CHAPTER 4. DISSOLVED OXYGEN SOURCE AND LINKAGE ANALYSIS

4.1 Introduction

This chapter identifies the processes that affect dissolved oxygen concentrations of the Shasta River and its tributaries and establishes a linkage between these processes and measured dissolved oxygen concentrations. First, the various processes that can affect dissolved oxygen concentrations in a surface waterbody are reviewed. Secondly, the chapter identifies the anthropogenic sources (or factors) that are affecting these processes and controlling dissolved oxygen concentrations in the Shasta River and its tributaries. The contributions from these sources are then quantified in Chapter 7.

4.1.1 Processes Affecting Dissolved Oxygen in Surface Waters

Dissolved oxygen levels in surface waters are controlled by a number of interacting processes (Figure 4.1), including:

- Photosynthesis;
- Respiration;
- Carbonaceous deoxygenation within the water column ;
- Nitrogenous deoxygenation ;
- Nitrification;
- Reaeration;
- Sediment oxygen demand; and
- Methanotrophy.

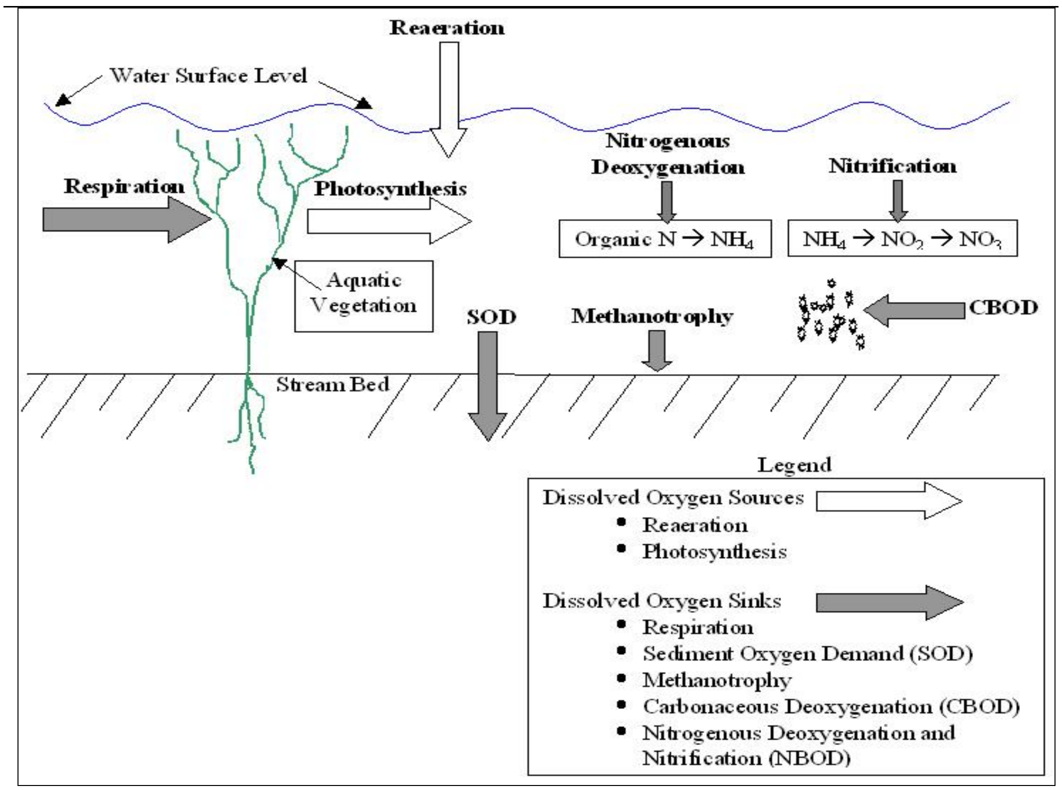

Figure 4.1: Physical, Chemical, and Biological Processes Affecting Dissolved Oxygen in Surface Water Bodies

- *Photosynthesis* is the process by which solar energy is stored as chemical energy in organic molecules. In this process, oxygen is liberated and carbon dioxide is sequestered.
- The organic matter produced by photosynthesis then serves as an energy source for nearly all other living organisms in the reverse processes of respiration and *decomposition* whereby oxygen is bonded with other elements.
- *Carbonaceous deoxygenation* is the technical term for decomposition, involving the consumption of oxygen by bacteria during the breakdown of organic material. Carbon dioxide is released as a byproduct of carbonaceous deoxygenation. When this oxidation is exerted on carbonaceous organic material that is suspended in the water column, it is measured as biochemical oxygen demand (BOD), typically measured as the amount of oxygen consumed during a five-day test period (BOD_5).
- *Nitrogenous deoxygenation* involves the conversion of organic nitrogen to ammonia (NH_4^+) by bacteria, a process that consumes oxygen.
- *Nitrification* is the process by which ammonia is oxidized to nitrite (NO^{2-}) and subsequently to nitrate (NO^{3-}); a process that also consumes oxygen.
- *Reaeration* is the process whereby atmospheric oxygen is transferred to a waterbody.
- *Sediment oxygen demand* refers to the consumption of oxygen by sediment and organisms (such as bacteria and invertebrates) through both the decomposition of organic matter and respiration by plants, bacteria, and invertebrates. Simplistically, sediment oxygen demand is carbonaceous deoxygenation and respiration occurring in the sediments.
- *Methanotrophy* is the process by which methane (CH_4) is biologically oxidized in aerobic environments, a process that consumes oxygen and forms carbon dioxide and water. Methanotrophy can occur in sediments and at the sediment-water interface. Where methanotrophy occurs, it can be measured as part of the overall sediment oxygen demand.

In addition to these processes, dissolved oxygen concentrations are affected by water temperature, salinity, and atmospheric pressure. Oxygen is soluble, or “dissolved” in water. The solubility of oxygen is a function of water temperature, salinity, and atmospheric pressure; decreasing with rising temperature and salinity, and increasing with rising atmospheric pressure. At sea level (1 atm of pressure) fresh water has a saturation dissolved oxygen concentration of about 14.6 mg/L at 0°C and 8.2 mg/L at 25°C. The connection between dissolved oxygen concentration and water temperature is important given the fact that the Shasta River is impaired by both high water temperatures and low dissolved oxygen concentrations.

4.2 Sources of Information

Much of the data and information used in the development of the dissolved oxygen TMDL was collected during the summers of 2002, 2003, and 2004 by Regional Water Board staff, with assistance from the U.S. Geological Survey and UC Davis Aquatic Ecosystems Analysis Laboratory. These data included:

- Hourly dissolved oxygen measurements at 16 sites;
- Hourly temperature measurements at 19 sites;

- Grab sample measurements of nutrients and oxygen-consuming parameters from 42 Shasta River, tributary, spring, and tailwater return sites;
- Sediment oxygen demand measurements at 18 Shasta River locations;
- Aquatic vegetation surveys of nearly 27 miles of the Shasta River and Lake Shastina;
- Light intensity measurements at 14 Shasta River sites;
- Stream bottom sediment characterization at 20 Shasta River sites;
- Riparian vegetation classification of 27 miles of the Shasta River;
- Flow measurements at 9 Shasta River locations;
- Stable isotope sample measurements from 21 Shasta River sites; and
- Text books and scientific literature.

Results of the 2002 and 2003 data collection efforts are reported in NCRWQCB (2004) and Flint and others (2005), which are included as Electronic Appendices C_e (*Shasta River Water Quality Conditions, 2002 and 2003*) and D_e (*Water-Quality Data from 2002 to 2003 and Analysis of Data Gaps for Development of Total Maximum Daily Loads in the Lower Klamath River Basin, California*). Data collected in 2004 are reported in NCRWQCB and University of California Davis, Aquatic Ecosystems Analysis Laboratory [UCD AEAL] (NCRWQCB and UCD AEAL 2005), which is included as Appendix A of this report.

4.3 Processes Affecting Dissolved Oxygen Concentrations in the Shasta River Watershed

Of the eight processes outlined in Section 4.1.1 Regional Water Board staff have identified four primary processes affecting dissolved oxygen concentrations in the Shasta River watershed. Human activities affect, or have a potential to affect, each of these processes, as discussed in Section 4.4. The four processes are:

- Sediment oxygen demand;
- Nitrification;
- Photosynthesis of aquatic plants; and
- Respiration of aquatic plants.

The effects of each of these processes on Shasta River watershed dissolved oxygen conditions are presented in the following sections. The roles of the other four processes on Shasta River watershed dissolved oxygen conditions are summarized below.

