0.34	3.56	4393
Reach Statistics	-	**1.5**	**0.91**	**0.30**	**2.79**	**4140**
	Average	**1.9**	**0.86**	**0.37**	**0.97**	**3408**

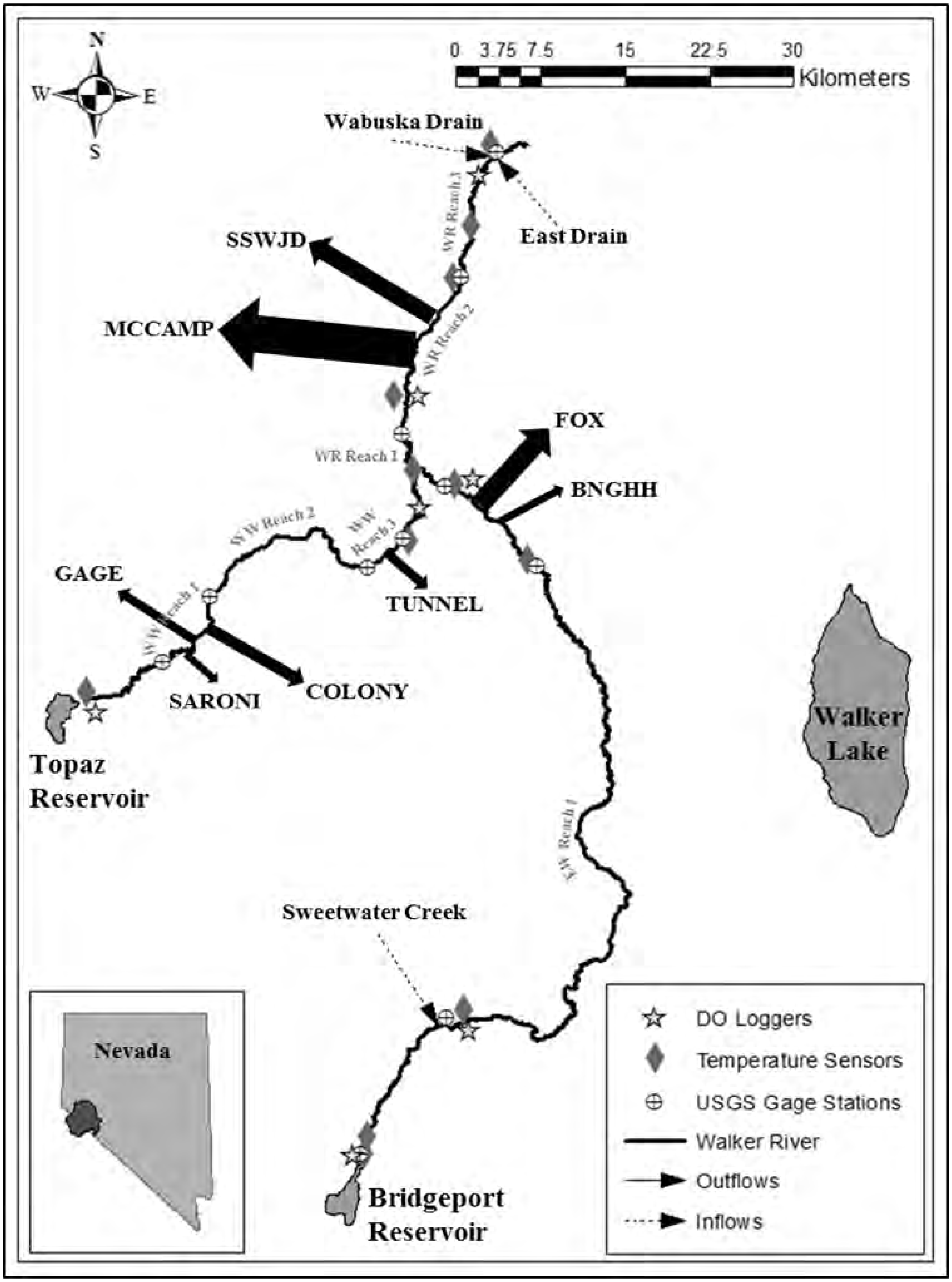

Fig. 24. River extent analyzed.

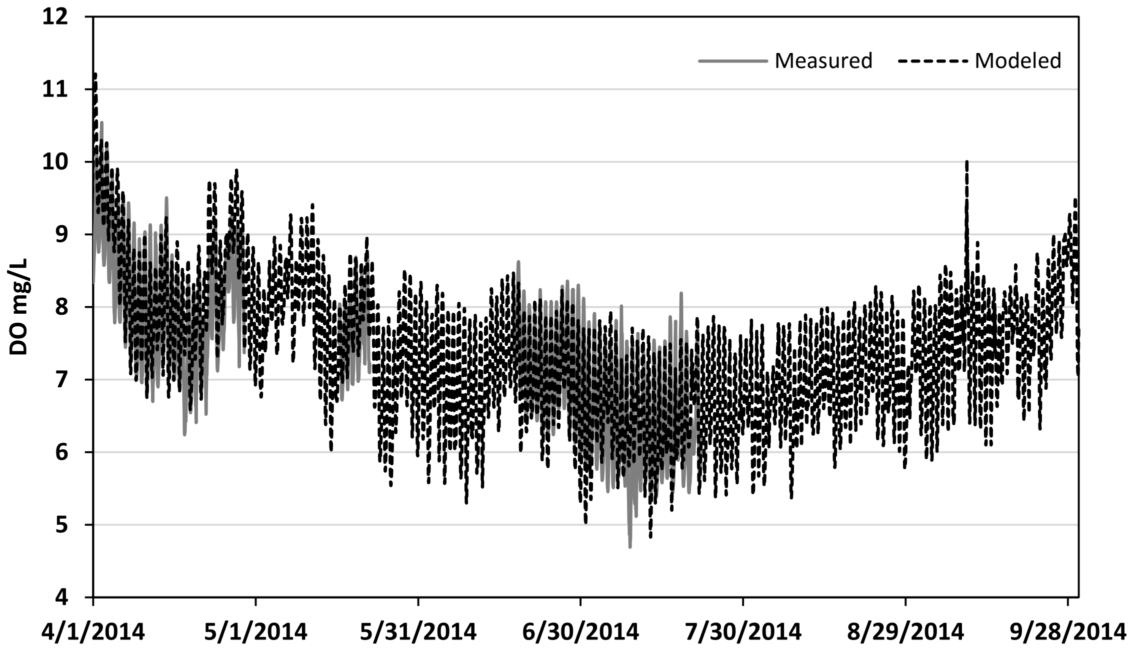

Fig. 25. Measured versus modeled hourly DO for WY2014 at rkm 77.83.

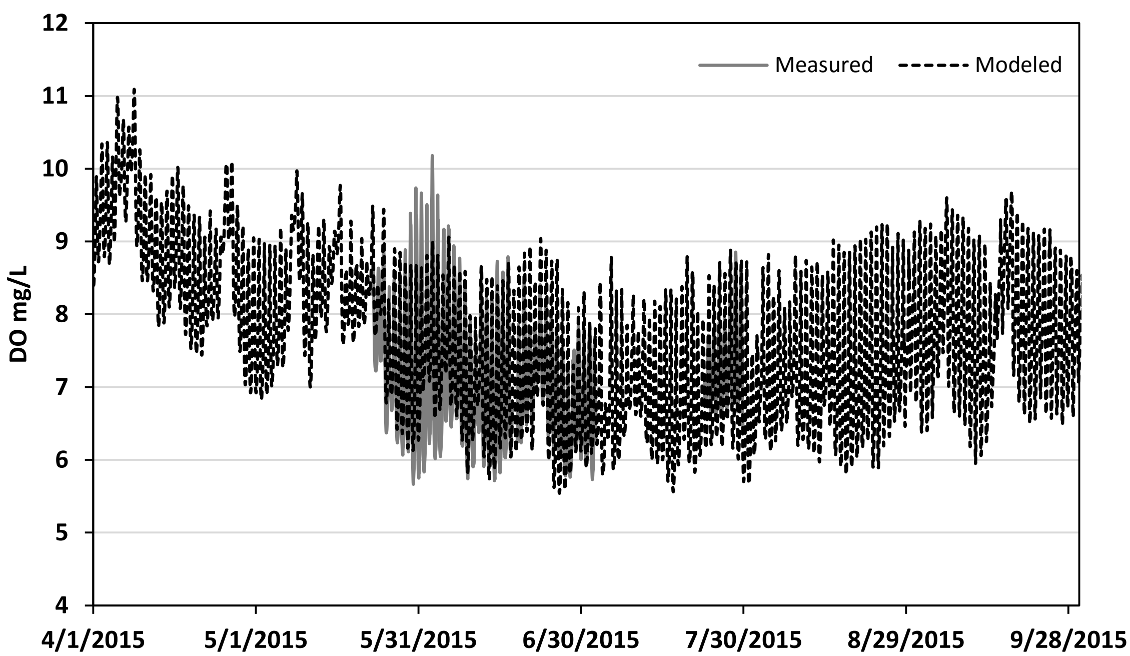

Fig. 26. Measured versus modeled hourly DO for WY2015 at rkm 77.83.

Table 14
Measured versus modeled WY2014 and WY2015 DO statistics

WY2014 ***River***	**River km**	**RMSE (mg/L)**	**NSE (unitless)**	**RSR (unitless)**	**PBIAS (%)**	**n (Hours)**
East Walker	225.37	0.8	0.86	0.37	0.36	4392
	121.51	0.6	0.92	0.28	0.92	2522
Reach Statistics	-	**0.7**	**0.89**	**0.33**	**0.64**	**3457**
Walker	111.74	0.5	0.91	0.30	1.40	3030
	87.60	0.5	0.95	0.22	2.16	1641
Reach Statistics	-	**0.5**	**0.93**	**0.26**	**1.78**	**2336**
West Walker	0.92	0.6	0.93	0.26	-2.30	997
Reach Statistics	-	**0.6**	**0.93**	**0.26**	**-2.30**	**997**
	Average	**0.6**	**0.91**	**0.29**	**0.51**	**2516**
WY2015 ***River***						
East Walker	225.37	0.9	0.77	0.48	-4.45	4392
	121.51	0.8	0.44	0.75	3.33	775
Reach Statistics	-	**0.8**	**0.60**	**0.62**	**-0.56**	**2584**
Walker	111.74	0.6	0.68	0.57	2.99	1926
	77.83	0.5	0.73	0.52	1.77	1142
Reach Statistics	-	**0.5**	**0.70**	**0.54**	**2.38**	**1534**
West Walker	0.92	0.4	0.78	0.47	0.00	2324
Reach Statistics	-	**0.4**	**0.78**	**0.47**	**0.00**	**2324**
	Average	**0.6**	**0.68**	**0.56**	**0.81**	**2112**

4.3 Historical Conditions

Modeled historical conditions show that temperatures sometimes exceeded acute and chronic LCT thermal thresholds during the warmest six week period for both years (June 17 to July 28) (Table 15). For WY2014, the modeled chronic average 7 day thermal limit (>24 °C) was never exceeded but temperatures near or exceeding acute limits (>28 °C) did occur. Modeled historical condition stream temperature was consistently underestimated for WY2014, remaining cooler than measured data throughout the summer irrigation season (refer to Fig. 22). Exceedances of acute thresholds occurred much more frequently in WY2015 at the warmest reach of rkm 121.51 on the East Walker River, however, WY2015 totaled 32 days compared to 6 days in WY2014. Chronic 7 day thermal limits were exceeded for two weeks in WY2015 at the lower reach of the East Walker River as well. For both years, the lower reaches of the East Walker River, from rkm 135.56 to the confluence, exhibited the highest 7 day average and maximum daily stream temperatures. Substantial amounts of East Walker River flow is diverted by the FOX and BNGHH irrigation canals, allowing warm atmospheric conditions to influence this reach.

