

# **Aquatic Vegetation Assessment of Putah Creek, Lake Solano, the Putah South Canal, and the Terminal Reservoir**

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## Executive Summary

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Every summer, excessive growth of aquatic plants (macrophytes) and algae chokes the Putah South Canal (PSC) and Terminal Reservoir, clogging screens and intakes and lowering water quality. The Solano County Water Agency incurs tremendous management costs controlling and removing this vegetation, and the removal activities negatively impact water users. Large amounts of plant material and reproductive propagules come through the PSC Headworks from Lake Solano and the stretch of Putah Creek immediately below the Monticello Dam (together, the interdam reach, or IDR), and this is thought to be the source of nuisance vegetation growth in the canal. SCWA is seeking greater understanding of the factors that influence vegetation growth in the canal and the IDR, with a goal of reducing these problems in the future.

In July 2011, the Solano County Water Agency granted a contract to Emily Pepper, graduate student in Ecology at the University of California, Davis, to conduct a study on the aquatic vegetation in the PSC, the Terminal Reservoir, and the IDR. The goals of the study were to characterize the patterns of aquatic weed presence in these water bodies in order to better understand the causes behind their excessive growth, and to develop management recommendations for reducing the impacts of this vegetation. Specific objectives included conducting a baseline survey of macrophytes and corresponding environmental factors in the IDR, PSC, and Terminal Reservoir, creating statistical models to identify which environmental factors are most influential for macrophyte growth, comparing the distribution and species composition of macrophytes in the PSC to past surveys and to the macrophyte distribution in Lake Solano, and preparing written and oral reports of these findings.

Surveys of the PSC, Terminal Reservoir, and IDR took place from August 2011 to May 2012. The PSC and Terminal Reservoir were sampled once over the summer, while Lake Solano was sampled over four seasons, and Putah Creek was sampled in both the fall and winter. Data analysis, summarization, and modeling occurred in the following year.

Four macrophyte species were found in abundance in the PSC: Eurasian watermilfoil, horned pondweed, sago pondweed, and leafy pondweed. Macrophytes were present in every check, and tended to be more abundant with distance downstream in the PSC overall, and within individual checks. Slower velocities upstream of the check structures may allow sediment to settle, creating habitable environments for macrophytes. *Ulva*, a filamentous alga, was abundant in Sweeney Check, and was especially thick in the area adjacent to the Hines Growers nursery. Downstream checks typically had

thick diatoms and *Nostoc* on the canal walls. The patterns of abundance and species presence found in this survey were similar to those found in a 2007 study conducted by Northwest Hydraulic Consultants.

Macrophytes appeared to cover the entire area of the Terminal Reservoir, except along the rocky eastern shore. Eurasian watermilfoil and elodea were the most abundant species in the reservoir.

Lake Solano had high macrophyte density (greater than 75% average cover) throughout most of the lake. All of the species found in the PSC were found in Lake Solano, and other common species included coontail and curly-leaf pondweed. Eurasian watermilfoil and elodea were the most prevalent species in the lake. Some seasonal variation in the macrophyte community occurred, and cover declined in the winter, but average cover stayed high (over 62%) throughout the year.

Putah Creek had more variation in environmental factors (e.g., substrate type, water velocity) than Lake Solano, and overall had lower macrophyte cover. Most of the species found in Lake Solano were also present in Putah Creek. Notable differences were a lack of sago pondweed in Putah Creek, and the presence of moss in many faster flowing sites.

Statistical models were developed from Lake Solano and Putah Creek survey data using boosted regression trees. This modeling exercise identified sun hours (average yearly amount of solar radiation reaching a location in a day), proportion of soft substrate, proportion of boulders, depth, sediment total nitrogen, and water velocity as the most important drivers of macrophyte cover in the IDR. Macrophyte cover is predicted to increase with greater sun hours, higher proportion of soft substrate, lower proportion of boulders, shallower water, higher sediment total nitrogen, and lower water velocity.

In the IDR, current conditions are ideal for macrophyte growth- the open, shallow environment allows optimal light for photosynthesis, and the substrate of primarily fine sediment supports abundant plant growth. Any successful efforts to reduce macrophyte production in the IDR will need to address these underlying conditions. Recommendations are to reduce the amount of fine sediment through flow and/or channel morphology modifications. Planned flushing flows from the dam may be able to remove some macrophyte biomass and sediments, but could have negative downstream impacts. Ultimately, converting the wide, shallow section of Lake Solano near the Putah Diversion Dam to a marsh or floodplain may have the greatest long-term benefit in reducing macrophyte production.

Reducing light levels and sediment in the PSC is probably the best way to reduce the growth of macrophytes in the canal. Erecting shade structures over the canal or placing floating “shade balls” or opaque material directly on the water’s surface could be effective at reducing light but may be difficult given the flowing conditions. Better canal cleaning methods may help remove sediments and small seeds and tubers, but addressing sediment inputs by reducing erosion around and upstream of the canal

may help as well. Other methods that could potentially lessen the impact of macrophytes in the canal include macrophyte disturbance through flushing flows or physical disturbance (e.g., chaining) in the early summer, before the growth becomes excessive. Reducing influx of stem fragments into the canal may help with nuisance macrophyte growth, but evidence suggests that macrophytes may be regenerating from either smaller seeds or reproductive structures left behind during canal cleaning, or from smaller propagules coming in from the IDR. Sterile grass carp have been used in similar systems to control vegetation, and may be a potential management solution in the PSC.

There is probably little that can be done to prevent macrophytes from growing in the Terminal Reservoir. Dredging out macrophytes, propagules, and sediment may help in the short term, but macrophytes are likely to quickly reestablish. As long as reduced capacity does not become an issue, there is probably no need to take action.

No panacea appears to exist for the difficult issue of nuisance macrophyte growth in the PSC and Terminal Reservoirs, though certain actions may lessen the problems. Any management actions based on the findings of this report should be considered carefully, with more detailed analysis of pros, cons, and potential alternatives.



# 1 Introduction

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## 1.1 Overview

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This report presents the results of a study funded by the Solano County Water Agency (SCWA) to determine the extent of aquatic weed infestations in the section of Putah Creek below Monticello Dam, Lake Solano, the Putah South Canal, and the Terminal Reservoir, and to recommend potential solutions to reduce these infestations. This study was conducted by Emily Pepper, a PhD student in Ecology at the University of California at Davis, from the summer of 2011 through the summer of 2013, with logistical support from SCWA.

## 1.2 The Solano Project

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The Solano Project was implemented in the 1950s by the United States Bureau of Reclamation (USBR) to store and divert water from Putah Creek primarily for irrigation, and also for municipal and industrial use. The four main features of the Solano Project are the Monticello Dam, the Putah Diversion Dam (PDD), the Putah South Canal (PSC), and the Terminal Reservoir. The Monticello Dam can hold up to 1.6 million acre-feet of water from upper Putah Creek, and forms Lake Berryessa. From the Monticello Dam, water flows through the interdam reach (IDR) to the Putah Diversion Dam. The IDR consists of approximately four miles of riverine habitat (Putah Creek), and transitions into approximately two miles of slow-moving lacustrine habitat (Lake Solano). At the PDD, water is diverted to Putah Creek, which runs east to the Yolo Bypass, and to the Putah South Canal. The PSC is a 33 mile-long, open, concrete channel that conveys water southward throughout Solano County, California. The canal is divided into thirteen checks and discharges into the Terminal Reservoir. SCWA is granted the authority by USBR to maintain and operate the PDD and PSC, and the Solano Irrigation District is contracted by SCWA to carry out these activities.

## 1.3 Problem Statement

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Every year, over the course of the spring and summer, algae and macrophytes (collectively, “vegetation”) proliferate in the PSC. In the upstream reaches where water velocity is high, filamentous algae grows on the canal walls. Water velocity decreases with distance as water is diverted from the canal, allowing sediment to accumulate in downstream reaches. The accumulation of sediment allows

macrophyte propagules to establish and grow, which creates a positive feedback loop as vegetation traps more sediment, which then encourages more macrophyte growth. This excessive vegetation growth poses significant management challenges, as outlined below in order of importance to SCWA.

1) The canal must be drained and cleaned every year to remove sediment and macrophytes. Canal cleanout results in disruptions in water delivery to water users and reduced water quality to municipal water treatment plants. Removal of vegetation and sediment is difficult and costly, and fine organic material is often left behind.

2) Copper sulfate is applied within the PSC to control the growth of algae and macrophytes. Water is unfit for use during applications, causing temporary shutdowns for users. It is unclear whether these costly copper sulfate applications are effective in reducing the growth of algae or (especially) macrophytes.

3) Dislodged and fragmented vegetation clogs intake pumps, screens, and life racks, necessitating occasional cleaning of the PSC during normal operations to remove large mats of aquatic vegetation.

Due to the high financial and logistical costs of dealing with the problems posed by excessive vegetation growth, SCWA is seeking greater understanding of the factors that influence the growth of vegetation in the canal, with a goal of reducing these problems in the future. A recent report by Northwest Hydraulic Consultants (NHC) documents the tremendous number of plant propagules from the IDR that float into the PSC through the Headworks at the Putah Diversion Dam (Northwest Hydraulic Consultants 2010a). In particular, the wide, shallow bathymetry and slow-moving water of Lake Solano facilitate abundant macrophyte growth (Figures 1.1 and 1.2). NHC recommended that the best way to reduce plant growth within the PSC would be to reduce the number of propagules floating into the canal from the IDR (Northwest Hydraulic Consultants 2010a). However, the aquatic plant communities in the IDR and the environmental factors that control their growth have never been thoroughly characterized.

### 1.3.1 Study Goals

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- 1) Determine the current extent of aquatic weed infestations in the interdam reach, and in the Putah South Canal and Terminal Reservoir.
- 2) Identify the environmental factors that may facilitate or hinder these invasions above the PDD and in the PSC.
- 3) Develop recommendations (environmental or other) to help reduce current and future aquatic weed infestation in the IDR and the PSC.

### 1.3.2 Objectives

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- 1) Conduct a baseline survey of aquatic plant species composition and abundance and corresponding environmental factors in the IDR, PSC, and Terminal Reservoir.
- 2) Use statistical models to identify the factors that have the greatest influence on aquatic weed presence and abundance, including water velocity, substrate, light, and water and sediment quality parameters.
- 3) Determine how the Lake Solano aquatic vegetation distribution and species composition compare to the PSC.
- 4) Determine how the PSC aquatic vegetation has changed since the last survey in October 2007.
- 5) Prepare written and oral reports of findings and recommendations for SCWA.



*Figure 1.1. Excessive macrophyte growth in Lake Solano. Photo taken August 28, 2011, looking downstream towards the PDD.*



*Figure 1.2. Abundant macrophyte growth in Putah Creek (IDR). Photo taken November 1, 2011.*



## 2 Methods

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### 2.1 Putah South Canal

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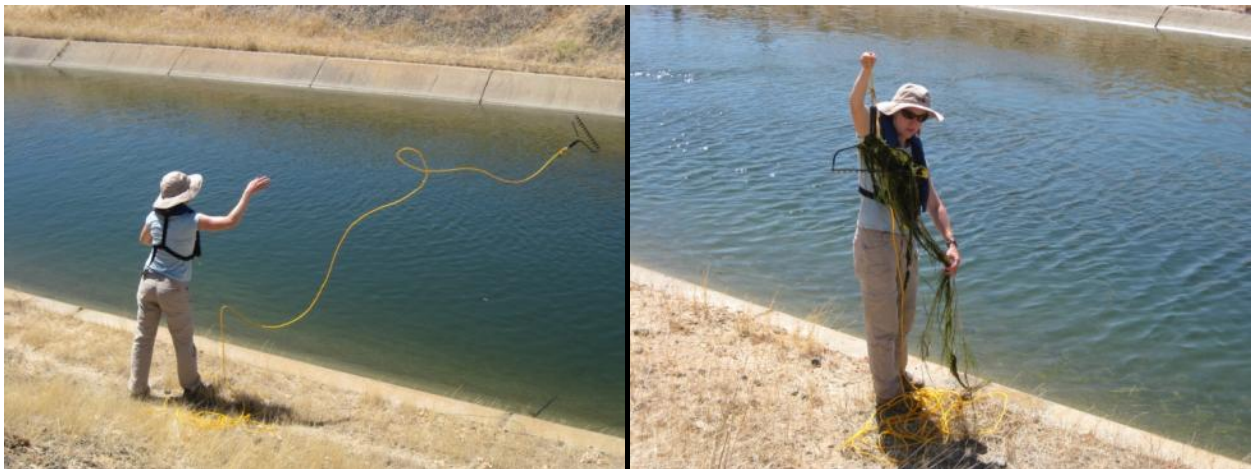
The PSC was sampled in August 2011. Beginning near the Headworks, sampling points in the PSC were systematically chosen at 250 m intervals, resulting in a total of 204 sampling points. (Two of these locations were inaccessible, so 202 total locations were sampled.)

#### 2.1.1 Macrophyte and algae sampling

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At each sampling point, presence/absence surveys of macrophytes and algae were conducted by throwing a sampling rake into the canal at least three times (Figures 2.1 and 2.2). All vegetation pulled up by the rake was identified and all species found were marked as present. At each sampling point, visual estimates were made of the percent volume of the canal occupied by macrophytes, and the percent area of canal walls covered by algae.

Algae samples were taken to Frank Morris at the Solano Irrigation District, and Dr. Jeff Janik, California Department of Water Resources, for identification.



*Figure 2.1. Sampling aquatic vegetation in the Gibson Check, 8/15/2011.*



*Figure 2.2. Macrophyte sampling in the Rockville check, 8/19/2011.*

### 2.1.2 Sediment and water sampling

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Where possible, sediment was sampled at every 20<sup>th</sup> sampling point (every 5 km). This was done by pulling up macrophytes in the rake and collecting sediment attached to the roots (Figure 2.3). Sediment was not collected if macrophytes were not present. Sediment samples were put on ice immediately after sampling, and frozen before analysis.

Sediment samples were analyzed for nitrate and ammonium using a KCl extraction, and plant-available inorganic phosphorus using the Olsen-P method (Murphy and Riley 1962) in Eliska Rejmakova's Wetland Ecology laboratory at UC Davis, Davis, CA. Samples were analyzed for total nitrogen and carbon using a combustion method (AOAC International 1997) at the UC Davis Analytical Laboratory, Davis, CA.

Water samples were collected in three locations along the canal, put on ice immediately, and then frozen before analysis. Samples were analyzed for nitrate and ammonium using a diffusion-conductivity



analyzer method (Carlson 1978) and for orthophosphate using a flow-injection analyzer method (Clesceri, Greenberg, and Eaton 1998) at the UC Davis Analytical Laboratory, Davis, CA.



*Figure 2.3. Pulling up sediment caught in macrophyte roots, 8/19/2011.*

### 2.1.3 Physical/chemical parameters

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Measurements of water parameters were taken at accessible locations along the PSC (e.g., bridges across the canal). Dissolved oxygen, specific conductance, pH, temperature, and turbidity were measured using a YSI multi-probe sonde. Flow measurements were taken using a stream flow meter near the surface of the water (apx. 10 cm deep). Photosynthetically active radiation (PAR), defined as light within wavelengths of 400-700 nanometers, was measured using a LI-COR LI-193 spherical quantum sensor.

## 2.2 Terminal Reservoir

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The Terminal Reservoir was sampled on Sept. 3, 2011. Sampling points were located at 18 points spaced around the perimeter of the reservoir (Figure 2.4). Due to extremely high winds, all data were collected near the shore.



*Figure 2.4. Sampling locations in the Terminal Reservoir.*

### 2.2.2 Macrophyte and algae sampling

---

At each sampling point, presence/absence surveys of macrophytes and algae were conducted. A sampling rake was thrown out as far as possible into the reservoir at least three times, and species of macrophytes and algae identified in the vegetation were marked as “present”. Emergent macrophytes (plants rooted in the water, but with most of their biomass out of the water) near the sampling location were also noted.



### 2.2.3 Sediment and water sampling

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The substrate near the shore of most of the reservoir was very rocky, but two sediment samples were taken on the west side of the reservoir with an AMS Multi-stage sludge and sediment sampler. One water sample was taken as well. Samples were put on ice and then frozen before analysis. Sediment samples were analyzed for nitrate, ammonium, soluble phosphorus, total carbon, and total nitrogen, and the water sample was analyzed for nitrate, ammonium, and orthophosphate by the methods previously described. In addition, sediment was analyzed for particle size (% sand, silt, clay) at the UC Davis analytical lab using a hydrometer (Sheldrick and Wang 1993).

### 2.2.4 Physical/chemical parameters

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At ten sampling points, dissolved oxygen, specific conductance, pH, temperature, and turbidity were measured using a YSI multi-probe sonde. Photosynthetically active radiation was measured at five points with a LI-COR LI-193 spherical quantum sensor. In addition, two HOBO temperature loggers were deployed at point 4W (Figure 2.4): one at the surface of the water, and one 0.6 m under the surface. The loggers recorded temperature every two hours for one year.

## 2.3 Lake Solano

Lake Solano, defined for this study as the portion of the IDR between the PDD and the first fork upstream of the Pleasants Valley Road bridge (apx. 2 mi stretch), was surveyed by canoe for macrophytes, sediment, and water parameters towards the end of each season: Summer sampling occurred from August 23-26, 2011, fall sampling on November 17 and 19, 2011, winter sampling on March 8, 2012, and spring sampling on May 31, 2012. Lake Solano was divided into 24 transects perpendicular to the channel at 175 m intervals. On each transect, three sampling points were established: 1 m inward from the each bank, and in middle of channel (Figure 2.5). Data were collected at each sampling point during the summer sampling event, and at one randomly chosen point on each transect for the fall, winter, and spring sampling events.

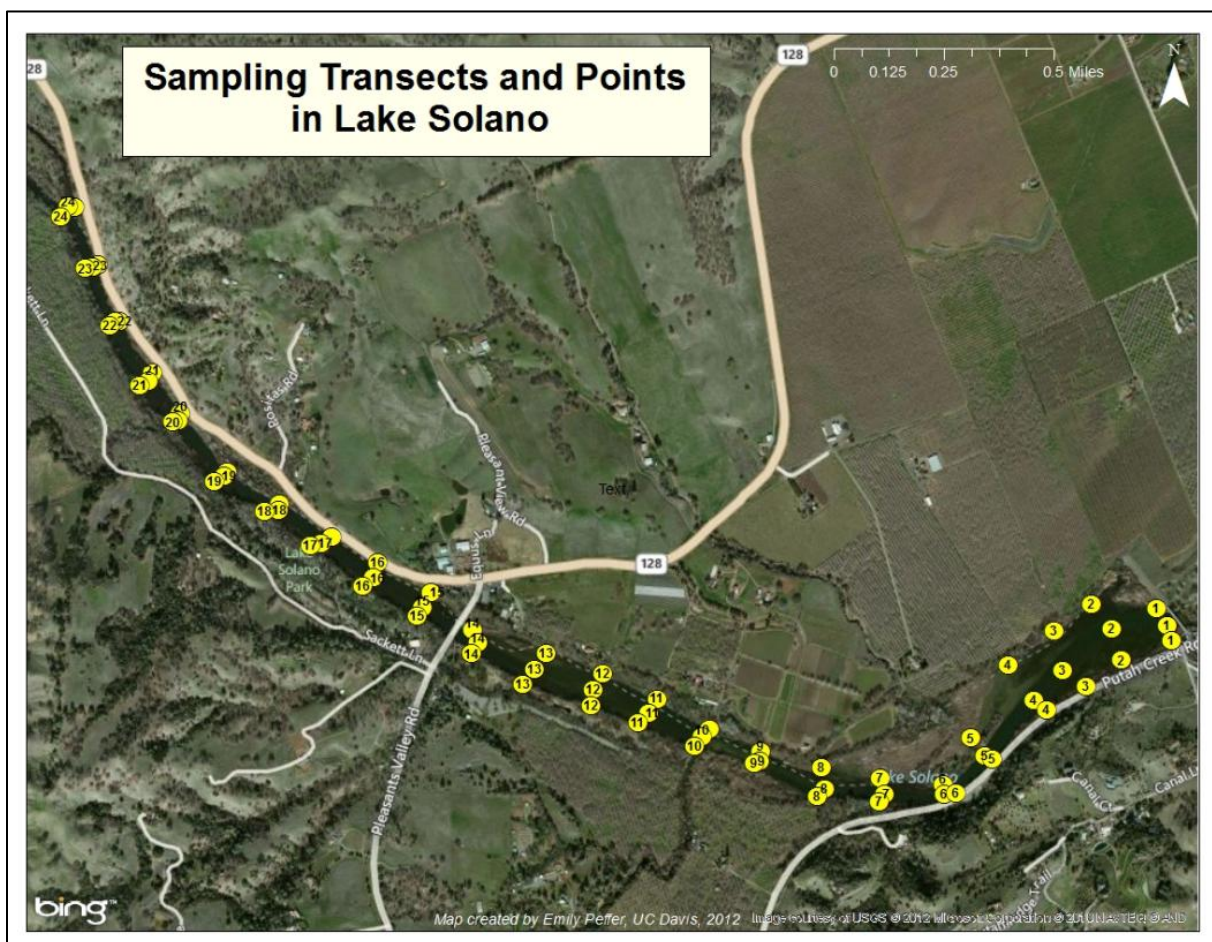


Figure 2.5. Map showing all 24 sampling transects on Lake Solano. Yellow dots indicate sampling points (middle and both edges of channel).