Though the data are limited, BOD_5 concentrations (a measure of carbonaceous deoxygenation in the water column) in the Shasta River indicate that carbonaceous oxygen demand exerted in the water column is only a minor component of the total oxygen demand in the Shasta River. BOD_5 concentrations in the Shasta River range from 1.0 to 15.0 mg/L, with an average of 2.1 mg/L. For comparison, biochemical oxygen demand concentrations in the Klamath River near the outlet of hyper-eutrophic Upper Klamath Lake range from approximately 5 to 25 mg/L. Also for comparison, a typical biochemical oxygen demand concentration of untreated domestic sewage in the United States is 220 mg/L (Chapra 1997, p. 358).

There is insufficient data to determine the extent to which nitrogenous deoxygenation (the conversion of organic nitrogen to ammonia) affects dissolved oxygen concentrations in the Shasta River watershed. The oxygen consumption associated with this conversion is minor compared with that of nitrification the conversion of ammonia to nitrite and nitrate, which is significant in the Shasta River watershed and is discussed in Section 4.3.2.

Reaeration plays a key role affecting dissolved oxygen concentrations in the Shasta River. The water quality model used in the development of the dissolved oxygen TMDL accounts for reaeration and is outlined in Chapters 5 and 7.

There is insufficient data to determine whether methanotrophy contributes to oxygen consumption in the Shasta River. Methane has not been measured in the Shasta River; however, Regional Water Board staff never detected odors associated with methane production in the river or at the outlet of Lake Shastina in the Main Canal. If methanotrophy does occur in the Shasta River, its contribution to oxygen demand would likely be accounted for in the sediment oxygen demand measurements.

4.3.1 Sediment Oxygen Demand

Sediment oxygen demand (SOD) rates in the Shasta River are relatively high, indicating a system with organic material that is decomposing within the sediment at a moderate rate (Flint et al. 2005, p. 38). SOD is the rate of dissolved oxygen loss from a waterbody through uptake and consumption of oxygen by biotic or abiotic reactions in surficial sediments. In most systems, such oxygen consumption is dominated by microbially-mediated decomposition processes. In other words, organic materials in the waterbody's sediments rot and decompose; that process requires oxygen, which is supplied from the overlying water. SOD can be an important part of the stream's dissolved oxygen budget, particularly in rivers with an abundance of sedimentary organic material. This sedimentary organic material may have been deposited in the channel from various sources, including bank erosion and settleable solids from irrigation return flows, as well as an accumulation of plant and algal detritus.

In August 2003, the U.S. Geological Survey measured SOD rates at six locations in two reaches of the Shasta River (Flint et al. 2005). The measurement sites were chosen because they are located in a reach of the river with measured low dissolved oxygen concentrations and observed accumulation of fine sediment and aquatic plant detritus. Other considerations for site selection included access, type of stream substrate, and the amount of macrophyte (aquatic plant) growth. Procedures for measuring SOD rates in the Shasta River and results are discussed in detail by Flint and othersl. (2005). The measured SOD_{20}[1] rates in the Shasta River range from 0.1 to 2.3 g/m^2-d with a median of 1.5 g/m^2-d [2]. A SOD_{20} rate of 1 to 2 g/m^2-d indicates a system with organic material that

[1] SOD_{20} rate is the SOD corrected to a temperature of 20°C.
[2] g/m^2-d is grams per square meter per day.

is decomposing at a moderate rate. A moderate SOD rate indicates that the decomposing organic material is neither extremely labile nor extremely refractory (Flint et al. 2005). Labile organic material is readily decomposed, while refractory organic material is more resistant to decomposition. According to Flint and coworkers (2005) the amount of dissolved oxygen that can be consumed by SOD over the course of a day is a function of stream depth and is calculated as the SOD rate in g/m^2-d divided by the stream depth in meters. Assuming an average depth of 1 meter, and applying the median Shasta River SOD rate of 1.5 g/m^2-d, then 1.5 mg O_2 is consumed per liter of water by SOD over the course of 1 day, representing a significant component of the total oxygen demand in the Shasta River. During summer months, the depth of flow in the Shasta River varies from approximately 0.1 to 1 meter in most reaches, with depths up to 3 meters in some impounded areas.

4.3.2 Nitrification

Nitrogenous deoxygenation involves the conversion of organic nitrogen to ammonia and the subsequent oxidation of ammonia. Nitrification is the oxidation of ammonia to nitrate represented by equation 4.2 in the two-step process presented below:

$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + H_2O + 2\ H^+$ (Eq. 4.1)
$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$ (Eq. 4.2)

Stoichiometrically, 3.43 and 1.14 grams of oxygen are required to transform each gram of ammonia nitrogen to nitrite nitrogen (Eq. 4.1) and nitrite nitrogen to nitrate nitrogen (Eq. 4.2), respectively. The total amount of oxidizable nitrogen is equal to the sum of organic- and ammonia-nitrogen, and is measured as Total Kjeldahl Nitrogen (TKN). The oxidation of organic- and ammonia-nitrogen consumes 4.57 grams of oxygen per gram of TKN. For water quality monitoring purposes, nitrogenous deoxygenation is estimated as 4.57 * the ambient TKN concentration (Chapra 1997, p. 424). For example, if the TKN concentration in a river is 1.0 mg/L, then 4.57 mg/L of dissolved oxygen is consumed when the organic- and ammonia-nitrogen are oxidized. If dissolved oxygen is available it will oxidize available ammonia nitrogen and nitrite nitrogen.

From 1993 through 2003, TKN concentrations in the Shasta River ranged from 0.1 to 4.0 mg/L, with an average of 0.50 mg/L (see Table 2.8 in Chapter 2). At this average TKN concentration, approximately 2.3 mg/L of oxygen would be consumed. This 2.3 mg/L of oxygen consumption occurs spread over an unknown period that is likely at least five days long, thus representing only a moderate component of the total oxygen demand exerted in the Shasta River.

4.3.3 Photosynthesis and Respiration of Aquatic Plants

During summer months (generally June through August), dissolved oxygen concentrations in the Shasta River follow a distinct diurnal pattern, with high concentrations (near or above saturation) during daylight hours and lower concentrations (near or below saturation) during nighttime hours. This dissolved oxygen signal is typical of productive river systems experiencing high photosynthesis and respiration rates of aquatic plants. Based on measured data, one of the most extreme examples of this diurnal pattern is exhibited in the Shasta River at Highway 3 between June and September 2003 (Figure 4.2).

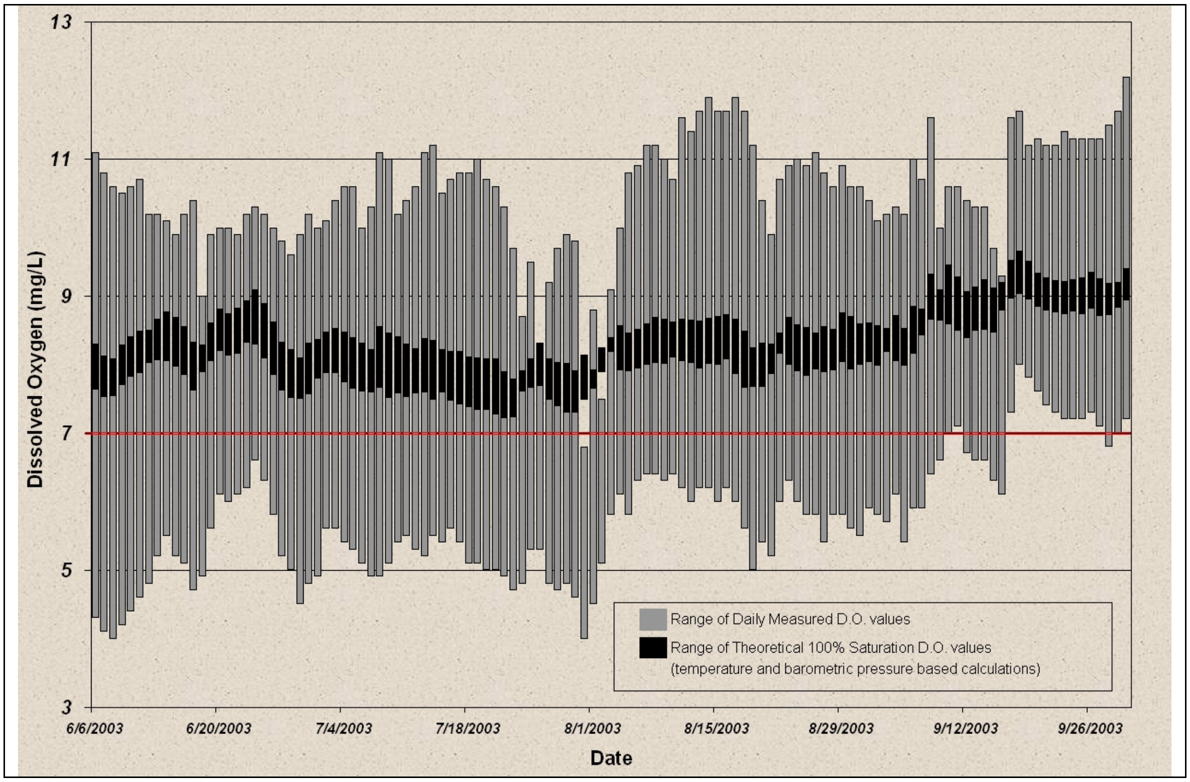

Figure 4.2: Daily measured dissolved oxygen concentration ranges versus calculated dissolved oxygen saturation concentrations, Shasta River at Highway 3, June through September 2003