The West Walker River remained relatively cooler for both WY2014 and WY2015, nearing or surpassing thermal thresholds less frequently and only in the lower reach. Temperatures just below the confluence, at rkm 111.74, remained more closely correlated with West Walker River temperatures than with East Walker River temperatures. West Walker River contributes more flow volume during the irrigation season, providing a seasonal average of 2.24 cms and 2.50 cms for WY 2014 and 2015, respectively, compared to East Walker River's 0.37 cms for WY2014 and 0.26 cms for WY2015.

Modeled historical DO conditions are spatially and temporally variable in WY2014 and WY2015. In WY2014, water quality is degraded in the upper reaches of East Walker River near rkm 225.37. DO concentrations drop below 5.0 mg/L on 8 days and remain below 6.0 mg/L on 108 days (Table 16). Water quality generally improves downstream with DO exceeding 5.0 mg/L until rkm 87.60 when DO concentrations again drop below 5.0 mg/L. West Walker River also exhibits degraded water quality with

Table 15

Seven day average, minimum daily temperatures, and maximum daily temperatures with modeled Historical conditions at selected river kilometers for WY2014 (top) and WY2015 (bottom). Shaded cells show acute or chronic temperature thresholds exceedances

WY2014	**River km**	**6/17/2014**			**6/24/2014**			**7/1/2014**			**7/8/2014**			**7/15/2014**			**7/22/2014**		
		7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max
EW	**225.37**	18.3	13.2	24.8	19.8	14.8	25.7	21.2	16.4	27.0	21.8	18.3	27.3	21.4	17.2	26.2	21.5	16.9	26.2
	135.56	19.0	13.6	24.9	20.2	15.7	26.4	21.8	17.2	25.8	22.6	19.0	28.0	21.7	16.8	26.0	21.7	17.1	25.5
	121.51	19.1	11.5	27.0	20.2	13.7	28.3	21.7	14.6	30.8	22.6	18.3	28.6	21.7	16.3	26.8	21.7	16.2	26.4
WR	**111.74**	19.0	14.5	24.3	20.3	15.8	26.2	21.8	17.3	25.8	22.6	18.7	28.1	21.7	16.8	26.0	21.7	17.1	25.7
	87.69	19.1	13.5	25.3	20.2	15.1	27.3	21.6	15.9	26.6	22.6	18.0	28.6	21.6	16.1	26.7	22.7	16.5	26.0
	77.83	19.0	14.2	24.0	20.2	15.8	25.9	21.7	17.4	25.3	22.6	18.5	27.5	21.6	16.7	25.5	21.7	17.5	24.9
WW	**39.72**	19.0	14.7	23.2	20.5	16.7	24.8	21.8	18.1	25.1	22.9	19.9	26.3	22.2	18.2	25.1	22.2	18.6	24.6
	10.09	19.0	14.8	24.2	20.3	16.0	26.1	21.8	17.7	25.5	22.6	19.1	27.8	21.8	17.1	25.8	21.8	17.5	25.4

WY2015	**River km**	**6/17/2015**			**6/24/2015**			**7/1/2015**			**7/8/2015**			**7/15/2015**			**7/22/2015**		
		7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max
EW	**225.37**	21.0	16.6	26.4	22.1	17.9	26.8	22.5	18.0	28.5	21.0	16.5	26.0	21.6	16.1	26.8	21.5	16.0	26.7
	135.56	22.1	16.8	26.3	24.7	20.5	28.6	23.9	20.6	27.4	22.5	18.9	27.2	24.3	19.8	28.7	22.8	18.2	26.2
	121.51	22.0	14.0	30.4	24.8	18.3	31.9	23.9	19.4	31.4	22.5	18.6	28.4	24.3	18.1	31.0	22.8	16.3	27.8
WR	**111.74**	22.0	17.3	25.3	24.2	21.0	27.3	23.7	20.2	27.8	22.4	18.7	26.6	24.1	19.9	28.2	22.7	18.8	25.8
	87.69	22.0	15.0	27.1	24.7	20.1	29.3	23.8	19.3	28.8	22.4	17.9	27.4	24.3	19.2	29.2	22.7	17.6	26.6
	77.83	22.0	16.3	25.9	24.8	21.4	28.4	23.8	20.3	27.2	22.4	18.4	26.7	24.3	20.2	28.1	22.8	18.6	25.6
WW	**39.72**	21.8	18.0	24.2	22.9	18.9	25.5	23.1	19.6	26.4	22.1	19.4	25.2	23.2	20.0	26.2	22.4	19.3	25.0
	10.09	21.9	17.5	25.2	23.9	20.9	27.1	23.5	20.1	27.4	22.3	18.7	26.5	24.0	19.7	28.0	22.6	18.9	25.7

Table 16
Total number of days, hours, and longest consecutive period (hours) at select river locations below DO concentrations with modeled Historical conditions for WY2014 (top) and WY2015 (bottom)

			Total days below concentration			Total hours below concentration			Longest consecutive hours below concentration		
	Reach	**River km**	**6.0 mg/L**	**5.5 mg/L**	**5.0 mg/L**	**6 mg/L**	**5.5 mg/L**	**5 mg/L**	**6 mg/L**	**5.5 mg/L**	**5 mg/L**
WY2014	**EW**	225.37	108	55	8	711	182	15	15	10	4
		121.51	33	3	0	107	6	0	9	4	0
	WR	111.74	4	0	0	13	0	0	8	0	0
		87.60	63	14	2	316	50	4	14	8	3
		77.52	49	4	0	251	14	0	13	8	0
	WW	0.92	64	25	2	422	82	4	14	10	4
WY2015	**EW**	225.37	116	73	15	827	287	34	14	11	5
		121.51	113	73	20	944	364	66	18	12	7
	WR	111.74	8	0	0	18	0	0	6	0	0
		87.60	27	0	0	80	0	0	8	0	0
		77.52	35	0	0	159	0	0	10	0	0
	WW	0.92	0	0	0	0	0	0	0	0	0

modeled DO concentrations below 5.0 mg/L on two days, below 5.5 mg/L on 25 days, and below 6.0 mg/L on 64 days. For the most part, DO concentrations below the confluence are suitable for aquatic ecosystems (e.g., > 6.0 mg/L) throughout WY2014. In WY2015, persistent periods when DO concentrations fall below 6.0 mg/L exist for nearly all of the East Walker River, with 15 days below 5.0 mg/L at rkm 225.37 and 20 days below 5.0 mg/L at rkm 121.51. Unlike WY2014, DO concentrations do not improve in downstream reaches of East Walker River in WY2015. But, DO in the entire West Walker River and Walker River below the confluence generally remain above 6.0 mg/L, with a maximum of 35 days below 6.0 mg/L near rkm 77.52. These reaches always exceed 5.5 mg/L for the entire WY2015 irrigation season.

4.4 Environmental Water Transfers

A number of environmental water transfer alternatives were modeled to evaluate the effects that increased streamflow had on stream temperatures and DO concentrations. Existing transfers totaling 1,780,000 m^3 (a daily average of 0.11 cms) of additional flow throughout irrigation season have been purchased to date. Potential future environmental water transfer alternatives are made in addition to existing transfers. For instance, for the scenario of Bridgeport +1.41 cms, the added daily increase of 1.41 cms from Bridgeport Reservoir is in addition to the added water from Existing transfers. In this way water managers can assess the benefits of increased water purchases to current purchases.

Results focus on only larger (+1.41 cms) reservoir releases on stream temperature as they provide the strongest effects of all environmental water transfer scenarios. For DO, both existing transfers and the larger reservoir releases assess how environmental water transfers affect DO response.

Modeled environmental water transfers consistently decreased the daily high temperature and increased the nightly low temperature, with little to no change in the 7 day average temperature (Fig. 27; Fig. 28; Table 17). The largest stream temperature changes occurred in the lowest reach of East Walker River at rkm 121.51 for both WY2014 and WY2015. Bridgeport Reservoir releases of 1.41 cms per day decreased daily maximum stream temperatures by up to 5.0 °C and increased nightly low temperatures by 2.7 °C during WY2014 for the week starting July 1 at rkm 121.51 (Table 17). However, these changes resulted in a negligible 0.1 °C 7 day average increase for that week. For WY2015, maximum daily temperatures were reduced by up to 4.1 °C, and