### 2.3.2 Macrophyte and algae sampling

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At each sampling point, percent cover and height of all macrophyte species found in a 0.25 m<sup>2</sup> quadrat were recorded. During the summer only, presence/absence of algal species was also recorded. Dominant emergent vegetation around the shores of the lake was also noted in the summer.

### 2.3.3 Sediment and water sampling

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A qualitative estimate of sediment grain size (silt and clay, sand, gravel, rocks, and boulders) was made at each sampling point (Table 2.1). Sediment samples were obtained using an AMS Multi-stage sludge and sediment sampler. Cores measuring 2 inches in diameter and approximately 6 inches deep were taken (when possible) at one randomly selected point on each transect during the summer, and at one third of these points in the fall, winter, and spring. Three water samples were taken near the downstream, middle, and upstream portions of the lake each season.

Sediment and water samples were put on ice immediately and then frozen before analysis. Sediment samples were analyzed for nitrate, ammonium, soluble phosphorus, total carbon, total nitrogen, and particle size, and water samples were analyzed for nitrate, ammonium, and orthophosphate by the methods previously described.

Substrate Qualitative Assessment Scale	
Boulder	>10 inches (256 mm)
Rock	10 inches to 2.5 inches (64mm)
Gravel	2.5 inches to 1 mm
Sand	1mm to 1/16 mm
Silt/Clay (Soft Substrate)	< 1/16 mm

*Table 2.1. Size classes of substrate assessed tactilely and visually*

### 2.3.4 Physical/chemical parameters

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At each sampled point in the summer and winter, dissolved oxygen, specific conductance, pH, temperature, and turbidity were measured using a YSI multi-probe sonde. These measurements were

taken near the water's surface, (~20-30 cm depth). Flow measurements were taken at each point near the surface (apx. 10 cm deep) using a stream flowmeter, and water depth was recorded.

Photosynthetically active radiation was measured at in the middle point of each transect over the summer with a LI-COR LI-193 spherical quantum sensor. Readings were taken immediately under the water's surface, and then every 0.5m down until reaching the bottom. From this data, vertical extinction coefficients were calculated using the formula  $k_d = \frac{\ln I_0 - \ln I_z}{z}$ , where  $k_d$  is the vertical extinction coefficient,  $I_0$  is the light intensity just below the water's surface, and  $I_z$  is the light intensity at depth  $z$ . These values indicate the reduction of light per meter in depth, and are an indicator of water clarity. Light measurements were also taken at several points in the fall, winter, and spring.

Canopy cover, the amount of shade over the water at a sampling point, was assessed in the summer using a Solar Pathfinder<sup>TM</sup>. With this device and its associated software, the amount of solar energy reaching each sampling point per day was calculated, averaged over both the growing season (March-October) and the whole year.

On August 28, 2011, HOBO Pro V2 temperature loggers were deployed in three locations in Lake Solano- in a shallow, macrophyte- filled area near the diversion dam (Location 1), near the SCWA water quality station downstream of Pleasants Creek (Location 2), and near the fork at the upstream portion of the lake (Location 3) (Figure 2.6). At each location, two loggers were deployed, with one just below the surface, and one approximately half a meter below the surface (Figure 2.7). The loggers recorded temperatures every two hours for one year.





*Figure 2.6. Locations of temperature loggers in Lake Solano.*

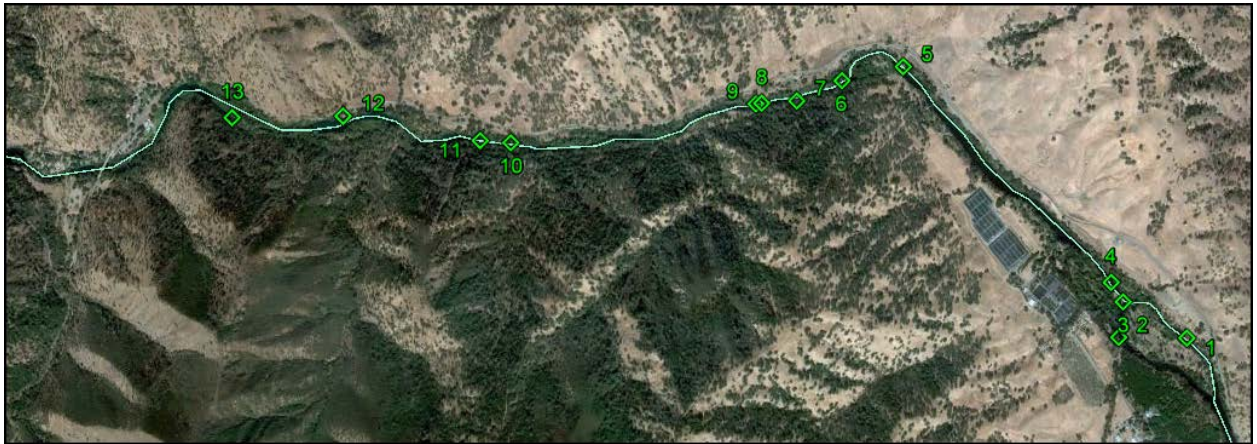


*Figure 2.7. Temperature logger deployed in Lake Solano near the water's surface. Loggers recorded temperatures every two hours for one year.*

## 2.4 Putah Creek

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Putah Creek between Lake Solano and the Monticello Dam was surveyed on November 12 and 21, 2011 (fall), and March 11 and 18, 2012 (winter). Sampling points were chosen based on accessible locations. Thirteen transects across the channel were established, and when possible, three points on each transect (one meter from each bank and the center) were sampled (Figure 2.8).



*Figure 2.8. Points show the locations of the thirteen sampling transects in Putah Creek surveyed for this study. In most locations, three points on each transect were sampled.*

### 2.4.2 Macrophyte sampling

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Percent cover of each macrophyte species in a 0.25m<sup>2</sup> quadrat placed at each sampling point was recorded.

### 2.4.3 Sediment and water sampling

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At each sampling point, a qualitative estimate of substrate (silt and clay, sand, gravel, rocks, and/or boulders) was made (Table 2.1, above). Sediment cores measuring 2 inches in diameter and approximately 6 inches deep were taken (when possible) using an AMS Multi-stage sludge and sediment sampler at five sampling points each season. Two water samples were taken each season.

Sediment and water samples were put on ice immediately and then frozen before analysis. Sediment samples were analyzed for nitrate, ammonium, soluble phosphorus, total carbon, total nitrogen, and particle size, and the water sample was analyzed for nitrate, ammonium, and orthophosphate by the methods described above.



#### 2.4.4 Physical/chemical parameters

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At every sampling point, flow measurements were taken at approximately 10 cm below the surface using a stream flow meter, and water depth was recorded.

Canopy cover above the water was assessed at each sampling point in the summer using a Solar Pathfinder<sup>TM</sup>. The amount of solar energy reaching each sampling point per day was calculated, averaged over both the growing season (March-October) and the whole year.

## 3 Results and Discussion

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### 3.1 Putah South Canal

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#### 3.1.1 Algae

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Several types of filamentous algae were found in the PSC, mainly species in the following genera: *Ulva*, *Cladophora*, *Tetraspora*, *Spirogyra*, and *Nostoc*. *Ulva*, a green algae forming long tubular strands, was found growing on the walls of the canal in most sections upstream of Peabody Rd (McCoy check). Downstream of Peabody road, *Ulva* was not present. The green algae *Cladophora* was frequently found tangled in the macrophytes in vegetation samples, and in the *Ulva* growing on the canal walls. *Cladophora* was the most common algal taxa throughout the canal. *Spirogyra*, another green algae, was also found tangled in vegetation in a smaller number of sampling points near the upstream portion of the canal, and was less abundant than *Cladophora*. *Tetraspora*, a green algae, was found in very small amounts in most sampling points above the Highway check structure, and in zero points below the Highway check. Species of green algae in the genera *Mougeotia* and *Zygnema* were also found in samples identified by Jeff Janik, but they were a small component compared to the other species.

Much of the canal walls were coated in a thin layer of algae. *Nostoc*, a cyanobacteria, was attached to the canal walls, appearing as small (<1 cm) greenish-brown spheres, in various places throughout the canal. A thick layer of diatoms (Bacillariophyta), appearing as a light brown coating on the canal walls, was present at many sampling points from just upstream of the Mankas check structure to the end of the canal. The percent of sampling points in which each of the six most common algal types in the PSC were found are shown in Figure 3.1. All of the identified taxa are native, and widespread in water bodies throughout the world (Jeff Janik, personal communication).

In general, the amount of algae in the canal was low (around 1% cover) (Figure 3.2). The percent cover of algae growing on the walls of the canal peaked near the middle of Sweeney Check, where the filamentous algae *Ulva* was present in high amounts. This area of high algal growth corresponds to the location of Hines Growers nursery in Winters, which suggests that fertilizers used at the nursery could be promoting algal growth in the canal. Further research could address this question directly.

There also tended to be higher percent cover of algae for much of the canal downstream of the Mankas check structure, but the algae in this section were mostly diatoms and *Nostoc*, and while cover



was high, the biomass of these algae were relatively small. The spatial distribution of algal density in the PSC is shown in Figure 3.3.

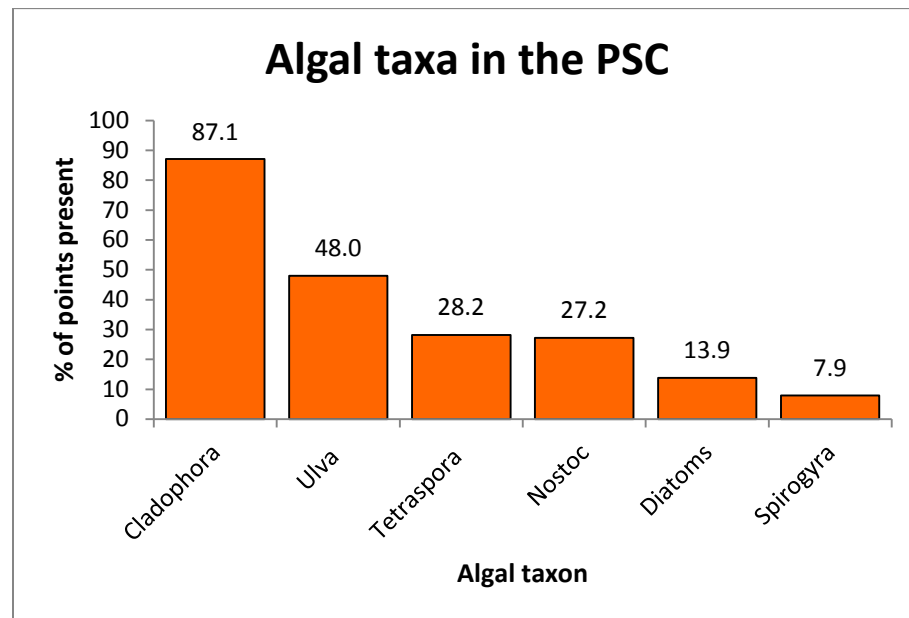


Figure 3.1. Percent of sampling points in which each algal taxon was found in the Putah South Canal

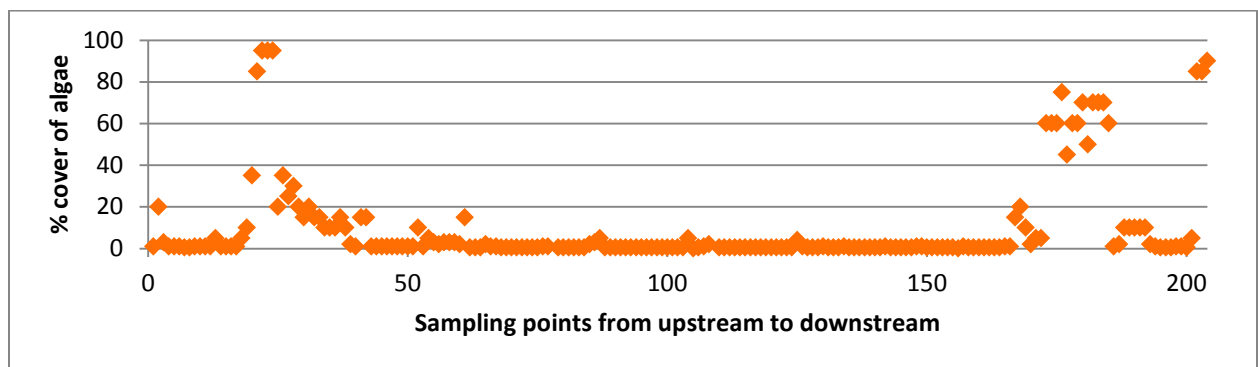


Figure 3.2. Algal percent cover from upstream (left) to downstream (right). The first peak shows high densities of *Ulva* while the second peak shows high cover of diatoms and *Nostoc*. Note that the biomass represented by this second peak was relatively small, though cover was high.

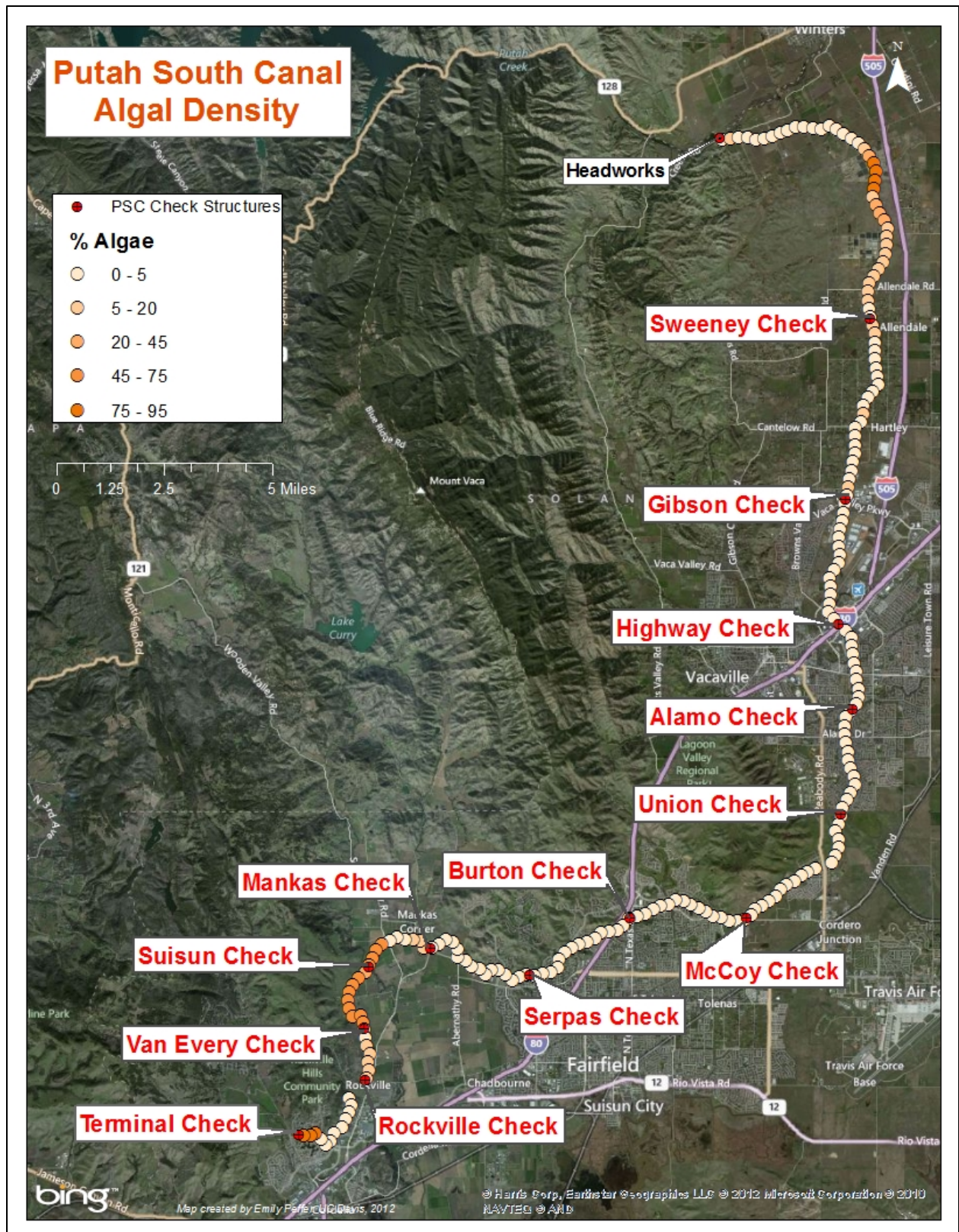


Figure 3.3. Map showing algal cover along the Putah South Canal. Sampling points are represented as colored circles, with darker colors indicating higher algal percent cover.

### 3.1.2 Macrophytes

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Four species of macrophytes were found in abundance in the PSC: sago pondweed (*Stuckenia pectinata*), horned pondweed (*Zannichellia palustris*), Eurasian watermilfoil (*Myriophyllum spicatum*), and leafy pondweed (*Potamogeton foliosus*) (see Appendix A for detailed descriptions of these species). Though horned pondweed was present at the greatest number of sampling points (Figure 3.4), personal observations indicate that sago pondweed was the species with the greatest biomass throughout the canal, followed by Eurasian watermilfoil, then horned pondweed, with leafy pondweed being the least abundant of the four. Moss (*Bryophyta*), a non-vascular plant, was found only in a few samples in the upstream, fast-flowing portion of the canal (Sweeney and Gibson checks). Other species found in a small number of samples (5% or less) included elodea (*Elodea spp.*), coontail (*Ceratophyllum demersum*), curly-leaf pondweed (*Potamogeton crispus*), and an unknown plant with long, grass-like submersed leaves. No evidence was found of elodea, coontail, or curly-leaf pondweed actually being rooted and growing in the canal. Rather, these plants were found as fragments that probably floated in from Lake Solano and got caught on other macrophytes. All of these species are native, except for Eurasian watermilfoil and curly-leaf pondweed.

Macrophyte density, estimated as the percent volume of the channel occupied by macrophytes, was highly variable throughout the canal, but overall tended to increase with distance downstream (Figure 3.6). Macrophytes were absent in most of Sweeney check, and began to appear at low density in the downstream portion of that check. Macrophytes were then present in most of the sampling locations downstream from there.

Within each check, macrophyte density tended to increase with distance downstream. This is probably due to attenuation of water velocity and greater accumulation of sediment in the downstream portions of each check. Notable exceptions to this trend are the Mankas and Van Every checks, where density was variable throughout the check. Macrophyte density trends within each check are shown using LOESS smoothing in Figure 3.6.

Another trend observed in the data was higher macrophyte density downstream of siphons, when the upstream and downstream ends of the siphons occurred *within* the same check (Figure 3.7). Out of twelve such siphons, nine had higher plant volume in the first sampling point downstream of a siphon compared to the point immediately upstream of the siphon, while in only one case the plant volume was lower downstream, and in two cases they were the same. This might be due to higher sediment accumulation in areas downstream of siphons. This trend was not observed when the sampling points

immediately upstream and downstream of a given siphon were in two different checks (i.e., across the check structures). In seven out of eight of these cases, the plant cover was higher in the point upstream of the siphon. This is consistent with the pattern of plant volume increasing with distance downstream within a given check (high plant density at the downstream-most point before a check structure, and low plant density at the upstream-most point of a check).