Figure 4.2 shows the daily range of measured dissolved oxygen concentrations and 100-percent saturation concentrations in the Shasta River at Highway 3. The saturation dissolved oxygen concentration is calculated based upon water temperature, salinity, and atmospheric pressure. As shown in Figure 4.2 dissolved oxygen concentrations can move above (termed supersaturation) and below (under-saturation) 100-percent saturation values. Supersaturated conditions occur when the oxygen-generating factors (i.e. reaeration and photosynthesis) exceed the oxygen-consuming factors (i.e. carbonaceous and nitrogenous oxygen demand, SOD, and respiration). Conversely, under-saturated conditions occur when the oxygen-consuming factors exceed the oxygen-generating factors. USGS has reported cases of supersaturated conditions in Oregon water bodies attributed to aquatic plant growth persisting for several days or more, with saturations as high as 250 percent (Flint et al. 2005, p. 60).

Generally, during summer months, Shasta River dissolved oxygen concentrations are above the Basin Plan objective of 7.0 mg/L during daylight hours, and fall below 7.0 mg/L during nighttime and early morning hours of the day. Figure 4.3 presents the range of *hourly* dissolved oxygen concentrations during summer months in Shasta River reaches. This pattern is typical of productive river systems with prolific aquatic plant growth. Photosynthesis by aquatic plants occurs in sunlight and generates oxygen.

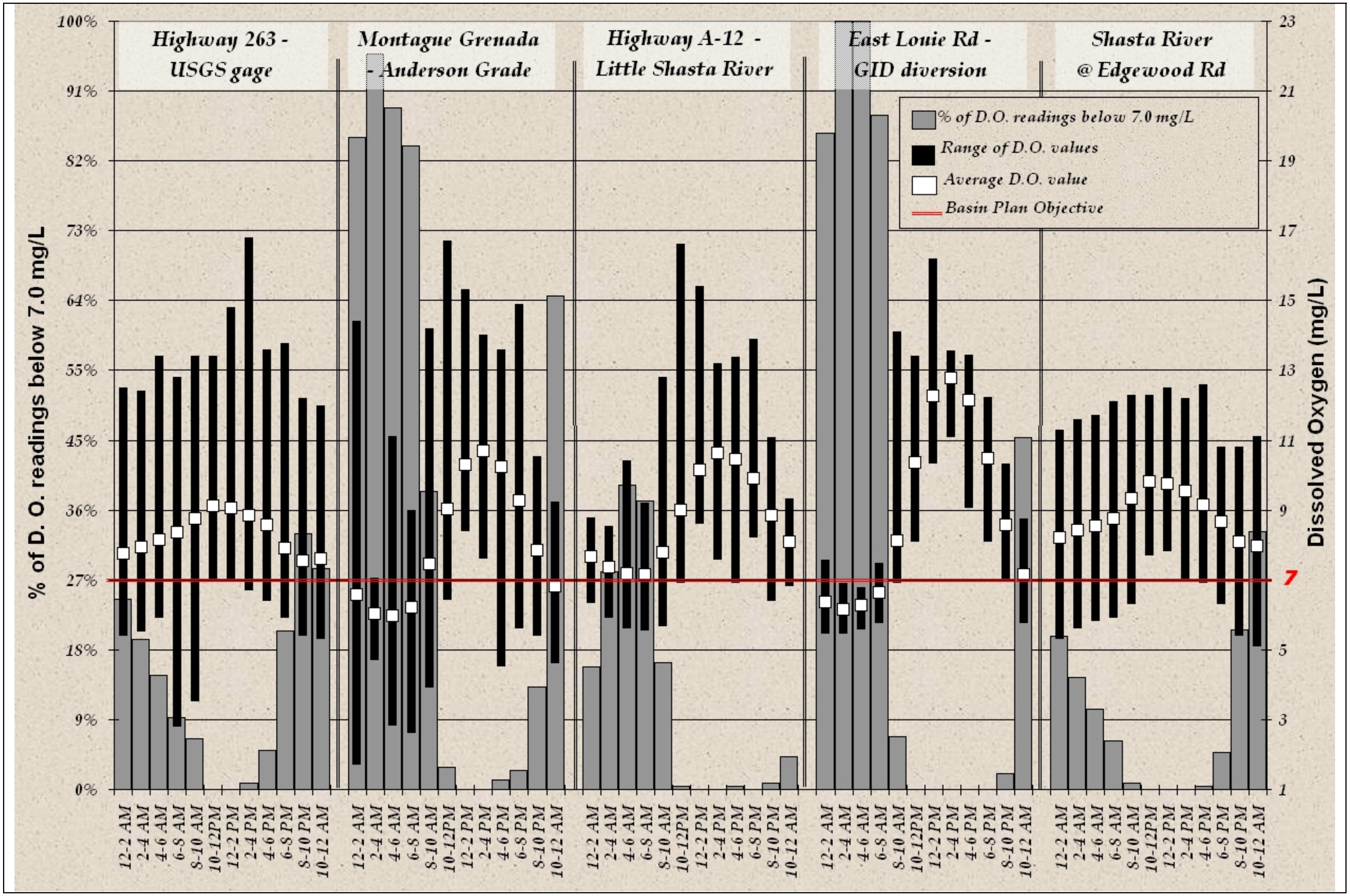

Figure 4.3. Hourly dissolved oxygen concentration ranges, mainstem Shasta River reaches, May through September 1994-2004.

Respiration by aquatic plants is constant, and consumes oxygen. During daylight hours when photosynthetic rates exceed respiration and SOD rates, there is a net increase in dissolved oxygen in the water column. During nighttime hours when aquatic plants do not photosynthesize, there is a net decrease in dissolved oxygen in the water column. Figures 4.2 and 4.3 demonstrate the dramatic effect of photosynthesis and respiration by aquatic plants on Shasta River dissolved oxygen concentrations. Section 4.3.3.1 summarizes the aquatic vegetation conditions in the Shasta River and Lake Shastina and establishes a link between aquatic vegetation productivity and measured dissolved oxygen conditions. Section 4.3.3.2 evaluates the factors that affect aquatic vegetation productivity in the Shasta River and Lake Shastina. Section 4.4 then identifies the sources (or factors) that affect photosynthetic and respiration rates of aquatic plants, sediment oxygen demand rates, and nitrification in the Shasta River and Lake Shastina.

4.3.3.1 <u>Aquatic Vegetation Conditions of the Shasta River and Lake Shastina</u>
High aquatic plant biomass can result in severe diurnal swings in dissolved oxygen. (USEPA 2000, p.5). In order to better understand the role of Shasta River aquatic vegetation on dissolved oxygen concentrations, Regional Water Board staff conducted a survey of the aquatic vegetation of the Shasta River in the summer of 2004, with technical assistance from UC Davis Aquatic Ecosystems Analysis Laboratory (UCD AEAL). The purpose of the aquatic vegetation survey was to characterize the spatial distribution, composition, and biomass of aquatic plants in the Shasta River and Lake Shastina. The methods and results of the aquatic vegetation survey are described in Appendix A.

The aquatic vegetation survey was conducted in the riverine reach from the mouth of the Shasta River to Dwinnell Dam and at two open water locations in Lake Shastina. Due to access limitations, the survey was conducted on 26.9 miles of the 40.6-mile reach from the mouth to Dwinnell Dam (two thirds of the river length from Dwinnell Dam to the mouth).