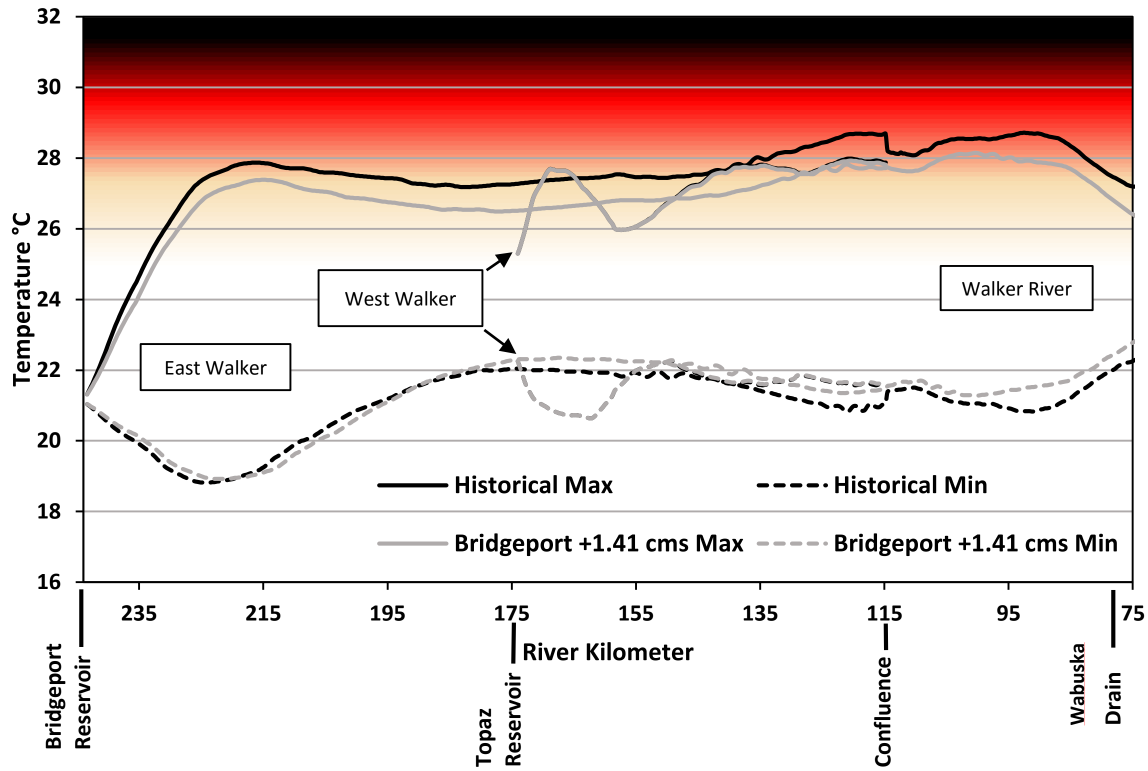

Fig. 27. Modeled maximum and minimum temperatures on July 13, 2014, under Historical and Bridgeport +1.41 cms conditions for WY2014. Black lines are Historical conditions and grey lines are Bridgeport +1.41 cms conditions. Red to black color gradient represents acute temperature thresholds for LCT.

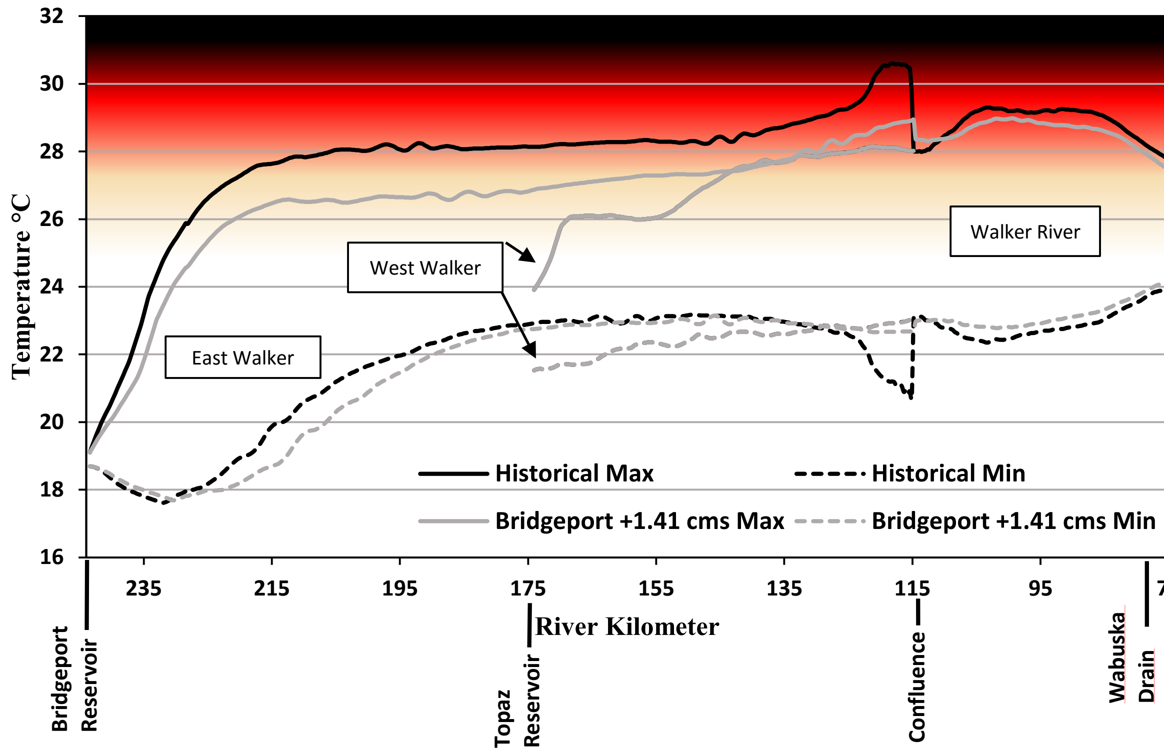

Fig. 28. Modeled maximum and minimum temperatures on July 16, 2015, under Historical and Bridgeport +1.41 cms conditions for WY2015. Black lines are Historical conditions and grey lines are Bridgeport +1.41 cms conditions. Red to black color gradient represents acute temperature thresholds for LCT.

Table 17

Change in Historical 7 day average, minimum daily temperature, and maximum daily temperature between Historical conditions and Bridgeport +1.41 cms at selected river kilometers. Green cells indicate a reduction in temperature, red cells indicate an increase in temperature, and white cells indicate no change in temperature. Top table is WY2014 and bottom is WY2015

WY2014	**River km**	**6/17/2014**			**6/24/2014**			**7/1/2014**			**7/8/2014**			**7/15/2014**			**7/22/2014**		
		7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max
EW	**225.37**	-0.2	+0.4	-0.8	-0.1	+0.3	-0.7	0.0	+0.2	-0.4	-0.1	+0.3	-0.6	0.0	+0.8	-0.5	0.0	+0.6	-0.4
	135.56	-0.1	+0.7	-1.2	0.0	+0.5	-0.8	0.0	+0.9	-0.8	-0.1	+0.3	-0.8	0.0	+0.7	-0.8	0.0	+1.0	-0.8
	121.51	-0.1	+2.2	-2.4	0.0	+2.0	-1.9	+0.1	+2.7	-5.0	0.0	+0.7	-0.8	0.0	+0.8	-1.0	0.0	+1.3	-1.1
WR	**111.74**	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	+0.2	-0.3	0.0	+0.2	-0.5	0.0	+0.2	-0.4	0.0	+0.4	-0.5
	87.69	0.0	+0.4	-0.8	0.0	+0.5	-0.8	+0.1	+1.2	-0.9	0.0	+0.8	-0.8	+0.1	+0.6	-0.9	0.0	+0.8	-0.8
	77.83	0.0	+0.2	-0.4	0.0	+0.3	-0.3	+0.1	+0.7	-0.3	0.0	+0.8	-0.5	+0.1	+0.6	-0.6	0.0	+0.5	-0.6
WW	**39.72**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

WY2015	**River km**	**6/17/2015**			**6/24/2015**			**7/1/2015**			**7/8/2015**			**7/15/2015**			**7/22/2015**		
		7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max	7 day Avg	Week Min	Week Max
EW	**225.37**	-0.1	+0.2	-0.5	-0.3	+0.2	-0.8	-0.2	+0.7	-0.9	-0.3	+0.3	-1.2	-0.6	+0.4	-1.2	-0.3	+0.9	-0.6
	135.56	-0.1	+0.7	-0.8	-0.3	+0.3	-0.9	-0.2	+0.4	-0.7	-0.2	+0.1	-0.7	-0.3	+0.2	-1.0	-0.1	+1.0	-0.9
	121.51	0.0	+2.8	-4.1	-0.2	+2.0	-3.3	-0.1	+1.1	-3.5	-0.1	+0.2	-1.1	-0.2	+1.6	-2.5	0.0	+2.1	-1.7
WR	**111.74**	0.0	-0.1	+0.2	+0.1	0.0	+0.4	0.0	+0.1	-0.2	0.0	+0.1	+0.2	0.0	+0.1	+0.1	0.0	-0.1	0.0
	87.69	+0.1	+1.4	-0.6	-0.1	+0.5	-0.8	+0.1	+0.8	-0.1	0.0	+0.5	-0.3	0.0	+0.7	-0.5	+0.1	+0.8	-0.6
	77.83	+0.1	+0.9	-0.2	-0.1	+0.1	-0.3	0.0	+0.4	-0.6	0.0	+0.2	-0.2	0.0	+0.3	-0.2	+0.1	+0.5	-0.2
WW	**39.72**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

nightly low temperature increased by up to 2.8 °C at rkm 121.51. Again, these temperature changes did not change the 7 day average for that week and location. Modeled environmental water transfers exhibited more nuanced changes to DO concentrations than to stream temperatures. Overall, response to increased streamflow was reach and year specific, although some clear patterns developed.

Existing transfers (which were small) had little to no effect on DO concentrations in WY2014, contributing to only minor improvements or deterioration in individual reaches (Table 18). For instance, existing transfers marginally improved all DO concentrations at rkm 77.52, reducing the number of days below 6.0 mg/L from 49 days to 46 days and reducing the total number of hours below 6.0 mg/L from 251 to 242. Existing transfers also reduced the number of hours below 5.5 mg/L by one hour at rkm 77.52. But, existing transfers increased the total number of hours of DO concentrations below 6.0 mg/L at rkm 121.51 and below 6.0 mg/L and 5.5 mg/L at rkm 87.60. Although the total number of hours below 6.0 mg/L increased from 316 to 321 and below 5.5 mg/L increased from 50 to 51, the total number of hours below 5.0 mg/L decreased by one and the total number of day below 6.0 mg/L improved from 63 to 62 at rkm 87.60.

For WY2015, two locations, rkm 87.60 and rkm 77.52, exhibited minor improvements under modeled existing transfers with decreases in both the number of days, by 2 days at rkm 87.60 and 1 day at rkm 77.52, and the total hours below 6.0 mg/L, from 80 hours to 78 hours at rkm 87.60 and from 159 hours to 155 hours at rkm 77.52 (Table 19). The only negatively affected location in WY2015 was rkm 121.51. At this location, adding an average daily streamflow of 0.11 cms throughout the irrigation season increased the number of hours of DO concentrations below 6.0 mg/L, 5.5 mg/L, and 5.0 mg/L.