Macrophyte density peaked in the Mankas, Suisun, and Van Every checks. Macrophyte density was notably lower in the Union Check compared to other portions of the canal (Figure 3.5) for unknown reasons. Water velocity was not higher in Union Check compared to other checks (Appendix B), but higher wind velocity in that area may play a role. Figure 3.8 shows a map of the density of macrophytes found at each sampling point.

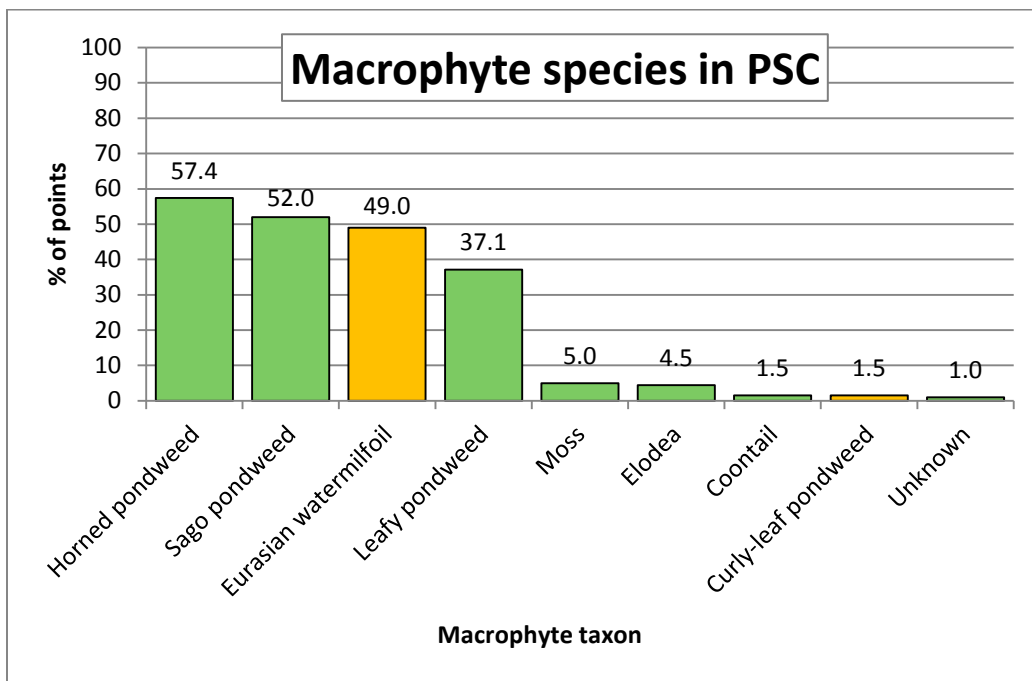


Figure 3.4. Percent of sampling points in which each macrophyte taxon was found in the Putah South Canal. Non-native species are indicated with orange bars, while native species are indicated with green bars.

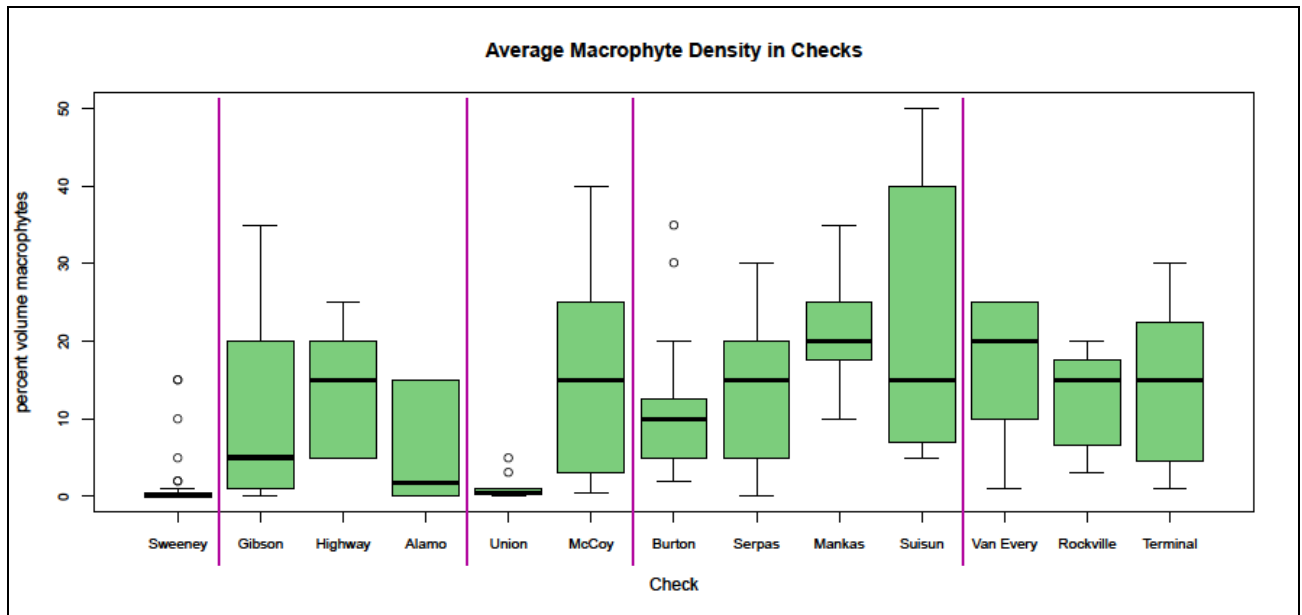


Figure 3.5. Density of macrophytes in each check. The dark line in the boxplot shows the median percent volume of macrophytes in the check structure. The box encompasses the 25th and 75th percentiles, whiskers show extreme values, and additional points show outliers. Vertical lines separate the five geometric reaches of the PSC.

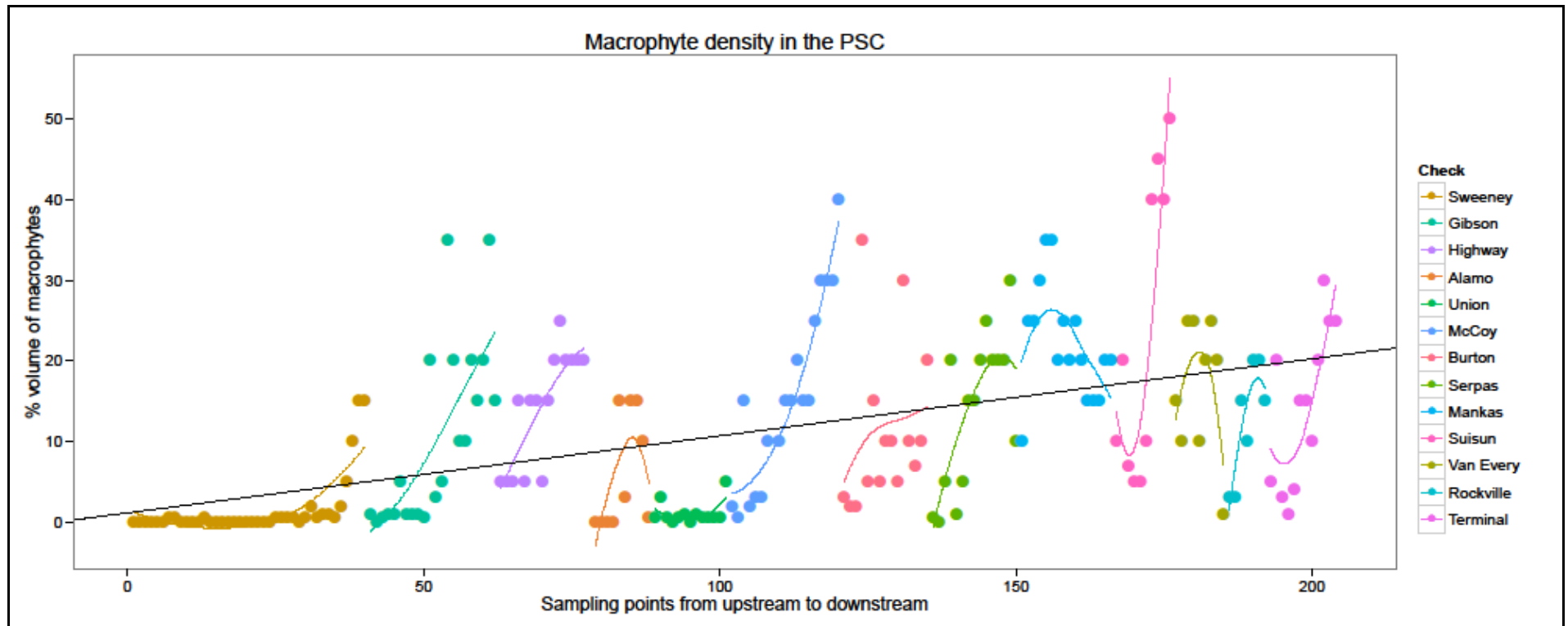


Figure 3.6. Macrophyte density in the PSC from upstream to downstream (left to right), by check. Smoothed LOESS curves for the data in each check show that for most checks, macrophyte density increases with distance downstream (toward the check structure). Linear best fit line shows an overall increasing trend with distance downstream.



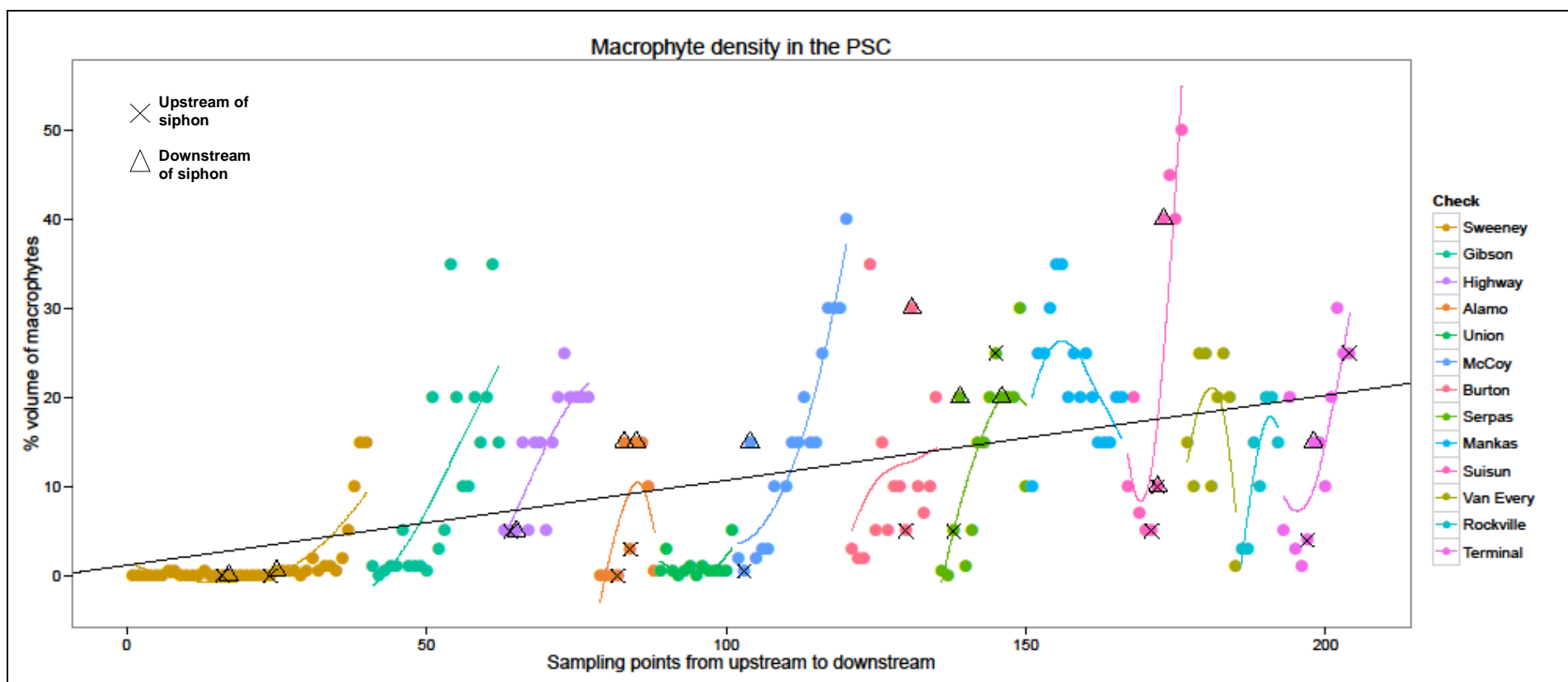


Figure 3.7. Macrophyte density in the PSC, showing sampling points upstream and downstream of siphons within a check. (Points that are upstream and downstream of a check structure are not shown.) Triangles show points downstream of a siphon, while X's show points upstream of a siphon. In most cases, the downstream points have higher macrophyte densities than upstream points.

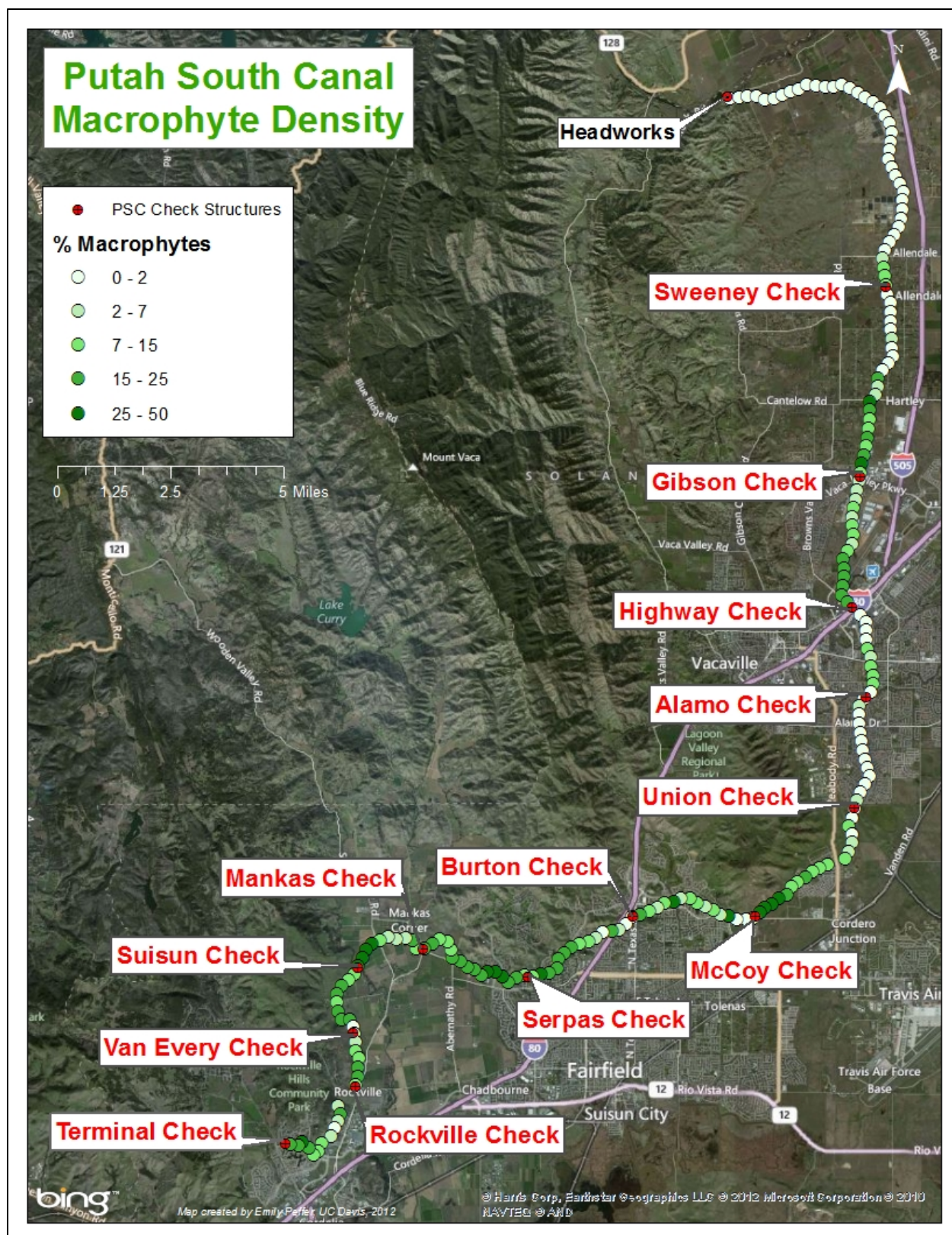


Figure 3.8. Map showing macrophyte density along the Putah South Canal. Sampling points are represented as colored circles, with darker colors indicating higher macrophyte density.



### 3.1.3 Comparison of 2011 PSC vegetation survey with 2007 survey

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In 2007, Northwest Hydraulic Consultants and Dr. Lars Anderson, researcher for the U.S. Dept. of Agriculture - Agricultural Research Service Exotic and Invasive Weeds Research Unit at UC Davis, conducted a survey of macrophyte species presence throughout the PSC. Their report stated that the most abundant macrophyte species in the canal were Eurasian watermilfoil, sago pondweed, horned pondweed, and elodea (Northwest Hydraulic Consultants 2010b). The first three species match the most abundant species found in the 2011 survey, indicating that the species composition of the canal may be relatively consistent over time. While elodea was listed as a primary species in the canal in section 9.4, it was not noted on the raw data sheets shown in Appendix D-9.1, which would be consistent with these findings from 2011 (very little elodea, and none apparently rooted and growing). Leafy pondweed, however, was common in the 2011 survey, while it was not noted as a prevalent species in the 2007 survey (though it was noted as present on the data sheets).

The 2007 survey found that *Nostoc*, *Cladophora*, *Rhizoclonium*, and *Tetraspora* were the predominant algal taxa found in the PSC<sup>7</sup>. The main difference in the 2011 survey was the prevalence of *Ulva*, which was not mentioned in the NHC report. Also, *Rhizoclonium* was not identified in the 2011 samples, but it may have been present and identified as *Cladophora*, as these two genera are in the same family and could have been conflated.

The methods for measuring algal density were different for the two surveys (percent cover in 2011, and a scale of 1-3 in 2007), and sampling points were located using different methods, but through comparing datasheets from 2007 to the data from 2011, it appears that the density of filamentous algae peaked in similar locations both years (near the middle of Sweeney Check).

### 3.1.1 Water samples

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Water samples were taken from the Gibson, McCoy, and Mankas checks. All samples were below detection limits (0.05 mg/L) for nitrate, ammonium, and soluble phosphorus (PO<sub>4</sub>).

### 3.1.2 Sediment samples

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Sediment samples were taken from points in seven of the checks in the PSC. Nutrient levels did not show any obvious trends from upstream to downstream. The percent of dried sediment composed of nitrogen ranged from 0.79 - 1.53%, and the percent composed of carbon ranged from 3.39 - 12.21%, indicating highly organic sediments. Ammonium ranged from 113.4 - 393.1 µg/g dried sediment, and soluble phosphorus ranged from 56.1-313.2 µg/g dried sediment (Table 3.1). Nitrate was below the

detection limit in all samples. The high ammonium and low nitrate concentrations indicate that sediments in the PSC are anoxic. Ammonium is produced from the decomposition of organic material, such as macrophytes and algae, and can be converted to nitrate in the presence of oxygen (Kalff 2002). The carbon : nitrogen (C:N) ratio of 6-7 suggests that the bulk of the sediment in the PSC comes from aquatic sources (i.e., algae and macrophytes) as opposed to terrestrial sources such as leaf litter. (Meyers and Ishiwatari 1993). As discussed in following sections, the concentrations of nutrients found in the PSC sediments are much higher than in sediments taken from the Terminal Reservoir or the IDR.

Putah South Canal Sediment Nutrients						
Check	Total N (%)	Total C (%)	C:N ratio	Nitrate (µg/g)	Ammonium (µg/g)	Soluble P (µg/g)
Gibson	0.79	4.95	6.3	bdl	113.4	56.1
Highway	1.09	7.32	6.7	bdl	317.7	242.0
McCoy	1.20	7.30	6.1	bdl	260.9	313.2
Burton	0.52	3.39	6.6	bdl	217.1	282.6
Mankas	1.13	8.19	7.2	bdl	393.1	231.1
Suisun	1.24	8.61	7.0	bdl	228.7	159.9
Rockville	1.53	12.21	8.0	bdl	251.4	254.3
<b>Average</b>	<b>1.07</b>	<b>7.42</b>	<b>6.8</b>	<b>bdl</b>	<b>254.6</b>	<b>219.9</b>

Table 3.1. Nutrients in dried sediment from the Putah South Canal, ordered from upstream to downstream (top to bottom). Bdl=below detection limit of 0.1µg/g.