The types of aquatic plants in the Shasta River and Lake Shastina include: (1) benthic algae, called periphyton, which generally grow attached to rocks, gravel, and other plants; (2) vascular plants (primarily rooted), called macrophytes; and (3) suspended algae, called phytoplankton. The survey identified a total of 95 different species of aquatic plants in the Shasta River and Lake Shastina, including 75 total algal species (47 species present in the river samples and 35 species present in the Lake Shastina samples) and 20 macrophyte species.

The aquatic vegetation survey included several measures of abundance -- percent cover (a visual estimation performed in the riverine reaches dominated by macrophytes), density (measured as number of periphyton cells/cm^2 and number of phytoplankton cells/mL), ash free dry weight (AFDW), and chlorophyll a and pheophytin a concentrations for periphyton and phytoplankton.

The assemblage, distribution, and quantity of aquatic plants in the Shasta River are variable and complex. Generally, rooted macrophytes dominate the assemblage of aquatic vegetation in much of the Shasta Valley, where the river is typically slow-moving, meandering, and generally depositional. In the higher gradient reaches, most notably the canyon, periphyton is the dominant aquatic vegetation type. Due to the varying water depth in Lake Shastina, rooted macrophytes are uncommon in the shallow, near-shore zones of the lake, however the lake contains many species of phytoplankton.

Macrophytes

The rooted macrophytes of the Shasta River include two primary morphological groups: (1) emergent reeds, sedges, and rushes, which grow rooted in the shallow zones of the river at the banks, and (2) emergent and submerged broad-leaved plants, which grow in shallow as well as deep (up to approximately 10 feet) zones of the river. The dominant macrophyte species[3] in the river include *Potamogeton spp*., *Scirpus spp*., and *Elodea canadensis*. *Elodea canadensis* and *Scirpus spp*. prefer a peat channel substrate over a silt, clay, or sand substrate; *Potamogeton spp*. prefer a silt substrate over clay, sand, or gravel/pebble. Each of these dominant macrophyte species prefers a "no perceptible flow" type (see Appendix A). Free-floating macrophytes, primarily *Lemna minor*, also occur in the deeper, impounded reaches of the river.

The percent cover of macrophytes ranged from 5 to 95%, with nearly 42 percent of the river surveyed having 50% or higher total macrophytes cover. The biomass of the macrophyte-dominated reaches ranged from 8 to 309 milligrams per square centimeter (mg/cm^2), with an average of 76 mg/cm^2.

A review of the literature did not find specific macrophyte density or biomass values that are indicative of water quality conditions. However, USEPA (2000, p. 35) reports that excess macrophytes biomass, like that found at many locations on the Shasta River, can produce large diurnal fluctuations in dissolved oxygen. In addition, excessive macrophyte abundance can represent a nuisance to water recreation (Welch 1992, p. 200). On the other hand, macrophytes can provide important habitat for fish and macroinvertebrates, a benefit that must be balanced with the effects on dissolved oxygen.

Periphyton

The dominant periphyton species[4] in the river include *Cocconeis placentula and C. pediculus*, *Epithemia sorex*, and *Rhoicosphenia curvata*. These diatoms are common in flowing environments and prefer water that is both alkaline and eutrophic (Carpenter 2003, p.100; Fore and Grafe 2002). *C. placentula* prefers higher water temperatures (DeNicola 1996). *E. sorex* is often found in waters with an elevated nutrient content (Eilers 2005) and is favored in nitrogen limited water due to its ability to fix atmospheric nitrogen (Borchardt 1996; Carpenter 2003, p.100).

The biomass (AFDW) of the periphyton-dominated communities in the Shasta ranged from 2.0 to 19.1 mg/cm^2, with an average of 5.9 mg/cm^2. Periphyton chlorophyll a and pheophytin a concentrations ranged from 29.5 to 271.5 milligrams per square meter (mg/m^2) and from 22.5 to 227.4 mg/m^2, respectively. Average periphyton chlorophyll a

[3] In this context, dominance is attributed to those macrophyte species that have the greatest percentage of cover within the river reaches surveyed.
[4] In this context, dominance is attributed to those periphyton species that have the greatest percentage of cell density ($\#/cm^2$) with respect to the total periphyton community cell density.

and pheophytin a concentrations were 153.5 and 80.7 mg/m^2, respectively. Note that units of measurement for chlorophyll a and pheophytin a differ from those for AFDW biomass (mg/m^2 and mg/cm^2, respectively).

USEPA (2000, p.31) finds that benthic chlorophyll a values for unenriched, light-limited, or scour-dominated stream systems are typically much less than 50 mg/m^2. Most of the chlorophyll a values for the Shasta River are above this value for “unenriched streams.” The average of periphyton chlorophyll-a samples for the Shasta River exceeds 150 mg/m^2, which is described as the level indicative of highly enriched sites according to Lohman and others 1992 (as cited by Tetratech 2005).

Literature values for “nuisance” levels of benthic algae chlorophyll a range from 100 to 200 mg/m^2 (Dodds et al. 1998; Dodds and Welch 2000; Sosiak 2002; USEPA 2000 as cited by Tetratech 2005; Welch et al. 1988). The average value of benthic chlorophyll a in the Shasta is over 150 mg/m^2, which USEPA (2000, p.102) considers a generally agreed upon criterion to prevent nuisance conditions and impacts to aesthetic values.

Dodds and others (1998) created a classification system for stream trophic state based on frequency distributions of chlorophyll-a, total nitrogen, and total phosphorous data from 200 streams in North America and New Zealand. Table 4.1 presents their findings for classification of trophic status based on benthic chlorophyll a levels. Based on this classification scheme, the measured Shasta River benthic chlorophyll a values reflect eutrophic conditions.

Table 4.1: Boundaries for Trophic Classification of Streams

Parameter	Oligotrophic-mesotrophic boundary	Mesotrophic-eutrophic boundary	Sample size
Mean benthic chlorophyll-a (mg/m^2)	20	70	286
Maximum benthic chlorophyll-a (mg/m^2)	60	200	176

Source: Modified from Dodds et al. 1998

Phytoplankton

The dominant phytoplankton species[5] in Lake Shastina include *Anabaena flos-aquae*, *Rhodomonas minuta*, and *Tetraedron minimum*. *Anabaena flos-aquae* is a blue green algae, also called cyanobacteria, that is widespread in eutrophic lakes. Like many blue green algae, it can produce toxins that can be harmful to humans, livestock, and pets. *Tetraedron minimum* is a green algae that grows in mesotrophic or eutrophic environments, and is not commonly found in lakes, while *Rhodomonas minuta* occurs in a wide range of habitats including lakes (Sweet 2004).

The biomass of phytoplankton in Lake Shastina ranged from 33.4 to 66.4 mg/L, with an average of 52.5 mg/L. Phytoplankton chlorophyll a and pheophytin a concentrations ranged from 5.5 to 46.7 micrograms per liter (ug/L) and from 0.9 to 21.8 ug/L, respectively. Average phytoplankton chlorophyll a and pheophytin a concentrations were 27.15 and 6.1 ug/L, respectively. Literature values which associate chlorophyll levels in

[5] In this context, dominance is attributed to those phytoplankton species that have the greatest percentage of cell density (#/mL) with respect to the total phytoplankton community cell density.

lakes and reservoirs to trophic status are presented in Table 4.2. Measured chlorophyll a concentrations in Lake Shastina are within the mesotrophic to hypereutrophic classification ranges, with the majority of the values within the eutrophic-hypereutrophic classification range, and the average value indicating eutrophic conditions.

Table 4.2: Boundaries for Trophic Classification of Lakes and Reservoirs

Parameter	**Oligotrophic**	**Mesotrophic**	**Eutrophic**	**Hyper-eutrophic**	**Source**
Chlorophyll-a (ug/L)	<4	4-10	10-25	>25	Carlson (1977), Olem and Flock (1990, p.80-84)
Chlorophyll-a peak (ug/L)	<2	2-9	>9	-	Vignola and Deas (2005)
Tot Chlorophyll (ug/L)	<3	3-9	9-40	>40	Forsberg and Ryding (1980, as cited by Florida Lake Watch Undated)

Note: Authors cited used different chlorophyll measures

Summary
The aquatic vegetation survey documented the abundance of aquatic vegetation in the Shasta River and Lake Shastina. The Shasta River falls within the eutrophic boundary classification, and Lake Shastina falls within the eutrophic to hyper-eutrophic boundary classification. The abundance of aquatic vegetation in the Shasta River and Lake Shastina means the photosynthetic and respiration activity of the vegetation has a significant effect on the diurnal fluctuation of dissolved oxygen concentrations. In addition, when the aquatic vegetation dies and is decomposed an oxygen demand is exerted via carbonaceous deoxygenation.