Larger environmental water transfers had more effect on DO concentrations. Model results suggest that DO conditions could be improved, degraded, or have mixed effects for different DO thresholds depending on year, season, and reach location. For example, sometimes large environmental water transfers reduce the amount of time DO concentrations are below 5.0 mg/L, but increase the duration that it was below 5.5 mg/L or 6.0 mg/L. In WY2014 at rkm 225.37 on East Walker River and all locations below the confluence on the mainstem Walker River, Bridgeport Reservoir release increases of 1.41 cms daily flow decreased the total number of days with DO concentrations below both 6.0 mg/L and 5.5 mg/L, but increased the total number of hours below those concentrations (Table 18). In other words, DO was below 5.5 mg/L for fewer days, but for a longer period of time when poor DO conditions occurred. At rkm 0.92 on West Walker River, daily additions of 1.41 cms from Topaz Reservoir degraded DO concentrations below the 6.0 mg/L and 5.5 mg/L thresholds by increasing both the total number of days and total hours under 6.0 mg/L and 5.5 mg/L in WY2014. Interestingly, daily additions of 1.41 cms in all reaches improved the lowest concentrations of 5.0 mg/L and the total number of days and total hours below 5.0 mg/L were reduced in all reaches in WY2014.

The second prominent effect from larger water transfers is a complete degradation of DO concentrations at a handful of specific reaches. This occurred at rkm 111.74 in WY2014 where daily additions of 1.41 cms from both East Walker and West Walker

Table 18
DO concentration water quality metrics for WY2014 with Historical conditions, Existing transfers, and +1.41 cms releases from Bridgeport and Topaz Reservoirs. Green cells indicate water quality improvement, red cells indicate deterioration, and white cells indicate no change

WY2014				Total days below concentration (mg/L)			Total hours below concentration (mg/L)			Longest consecutive hours below concentration (mg/L)		
Reach	**River km**	**Model Run**	**Additional Flow (cms)**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**
EW	**225.37**	Historical	-	108	55	8	711	182	15	15	10	4
		Existing	0.02	108	54	8	711	180	15	15	10	4
		Bridgeport +1.41	1.41	103	42	3	748	161	7	17	12	3
	121.51	Historical	-	33	3	0	107	6	0	9	4	0
		Existing	0.02	33	3	0	109	6	0	9	4	0
		Bridgeport +1.41	1.41	28	1	0	91	1	0	11	1	0
WW	**0.92**	Historical	-	64	25	2	422	82	4	14	10	4
		Existing	0.05	64	25	2	422	82	4	14	10	4
		Topaz +1.41	1.41	66	26	1	508	101	3	15	11	3
WR	**111.74**	Historical	-	4	0	0	13	0	0	8	0	0
		Existing	0.07	4	0	0	13	0	0	8	0	0
		Bridgeport +1.41	1.41	7	0	0	22	0	0	9	0	0
		Topaz +1.41	1.41	9	0	0	37	0	0	9	0	0
	87.60	Historical	-	63	14	2	316	50	4	14	8	3
		Existing	0.11	61	14	1	321	51	3	14	8	3
		Bridgeport +1.41	1.41	59	10	1	352	36	1	15	9	1
		Topaz +1.41	1.41	60	12	1	368	39	2	15	9	2
	77.52	Historical	-	49	4	0	251	14	0	13	8	0
		Existing	0.11	46	4	0	242	13	0	13	8	0
		Bridgeport +1.41	1.41	43	3	0	259	13	0	13	8	0
		Topaz +1.41	1.41	43	3	0	262	13	0	14	8	0

tributaries increased the total days, total hours, and longest consecutive time period of DO concentrations below 6.0 mg/L (Table 18). WY2015 also exhibited the same degradation pattern at rkm 111.74, but only for flow originating from East Walker tributary (Table 19).

Finally, the third major pattern is a complete improvement for all DO concentrations and metrics in some reaches. Complete improvement occurred in WY2015 with daily additions of 1.41 cms at rkm 87.60 and rkm 77.52 (Table 19).

Improvements to all DO metrics also occurred at rkm 111.74, but only from additions originating from West Walker River in WY2015.

4.5 Sensitivity Analyses

Results from sensitivity analyses suggest that low DO concentrations can be improved by reducing respiration rate, SOD, or a combination of both (Table 20, Table 21). When respiration rate or SOD were reduced at rkm 121.51, the reach with the most degraded DO concentrations for both years, the number of days, total hours, and longest duration of impaired DO concentrations dropped, even without additional streamflow through environmental water purchases. Reducing SOD rates improved DO conditions more than equivalent percentage reductions in respiration rates. In fact, lowering SOD by just 10% improved DO conditions so that the number of days with DO below 6.0 mg/L fell by 27%, total hours under 6.0 mg/L concentration dropped by 29%, and the longest consecutive period under 6.0 mg/L was shortened by one hour. Comparable DO metrics from daily releases of 1.41 cms from Bridgeport Reservoir improved instream water quality by 15%, 16%, and 2 hours, respectively, in WY2014. In WY2015, the addition of 1.41 cms from Bridgeport changed instream water quality by decreasing the number of total days under 6.0 mg/L, but increased both total hours and longest consecutive hours under 6.0 mg/L. Respiration and SOD reductions deceased all DO metrics, improving instream water quality. A combined reduction in respiration and SOD rates of 30% completely eliminated instances when DO fell below 5.0 mg/L in WY2015.

Table 19
DO concentration water quality metrics for WY2015 with Historical conditions, Existing transfers, and +1.41 cms releases from Bridgeport and Topaz Reservoirs. Green cells indicate water quality improvement, red cells indicate deterioration, and white cells indicate no change

WY2015				Total days below concentration (mg/L)			Total hours below concentration (mg/L)			Longest consecutive hours below concentration (mg/L)		
Reach	**River km**	**Model Run**	**Additional Flow (cms)**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**
EW	**225.37**	Historical	-	116	73	15	827	287	34	14	11	5
		Existing	0.02	116	73	15	827	286	34	15	11	5
		Bridgeport +1.41	1.41	103	58	2	797	217	3	15	11	2
	121.51	Historical	-	113	73	20	944	364	66	18	12	7
		Existing	0.02	112	74	20	982	384	71	18	12	7
		Bridgeport +1.41	1.41	100	66	9	995	345	27	19	14	6
WW	**0.92**	Historical	-	0	0	0	0	0	0	0	0	0
		Existing	0.02	0	0	0	0	0	0	0	0	0
		Topaz +1.41	1.41	0	0	0	0	0	0	0	0	0
WR	**111.74**	Historical	-	8	0	0	18	0	0	6	0	0
		Existing	0.04	8	0	0	18	0	0	6	0	0
		Bridgeport +1.41	1.41	11	0	0	32	0	0	7	0	0
		Topaz +1.41	1.41	2	0	0	4	0	0	4	0	0
	87.60	Historical	-	27	0	0	80	0	0	8	0	0
		Existing	0.08	25	0	0	78	0	0	8	0	0
		Bridgeport +1.41	1.41	21	0	0	67	0	0	8	0	0
		Topaz +1.41	1.41	21	0	0	66	0	0	8	0	0
	77.52	Historical	-	35	0	0	159	0	0	10	0	0
		Existing	0.08	34	0	0	155	0	0	10	0	0
		Bridgeport +1.41	1.41	27	0	0	145	0	0	10	0	0
		Topaz +1.41	1.41	27	0	0	143	0	0	10	0	0

Table 20
Sensitivity analysis of reducing respiration and SOD rates on DO concentrations for WY2014. Green cells indicate improvement, red cells indicate deterioration, and white cells indicate no change

WY2014			**Total days below concentration (mg/L)**			**Total hours below concentration (mg/L)**			**Longest consecutive hours below concentration (mg/L)**		
Rkm 121.51	**Model Run**	**Additional Flow (cms)**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**
	Historical	-	33	3	0	107	6	0	9	4	0
	Existing	0.02	33	3	0	109	6	0	9	4	0
	Bridgeport +1.41	1.41	28	1	0	91	1	0	11	1	0
	SOD 10%	-	24	2	0	77	5	0	8	3	0
	SOD 20%	-	18	1	0	52	1	0	7	1	0
	SOD 30%	-	12	0	0	28	0	0	7	0	0
	RESP 10%	-	30	2	0	91	5	0	8	3	0
	RESP 20%	-	24	2	0	73	4	0	8	3	0
	RESP 30%	-	21	1	0	61	1	0	7	1	0
	SOD & RESP 10%	-	21	1	0	63	3	0	8	3	0
	SOD & RESP 20%	-	10	0	0	25	0	0	6	0	0
	SOD & RESP 30%	-	6	0	0	13	0	0	5	0	0

Table 21
Sensitivity analysis of reducing respiration and SOD rates on DO concentrations for WY2015. Green cells indicate improvement, red cells indicate deterioration, and white cells indicate no change

WY2015			**Total days below concentration (mg/L)**			**Total hours below concentration (mg/L)**			**Longest consecutive hours below concentration (mg/L)**		
Rkm 121.51	**Model Run**	**Additional Flow (cms)**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**	**6.0**	**5.5**	**5.0**
	Historical	-	113	73	20	944	364	66	18	12	7
	Existing	0.02	112	74	20	982	384	71	18	12	7
	Bridgeport +1.41	1.41	100	66	9	995	345	27	19	14	6
	SOD 10%	-	107	58	14	810	267	34	16	11	4
	SOD 20%	-	102	46	9	673	180	18	15	9	4
	SOD 30%	-	88	32	1	548	109	2	14	8	2
	RESP 10%	-	110	68	17	891	319	47	17	11	5
	RESP 20%	-	108	62	14	836	279	34	17	11	4
	RESP 30%	-	106	56	12	774	235	30	15	10	4
	SOD & RESP 10%	-	105	56	12	750	222	30	15	9	4
	SOD & RESP 20%	-	89	34	1	560	114	2	15	8	2
	SOD & RESP 30%	-	73	17	0	373	51	0	12	5	0

CHAPTER 5

DISCUSSION

Overall, environmental water transfers decrease daily maximum stream temperatures, increase daily minimum stream temperatures, and have little effect on 7 day average stream temperatures because cooled daily high temperatures and warmed nightly low temperatures are attenuated. These changes occur from increased thermal mass provided by streamflow additions and confirm results by Elmore et al. (2015). Effects of environmental water transfers on DO concentrations are more variable, however. Sometimes increasing instream flow improved DO conditions, sometimes it further degraded DO conditions, and sometimes some DO metrics were enhanced while others were impaired. Further, these results were not spatially or temporally uniform throughout the Walker Basin. Because DO is inversely correlated to stream temperature, some of these trends are driven by stream temperature change. But, temperature is not the only driver affecting DO concentrations from increased environmental water purchases.