### 3.1.3 Physical/chemical parameters

Water temperature in the canal averaged 62°F, and increased approximately 10°F from upstream to downstream (Figure 3.9). The dissolved oxygen in the canal was generally high (between 87.6 and 168.7 percent saturated), and also showed a slight increasing trend with distance downstream, possibly caused by photosynthesis of algae and macrophytes (Figure 3.9). Supersaturated values of dissolved oxygen (>100%) indicate high photosynthetic activity in the canal. High dissolved oxygen values could also be associated with areas where aeration is occurring, as water chemistry was often sampled from

bridges or at check structures. The pH in the canal showed a slight increasing trend from upstream to downstream as well, and had a logarithmic average of 8.46 (Figure 3.10). Deviations from the linear trend for temperature, dissolved oxygen, and pH are most likely due to points being sampled at different times of day. Photosynthesis by plants and algae tends to increase dissolved oxygen and pH over the course of the day. Vegetation increases the pH of the water during the day by removing CO<sub>2</sub> from the water column.

Conductivity averaged 344  $\mu\text{S}/\text{cm}$ , and was relatively constant throughout the canal. Measurements of turbidity showed a very gradual decreasing trend from upstream to downstream (Figure 3.11). This could be caused by sediment particles dropping out at slower water velocities. The vertical extinction coefficients, measurements of the attenuation of light (PAR) through the water column, averaged 0.42  $\text{m}^{-1}$ , and showed no obvious pattern throughout the canal. Measurements of PAR indicate more than enough light available for macrophyte growth in the canal.

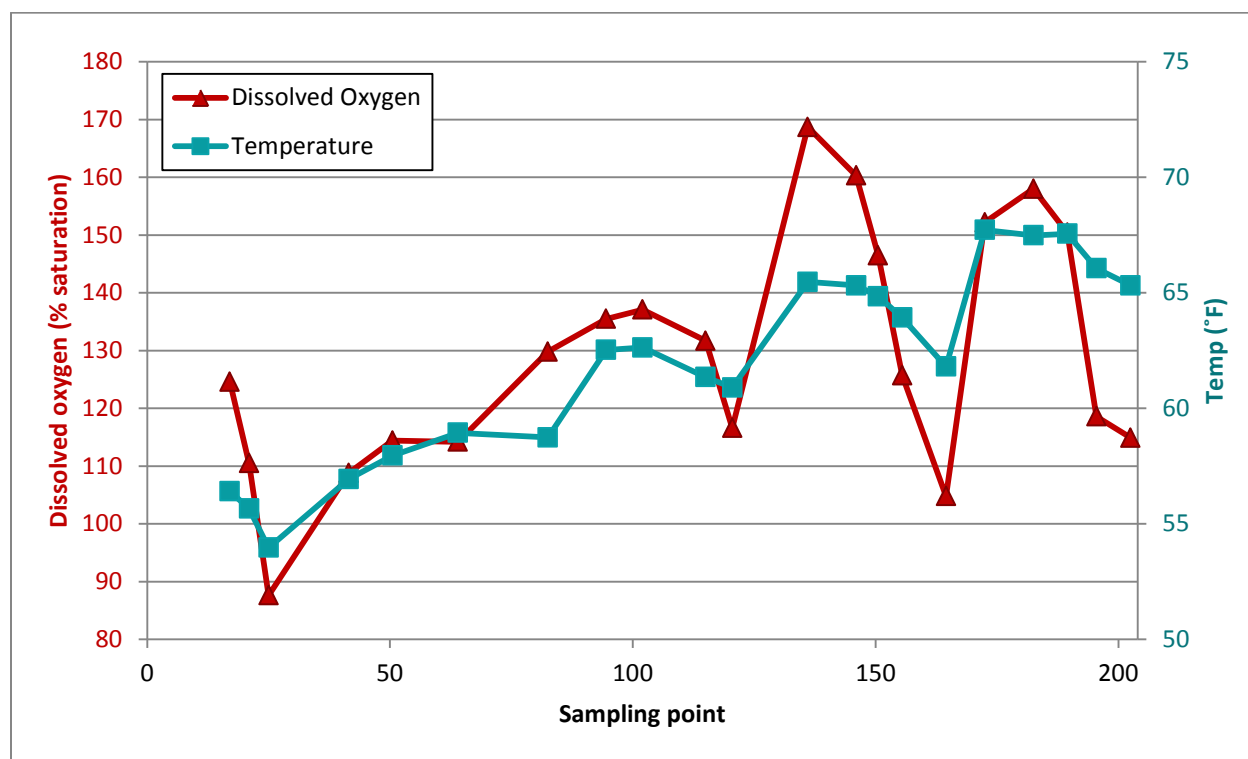


Figure 3.9. Percent saturation of dissolved oxygen (left axis), and temperature (right axis) in the Putah South Canal. Fluctuations are mostly caused by time of sampling. Points are listed from upstream (left) to downstream (right).

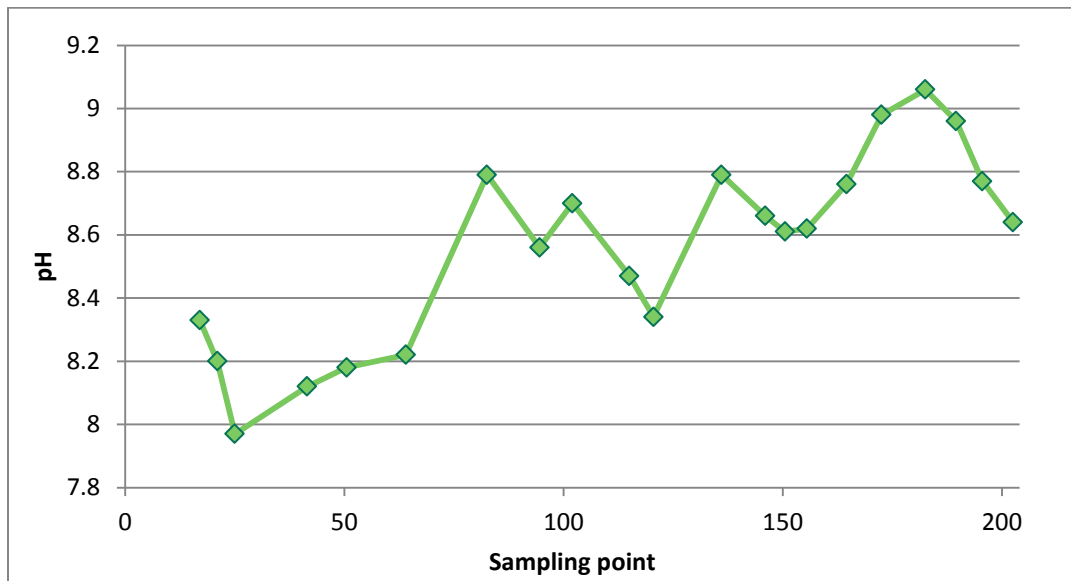


Figure 3.10. Putah South Canal water pH. Points are listed from upstream (left) to downstream (right).

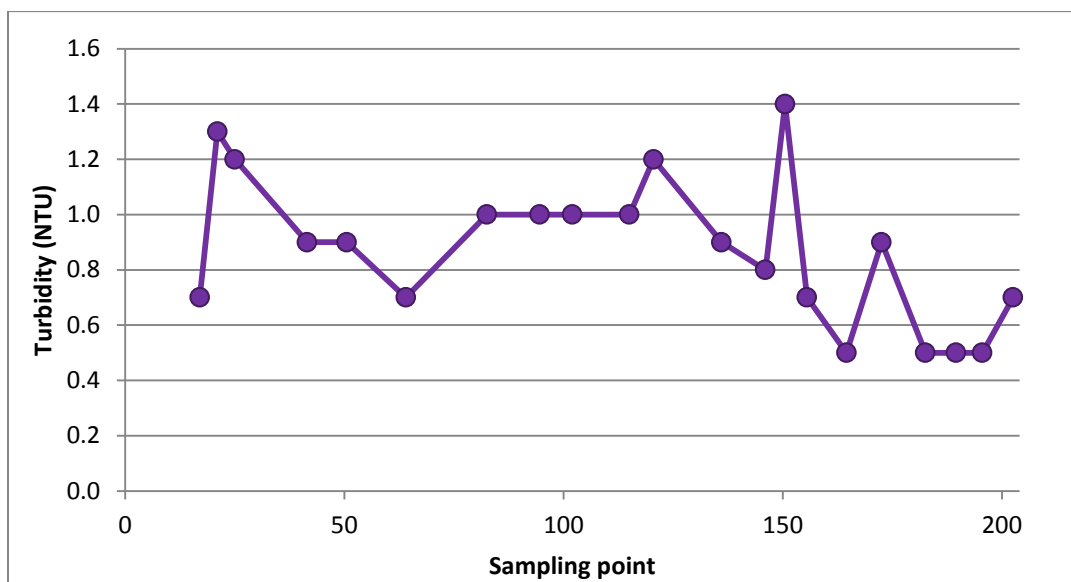


Figure 3.11. Turbidity measurements in the Putah South Canal. Points are listed from upstream (left) to downstream (right).

## 3.2 Terminal Reservoir

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### 3.2.1 Plants and Algae

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The eastern edge of the Terminal Reservoir was very rocky, and few emergent or submersed macrophytes were found growing near the shoreline, probably due to wave action. The western edge of the reservoir was sandy, and had a number of emergent and submersed macrophyte species. Emergent species included bulrushes, sedges, grasses, rushes, and smartweeds. Throughout the reservoir, only four submersed macrophyte taxa were found: Eurasian watermilfoil (*Myriophyllum spicatum*), elodea (*Elodea* spp.), leafy pondweed (*Potamogeton foliosus*), and horned pondweed (*Zannichellia palustris*) (Figure 3.12). Stonewort (*Chara* sp.), a multicellular macroalga that is physically very similar to some submersed plant species, was also found at several locations.

Based on the rake samples, Eurasian watermilfoil was the most abundant species, and appeared to occur throughout the majority of the reservoir, forming a canopy at the surface of the water. Elodea, a highly shade-tolerant species, appeared to form a subcanopy under the milfoil in most locations. Interestingly, sago pondweed, which was the most abundant species in the PSC, was not found in the Terminal Reservoir, and elodea, which was not found growing in the PSC, was well established. For the latter, this may be due to a greater ability of elodea stem fragments (which is the primary way elodea reproduces) to establish in calmer conditions with greater sediment depth. Sago pondweed may not be as good of a competitor in non-flowing conditions and may be outcompeted by Eurasian watermilfoil and elodea in the reservoir.

Little algal growth was observed in the Terminal Reservoir on the sampling date. Only *Cladophora*, *Chara*, and diatoms were found, and none were abundant. Large amounts of macrophyte growth may be suppressing algal growth, through both competition for nutrients, space, and light, and also by excreting allelochemicals that inhibit algae (Gross 2003).

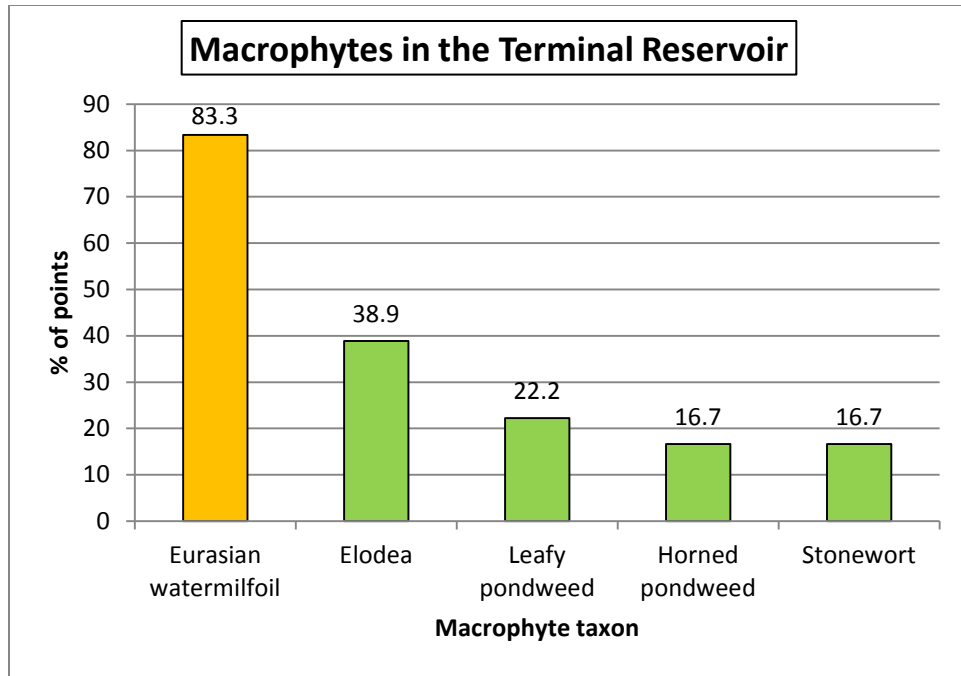


Figure 3.12. Percent of sampling points in which each macrophyte taxon was found in the Terminal Reservoir. Non-native species are indicated with orange bars, while native species are indicated with green bars.

### 3.2.2 Sediment samples

The nutrient levels in the Terminal Reservoir sediment samples were lower than those found in the Putah South Canal, probably due to higher amounts of inorganic material. The average percentage of nitrogen and carbon in dried sediment were 0.11% and 1.24%, respectively. Nitrate was below the detection limit in one sample and 0.13  $\mu\text{g/g}$  in the other, ammonium averaged 7.3  $\mu\text{g/g}$ , and soluble phosphorus averaged 7.1  $\mu\text{g/g}$ . The more northern sampling point (2W) had a high percentage of sand, while the other point (5W), taken near the middle on the western side, had more even distributions between sand, silt, and clay (Table 3.2).

Terminal Reservoir Sediment Data									
Sampling point	Total N (%)	Total C (%)	C:N ratio	Nitrate (µg/g)	Ammonium (µg/g)	Soluble P (µg/g)	Sand (%)	Silt (%)	Clay (%)
2W	0.11	1.01	9.2	0.13	2.9	1.8	81.5	9	9.5
5W	0.12	1.47	12.3	bdl	11.7	12.5	43	35	22
<b>Average</b>	<b>0.11</b>	<b>1.24</b>	<b>10.7</b>	<b>-</b>	<b>7.3</b>	<b>7.1</b>	<b>62.3</b>	<b>22</b>	<b>15.8</b>

Table 3.2. Sediment characteristics from two sampling points in the Terminal Reservoir. (See Figure 2.4 above for a map of sampling points.)

### 3.2.3 Water samples

The water sample taken from the Terminal Reservoir was below detection limits (0.05 mg/L) for nitrate, ammonium, and soluble phosphorus ( $\text{PO}_4$ ). Low nutrients may be expected, due to uptake by the abundant vegetation during the growing season.

### 3.2.4 Physical/chemical parameters

The physical/chemical water parameters were relatively constant across the points sampled throughout the Terminal Reservoir, and similar to the values found in the PSC. Turbidity was higher than in the canal, averaging 8.25 NTU, which may be the result of turbulent wave action in the reservoir. Measurements of PAR show an average vertical extinction coefficient ( $k_d$ ) of  $0.49 \text{ m}^{-1}$ , which, at the depth range present in the Terminal Reservoir, indicates plenty of light available for photosynthesis. Average values are shown in Table 3.3.

The average monthly temperatures in the Terminal Reservoir ranged from a low of  $47.2^\circ\text{F}$  in December (at mid-depth), to a high of  $68.7^\circ\text{F}$  in July (at the surface) (Table 3.4 and Figure 3.13). Temperatures were an average of  $0.6^\circ\text{F}$  cooler at mid-depth than at the surface, but this varied throughout the year. See Appendix D for a graph of temperatures over time.

Physical/ Chemical Measurements in the Terminal Reservoir						
	Temperature (°F)	Specific Conductance ( $\mu\text{S}/\text{cm}$ )	pH	Dissolved oxygen (%)	Turbidity (NTU)	$k_d$ ( $\text{m}^{-1}$ )
<b>Average values</b>	66.4	318.5	8.83	117.2	8.25	0.49

Table 3.3. Average values of physical/chemical parameters from ten sampling points in the Terminal Reservoir.

Temperature (°F) in the Terminal Reservoir		
Month-Year	surface	mid-depth
<i>Sep-11*</i>	67.3	66.6
<i>Oct-11</i>	65.5	64.2
<i>Nov-11</i>	55.2	54.9
<i>Dec-11</i>	47.3	47.2
<i>Jan-12</i>	48.7	48.6
<i>Feb-12</i>	53.7	53.6
<i>Mar-12</i>	56.3	56.0
<i>Apr-12</i>	64.1	63.2
<i>May-12</i>	66.3	64.9
<i>Jun-12</i>	68.6	66.9
<i>Jul-12</i>	68.7	68.2
<i>Aug-12</i>	67.5	67.9

Table 3.4. Average monthly temperatures from loggers at two depths in the Terminal Reservoir.

\*September values began Sept. 4. All other monthly averages are for the whole month.



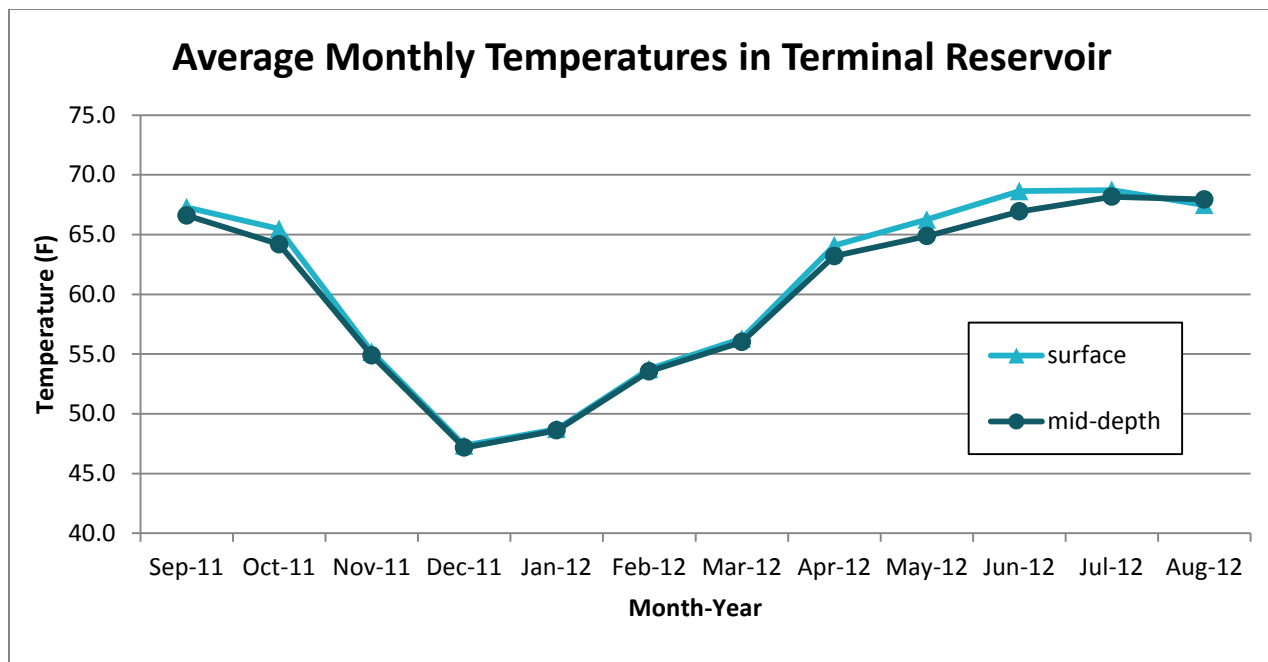


Figure 3.13. Average monthly temperatures in the Terminal Reservoir, from loggers at the surface and mid-depth.

### 3.3 Lake Solano

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#### 3.3.1 Algae

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Though algae in Lake Solano were not a focus in this study, several algal taxa were noted as present during the summer. *Cladophora* was found in 42% of the sampling points, and *Spirogyra* in 19%. The macrophytes were coated with a thick layer of diatoms in many locations. *Ulva* and *Nostoc* were found in a smaller percentage of samples (8% and 1%, respectively). All of these species are widespread natives. Data on algal presence were not recorded in the fall, winter, and spring.