4.3.3.2 Factors Affecting Aquatic Vegetation Productivity in the Shasta River
The primary factors that can limit aquatic vegetation productivity include light availability, nutrient concentrations, channel substrate composition, flow, current velocity, and temperature. This section provides a brief review of the literature with respect to these limiting factors and summarizes Shasta River conditions. Biggs (2000) provides a comprehensive review of the factors affecting periphyton growth.

Stream Temperature
Higher stream temperatures tend to enhance aquatic vegetation growth and may increase photosynthesis and respiration, resulting in greater variation in diurnal dissolved oxygen concentrations (USEPA 2000, p. 35). The maximum growth rate of aquatic vegetation occurs at a corresponding optimal stream temperature. Maximum growth rates of benthic algae often correspond with reference temperatures of 20°C (USEPA 1985, p. 293). During summer months when dissolved oxygen concentrations reach critical levels in the Shasta River, stream temperatures regularly exceed 20°C and do not limit aquatic vegetation growth.

Flow and Current Velocity
Current velocity is an important factor controlling aquatic vegetation assemblage. Generally, macrophytes are more adapted to slow moving river systems, while periphyton can withstand higher current velocities. As discussed in Section 4.3.3.1,

macrophytes dominate the assemblage of aquatic vegetation in much of the Shasta Valley, where the river is characterized by slow velocity. In the higher gradient and faster velocity reaches, periphyton are dominant.

Under high current velocities, the frictional shear stress created on a periphyton mat can scour the attached algae from the substratum (Horner and Welch 1981, as cited by Welch 1992, p. 245). High current velocity can also scour rooted macrophytes. Local observers have noted that the amount of aquatic vegetation washed from the Shasta River in the fall increases when flows increase at the conclusion of the irrigation season. Removal of aquatic vegetation via scour decreases photosynthetic oxygen gain and respiratory oxygen loss to the water. In addition, when a scour-event washes the vegetative material out of the Shasta system, there may be a decrease in the oxygen demand exerted on the Shasta River, and consequently there may be an increased oxygen demand on the Klamath River.

Dwinnell Dam (located at River Mile 40.6) impounds the Shasta River, capturing all flow originating in the headwaters, as well as Parks Creek flow diverted to Lake Shastina, thereby storing water from wet periods for use in dry periods. Only in above-normal rainfall years has Lake Shastina over-topped its spillway during the winter months. Since 1956, the reservoir has reached its capacity of 50,000 acre-feet on approximately 10 occasions or an average of twice in every ten-year period (Vignola and Deas 2005). The modification of Shasta River flows, and particularly the reduction in peak flow rates caused by the dam and diversions, both limit scour of the riverbed. The implication is that fine sediments and aquatic vegetation are not scoured from the channel as much as they would be if the dam were not in place. Consequently, fine sediments and aquatic vegetation build-up in the system. This build-up of organic material contributes a significant oxygen demand on the river. One local resident observed that aquatic vegetation densities were greatly reduced for several years following relatively high rainfall in the winter 1997/1998.

Substrate Composition

Periphyton prefer cobble or gravel substrates, whereas rooted macrophytes prefer finer substrates, such as peat, silt, sand, or clay. As mentioned in Section 4.3.3.1, most of the macrophyte species found in the Shasta River prefer peat or silt substrates. As part of the aquatic vegetation survey, Regional Water Board and UC Davis staff made visual estimates of channel substrate composition (Appendix A). Shasta River substrate composition is variable. Gravel, sand, and fines predominate. The percentage of fines is greatest in the meandering, slow moving reaches of the river.

Macrophyte abundance tends to be the greatest in those reaches with the highest percentage of fine sediments. Regional Water Board staff also observed that submerged and emergent macrophytes trap fine sediment and organic material, thereby contributing to the sediment oxygen demand of the river, as well as enhancing the suitability of the substrate conditions for macrophyte establishment and proliferation. This sediment trapping capacity of macrophytes is also reported by Welch (1992, p. 200).

Light

Aquatic plants require light to grow. Light limitation can be an important control on diurnal dissolved oxygen swings in enriched rivers (USEPA 2000, p. 35). The growth rate of algae is a function of light as well as temperature and nutrient concentrations. Most models predict algal growth rates, or rates of photosynthesis, according to saturation-type relationships in which the growth rate increases linearly with light at low intensities but gradually levels off at high intensities to reach a maximum value at saturated light intensity (USEPA 1985, p. 311).

Light availability to aquatic plants in rivers is controlled by riparian canopy as well as water depth and clarity. Riparian canopy serves to block or filter incoming light. Reductions in riparian canopy therefore increase the availability of light and, conversely, increases in riparian canopy decrease light availability.

Submerged macrophytes are adapted to high light intensities. For example, photosynthetic rates (measured as ^{14}C assimilation) of *Elodea canadensis* (one of the dominant species in the Shasta River) were optimum between 75 and 100% of full sunlight (Hartman and Brown 1967, as cited by Welch 1992, p. 202). Further, incidence of nuisance growths of macrophytes in an Alabama reservoir corresponded with years of high mean daily incident light and low rainfall (less runoff and thus less turbidity) during the spring growth period (Peltier and Welch 1970, as cited by Welch 1992, p. 204).

Periphyton also respond to light availability. The species composition of periphyton can vary depending on light availability. One study found that light-adapted species had a slightly higher rate of photosynthesis at high light intensities, compared with shade-adapted species grown in artificial streams (McIntire and Phinney 1965, as cited by Welch 1992, p. 242). Further, the periphyton community grown in the lighted stream reached a saturated biomass level in two-thirds the time of the periphyton growing in the shaded stream.

A study of headwater streams in southwestern British Columbia found that the mean solar flux to stream reaches with no riparian buffer (i.e. clear-cut) was 58 times greater than the solar flux to uncut (i.e. control) riparian buffer stream reaches (Kiffney et al. 2003). Further, Kiffney et al. (2003) concluded that light was the primary constraint on accrual of periphyton biomass, with periphyton ash free dry mass in the clear-cut treatment reaches exceeding that of the control reaches by six times during the summer.

While riparian vegetation conditions are variable in the Shasta River watershed, there are many reaches with little or no riparian cover (see Section 1.4.7.1). Further, topographic shade is minimal to non-existent in the Shasta Valley, though it is more prominent in the Shasta canyon. Given these conditions, much of the Shasta River and its tributaries are exposed to ample light, which promotes prolific growths of aquatic vegetation.

Nutrient Concentrations

Aquatic vegetation requires nutrients to grow. Nuisance levels of periphyton and macrophytes can develop rapidly in response to nutrient enrichment when other factors such as light, temperature, substrate, etc. are not limiting (USEPA 2000, p. 4). Nitrogen and phosphorus are the primary macro-nutrients that enrich freshwater aquatic systems. Ammonia (NH_4^+), nitrate (NO_3^-), and ortho-phosphate (PO_4^{3-}) are the soluble fractions of nitrogen and phosphorus and are the forms directly available to aquatic plants.

The role of nutrients in aquatic ecosystems is complex, and is confounded by other factors such as light availability, flow, and temperature. Similar nutrient concentrations may not cause similar environmental responses (such as aquatic vegetation productivity and dissolved oxygen concentrations) because of the non-nutrient factors. Despite this complexity, studies have developed quantitative relationships between nutrient concentrations and mean or maximum chlorophyll levels in periphyton (for a review see Tetra Tech 2005). These correlations tend to be waterbody-specific, and there is a lot of variability between waterbodies.

Rooted macrophytes assimilate nutrients from both the sediments and water column, though the dominant assimilation pathways are not well described for different species. Welch (1992, p. 198-208) states that rooted submerged macrophytes (the predominant type in the Shasta River) depend largely on the sediments for their nutrients. Tetra Tech (2005) notes that attempts to predict macrophytes' response to water column nutrient concentrations are fraught with difficulties, and that analysis of these effects must be done on a site-specific basis or using surrogate variables such as periphytic algae biomass.

Section 2.5 provides an overview of nutrient conditions in the Shasta River watershed as they compare to USEPA national and ecoregional criteria. Total phosphorus and total nitrogen concentrations of the Shasta River and its tributaries are biostimulatory and promote aquatic growth, reflecting nutrient overenrichment from anthropogenic sources. In Lake Shastina, total phosphorus and total nitrogen concentrations are biostimulatory, generally falling within eutrophic to hypereutrophic classification boundaries.