DO concentrations are likely driven by stream temperature for model alternatives that decreased the total number of days under a concentration but subsequently increased the total number of hours below that concentration. This pattern is evident in WY2014 near rkm 87.69 (Fig. 29). The lowest (acute levels) DO concentrations are improved whereas the duration of more chronic DO concentrations is lengthened. The timing of daily DO highs and lows indicate that stream temperatures drive DO response (Butcher and Covington, 1995). Stream temperature, a physical process, controls the DO saturation concentration of a water body.

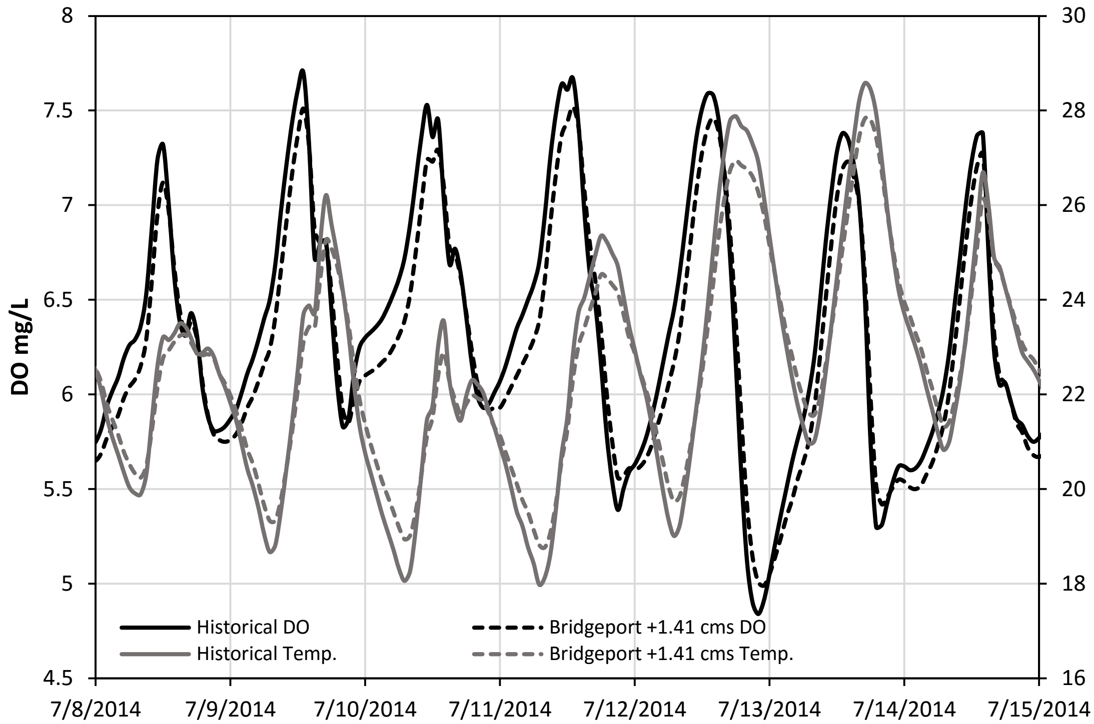

Fig. 29. DO concentrations and temperatures near rkm 87.69 under Historical and Bridgeport +1.41 cms conditions for WY2014.

However, DO concentrations vary due to physical, biological, and chemical processes. Actual DO concentrations also change from biological and chemical production and consumption of DO. The point at which DO is dominated by a physical, biological, or chemical process can be observed in daily high and low DO concentration timing (Riley and Dodds 2013). During the day, photosynthesis adds DO to streams, even though warmer stream temperatures lower the DO saturation concentration. In the Walker River, DO concentration maxima typically occurred between 13:00 and 14:00. At that time, warmer water overrides the production of DO by photosynthesis. Photosynthesis occurs as long as sunlight is available, but increased stream temperatures reduce DO saturation concentration, forcing the added DO out of solution and into the atmosphere (Butcher and Covington, 1995). At night, the opposite effect takes place.

Nightly low DO concentrations are driven by the same factors controlling daily highs, but in an opposite direction. Nighttime lows for DO occur between approximately 21:00 and 22:00 in the Walker River. Once sunlight is no longer available, respiration and SOD consume DO. Depletion of DO should occur throughout the night (Allan and Castillo, 2007), but in the Walker River an increase in DO begins well before sunrise. DO concentrations begin to rise as cooling stream temperatures increase the DO saturation concentration, overriding the rate of consumption from respiration and SOD. Increasing stream volume from environmental water transfers warms nightly low temperatures and decreases the rate at which stream temperatures cool. For this reason, chronic concentrations (<6.0 mg/L) of DO may persist for longer periods of time at night.

The pattern seen in Fig. 29 is not explained by temperature alone. Clearly, daytime DO highs have been reduced and the lowest nighttime concentrations have sometimes increased. Photosynthesis, respiration, and SOD were held constant with model runs. With added streamflow, the degree which these biological processes contribute to DO concentrations is diluted, reducing their effect on the overall DO concentration cycle. DO production rates, subjected to a larger volume of water, will not affect overall DO concentrations to the same degree that those same rates will have on a smaller volume of water. In this way, photosynthesis will not produce enough DO to raise DO concentrations as high and, conversely, respiration and SOD will not draw down DO concentrations as low.

In some instances, modeled environmental water transfers worsened DO conditions. This is most prominent at rkm 111.74, just below the confluence of East and West Walker Rivers. In WY2014, additions of 1.41 cms from both East and West Walker River resulted in slightly degraded DO concentrations in the mainstem at rkm 111.74 (Fig. 30). But, in WY2015 additions of 1.41 cms from West Walker River improved DO concentrations at rkm 111.74 while additions of the same volume from East Walker River continued to deteriorate water quality (Fig. 31).

Differences in the calibrated photosynthesis, respiration, and SOD rates between the two years explain why one year exhibited degraded DO from both tributaries and one year exhibited a mixed reaction. In WY2014, all three rates were calibrated with higher values on both the East and West Walker Rivers than for below the confluence at rkm 111.74. In WY2015, only the East Walker River was calibrated to have higher of rates photosynthesis, respiration, and SOD. Of those three parameters, sensitivity analyses indicate SOD had the largest calibrated difference between WY2014 and WY2015 (see Table 10). In WY2014, SOD on the East Walker River was 3.75 $gO_2/m^2/day$, the West Walker River was 3.20 $gO_2/m^2/day$, and the mainstem was 1.98 $gO_2/m^2/day$. In contrast, WY2015 was calibrated with SOD values of 5.65 $gO_2/m^2/day$ in the East Walker River, 0.57 $gO_2/m^2/day$ in the West Walker River, and 1.05 $gO_2/m^2/day$ in the mainstem. Increasing environmental water transfers can degrade DO concentrations in downstream reaches if upstream reaches have poor environmental (photosynthesis, respiration, or SOD) conditions from excess nutrients, algal blooms, or high SOD. For this reason, downstream water quality was degraded from both tributaries in WY2014 but was improved with environmental water transfers originating from the West Walker River in WY2015.

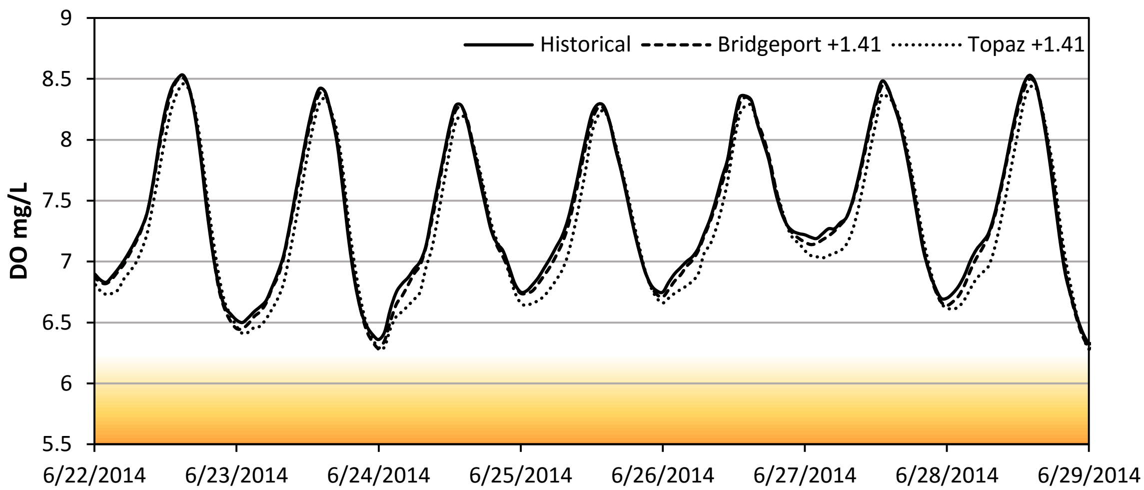

Fig. 30. DO concentrations for WY2014 at rkm 111.74 under Historical, Bridgeport +1.41 cms, and Topaz +1.41 cms.

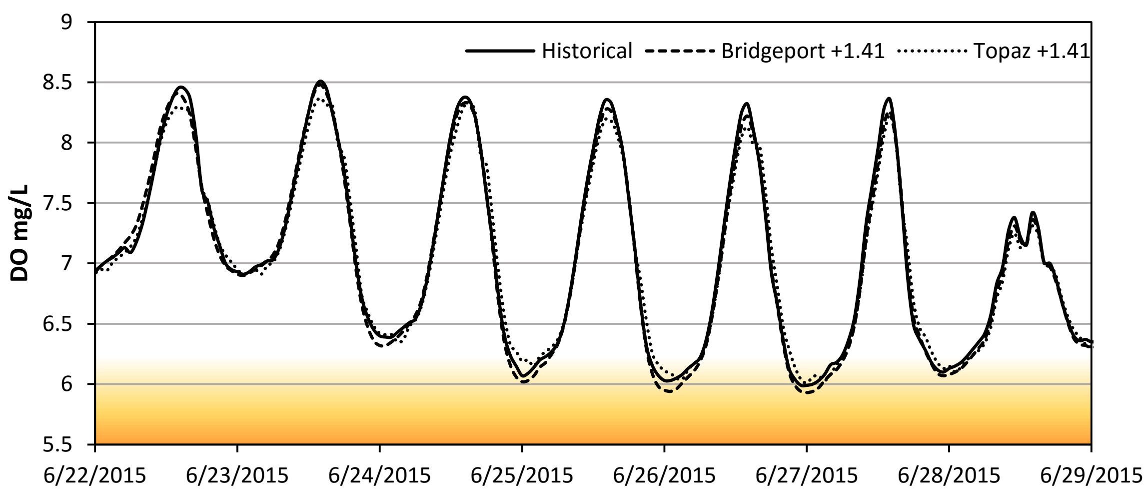

Fig. 31. DO concentrations for WY2015 at rkm 111.74 under Historical, Bridgeport +1.41 cms, and Topaz +1.41 cms.