#### 3.3.2 Macrophytes

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##### *Summer 2011*

Common emergent macrophytes around the shoreline of Lake Solano included bulrushes (*Schoenoplectus* spp.), cattails (*Typha* spp.), sedges (Cyperaceae), grasses (Poaceae), and willows (*Salix* spp.), with some water primrose (*Ludwigia* sp.) and smartweeds (*Polygonum* spp.)

The submersed macrophytes found in Lake Solano in the summer, in order of greatest to least average percent cover, were Eurasian watermilfoil (*Myriophyllum spicatum*), elodea (*Elodea* spp.), Coontail (*Ceratophyllum demersum*), sago pondweed (*Stuckenia pectinata*), curly-leaf pondweed (*Potamogeton crispus*), leafy pondweed (*Potamogeton foliosus*), and horned pondweed (*Zannichellia palustris*) (Figure 3.15). Some small floating plants were found as well: duckweed (*Lemna* sp.) and mosquito fern (*Azolla* sp.). All of these species are native to California except Eurasian watermilfoil and curly-leaf pondweed.

Total percent cover of macrophytes in the summer was high throughout most of the lake, averaging 81% (Figure 3.15). Total cover was largely driven by Eurasian watermilfoil, which was the dominant species in many sampling points (Figure 3.16).

Submersed macrophyte height (vertical distance from the lake bottom to the top of the macrophytes) averaged 0.5 m (1.6 ft). In 30% of sampling points, macrophytes grew to within 10 cm (3.9 in) or less from the surface of the water. In other words, macrophytes filled almost the entire water column in almost 1/3 of all the sampled points. Only 4 out of 72 sampling points had zero macrophytes.

##### *Fall 2011-Spring 2012*

For most macrophyte taxa, presence in Lake Solano (measured as the percent of sampling points where each species was found) peaked in the fall (Figure 3.17). At the time of fall sampling (mid-

November), plant biomass had accumulated over the summer growing season and had apparently not yet begun to die back. Fragments in the water were plentiful, and may have been getting flushed out of the lake at a lower rate due to the slower flow during that time of year (Table 3.10). Total percent cover of macrophytes was also highest in the fall, averaging 82.5%. Though not measured, observations indicate that filamentous algae biomass was also very high in the fall.

Most macrophytes died back somewhat over the winter, showing reduced percent cover and, for some taxa, reduced presence in sampling points (Figures 3.17 and 3.18). Macrophytes were least dense in the winter, averaging 62.6% cover. By spring, total average percent cover had increased to 66.0%, showing an increase due to the start of the growing season.

Interestingly, the three most prevalent macrophyte taxa in Lake Solano showed different patterns of seasonal abundance. Elodea and Eurasian watermilfoil had very similar patterns of presence across the seasons, but had almost opposite responses in terms of cover, with elodea being more prevalent in winter and spring, and Eurasian watermilfoil being more prevalent in the summer and fall (Figures 3.17 and 3.18). Coontail showed a large peak in fall, which may be related to the lower flows at that time (coontail is a non-rooted submersed plant that thrives in more stagnant conditions).

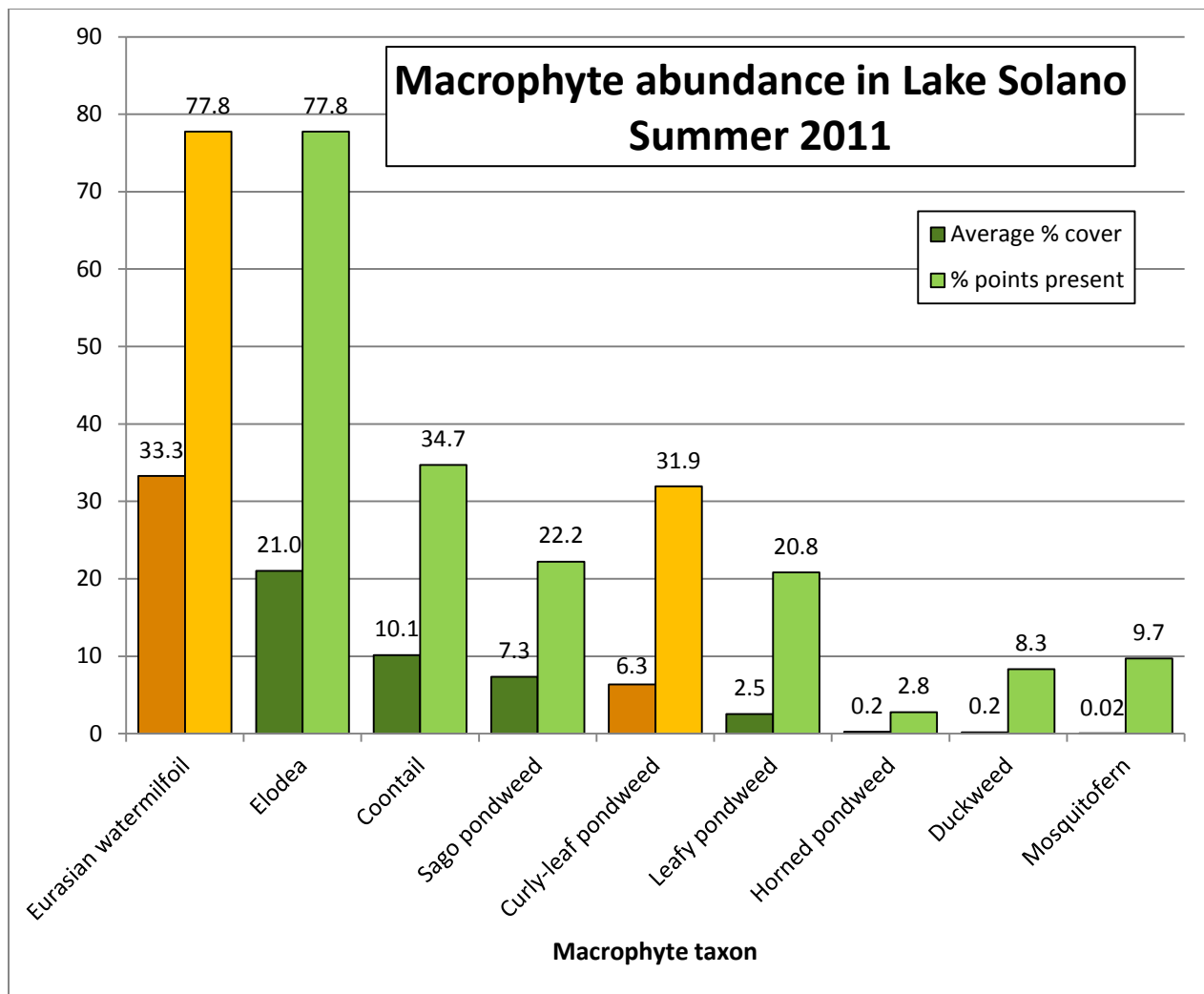


Figure 3.14. Dark bars show the average percent cover of each macrophyte taxon across 72 sampling points in Lake Solano. Light bars show the percent of points sampled in which the macrophyte taxon was present. Non-native species are indicated with orange bars, while native species are indicated with green bars.

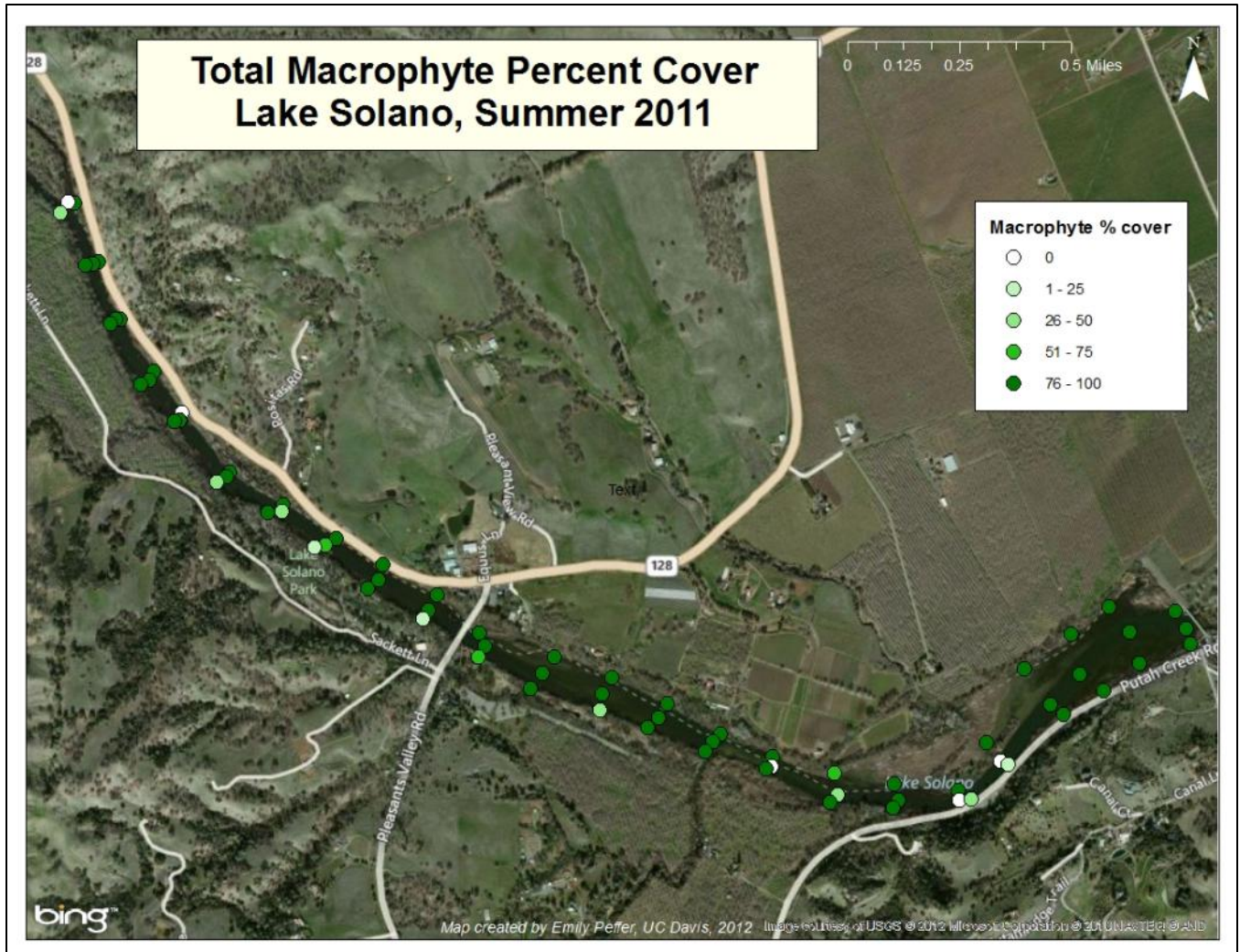


Figure 3.15. Map showing the total percent cover of macrophytes in all 72 points sampled in Lake Solano in summer, 2011.



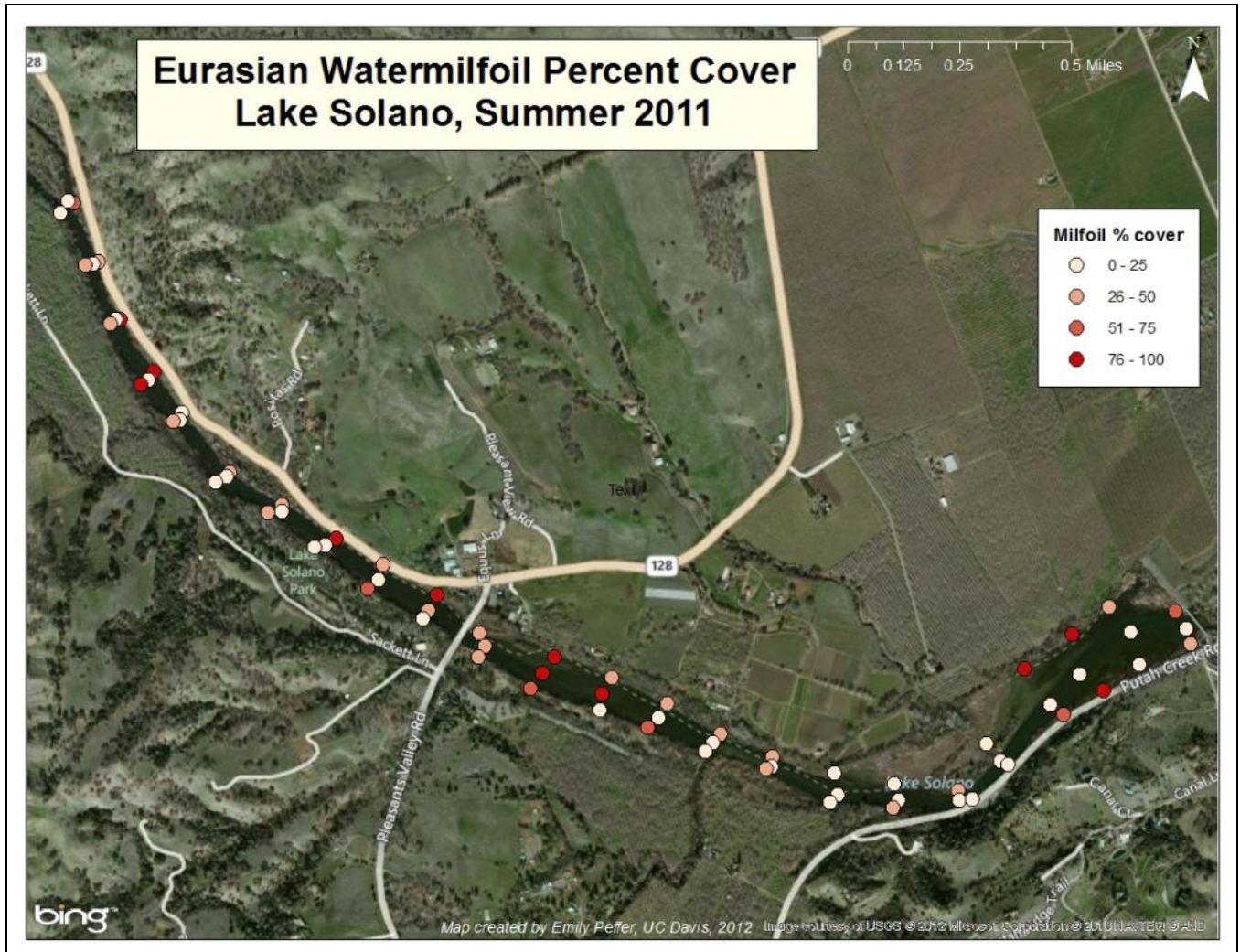


Figure 3.16. Map showing percent cover of the dominant macrophyte in Lake Solano, Eurasian watermilfoil, in summer 2011.

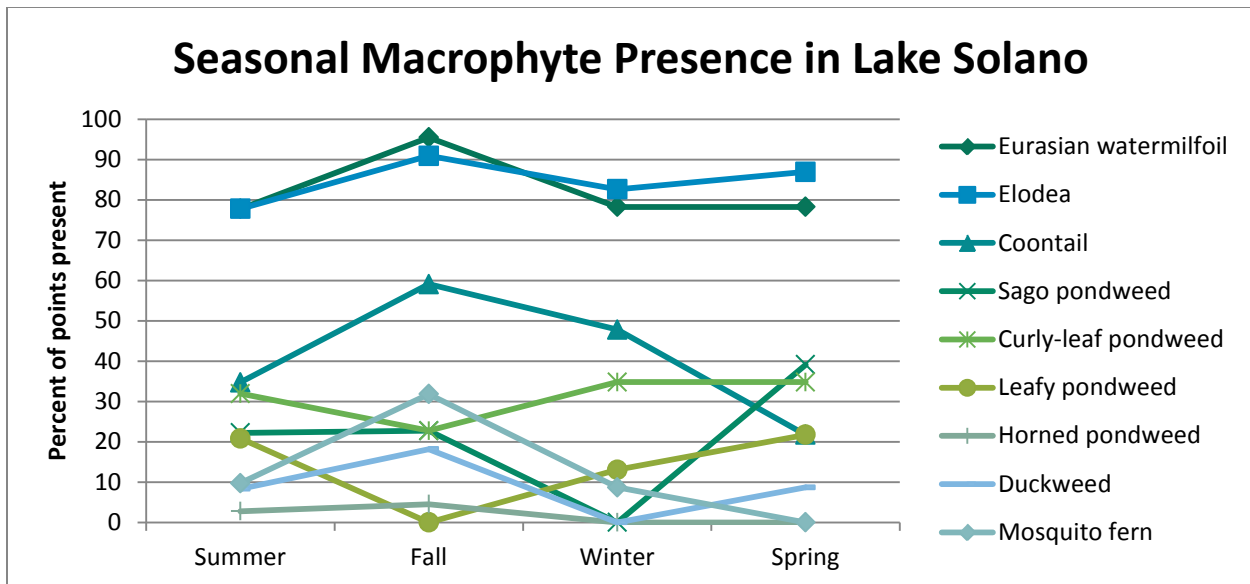


Figure 3.17. Graph of macrophyte presence by taxon at sampled points over four seasons. Note that summer had a larger number of points sampled compared to fall-spring.

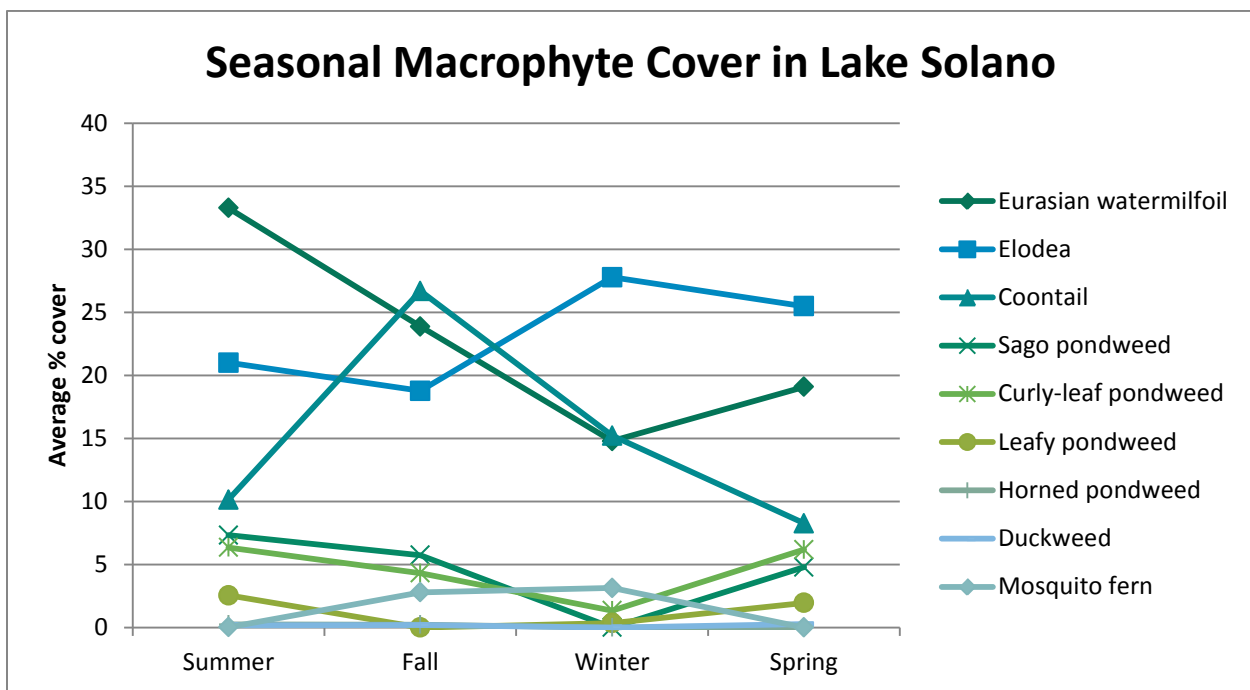


Figure 3.18. Graph of macrophyte average percent cover by taxon at sampled points over four seasons. Note that summer had a larger number of points sampled compared to fall-spring.

### 3.3.3 Sediment

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#### *Summer 2011*

The qualitative sediment assessment found that 88% of sampled points had soft substrate (clay, silt, and/or sand). Nine percent of points had gravel, 5% had rock, and 4% contained boulders. (Note: These percentages sum to greater than 100% because some points had more than one type of substrate. Also, 16 points were too deep to sample, and are not included in the calculation.)