The concentrations of total phosphorus in the headwaters of the Shasta River (originating as snow melt from Mount Eddy) are generally below biostimulatory levels. However, total phosphorus and total nitrogen concentrations of springs and spring-fed streams are quite high and biostimulatory.

4.4 Anthropogenic Effects on Shasta River Dissolved Oxygen Conditions

Section 4.3 identified that sediment oxygen demand, nitrification, and photosynthesis and respiration of aquatic vegetation are the primary processes affecting dissolved oxygen concentrations in the Shasta River. In addition, Section 4.3.3.2 demonstrated that the conditions of light availability, nutrient concentrations, channel substrate composition, flow, current velocity, and stream temperature in the Shasta River and Lake Shastina sustain prolific growth of aquatic plants. This section identifies the anthropogenic sources or factors that promote aquatic plant growth (and thereby promote photosynthetic production and respiratory consumption of dissolved oxygen), increase sediment oxygen demand rates, and/or increase nitrification in the Shasta River watershed. In Chapter 7, the effect of these sources on dissolved oxygen concentrations in the Shasta River is quantified.

Regional Water Board staff identified five anthropogenic sources or factors affecting dissolved oxygen conditions of the Shasta River, including:

- Tailwater return flow,
- City of Yreka non point and wastewater infiltration sources,
- Lake Shastina and minor impoundments,
- Riparian shade, and
- Flow.

4.4.1 Tailwater Return Flow Quality

In this document "tailwater return flow" is defined as surface runoff of irrigation water to a surface water body, and is synonymous with "irrigation return flow." The quality of tailwater return flows in the Shasta River watershed has not been well documented. In the summer of 2003, Regional Water Board staff collected a total of 16 water samples from 13 locations with tailwater return flows to the Shasta River. Summary statistics are presented in Table 4.3. For comparison, average Shasta River concentrations are also shown in Table 4.3. The tailwater samples were collected from 13 locations in the watershed, and primarily included flow in ditches as opposed to sheet flow across a field.

Table 4.3: Summary of Shasta River tailwater return flow quality, and average water quality of the Shasta River below Dwinnell Dam

Location	Statistic	Ortho P	Total P	Ammonia as N	NO2+NO3 as N	TKN	BOD_5	TSS	TOC
Tailwater	Minimum	0.03	0.03	0.03	0.03	0.3	1.5	5	0.5
	Maximum	0.79	0.88	0.65	0.52	3.9	7.0	140	24
	Average	***0.20***	***0.26***	***0.10***	***0.10***	***1.2***	***2.7***	***16.8***	***8.2***
	Median	0.18	0.25	0.06	0.08	0.9	2.0	5	5.1
	Count	16	16	15	15	15	11	16	16
Shasta River[1]	***Average***	***0.14***	***0.19***	***0.025***	***0.087***	***0.50***	***1.5***	***5.0***	***4.3***

Notes: Units for all parameters are mg/L.
1. Shasta River data is a compilation of all Shasta River locations monitored downstream of Dwinnell Dam.

Despite the limited tailwater measurements, several important conclusions can be made about tailwater return flow quality in comparison to the average water quality of the Shasta River:

- Tailwater return flows contribute to the oxygen demand exerted on the Shasta River. The average TKN concentration of tailwater return flows is over two times that of the average Shasta River concentration during the irrigation season (1.2 and 0.5 mg/L, respectively). In other words, tailwater return flows contribute significantly to the overall nitrogenous oxygen demand of the Shasta River.
- Ammonia and nitrate (NO_3^-) are the forms of nitrogen directly available to aquatic plants. Average ammonia concentrations of tailwater return flows are four times that of the average Shasta River concentrations during the irrigation season. This contribution of ammonia to the Shasta River stimulates the growth of aquatic plants, representing a significant contribution to the total oxygen demand by increasing respiration.
- The average BOD_5 concentration of tailwater return flows is nearly two times higher than that of the average Shasta River concentration (2.7 and 1.5 mg/L, respectively).

- The carbonaceous oxygen demand associated with tailwater return flows contributes to the overall carbonaceous oxygen demand of the Shasta River and tributaries, both in the water column and in the stream sediments.
- Total suspended solids (TSS) and total organic carbon (TOC) concentrations can provide some input into potential carbonaceous oxygen demand not measured as $BOD_{5.}$ The average TSS concentration of tailwater return flows is over three times that of the average Shasta River concentration (16.8 and 5.0 mg/L, respectively). Similarly, the average TOC concentration of tailwater return flows is approximately twice that of the average Shasta River concentration (8.2 and 4.3 mg/L, respectively). These results indicate tailwater return flows may contribute to the carbonaceous oxygen demand of the Shasta River.

Tailwater return flows are common in the Shasta River watershed. As mentioned in Section 1.4.9, due to the appropriated water rights in the watershed, irrigation return flows to the Shasta River are used to meet downstream water rights. There is no formal system to measure the rates of tailwater return flows within the watershed. Therefore, it is not possible to calculate exact pollutant loads associated with tailwater return flows.

In the course of conducting the 2004 aquatic vegetation survey, Regional Water Board staff observed numerous discharges of tailwater returns flows to the Shasta River from ditches draining from pasture and fields. Regional Water Board staff estimate the flow rates of observed return flows ranged from 0.5 to 5 cubic feet per second (cfs). Typically, there were deltas of settleable solids and fine sediment at these discharge locations. Regional Water Board staff observed that disruption of some of these accumulations of settled materials caused a distinct hydrogen sulfide (i.e., rotten egg) smell. In the absence of dissolved oxygen and nitrates, sulfates serve as a source of oxygen for biochemical oxidation by anaerobic bacteria. While not definitive, this observation indicates that the settled material near tailwater discharge locations contains organic material that undergoes decomposition by aerobic and anaerobic bacteria, contributing to oxygen loss from the water column.

4.4.2 City of Yreka Non Point and Wastewater Infiltration Sources

Yreka Creek flows north through the City of Yreka (Figure 1.4) and enters the Shasta River just above the Shasta canyon. Water quality monitoring of Yreka Creek has been conducted at four primary locations by the City of Yreka, with supplemental sampling by the California Department of Water Resources and NCRWQCB. From upstream to downstream these Yreka Creek monitoring locations are: (1) Oberlin Road, located on the south end of the city, (2) Highway 3, located on the north end of the city, (3) Nursery Bridge, located downstream of the City of Yreka wastewater treatment and disposal facility, and (4) Anderson Grade Road, located near the mouth of Yreka Creek. These monitoring locations were chosen in order to assess the water quality trends as the river passed through the city and passed by the wastewater treatment and disposal facility. A summary of water quality conditions of Yreka Creek at these locations is presented in Table 4.4.

Table 4.4: Yreka Creek water quality summary

Metric	Location	Ortho P	Total P	Ammonia as N	NO2+NO3 as N	NO3 as N	TKN	BOD_5	TOC	TSS
Minimum	Oberlin Road	0.025	0.005	0.025	0.098	-	0.1	-	2.4	0.5
	Highway 3	0.01	0.02	0.02	0.62	0.18	0.1	1.5	0.1	5
	Nursery Bridge	0.01	0.02	0.025	0.96	0.08	0.1	-	0.4	-
	Anderson Grade Rd.	0.02	0.02	0.025	0.86	0.31	0.1	1.5	0.3	0.5
Maximum	Oberlin Road	0.025	0.062	0.076	0.170	-	0.2	-	10	7
	Highway 3	0.03	0.63	0.77	1.23	1.25	0.3	1.5	33.8	5
	Nursery Bridge	1.17	4.25	4.28	1.48	4.73	0.7	-	36.1	-
	Anderson Grade Rd.	1.22	1.7	0.76	1.6	4.02	0.75	1.5	25.7	10
Average	Oberlin Road	NA	0.022	0.031	0.126	NA	0.18	NA	5.5	1.7
	Highway 3	0.02	0.107	0.11	0.91	0.70	0.2	NA	4.46	NA
	Nursery Bridge	0.14	0.54	0.621	NA	1.19	0.3	NA	4.53	NA
	Anderson Grade Rd.	0.21	0.47	0.105	1.11	1.65	0.3	NA	3.7	2.1
Median	Oberlin Road	NA	0.02	0.025	0.11	NA	0.2	NA	4.1	0.5
	Highway 3	0.02	0.059	0.05	0.895	0.70	0.2	NA	1.2	NA
	Nursery Bridge	0.08	0.2	0.25	NA	1.04	0.2	NA	1.6	NA
	Anderson Grade Rd.	0.15	0.23	0.06	0.87	1.49	0.3	NA	1.7	1
n	Oberlin Road	2	15	8	3	0	5	0	3	12
	Highway 3	21	66	66	4	62	21	1	21	2
	Nursery Bridge	19	63	63	2	61	19	0	19	0
	Anderson Grade Rd.	27	63	55	3	45	27	1	28	19

Units for all parameters are mg/L.
Non Detect (ND) data were calculated as ½ the reporting limit.
NA = Not Applicable. Averages and medians cannot be calculated if $n \leq 2$.
n = number of samples
Data from 1999 to 2005, collected by Regional Water Board, CDWR, and City of Yreka.