Another example of deteriorating DO from environmental water transfers occurred with the Existing transfers scenario on the East Walker River at rkm 121.51 in WY2015. Adding a seasonal total of 371,000 m^3 (0.11 cms) of flow at this location increased the number of hours under both chronic (<6.0 mg/L) and acute (<5.0 mg/L) DO thresholds. This small volume of added streamflow was not enough to dilute the effects of respiration and SOD, allowing increased thermal mass to dominate nightly DO concentrations. However, this trend was reversed with larger modeled environmental water transfers of 1.41 cms from Bridgeport Reservoir, indicating that a turning point may occur in which larger flow contributions benefit DO concentrations at this location.

Multiple and complex DO conditions were exhibited according to location within the Walker River and environmental water transfer volumes. Sensitivity analyses indicate that reducing respiration and SOD rates by managing nutrients benefit all reaches. This research indicates that reducing respiration and SOD rates is a promising restoration action when increasing streamflow is not an option, or in addition to environmental water transfers, to restore water quality and aquatic habitat in the Walker Basin. SOD reductions most benefitted DO concentrations compared to equal percentage reductions of respiration. Since respiration is directly tied to photosynthesis, SOD rates are easier to perturb. Understanding the conditions that promote high SOD, like the accumulation of decomposing organic material, high ammonia loads from livestock, and excess nutrients from agriculture fields may enable managers to enhance instream water quality to complement environmental water purchases or when environmental water purchases are not available (Butts and Evans 1978; Lee and Jones-Lee 2007).

5.1 Limitations

RMS, like all models, simplifies river systems. Some calibration parameters in RMS are of a "one-size-fits-all" nature. Because of this, difficulties arise when simulating hourly water quality for a 300 km basin where environmental conditions change seasonally and from headwaters to downstream reaches. Calibrating variables sometimes results in tradeoffs, in which adjustments that improve one reach may decrease model performance in another. Also, critically low flows from persistent drought resulted in little hydrologic variability in the two years of this study. Small additions of modeled streamflow (< 0.1 cms) were needed in some locations to maintain model numerical stability. In this model, irrigation diversions were calculated based on percentages of depletions measured in reaches that contained diversion canals. Studies have shown that up to 33% of diverted water may return to the stream as shallow groundwater seepage later in the season (Fernald et al., 2010). This study does not explicitly include groundwater interactions and contributions. Seeps, springs, and groundwater gains and losses are lumped as accretions and depletions. This may cause canal diversions to be underestimated later in the irrigation season when groundwater supplements streamflow. Groundwater returns decrease streamflow depletion, reducing the estimated volume of diverted irrigation water and reducing potential environmental water purchases and contributed streamflow under particular model runs such as a Canal OFF alternative. Accurate measures of canal diversions would improve model accuracy, as would field measurements of SOD and nutrient concentrations.

CHAPTER 6

CONCLUSIONS

Identifying suitable cold-water trout habitat within the Walker River is complicated by the conflicting relationship between stream temperature and DO concentrations. River restoration that increases streamflow from environmental water purchases may reduce thermal stress but can increase the duration of low DO concentrations. While small streamflow additions always decrease daily high stream temperatures, warmer nightly stream temperatures can further depress DO concentrations.

Finding an acceptable balance between cost and stream temperature and DO concentration improvements is vital for restoring the biological health of the Walker River for native species. Results of this study show that reaches with suitable water quality habitat to support native species are the West Walker River and mainstem Walker River to rkm 77.52 near the Wabuska drain. On the West Walker River, daily high stream temperatures only surpass 7 day chronic and acute stream temperature thresholds during one week in WY2015 under modeled historical conditions. Although stream temperature thresholds were exceeded in the mainstem Walker River, modeled DO concentrations showed the most improvement from even minor additions of environmental water transfers. DO response to environmental water purchases is an important consideration for addressing water quality impairments which limit aquatic ecosystems and for determining environmental water transfer effectiveness. This research is also pertinent to highlight streamflow-water quality relationships for other types of environmental flows like pulse flows or reservoir releases.

Small additions of streamflow produced negative DO effects for much of the lower reaches of East Walker River. In those reaches, the thermal mass change from increased flow allowed respiration and SOD to further decrease DO concentrations. In this biologically productive reach, environmental water transfer volumes must be large enough to dilute the effect of oxygen consuming processes. Only larger transfers (+0.71 cms and greater) from Bridgeport Reservoir were enough to overcome the effects of thermal mass increase and begin to positively affect DO concentrations. Due to very high measured and modeled stream temperatures at this reach, large streamflow increases were also needed to improve thermal conditions. Reconnecting suitable habitat in the upper reaches of East Walker River could be achieved if lower reaches of East Walker River received flow additions of 0.71 cms or greater from Bridgeport Reservoir.

Although large flow additions on East Walker River can reverse degraded thermal and DO conditions in that reach, downstream reaches that currently have better DO water quality may be negatively impacted. Upstream reaches that have greater rates of oxygen consuming process (respiration and SOD) can magnify poor water quality in downstream reaches. In WY2014, environmental water transfers from both Bridgeport Reservoir and Topaz Reservoir led to lower DO concentrations below the confluence on the mainstem. Conversely, this trend remained only for water sourced from Bridgeport Reservoir in WY2015. Environmental water transfers originating from West Walker River improved conditions below the confluence. Evidence from model calibration suggests that lower

SOD rates in West Walker River in WY2015 improved water quality below the confluence, rather than degraded water quality. Understanding the conditions that lowered SOD rates in WY2015 will allow scientists to predict how environmental water purchases may affect DO in downstream reaches. Detailed measurement, modeling, and analysis of nutrients and SOD is outside the scope of this thesis, but is a promising direction for future research. Better understanding nutrients and SOD in the Walker River will improve understanding of environmental water purchase benefits for aquatic ecosystems and highlight promising restoration actions in addition to environmental water purchases.

The warm and dry conditions experienced during this work are anticipated to become more frequent in the future from climate warming (Ficklin et al., 2012; Knutti and Sedláček, 2013). Extended drought may alter or reverse restoration gains made during normal or high flows years. Focusing on river reaches that provide the most resilience to extended low flow conditions is a priority for long term benefits of restoration. From this research, my recommendations regarding where to focus environmental water purchases are West Walker River. Thermal and DO thresholds remained closest to acceptable levels during both of these extremely dry years. Flow additions from Topaz Reservoir improved DO concentrations downstream the most and maintained suitable temperature ranges. Topaz Reservoir is also a side-stream reservoir, allowing for upstream migration and maintaining connection with nearly pristine headwaters. Although all water additions (increased Topaz Reservoir releases and canal diversion reductions) reduced daily high stream temperatures, increased Topaz Reservoir releases showed the most optimal strategy for improving DO concentrations.

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APPENDICES

APPENDIX A:

EQUATIONS

1.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right]$$

2.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n}(Y_i^{obs})}\right]$$

3.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right]}$$

4.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y^{obs} - Y^{sim})^2}{n}}$$

APPENDIX B:

CLOUD COVER PERCENT DETERMINATION

For the WY2011-2012 Walker River RMS model, total daily incoming solar radiation data was grouped into seven day (weekly) periods. The highest daily total was assumed to be a cloud free day and all other days in the seven day period reduced from this maximum. Cloud cover fraction classifications were then assigned to each day based on its percentage from the highest day's solar radiation. Cloud cover was broken into quarter increments, from 0 to 100%, and assigned based on the following: >=95% was clear (0), 94%-85% was mostly sunny (0.25), 84%-65% was partly sunny (0.5), 64%-40% was mostly cloudy (0.75), and <40% was cloudy (1). A 95% agreement between days was chosen as clear because of the change, from day 1 to day 7, of the solar angle for a weekly period. All other percentage estimates were made based on best judgement of how varying cloud cover would affect the total solar insolation.

Visual inspection of graphed solar radiation data determined that some data anomalies in the measured values may pose a risk to proper cloud cover fraction assignment that would otherwise align within the classified percent values. These anomalies included data spikes that rose beyond the highest value for a specific time period compared to a nearby known clear day (Fig. B-1; Fig. B-2) as well as weekly stretches whose highest daily total was undoubtedly suppressed due to cloud cover (Fig. B-3).

To test the accuracy of these calculations, and to gauge how effective rigorous quality control measures could improve values, I conducted a 31 day study in Cache County, Utah, using visual comparisons matched to measured data. The overall study objective was to quantify if solar radiation spikes resulted in overestimation of cloud

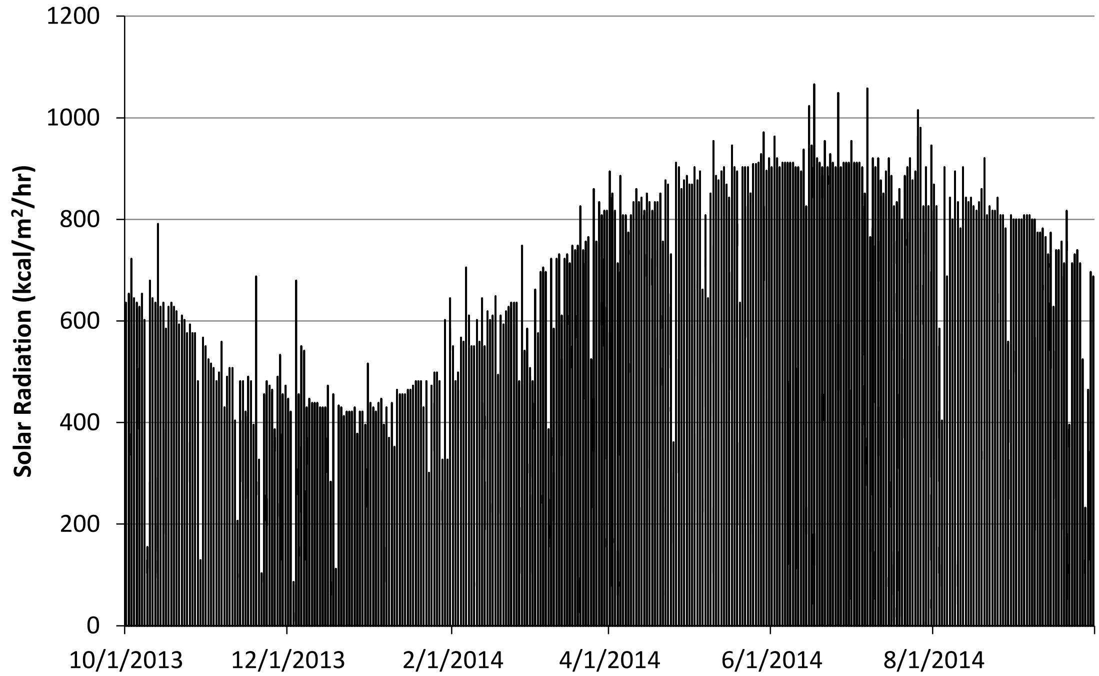

Fig. B-1. Hourly incoming solar radiation data for WY2014 measured at Smith Valley, NV.