Results from the sediment samples taken from Lake Solano in the summer of 2011 are shown in Table 3.5. The total nitrogen ranged from 0.02 to 0.19%, which is an order of magnitude lower than the percent nitrogen in sediments from the PSC. Percent nitrogen showed an increasing trend from upstream to downstream at the edges of the channel, but not in the middle (Figure 3.19).

The total carbon in sediments from Lake Solano ranged from 0.21- 1.89%, again an order of magnitude less than the percent carbon found in sediments from the PSC. The amount of carbon in sediments tended to increase with distance downstream, both in the middle of the channel and at the edges, though the trend was stronger at the edges (Figure 3.20).

Both nitrogen and carbon tended to be higher in sediments from the edges of the channel than in the middle. In the middle of the channel, water velocity is faster and may wash away organic matter, whereas at the edges, organic matter may accumulate in higher quantities.

The average C/N ratio in the sediment was 11.7. Carbon to nitrogen ratios are reflective of the sources of material to the sediments. Terrestrial vegetation has a higher C/N ratio than aquatic vegetation, so water bodies receiving a larger input of terrestrial material have higher sediment C/N values (Meyers and Ishiwatari 1993). The C/N ratio in Lake Solano suggests that the majority of decomposing organic material in the lake comes from aquatic sources, such as macrophytes, filamentous algae, and phytoplankton.

Nitrate concentrations were below the detection limit in most samples. Ammonium concentrations varied greatly, ranging from 1.7 to 121.0 µg/g dry sediment, and averaged 33.1 µg/g. No clear trends in these values were found from upstream to downstream, or relative to position (right, left, or middle). Ammonium concentrations in the PSC were on average almost eight times greater than in Lake Solano. Ammonium is formed by the decomposition of organic matter, fixation of N<sub>2</sub> by nitrogen-fixing bacteria, and through other processes. Ammonium is the form of nitrogen most easily taken up by plants.

Soluble, plant available phosphorus averaged 7.0 µg/g dry sediment, and showed no clear trends from upstream to downstream, or between middle vs. edge sampling points. Phosphorus concentrations in the PSC were on average 31 times higher than in Lake Solano.

Sediments were analyzed for particle size composition (percent sand, silt, and clay). Sand particles are larger than silt, which are larger than clay. Faster flowing water tends to wash away smaller particles, leaving coarser particles, so particle size composition is often correlated with flow. Some studies have shown that macrophytes have a higher growth rate on finer sediment compared to sand (Denny 1972). The sediment samples taken from the middle of the channel tended to have a greater percentage of sand than the samples at the edges. At the edges, there was a decreasing trend in the amount of sand with distance downstream (Figure 3.21). This is likely due to the decrease in water velocity with distance downstream (see Figure 3.27, below). Sand percentage was highest in the middle of the channel just downstream of the mouth of Pleasants Creek. Visually, in person and from aerial imagery, it appears that large amounts of sand enter the lake from this source (Figure 3.22).

Overall, sediment conditions in Lake Solano are highly suitable for macrophyte growth. Nutrients are abundant and not likely to be limiting, and the substrate is suitable for macrophyte root growth.

### *Fall 2011-Spring 2012*

Sediment nutrient averages in Lake Solano in the fall and winter were similar to those in the summer and were highest in the spring (Table 3.6). Over the winter, much of the aquatic vegetation senesces, and some sinks to the bottom and decays. The increase in ammonium and soluble phosphorus in the spring could be caused by higher temperatures resulting in increased microbial decomposition of vegetation in the sediments that had accumulated over the winter. High ammonium and soluble phosphorus and low nitrate indicate anaerobic conditions in the sediment, which is typical of wetland systems.

Sediment nutrient values may vary from point-to-point and season-to-season for several reasons. At a given location, macrophytes may be taking up nutrients (removing nutrients from the sediment), while microbes are decomposing organic material (releasing nutrients into the sediment). The rate at which both these processes occur tends to increase with temperature. However, the balance of the two (i.e., whether more nutrients are being taken up or being released) can be hard to predict. In addition, changes in flow rate can flush out or deposit material, causing changes in sediment nutrients over time.

Lake Solano Sediment Data- Summer 2011										
Transect	Position	Total N (%)	Total C (%)	C/N ratio	Nitrate (µg/g)	Ammonium (µg/g)	Soluble P (µg/g)	Sand (%)	Silt (%)	Clay (%)
1	R	0.19	1.89	9.9	bdl	121.0	9.6	27	52	21
2	L	0.12	1.23	10.3	0.36	53.5	10.3	33	47	20
5	R	0.14	1.41	10.1	bdl	25.0	7.2	15	64	21
7	L	0.14	1.32	9.4	0.26	69.6	10.5	33	48	19
8	M	0.07	0.73	10.4	bdl	6.1	10.2	61	23	16
9	L	0.08	1.03	12.9	bdl	3.7	–	56	29	15
9*	M	0.04	0.80	20.0	0.2	1.7	5.2	88	5	7
10	L	0.11	1.35	12.3	bdl	20.2	4.6	60	24	16
11	L	0.12	1.73	14.4	bdl	14.5	4.8	63	27	10
12	M	0.05	0.79	15.8	bdl	56.8	6.7	78	12	10
13	L	0.10	1.26	12.6	bdl	17.2	4.2	45	39	16
15	M	0.06	0.46	7.7	bdl	8.6	3.7	–	–	–
16	R	0.09	1.30	14.4	bdl	40.6	5.8	59	27	14
17	M	0.07	0.67	9.6	0.07	2.3	3.7	71	17	12
18	L	0.07	0.72	10.3	bdl	22.9	7.4	63	22	15
19	M	0.03	0.28	9.3	bdl	28.3	1.4	87	7	6
20	M	0.10	1.02	10.2	bdl	8.7	7.1	69	13	18
21	L	0.05	0.64	12.8	0.8	82.2	–	76	12	12
22	R	0.11	1.29	11.7	bdl	5.8	15.5	19	57	24
23	L	0.07	0.77	11.0	bdl	71.7	8.3	70	17	13
24	M	0.02	0.21	10.5	bdl	33.6	–	–	–	–
Average		0.09	1.00	11.8	–	33.1	7.0	57	29	15

Table 3.5. Results from sediment samples taken from Lake Solano in summer, 2011. Transects are shown in order from downstream near the PDD (top) to upstream at the start of Lake Solano (bottom). "Position" indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel. Bdl= below detection limit. Unlisted transects were too deep to sample. \*An additional sediment sample was taken in transect 9, which is downstream of Pleasants Creek.



Lake Solano Sediment Data- Fall, Winter, Spring											
Season	Transect	Position	Total N (%)	Total C (%)	C/N ratio	Nitrate (µg/g)	Ammonium (µg/g)	Soluble P (µg/g)	Sand (%)	Silt (%)	Clay (%)
Fall	1	R	–	–	–	–	–	–	–	–	–
	7	L	–	–	–	–	–	–	–	–	–
	13	L	0.14	1.39	9.9	bdl	66.7	7.7	35	49	16
	18	L	0.11	1.37	12.1	bdl	18.7	11.9	34	45	21
	22	R	0.09	1.20	13.0	bdl	11.2	3.3	54	33	13
	Average		0.12	1.32	11.7	bdl	32.2	7.6	41	42	17
Winter	1	R	0.20	2.11	10.5	bdl	101.1	13.5	17	58	25
	7	L	0.13	1.39	10.8	bdl	32.3	15.1	42	44	14
	13	L	0.11	1.26	11.1	bdl	34.3	7.6	58	27	15
	18	L	0.06	0.76	12.1	bdl	26.6	4.5	65	21	14
	22	R	0.10	1.20	11.7	bdl	52.7	8.7	54	29	17
	Average		0.12	1.34	11.2	bdl	49.4	9.9	47	36	17
Spring	1	R	0.24	3.00	12.6	bdl	126.7	10.8	19	55	26
	7	L	0.10	1.21	12.2	bdl	47.9	19.2	47	37	16
	13	L	0.10	1.25	13.2	0.33	73.8	18.7	35	45	20
	18	L	0.12	1.52	12.2	bdl	87.6	16.4	51	32	18
	22	R	–	–	–	–	–	–	–	–	–
	Average		0.14	1.75	12.5	–	84.0	16.3	38	42	20

Table 3.6. Results from sediment samples taken from Lake Solano in fall 2011, winter 2012, and spring 2012. Transects are shown in order from downstream near the PDD (top) to upstream near the start of Lake Solano (bottom). “Position” indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel. Bdl= below detection limit.

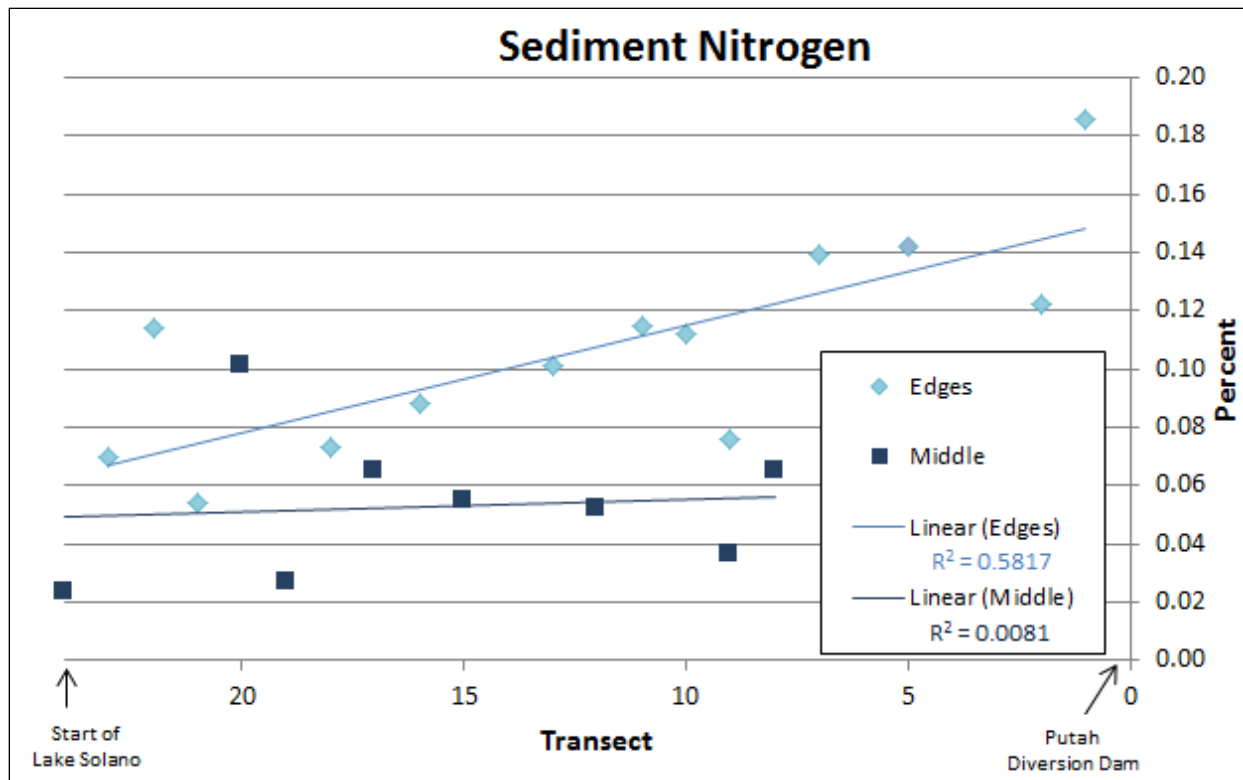


Figure 3.19. Percent nitrogen in sediment samples from Lake Solano in summer, 2011. Transects are ordered from upstream (left) to downstream (right). Best-fit lines show an increasing trend in sediment nitrogen from upstream to downstream on the edges but not in the middle.

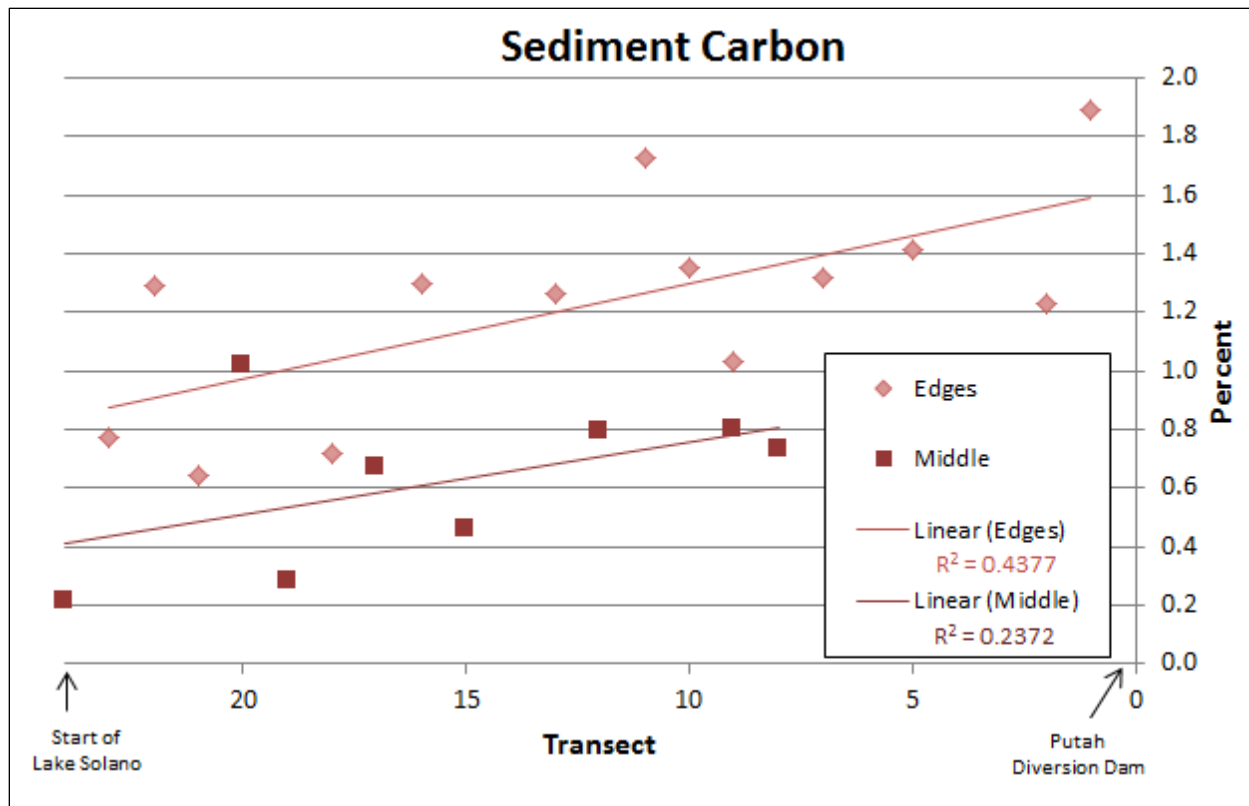


Figure 3.20. Percent carbon in sediment samples collected from Lake Solano in summer, 2011. Transects are ordered from upstream (left) to downstream (right). Best-fit lines show an increasing trend in sediment carbon from upstream to downstream in both the edges of the channel and the middle, though the trend is stronger at the edges.

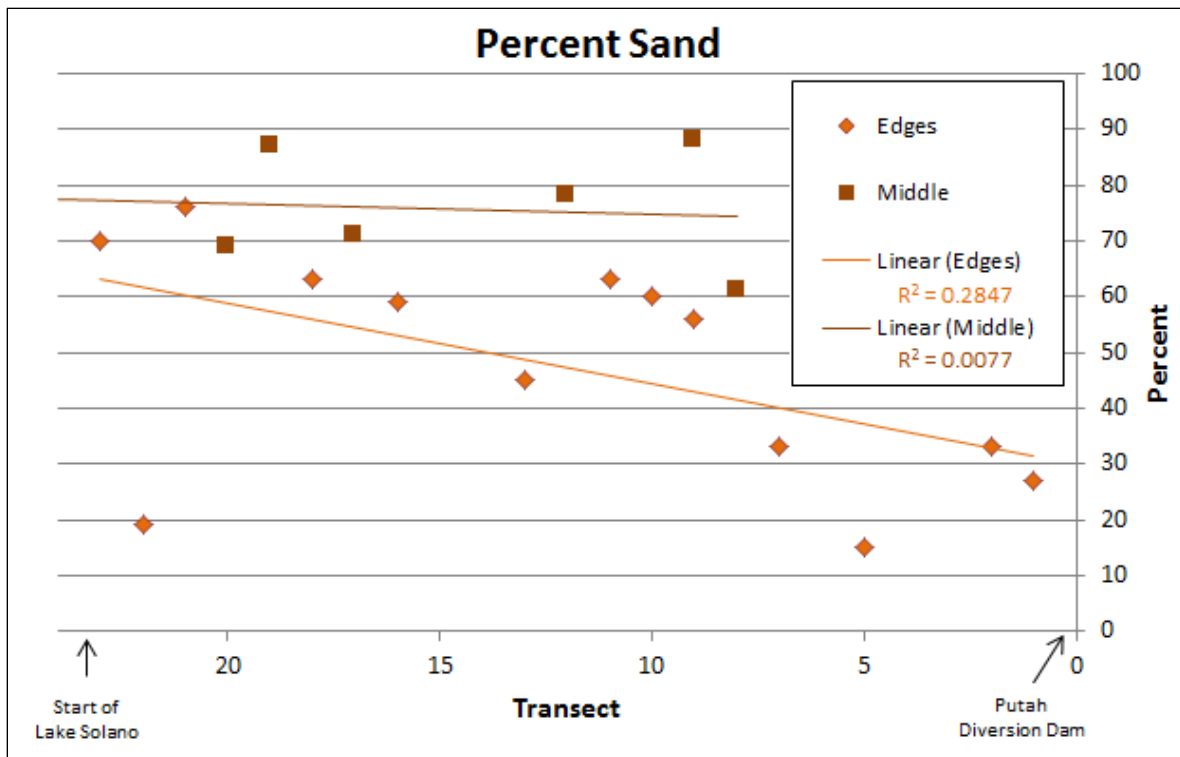


Figure 3.21. Percent sand in the sediments in Lake Solano in summer 2011. The sediments in the middle of the channel tended to have higher amounts of sand. On the edges, the amount of sand tended to decrease from upstream (left) to downstream (right).



Figure 3.22. Google Earth aerial photograph showing the sand deposited into Lake Solano at the mouth of Pleasants Creek.

### 3.3.4 Water samples

Results from water samples taken from points in the upstream, middle, and downstream sections of Lake Solano in each season are shown in Table 3.7. In the summer, all samples came back below detection limits (0.05 mg/L) for ammonium and soluble phosphorus. The samples from the middle and upstream points both had nitrate concentrations of 0.06 mg/L, while the downstream sample was below detection limits. In the fall, each sample was below detection limits (0.05 mg/L) for ammonium, soluble phosphorus, and nitrate, except the upstream sample which had a nitrate concentration of 0.07 mg/L. In the winter, all samples came back below detection limits for all parameters. In the spring, the downstream sample had an ammonium concentration of 0.17 mg/L and a phosphorus concentration of 0.12 mg/L. All other values were below detection limits.

Water Column Nutrients in Lake Solano				
Season	Sampling Location	Ammonium (mg/L)	Nitrate (mg/L)	Soluble phosphorus (mg/L)
Summer 2011	<i>Downstream</i>	bdl	bdl	bdl
	<i>Middle</i>	bdl	0.06	bdl
	<i>Upstream</i>	bdl	0.06	bdl
Fall 2011	<i>Downstream</i>	bdl	bdl	bdl
	<i>Middle</i>	bdl	bdl	bdl
	<i>Upstream</i>	bdl	0.07	bdl
Winter 2012	<i>Downstream</i>	bdl	bdl	bdl
	<i>Middle</i>	bdl	bdl	bdl
	<i>Upstream</i>	bdl	bdl	bdl
Spring 2012	<i>Downstream</i>	0.17	bdl	0.12
	<i>Middle</i>	bdl	bdl	bdl
	<i>Upstream</i>	bdl	bdl	bdl

Table 3.7. Nutrient data from water samples taken from three locations (upstream, middle, and downstream) in Lake Solano across four seasons. Bdl= below detection limits (0.05 mg/L for all parameters).