In 2000, the population of the City of Yreka was 7290 (Section 1.4.2). The City is characteristic of a small city, with land use dominated by urban single-family residential housing surrounding mixed commercial businesses. Monitoring has not been conducted in sufficient detail to determine the extent of non-point source pollution of Yreka Creek originating within the City. Water quality monitoring studies in other semi-urban cities, however, have revealed nutrients, pathogens, sediment, oil and grease, and total petroleum hydrocarbons in runoff.

The City of Yreka owns and operates wastewater collection and treatment and disposal facilities for the City's municipal wastewater, located north of the city. The wastewater treatment and disposal facility consists of secondary treatment by activated sludge, clarification, aerobic sludge digestion, chlorine disinfection, and subsurface disposal via drip irrigation to a 31-acre field. The disposal field is located adjacent to Yreka Creek, within a few feet of the creek elevation. The wastewater treatment facility is operated by the City under the terms of current waste discharge requirements (Order No. R1-2003-0047) issued by the Regional Water Board.

Cattle grazing occurs downstream of the wastewater treatment and disposal facility. In addition, the community of Hawkinsville is located downstream of the facility and is all on individual septic systems. These land uses contribute an unknown amount of pollutants to Yreka Creek.

Though the water quality data set at Oberlin Road (Table 4.4) is small, a comparison of water quality conditions in Yreka Creek at Oberlin Road versus conditions at Highway 3 can be made to assess non-point source contributions to Yreka Creek from within the City. This comparison suggests that runoff from the City may increase the total phosphorus, ammonia, and nitrite/nitrate.

A comparison of water quality conditions in Yreka Creek at Highway 3 versus conditions at the Nursery Bridge and Anderson Grade Road can be made to assess pollutant contributions to Yreka Creek from the City's wastewater collection, treatment, and disposal facilities. The average ammonia nitrogen and TKN concentrations increase by approximately 0.5 and 0.1 mg/L, respectively, from Highway 3 to the Nursery Bridge (equating to an increase in nitrogenous oxygen demand of approximately 0.46 mg/L).

Average total phosphorus and ortho-phosphate concentrations increase approximately 0.4 and 0.1 mg/L from Highway 3 to the Nursery Bridge, respectively. Ortho-phosphate concentrations increase another 0.1 mg/L approximately from the Nursery Bridge to Anderson Grade Road.

Based on these data, Regional Water Board staff identified the City of Yreka as a contributing source to the nutrient load and nitrogenous oxygen demand in Yreka Creek. The data indicate that the City's wastewater collection, treatment and disposal facilities are the primary source of both phosphorus and nitrogen loading to Yreka Creek.

4.4.3 Lake Shastina and Minor Impoundments

As discussed in Section 2.4.4, Lake Shastina regularly stratifies and becomes anoxic (near to complete absence of dissolved oxygen) in the hypolimnion (bottom layer). Nowhere else on the Shasta River has this been observed. Therefore, the presence of Dwinnell Dam and the creation of the reservoir promotes the stratification of the reservoir and the resulting low dissolved oxygen concentrations within the hypolimnion.

A comparison of available dissolved oxygen concentrations in the Shasta River above and below Lake Shastina shows that concentrations are consistently lower at the downstream location during summer months (Figure 4.4). The lower dissolved oxygen concentration in the Shasta River below Lake Shastina results primarily due to the fact that the outflow from Dwinnell Dam is discharged near the bottom of the reservoir, where anoxia is persistent in summer months. In addition, the downstream monitoring location is approximately 1.2 miles downstream of Dwinnell Dam; a reach of the river that has relatively dense riparian cover. Based on the relatively high percentage of fines and organic matter present in the channel substrate within this reach, it may have high SOD rates, which likely contribute to the measured low dissolved oxygen concentrations.

In addition to affecting dissolved oxygen levels in the Shasta River below Dwinnell Dam, Lake Shastina appears to affect dissolved oxygen concentrations in Hidden Valley Spring, which is located downstream of the dam. Dissolved oxygen levels were measured in six select springs located in the Shasta River watershed in 2003 in order to assess the nutrient contributions from springs in the watershed, and to measure physical properties of the river including dissolved oxygen. Measured dissolved oxygen concentrations were at or near saturation levels (8.0 – 13.0 mg/L for all but one of these springs). Hidden Valley Spring (located near Big Springs Road approximately 1.5 miles down-gradient of Dwinnell Dam and approximately 1000 feet from the Shasta River) had measured dissolved oxygen concentrations ranging from 1.34 to 8.38 mg/L, with an average concentration of 3.19 mg/L. Measured dissolved oxygen levels at the other springs ranged from 8.16 to 13.09 mg/L.

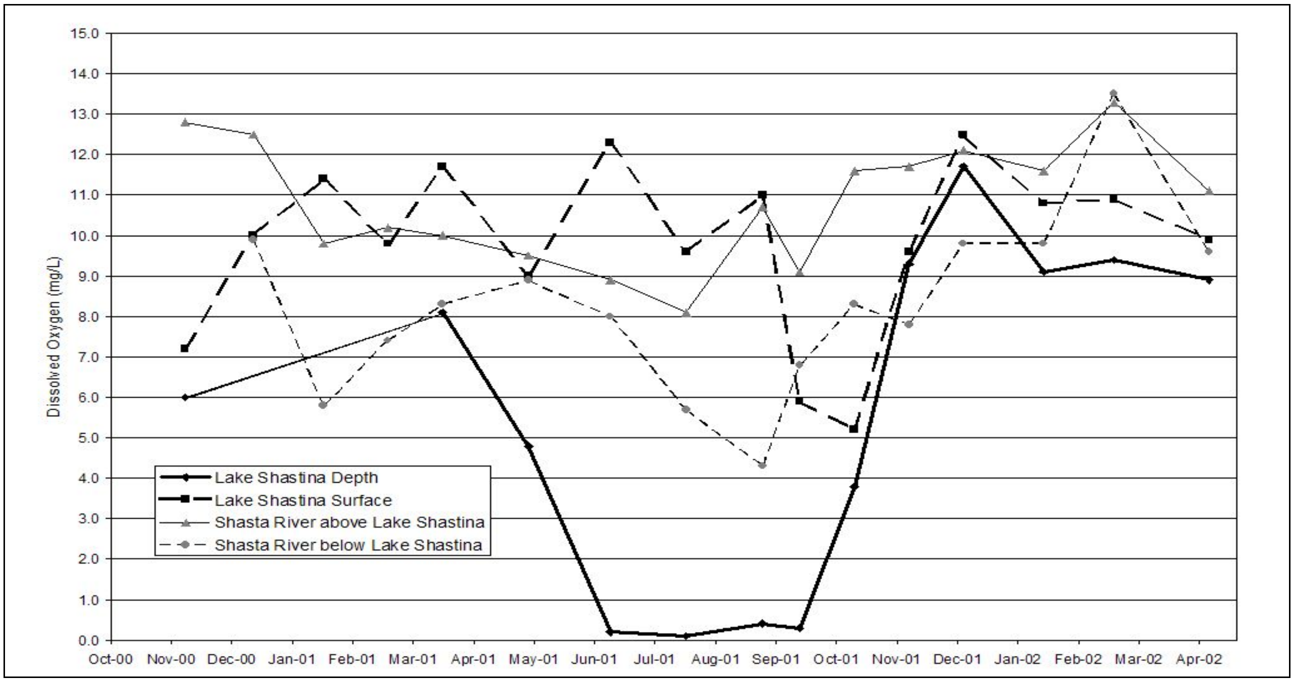

Figure 4.4: Dissolved oxygen concentrations of Lake Shastina and Shasta River, October 2000 – April 2002

Flow rates from Hidden Valley Spring vary seasonally, apparently in relation to the water surface elevation of Lake Shastina. Dwinnell Dam is leaky. Water can be heard and seen flowing from the toe of the dam. Based on available records, Lake Shastina loses from 6500 to 42,000 acre-feet annually to seepage and evaporation, with the variation largely a function of storage (Vignola and Deas 2005). Periods with more storage tend to have larger seepage losses. Given the leakiness of the dam and the change in flows from Hidden Valley Spring in relation to the storage level of the reservoir, it is likely that the spring is hydrologically connected to Lake Shastina, and that Lake Shastina is the source of low dissolved oxygen concentrations of the spring.