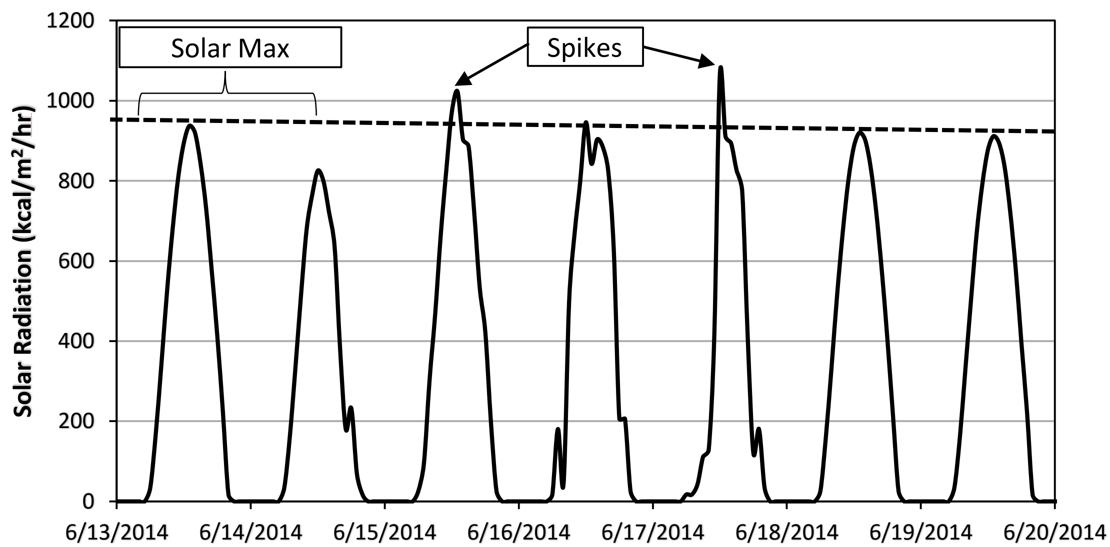

Fig. B-2. Smith Valley solar radiation data showing spiked data points above the solar maximum weekly trend.

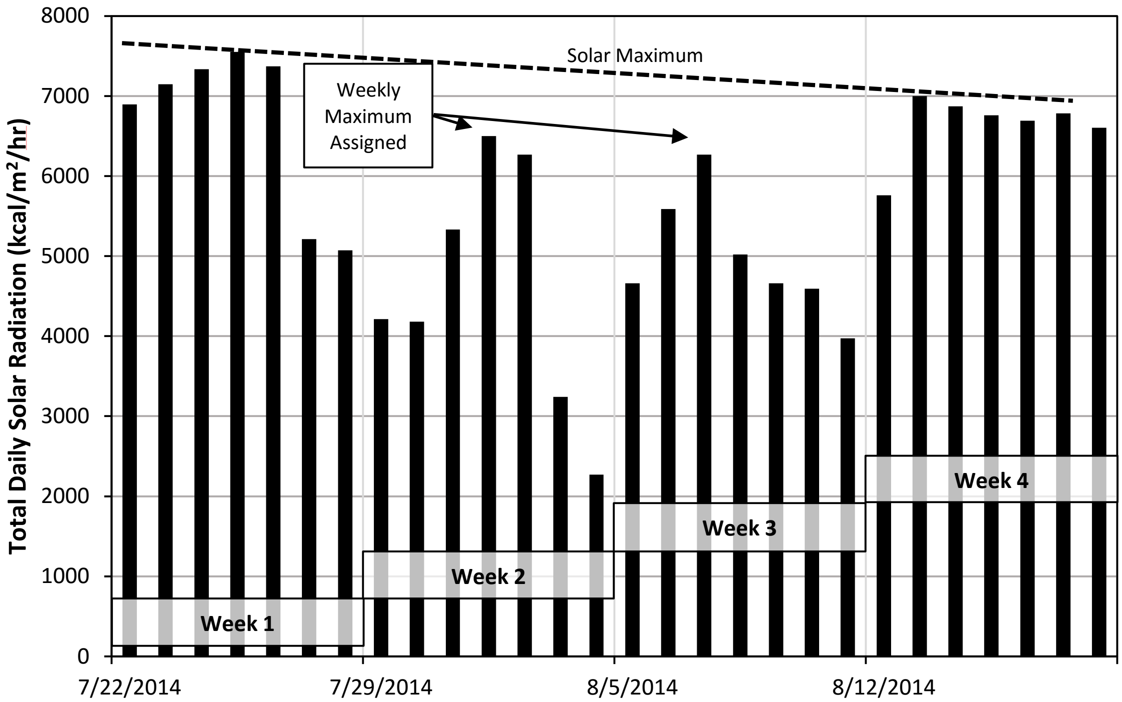

Fig. B-3. Seven day solar groupings showing maximum solar value that was used as reference day for each week.

cover fractions. The study began by recording cloud cover, through a combination of notes and photographs, for each day. Raw shortwave solar radiation data was obtained via the iUtah EPSCoR Time Series Analyst portal (iUtah, 2015). Raw data was then analyzed according to the 2011-2012 RMS model and compared to the numerical cloud cover fraction assigned during the visual assessment.

During the study, solar radiation spikes were observed and were associated with cumulus, stratocumulus, and some cumulonimbus cloud types. The cloud type most likely to create spikes in radiation was cumulus. Cumulus clouds typically have flat bases with vertical development resembling towers, cauliflower or cotton. When not directly blocking the sun, these bright, towering clouds act like lenses, reflecting incoming solar radiation and magnifying the solar intensity on the pyranometer. The majority of the spikes occurred on days categorized as a consistent 0.25 and 0.5 cloud cover fraction by visual assessment.

Cloud cover fraction was determined by five methods to discern the degree to which each method type deviated (Table B-1). The first method, visual daily assessment, occurred from March 19-April 18, 2015. Hourly observations were made with photographic documentation at 10:00, 13:00, and 16:00 MST. After sunset, the cloud cover fraction was estimated for the entire day. The second method was the original 7-day grouping technique utilized in the RMS modeling, years 2011 and 2012. The third and fourth methods required the data to be quality controlled (QC), requiring the creation of a theoretical cloud-free 31 day period. QC radiation data quantifies the effect that solar spikes had on the fraction percent assignment. Method three compared raw data to theoretical cloud-free day and the percentage total was subject to the same cloud cover fraction percentages used for RMS (≥95%, ≥85%, ≥65%, ≥40%, <40%). For method four, the QC data was also compared to the theoretical cloud-free day but spikes were reduced to the maximum value calculated in the theoretical data for that time period (Fig. B-4). Finally for method five, QC data was subjected to the 7-day groupings previously performed in RMS.

QC fractions that were compared to the theoretical cloud-free days performed the best, although the total sum of cloud cover for the 31 day period resulted in only a maximum of 6.8% difference (1-(Sum(7-Day Raw)/Sum(QC))*100). Due to the time investment needed to quality control 2 years of hourly incoming solar radiation data, the original 7-day RMS method was deemed the suitable and defensible method for cloud cover fraction determination.

Table B-1
Cloud cover fraction determination by method for March 19-April 18, 2015. Shaded rows indicate that cloud cover estimates vary by determination method

Day	Visually Assigned	7-Day Raw	Raw	QC	7-Day QC
1	0	0	0	0	0
2	0	0	0	0	0
3	0.25	0.25	0.25	0.25	0.25
4	0.5	0.5	0.5	0.5	0.5
5	1	1	1	1	1
6	1	1	1	1	1
7	0.25	0	0.25	0.25	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0.5	0.5	0.5	0.5	0.5
11	0	0	0	0	0
12	0	0	0	0	0
13	0.5	0.25	0.25	0.25	0.25
14	0.5	0.5	0.5	0.5	0.5
15	0.75	0.75	0.75	0.75	0.75
16	0	0	0	0	0
17	0.25	0	0	0.25	0.25
18	0	0	0	0.25	0
19	0.75	0.5	0.5	0.5	0.5
20	0.5	0.5	0.5	0.5	0.5
21	1	1	1	1	1
22	0.5	0.5	0.5	0.5	0.5
23	0	0.25	0	0	0.25
24	0.5	0.5	0.5	0.5	0.5
25	0	0	0	0	0
26	0	0	0	0	0
27	0.75	1	1	1	1
28	1	1	1	1	1
29	0.5	0.25	0.25	0.5	0.25
30	0	0	0	0	0
31	0	0	0	0	0

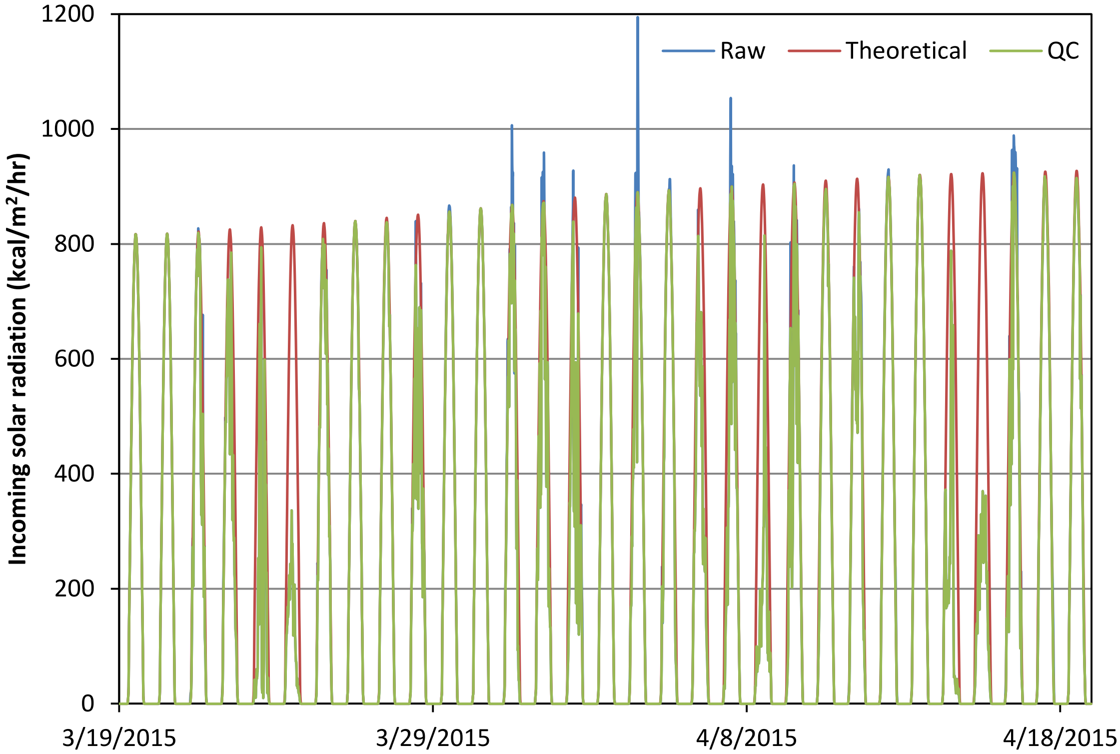

Fig. B-4. Cloud cover fraction results method 3 and 4. Raw data is actual measured values, theoretical data is under perfectly cloud-free conditions, and QC data is raw data with spikes reduced to maximum value for a cloud-free day.