### 3.3.5 Physical/chemical parameters

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#### *Summer 2011*

Water parameters measured with a YSI sonde at all sampling points in summer 2011 are shown in Table 3.8. Water temperature in Lake Solano averaged 56.5°F during the sampling period in late August, 2011. Temperatures in the middle of the channel varied more with time of day than with location (Figure 3.23). Because actual temperatures were measured at different times of the day, and thus not directly comparable, estimated temperatures for an August day at 12:00 PM were modeled in R (version 2.15.2) using a Generalized Additive Model (Hastie 2011). The resulting map of predicted temperatures shows that temperatures tend to increase with distance downstream, and that temperatures in the middle of the channel tend to be lower than at the edges. Temperatures were highest in the slow, shallow, macrophyte-choked section of the lake near the Putah Diversion Dam (Figure 3.24).

Specific conductivity averaged 318  $\mu\text{S}/\text{cm}$  in Lake Solano. Conductivity was often higher on the edges than in the middle of the channel, which may have been caused by sediments getting stirred up through sampling activity at the shallower edge points. Turbidity was around 8 NTU in most parts of the lake. Some higher values at the edges were recorded, but these values also may have been caused by sampling activity disturbing the sediment.

Lake Solano's pH was slightly basic, with a logarithmic average of 8.14. As with temperature, daily fluctuations can be clearly seen, and contributed more to the variability in the data than spatial differences (Figure 3.25). Acidity tends to decline in lakes during the day due to photosynthetic activity of plants and algae.

Dissolved oxygen was highly variable in Lake Solano. Again, much of the variability can be attributed to daily fluctuations, where photosynthesis increases concentrations throughout the day (Figure 3.26). Percent saturation was often over 100%, which can happen when large amounts of photosynthetic activity are taking place, which is certainly the case in Lake Solano.

Water velocity was higher in the middle of the channel than at the edges. Velocity averaged 0.29 ft/s on the edges and 0.73 ft/s in the middle. [Note: in places where water velocity could not be detected, the detection limit (0.16 ft/s) was used for calculating averages.] Water velocity generally decreased with distance downstream, particularly along the edges (Figures 3.27 and 3.28), and deviations from this pattern are likely due to variable channel morphology. A bit of caution should be taken when comparing the velocities at different points in the lake: sampling occurred from downstream to upstream over a period of four days when the flow was increasing (from 512-599 cfs). Therefore, some of the pattern of

increase in water velocity with distance upstream may be due to the increase in flow over the sampling period.

Water velocity was measured during the agricultural season, when flows in Lake Solano are higher than average. However, the highest flows occur during winter storm events. See Appendix C for data provided by SCWA on average daily flow rates over one year (October 2010-October 2011).

Water depth in the middle of the channel ranged from 0.8-3.8 m and averaged 2 m (Figure 3.29). Depths were greatest approximately 0.3-0.6 miles upstream of the PDD, and also approximately 0.5 miles upstream of the Pleasants Valley Rd. bridge.

### *Fall 2011-Spring 2012*

Measurements using the YSI multi-probe sonde were taken at all sampled points in winter 2012, and results are shown in Table 3.9. The average temperature on the day of sampling in the winter was 51.8°F, the average dissolved oxygen saturation was 108%, and the logarithmic average of pH was 8.35. All of these values appear to increase with distance upstream (from transect 1-24), but this was due to natural increases in these parameters over the course of the day, as sampling was conducted from downstream to upstream over a single day (Figure 3.30). Turbidity was low throughout most sampling points, and averaged 3 NTU.

There was no detectable flow at any of the sampling points in Lake Solano in the fall. Water velocities were higher in the winter, with measureable flow at most of the middle points, but none of the edge points. Velocities increased again in the spring, with detectable flows at the majority of the sampled points (Table 3.10).

Physical/Chemical Measurements in Lake Solano, Summer 2011								
Transect	Position	Date	Time	Temperature (°F)	Specific Cond. (µS/cm)	pH	Dissolved oxygen (%)	Turbidity (NTU)
1	R	8/23	12:01	56.4	325	7.96	84.3	11.5
	M	8/23	11:12	53.4	320	7.94	87.5	7.7
	L	8/23	11:45	61.1	325	8.24	96.9	9.0
2	R	8/23	12:40	63.6	315	8.84	140.8	14.1
	M	8/23	12:58	54.7	319	8.11	133.3	7.9
	L	8/23	13:16	65.7	315	9.07	152.0	9.4
3	R	8/23	14:07	69.2	338	8.00	64.0	22.0
	M	8/23	13:43	55.4	318	8.33	125.0	7.8
	L	8/23	14:45	62.1	329	7.71	75.3	31.1
4	R	8/23	15:43	73.2	327	8.56	66.5	53.5
	M	8/23	15:00	56.9	316	8.43	143.3	7.9
	L	8/23	15:20	60.7	321	8.46	119.5	14.0
5	R	8/23	15:59	62.7	340	7.95	69.0	23.3
	M	8/23	16:19	57.9	314	8.57	161.0	7.9
	L	8/23	16:35	57.9	314	8.80	163.0	8.0
6	R	8/24	9:53	53.4	321	7.91	86.5	9.3
	M	8/24	10:09	53.6	319	7.89	88.2	7.8
	L	8/24	10:19	53.3	319	7.96	91.2	8.0
7	R	8/24	11:08	60.6	323	7.75	53.8	12.5
	M	8/24	10:58	53.8	319	7.96	101.3	7.8
	L	8/24	10:38	53.8	319	8.00	98.8	8.1
8	R	8/24	11:20	58.4	342	7.22	24.7	39.7
	M	8/24	11:30	54.1	317	8.12	111.7	7.8
	L	8/24	11:56	56.7	318	8.24	119.7	7.9
9	R	8/24	13:32	56.4	316	8.66	140.7	8.3
	M	8/24	13:13	55.4	318	8.53	133.8	7.9
	L	8/24	12:49	56.8	315	8.63	143.9	11.0
10	R	8/24	13:49	56.4	315	8.65	147.9	7.9
	M	8/24	14:00	56.0	315	8.64	141.2	7.9
	L	8/24	14:17	57.7	313	8.84	167.8	10.2
11	R	8/24	15:17	59.7	313	8.78	166.8	10.6
	M	8/24	15:18	57.5	314	8.73	153.7	25.2
	L	8/24	14:55	57.0	315	8.36	142.7	8.0
12	R	8/24	15:52	61.5	312	8.94	182.6	8.0
	M	8/24	16:06	57.8	313	8.83	157.5	12.5
	L	8/25	9:20	52.8	319	7.87	90.7	8.0

Transect	Position	Date	Time	Temperature (°F)	Specific Cond. (μS/cm)	pH	Dissolved oxygen (%)	Turbidity (NTU)
13	R	8/24	17:03	60.5	310	9.03	180.9	23.1
	M	8/24	16:53	57.7	313	8.83	146.5	8.2
	L	8/24	16:39	57.8	314	8.71	143.0	12.0
14	R	8/25	10:00	53.4	319	7.98	96.8	8.8
	M	8/25	9:45	52.8	318	7.96	94.0	7.9
	L	8/25	9:38	54.0	318	7.93	98.6	9.1
15	R	8/25	10:07	53.0	320	7.87	87.6	8.5
	M	8/25	10:16	53.0	319	8.09	99.4	7.9
	L	8/25	11:00	53.9	318	7.97	107.4	7.9
16	R	8/25	11:35	53.9	318	8.10	104.1	9.3
	M	8/25	11:20	53.7	318	8.22	109.9	8.0
	L	8/25	11:12	54.6	318	8.15	114.3	8.1
17	R	8/26	9:57	52.9	320	7.82	86.2	9.0
	M	8/26	9:33	52.8	310	7.98	93.0	8.2
	L	8/26	9:21	54.1	320	7.60	83.2	8.7
18	R	8/26	10:06	52.9	319	7.91	88.2	8.0
	M	8/26	10:14	53.1	319	8.09	98.9	7.8
	L	8/26	10:32	54.1	319	8.28	109.7	9.7
19	R	8/26	11:34	54.0	318	8.28	111.6	7.9
	M	8/26	11:09	53.7	318	8.21	109.9	7.9
	L	8/26	11:01	54.8	319	8.19	111.9	8.1
20	R	8/26	11:50	54.3	317	8.31	115.1	7.9
	M	8/26	12:05	54.4	317	8.34	115.8	7.9
	L	8/26	12:26	54.9	317	8.45	121.2	7.9
21	R	8/26	13:50	56.1	315	8.59	135.6	8.3
	M	8/26	13:35	55.4	316	8.47	125.6	7.9
	L	8/26	13:18	55.2	316	8.21	123.1	8.0
22	R	8/26	14:01	55.9	316	8.53	129.4	8.3
	M	8/26	14:20	55.6	316	8.55	127.1	8.1
	L	8/26	14:34	55.6	316	8.54	124.2	7.9
23	R	8/26	15:18	56.0	316	8.61	128.8	8.0
	M	8/26	15:02	55.7	316	8.56	125.1	8.1
	L	8/26	14:45	55.7	316	8.52	121.3	8.1
24	R	8/26	15:35	56.1	317	8.56	128.1	8.1
	M	8/26	15:45	56.0	317	8.61	123.4	8.1
	L	8/26	16:14	55.6	316	8.53	120.0	8.0
<b>Averages</b>				<b>56.5</b>	<b>318.3</b>	<b>8.14</b>	<b>116.2</b>	<b>10.9</b>

Table 3.8. Multi-probe sonde measurements from Lake Solano, summer 2011. Transects are shown in order from downstream (top) to upstream (bottom). "Position" indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel.

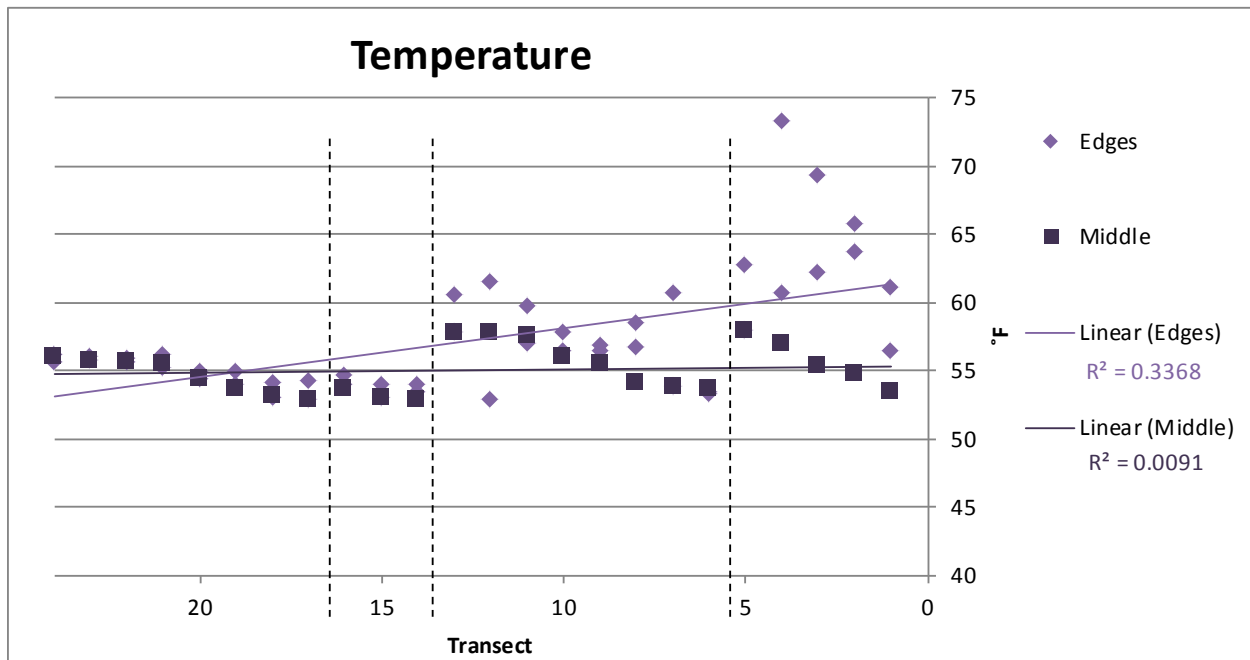


Figure 3.23. Temperatures in Lake Solano, summer 2011. Dashed vertical lines separate sampling days to show daily temperature fluctuations. Transects were sampled in order from downstream to upstream (right to left) on four different days.



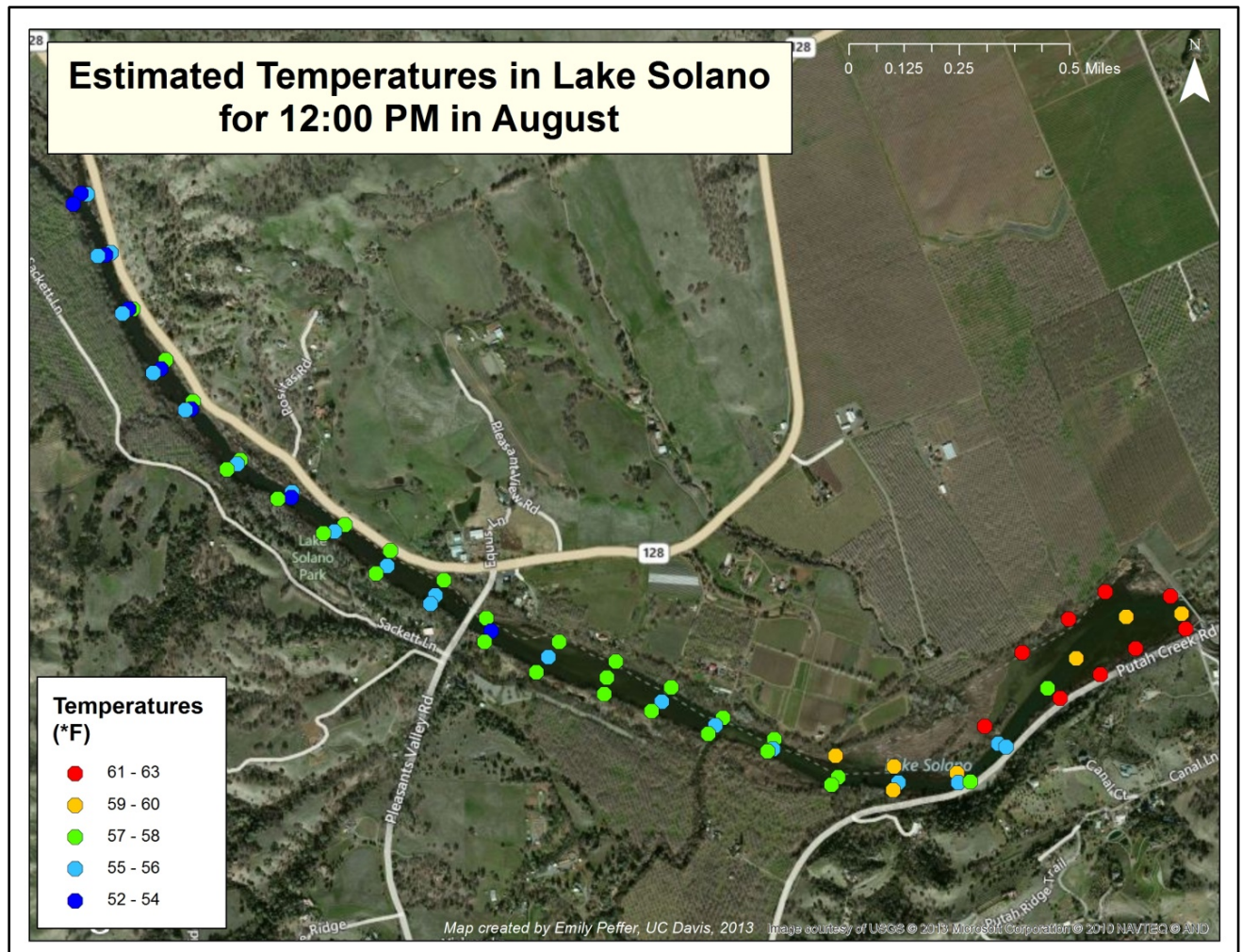


Figure 3.24. Estimated temperatures in Lake Solano for 12:00 PM in August. Warmer colors indicate warmer temperatures. Note: this map does not show actual measured temperatures at sampling points; these are predicted values based on a model using data collected over a period of several days and at different times.

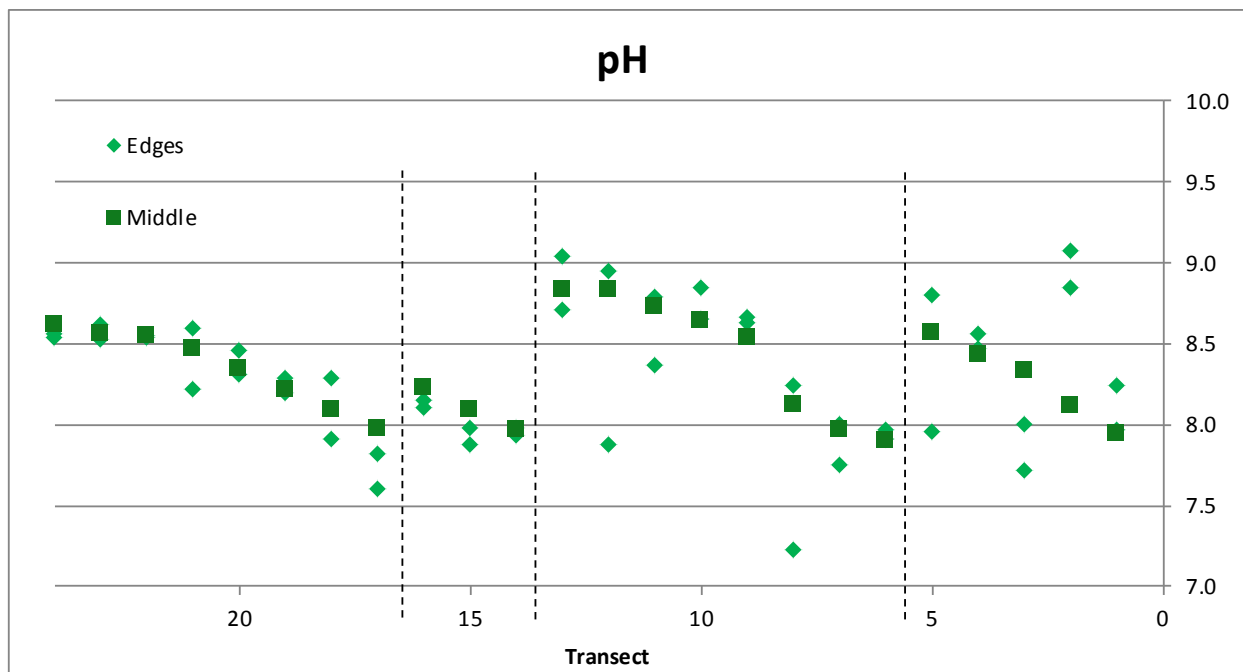


Figure 3.25. Lake Solano pH values in summer 2011. Dashed lines separate sampling days. Transects were sampled in order from downstream to upstream (right to left) on four different days. Time of day is the most important driver of pH in this dataset.

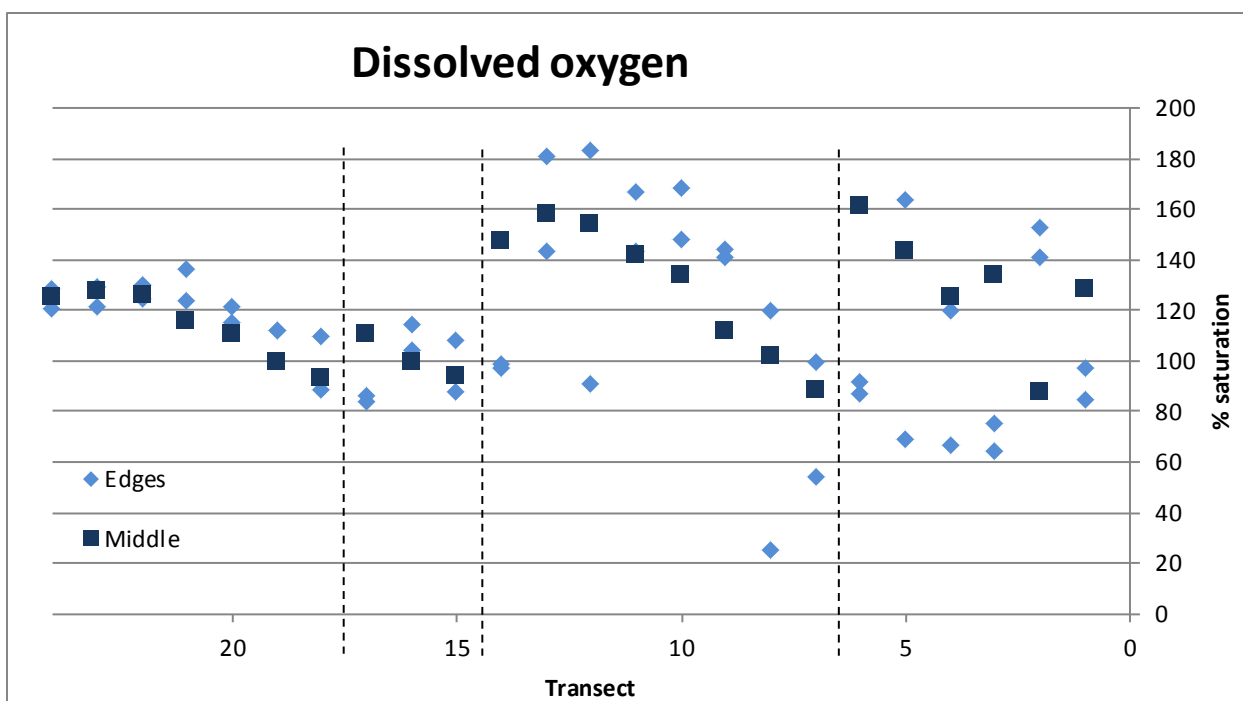


Figure 3.26. Percent saturation of dissolved oxygen in Lake Solano in summer 2011. Dashed vertical lines separate four sampling days to show daily temperature fluctuations. Transects were sampled in order from downstream to upstream (right to left).