A comparison of the available Lake Shastina inflow and outflow water quality data indicates that annually, the lake may serve as a sink for phosphorus, and a source for nitrogen (Table 4.5). Average annual outflow concentrations of ortho-phosphate and total phosphorus are lower than average annual inflow concentrations, indicating that phosphorus is being retained in the sediments on the bottom of the reservoir.

Average annual outflow concentrations of ammonia, nitrite plus nitrate, and TKN, on the other hand, are all higher than average annual inflow concentrations. A comparison of summertime data shows that average summer outflow concentrations of ammonia, nitrite plus nitrate, and TKN are all higher than average inflow concentrations, while average outflow orthophosphate concentrations are slightly lower than average inflow concentrations (Table 4.6). This observed increase in nitrogen concentrations downstream of Lake Shastina likely stimulates the growth of aquatic plants, which in turn contributes to oxygen demand by increasing respiration. These observed nutrient dynamics do not appear to be maintained during winter months (Table 4.7).

Table 4.5: Comparison of Year-Round Lake Shastina Inflow and Outflow Data

Metric	Location	Dissolved Ammonia as N	Total Ammonia as N	Dissolved NO2+NO3 as N	TKN	Dissolved Ortho P	Total P
Minimum	Inflow	0.005	0.02	0.005	0.16	0.005	0.02
	Outflow	0.005	0.025	0.005	0.25	0.005	0.025
Maximum	Inflow	0.02	0.09	0.31	0.32	0.14	0.75
	Outflow	0.02	0.2	3.07	1.2	0.11	0.43
Average	Inflow	0.008	0.032	0.091	0.215	0.048	0.11
	Outflow	0.008	0.054	0.182	0.563	0.032	0.108
Median	Inflow	0.005	0.025	0.05	0.2	0.04	0.08
	Outflow	0.005	0.025	0.025	0.6	0.03	0.07
Count	Inflow	14	24	32	6	32	39
	Outflow	46	24	64	40	64	68

Non Detect (ND) data were calculated as half the reporting limit.
Information is from 2000-2003.

Table 4.6: Comparison of Summer (June-September) Lake Shastina Inflow and Outflow Data

Metric	Location	Dissolved Ammonia as N	Total Ammonia as N	Dissolved NO2+NO3 as N	TKN	Dissolved Ortho P	Total P
Minimum	Inflow	-	0.02	0.025	0.16	0.04	0.07
	Outflow	-	0.025	0.025	0.25	0.02	0.025
Maximum	Inflow	-	0.09	0.08	0.32	0.08	0.75
	Outflow	-	0.2	0.24	0.6	0.11	0.39
Average	Inflow	-	0.035	0.035	0.288	0.059	0.176
	Outflow	-	0.088	0.125	0.46	0.053	0.175
Median	Inflow	-	0.025	0.025	0.215	0.06	0.1
	Outflow	-	0.065	0.118	0.53	0.04	0.2
Count	Inflow	-	9	8	4	8	11
	Outflow	-	10	8	3	8	11

Non Detect (ND) data were calculated as half the reporting limit.
Information is from 2001-2003.

Table 4.7: Comparison of Winter (October-May) Lake Shastina Inflow and Outflow Data

Metric	Location	Dissolved Ammonia as N	Total Ammonia as N	Dissolved NO2+NO3 as N	TKN	Dissolved Ortho P	Total P
Minimum	Inflow	0.005	0.025	0.005	0.18	0.005	0.02
	Outflow	0.005	0.025	0.005	0.3	0.005	0.025
Maximum	Inflow	0.02	0.076	0.31	0.2	0.140	0.32
	Outflow	0.02	0.09	3.07	1.2	0.08	0.430
Average	Inflow	0.008	0.031	0.109	NA	0.044	0.084
	Outflow	0.008	0.030	0.203	0.571	0.03	0.095
Median	Inflow	0.005	0.025	0.1	NA	0.035	0.06
	Outflow	0.005	0.025	0.025	0.6	0.03	0.07
Count	Inflow	14	15	24	2	24	28
	Outflow	45	13	52	37	53	57

Non Detect (ND) data were calculated as half the reporting limit.
Information is from 2000-2003.

The regular occurrence of algal blooms in Lake Shastina during summer months indicates that nutrient levels are biostimulatory. *Anabaena flos aquae* was a dominant species present in phytoplankton samples collected in Lake Shastina in July 2004. Many cyanobacteria (or blue-green algae) are capable of sequestering atmospheric nitrogen. The presence of *Anabaena flos aquae*, a cyanobacteria, indicates that this nitrogen input pathway may occur in the reservoir.

As observed in section 4.3.3.2, the presence of Dwinnell Dam reduces scouring peak flows, thereby enhancing the accumulation of organic matter and fine sediments in the river. These materials are the preferred substrates for rooted aquatic macrophytes, so this effect expands the area of suitable habitat for macrophytes, and contributes to the respiratory oxygen demand of the river.

As discussed in Section 3.3.6, there are several small impoundments on the Shasta River – often termed "flashboard" dams – that are used to raise the water level in the river to provide for diversion (either direct or pumping) for agricultural use. These small impoundments increase the hydraulic residence time and promote change in water quality conditions. Based on results of the 2004 aquatic vegetation survey (Appendix A), macrophyte densities are highest in slow moving, depositional reaches of the Shasta River. By increasing the residence time of the river, impoundments promote settling of particulate material. The minor impoundments on the Shasta River are all relatively shallow (mean depths less than 10 feet). Limited depth provides an opportunity for light to reach the bottom of the waterbody, thereby allowing rooted macrophytes to colonize much of the impounded area.

To our knowledge, no dissolved oxygen measurements have been made at sub-daily time steps at locations immediately behind a flashboard dam on the Shasta River. However, dissolved oxygen concentrations were measured hourly during summer months in 2002, 2003, and 2004 at Highway 3, located approximately 2000 feet upstream of a flashboard dam. Based on the channel morphology and flow characteristics, this location appears to be influenced by the downstream impoundment. Dissolved oxygen levels at this location include the lowest and highest concentrations measured in the river. These dissolved oxygen conditions are likely the result of macrophyte productivity and SOD rates in this reach of the river. Macrophyte density in this reach is among the highest observed in the river, and measured SOD rates in this reach were the highest measured in 2003. In addition, this reach had among the highest percentage of fine sediments observed in 2004. These conditions demonstrate the potential effect of small impoundments on dissolved oxygen conditions of the Shasta River.

4.4.4 Riparian Shade

As discussed in Section 4.3.3.2, aquatic plant productivity is highest under increasing light availability. Therefore, theory suggests that aquatic productivity would be less in shaded reaches compared with unshaded reaches, and thus dissolved oxygen fluctuations would be less in shaded compared with unshaded reaches. Regional Water Board staff observed that aquatic vegetation abundance is lower in shaded reaches of the river, and that dissolved oxygen fluctuations appear to be greatest (i.e. higher highs and lower lows) in reaches with abundant aquatic vegetation growth.

4.4.5 Flow

Theoretically, flow could affect dissolved oxygen in several ways. First, oxygen is added to a river by reaeration. Factors affecting reaeration rates include current velocity and turbulence, water column depth, temperature, and surface films. Current velocity is positively correlated with flow. Therefore, theory suggests that reaeration rates are higher under higher flows. During summer months Shasta River flows are decreased due to surface water diversions. Therefore, it appears that decreased flows in the Shasta River contribute to lower dissolved oxygen concentrations, at least locally. Second, flow affects the depth of water in the channel. Water causes light to scatter, and the amount of photosynthetically active range of light decreases with depth. Therefore, there is less light available to aquatic plants under higher flows, resulting in less fluctuation of dissolved oxygen concentrations caused by photosynthesis and respiration. Third, flow can affect dissolved oxygen through its effects on water temperature. Larger volumes of water have a higher thermal mass and are more resistant to heating and cooling. If a large volume of water is cold it can travel downstream and retain its low temperature. As described in section 4.1.1, colder water can hold more dissolved oxygen. Through this mechanism, flow can affect dissolved oxygen.