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APPENDIX C:

PHOTOSYNTHESIS, RESPIRATION, AND SEDIMENT OXYGEN DEMAND RATES

Two studies were used to judge the validity of the calibrated photosynthesis, respiration, and sediment oxygen demand rates for this Walker River study. Calibrated values for photosynthesis (PMAX20) ranged from a high of 3.15 $gO_2/m^2/hr$ on the Shasta River, CA, and a low of 0.2 $gO_2/m^2/hr$ for the Harpeth River, TN (Geilser, 2005; Westphal and Lefkowitz, 2011; Table C-1). Walker River PMAX20 values remained within the ranges of these two studies (high of 1.48 $gO_2/m^2/hr$, low of 0.29 $gO_2/m^2/hr$). Respiration (RESP20) rates for both Walker River and Shasta River were both held to 20% of their corresponding PMAX20 values. Harpeth River RESP20 rates varied between 10% and 0% of the corresponding PMAX20 values, however. Sediment oxygen demand (SK20) rates were more variable between the three studies with highs from both Shasta River and Harpeth River in the 2.0 to 2.3 $gO_2/m^2/day$ range whereas Walker River resulted in a maximum of 5.65 $g/O_2/m^2/day$ and frequent values above 2.5 $gO_2/m^2/day$.

Several factors may explain differences in these values. The first is the obvious differences in the environmental conditions of each river. The Walker River resides, predominantly, in the Great Basin desert, whereas the Harpeth River meanders through lowland hardwood forests and agriculture lands of north-central Tennessee. Further in contrast, the Shasta River drains the north slope of Mount Shasta through a wide agricultural valley and is a tributary to the Klamath River. These environmental conditions create varying responses to PMAX20, RESP20, and SK20 rates due to differences in solar radiation, shading, evaporation, and streambed material, among others.

Another important factor to consider when comparing theses calibrated rates is the reaeration equation chosen for each model. The Walker River reaeration equation used was the O'Connor-Dobbins equation, designated using the IK2EQ equation choice code 1. This equation accurately predicts reaeration coefficients for many different systems, but best predicts reaeration coefficients for slow velocity systems deeper than about 0.6 m (Covar, 1976) was found to produce the best overall response to reaeration, PMAX20, RESP20, and SK20 for the entire Walker River. The reaeration code chosen for the Shasta River was the Owens, et al. equation, and the Harpeth River study utilized the Tsivoglou equation. Substituting either of these other two reaeration equation choices into the Walker River model results in an under prediction of hourly DO concentrations, indicating that calibrated rates of PMAX20, RESP20, and SK20 would need to be increased, in some cases substantially, to better match daily magnitude and timing of DO (Fig. C-1).

Table C-1
Walker River, Shasta River, and Harpeth River calibrated PMAX20, RESP20, and SK20 rates

Walker River, NV				**Shasta River, CA**				**Harpeth River, TN**			
Reach 1				**rmi**	**PMAX20**	**RESP20**	**SK20**	**rmi**	**PMAX20**	**RESP20**	**SK20**
rmi	**PMAX20** WY2014 WY2015	**RESP20** WY2014 WY2015	**SK20** WY2014 WY2015	**40.62**	2.36	0.48	0.2	**114.60**	0.2	0.02	2
151.24	1.48 1.35	0.296 0.270	3.72 3.52	**39.94**	2.36	0.48	0.2	**89.00**	0.2	0.02	2
140.23	1.48 1.35	0.296 0.270	3.72 3.52	**38.65**	3.15	0.64	0.5	**88.10**	0	0	2.3

105.87	1.20 1.20	0.240 0.240	2.69 2.69	**32.03**	3.15	0.64	0.5	**76.17**	0.4	0	2.3
84.61	1.10 0.95	0.220 0.190	2.95 2.45	**30.65**	3.15	0.64	2.0	**75.95**	0.4	0	2
82.53	0.59 0.54	0.118 0.102	2.14 2.24	**27.50**	3.15	0.64	0.2	**66.00**	0.3	0	2
77.59	0.48 0.47	0.096 0.094	2.55 3.15	**25.79**	2.36	0.48	0.1	**62.40**	0.5	0.05	2
75.88	0.39 0.29	0.078 0.090	3.75 5.65	**24.10**	1.20	0.24	0.1	**32.40**	0.5	0.05	2
71.14	0.39 0.42	0.078 0.084	1.98 0.67	**19.11**	2.36	0.48	0.1				
69.62	0.34 0.42	0.068 0.084	1.98 1.05	**17.78**	2.36	0.48	5.0				
63.73	0.40 0.44	0.080 0.088	3.30 0.95	**15.40**	3.15	0.64	1.5				
54.62	0.36 0.45	0.072 0.090	4.85 0.95	**14.68**	1.20	0.24	1.5				
48.36	0.36 0.50	0.072 0.100	1.85 0.95	**13.74**	3.15	0.64	1.5				
44.75	0.50 0.50	0.100 0.100	4.85 1.10	**13.16**	2.36	0.48	2.0				
Reach 2				**12.50**	3.15	0.64	0.2				
37.02	1.30 1.30	0.260 0.260	3.80 1.60	**11.10**	2.36	0.48	0.2				
30.37	1.20 1.30	0.240 0.200	3.80 1.40	**10.69**	3.15	0.64	0.2				
14.43	1.10 1.10	0.220 0.220	3.70 1.00	**8.65**	2.36	0.48	0.2				
7.97	1.00 0.45	0.200 0.090	3.70 0.85	**6.42**	2.36	0.48	0.1				
6.27	0.95 0.43	0.190 0.086	3.20 0.67	**1.05**	1.20	0.24	0.1				

0.57	0.82 0.37	0.164 0.074	3.20 0.57	**0.72**	1.20	0.24	0.1	
0.01	0.82 0.37	0.164 0.074	1.98 0.57	**0.00**	1.20	0.24	0.1	

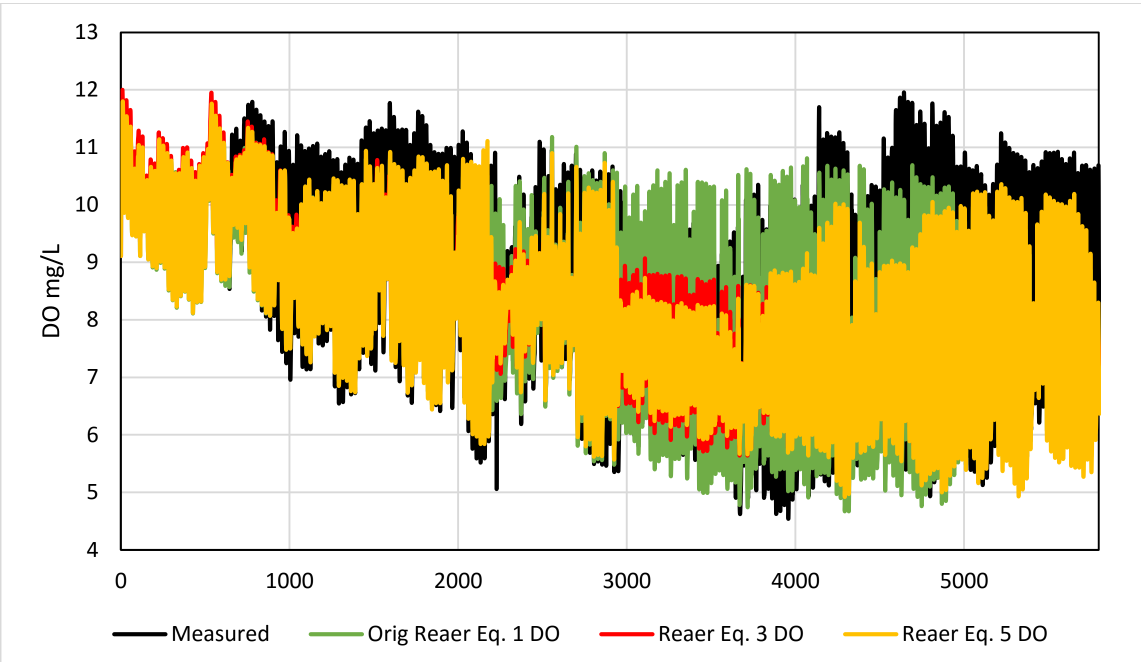

Fig. C-1. Walker River measured versus modeled DO concentrations under three reaeration equation scenarios, rkm 225.37.

Many studies have attempted to quantify photosynthetic oxygen production and respiration rates in rivers and streams (Bowie et al., 1985; Mulholland et al., 2001; Demars et al., 2015). Direct relationships with values found in these studies may not be comparable to the rates described in the Walker River study. Photosynthesis, respiration, and sediment oxygen demand rates calibrated in the Walker River are considered maximum values under specific temperatures, solar radiation conditions, and water volumes (Hauser and Schohl, 2002). PMAX20 are maximum 20°C photosynthetic rate at each node assumed to occur at 900 kcal/m^2/hr light level and RESP20 are maximum 20°C respiration rate at each node (Hauser and Schohl, 2002). Calculating gross primary or net primary production from the rates described in the Walker River study, Table 10, are not additive and should therefore not be considered values to directly determine Walker River net ecosystem production.

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