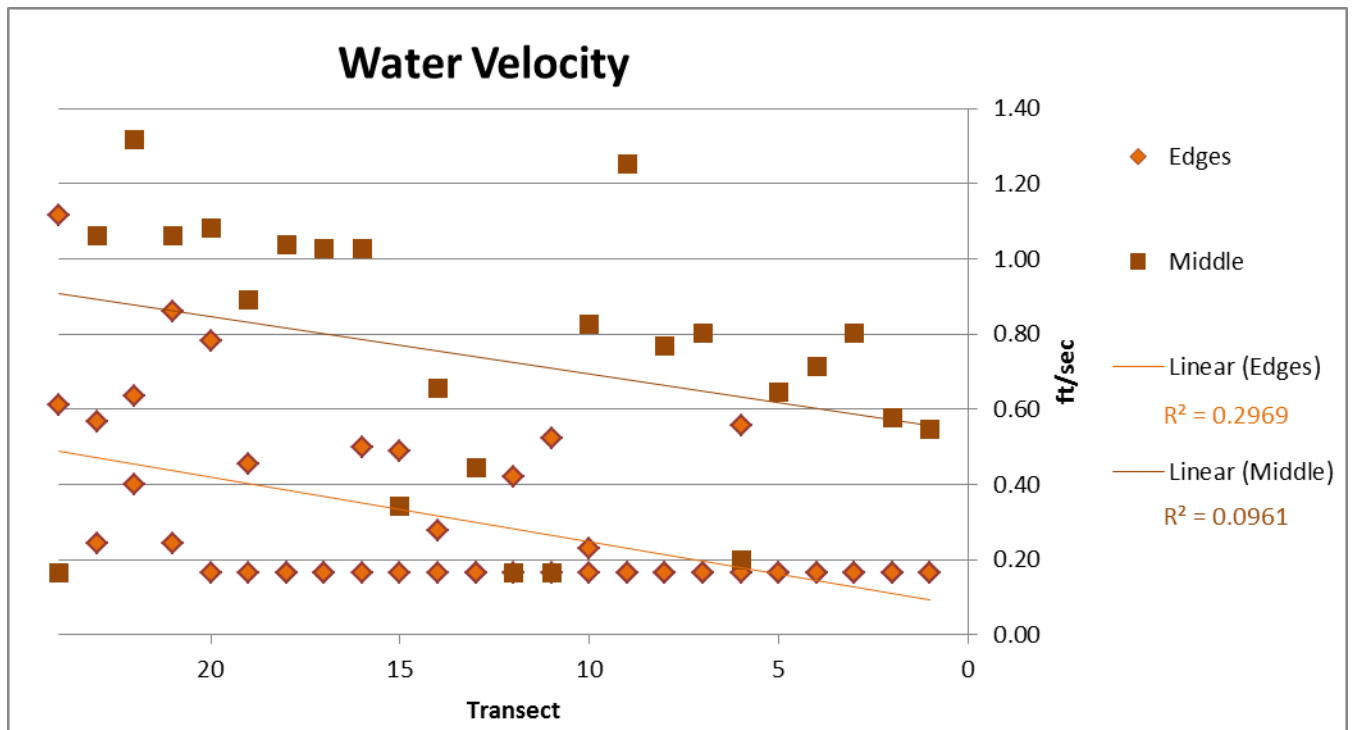


Figure 3.27. Water velocity in Lake Solano, summer 2011. The detection limit of 0.16 ft/s was assigned to points where flow was not detectable.

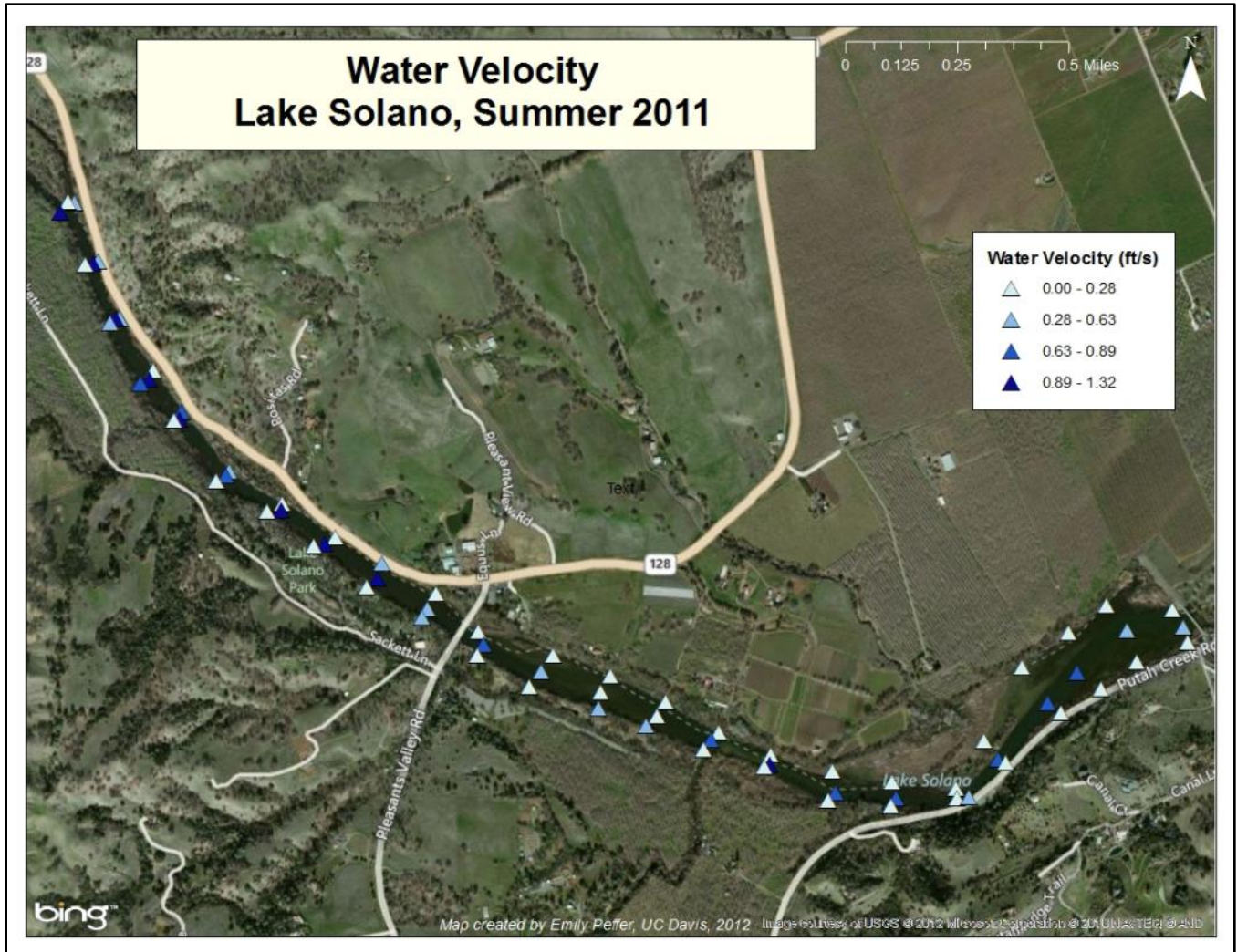


Figure 3.28. Map showing water velocity in Lake Solano. With few exceptions, velocities are higher in the middle of the channel and tend to attenuate with distance downstream.



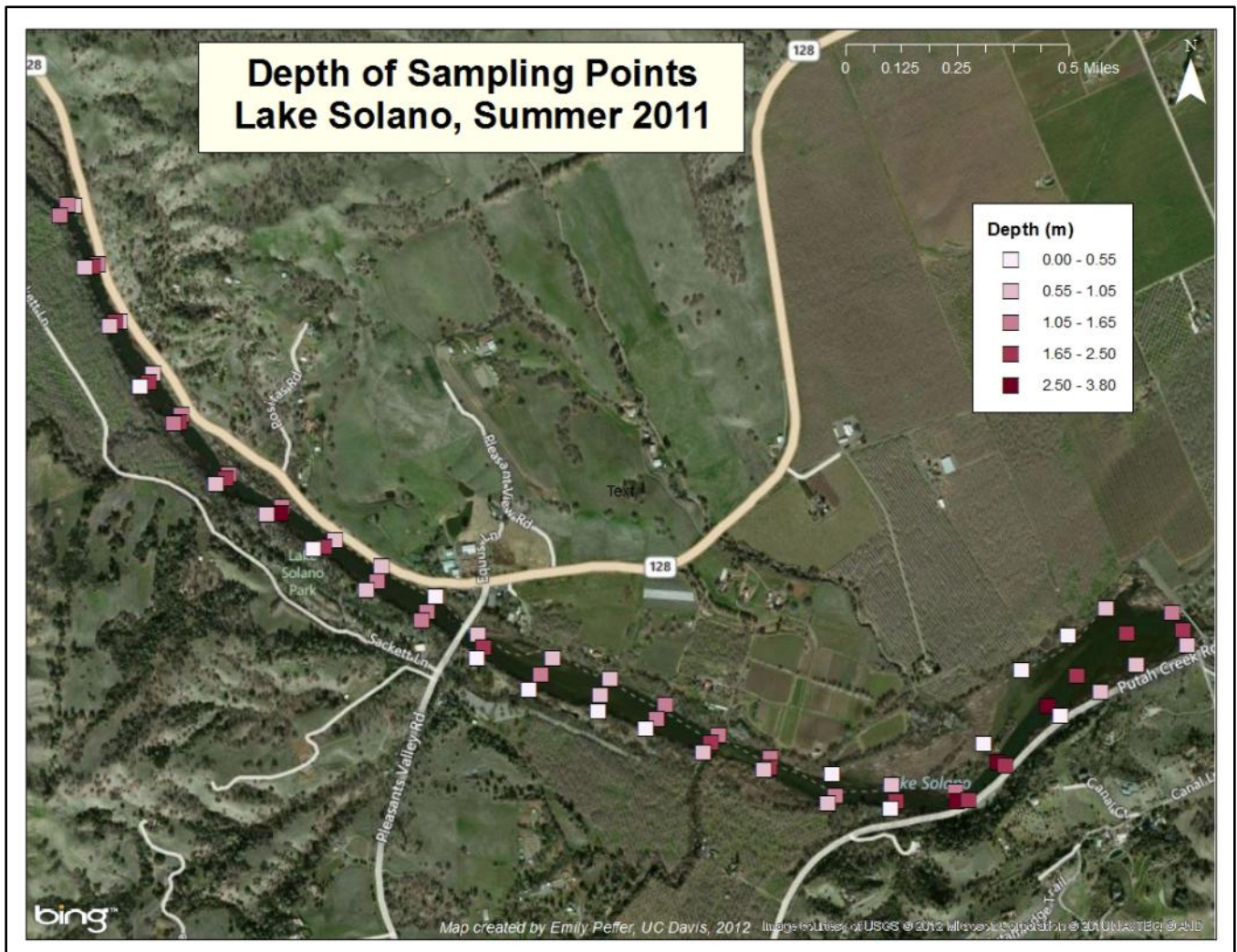


Figure 3.29. Water depth at sampling points in Lake Solano in August 2011.

Water Parameters in Lake Solano, Winter 2012						
Transect	Position	Time	Temperature (°F)	pH	Dissolved oxygen (%)	Turbidity (NTU)
1	R	9:38	49.5	7.72	54.1	19.7
2	L	10:00	49.0	8.24	67.4	16.2
3	M	10:10	49.9	8.18	84.8	0.9
4	M	10:20	50.7	8.27	88.6	1.4
6	M	10:44	50.3	8.26	91.2	0.8
7	L	10:58	50.9	8.27	95.0	4.6
8	M	11:12	50.2	8.28	98.2	1.6
9	L	11:26	51.8	8.39	103.6	4.6
10	L	11:38	51.7	8.50	116.9	3.3
11	L	11:51	50.5	8.35	105.7	0.7
12	M	11:58	50.7	8.36	110.3	0.1
13	L	12:10	50.9	8.40	110.4	6.9
14	M	12:22	51.0	8.43	112.6	0.1
15	M	13:22	52.1	8.55	123.3	0
16	R	13:36	54.5	8.53	129.7	0.3
17	M	13:45	52.8	8.58	125.1	0
18	L	14:00	52.6	8.56	123.0	0.8
19	M	14:13	53.3	8.62	125.5	0
20	M	14:23	53.4	8.61	125.4	0
21	L	14:35	53.2	8.60	124.8	0.4
22	R	14:44	55.3	8.70	142.1	2.0
23	L	14:58	53.2	8.57	122.0	1.6
24	M	15:06	53.7	8.63	119.9	0
Average			51.8	8.35	108.7	3.0

Table 3.9. Readings from the YSI multi-probe sonde in winter 2012. Transects are shown in order from downstream (top) to upstream (bottom). "Position" indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel.



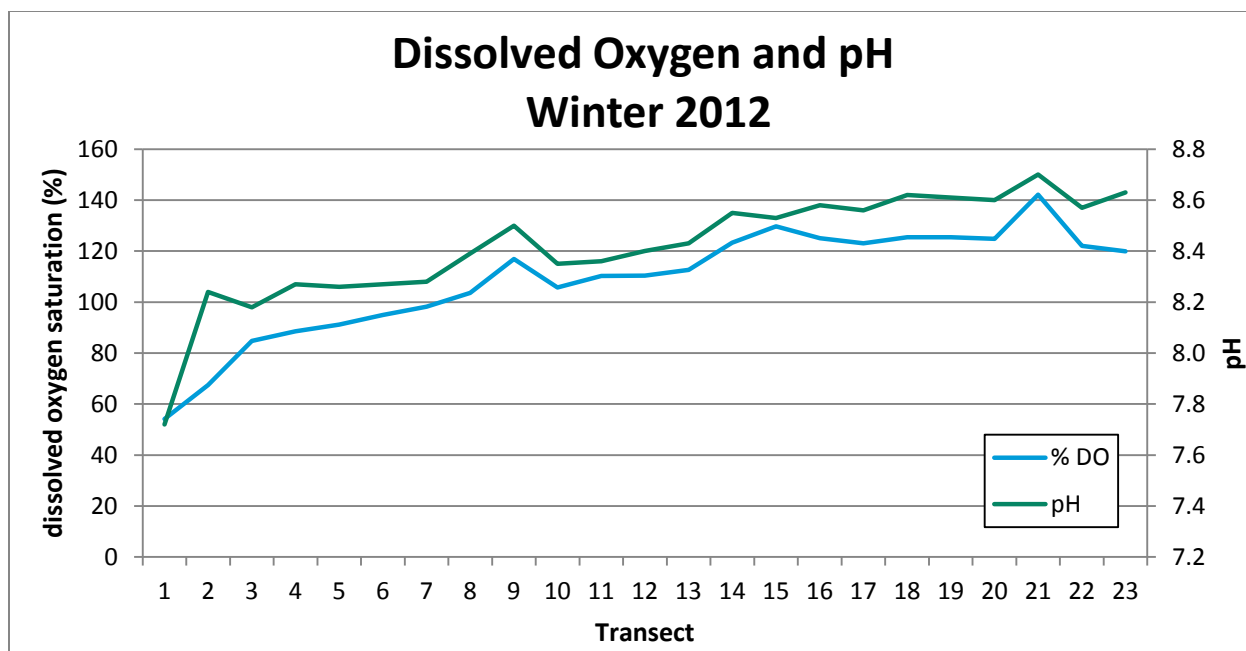


Figure 3.30. Dissolved oxygen and pH values both increased with distance upstream in Lake Solano in winter 2012, however, this increase is likely due to time of sampling rather than distance.

Water Velocity in Lake Solano: Fall, Winter, and Spring				
Transect	Position	Water Velocity (ft/s)		
		Fall 2011	Winter 2012	Spring 2012
1	R	ND	ND	ND
2	L	ND	ND	ND
3	M	ND	0.43	0.76
4	M	—	0.38	0.62
6	M	ND	ND	0.79
7	L	ND	ND	ND
8	M	ND	0.39	0.94
9	L	ND	ND	ND
10	L	ND	ND	ND
11	L	ND	ND	ND
12	M	ND	ND	0.58
13	L	ND	ND	ND
14	M	ND	ND	0.81
15	M	ND	0.51	0.78
16	R	ND	ND	0.28
17	M	ND	0.55	0.87
18	L	ND	ND	ND
19	M	ND	0.56	1.02
20	M	ND	0.56	1.12
21	L	ND	ND	0.62
22	R	ND	ND	ND
23	L	ND	ND	ND
24	M	ND	0.30	0.88

Table 3.10. Water velocity in Lake Solano in the fall, winter, and spring. Transects are shown in order from downstream (top) to upstream (bottom). “Position” indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel. ND= not detected (less than 0.16 ft/s).

### 3.3.6 Year-long temperature data

Temperature data was collected from loggers that had been left in Lake Solano for one year. The loggers at Location 1, in a shallow area near the PDD (Figure 2.6) could not be found and were not recovered. The loggers at Location 3, near the island that marks the boundary between Lake Solano and Putah Creek, were recovered approximately 10m downstream of their original location, and at greater depth (the surface logger was 0.5m below the water’s surface and the mid-depth logger was at a depth

of 1.1 m. This movement occurred sometime between June and September 2012, possibly due to increased flows. Average monthly temperatures are shown for the two loggers at Locations 2 and 3 in Table 3.11 and Figure 3.31. Appendix D shows graphs of all temperature data points.

Monthly average temperatures were highest, and relatively similar (around 58°C) in September, October, April, May, June, July, and August. Rather than increasing from April to May, a slight decrease in temperature occurred, which may have been due to increased releases of cold hypolimnetic water from Lake Berryessa as the irrigation season ramped up. The coldest temperatures occurred in December for Location 2, and in January for Location 3. Greater annual temperature fluctuations occurred at Location 2, which is downstream of Location 3; the water reaching this point has more time to be influenced by air temperatures. Surface temperatures tended to be higher than mid-depth temperatures by around 0.6°F in Location 2. The two loggers in location 3 had very similar temperatures throughout the year. These data show that temperatures increased with distance downstream, except from November-January when the opposite was true. Typical daily fluctuations were around 3-5°F (data not shown).

Month-Year	Temperature (°F)			
	<i>Location 2</i>		<i>Location 3</i>	
	surface	mid-depth	surface	mid-depth
Sep-11	57.9	56.8	54.4	54.4
Oct-11	58.2	57.2	56.2	55.4
Nov-11	52.1	51.8	52.7	51.9
Dec-11	48.1	47.6	49.6	49.8
Jan-12	48.5	48.1	49.2	49.3
Feb-12	51.5	51.1	50.7	50.8
Mar-12	53.1	52.7	51.8	51.8
Apr-12	57.6	56.7	54.3	54.2
May-12	57.1	56.8	53.4	53.5
Jun-12	57.8	57.3	53.8	53.8
Jul-12	58.1	57.4	54.2	54.2
Aug-12	58.5	57.3	54.4	54.4

Table 3.11. Average monthly temperatures in Lake Solano from two depths at two different locations.

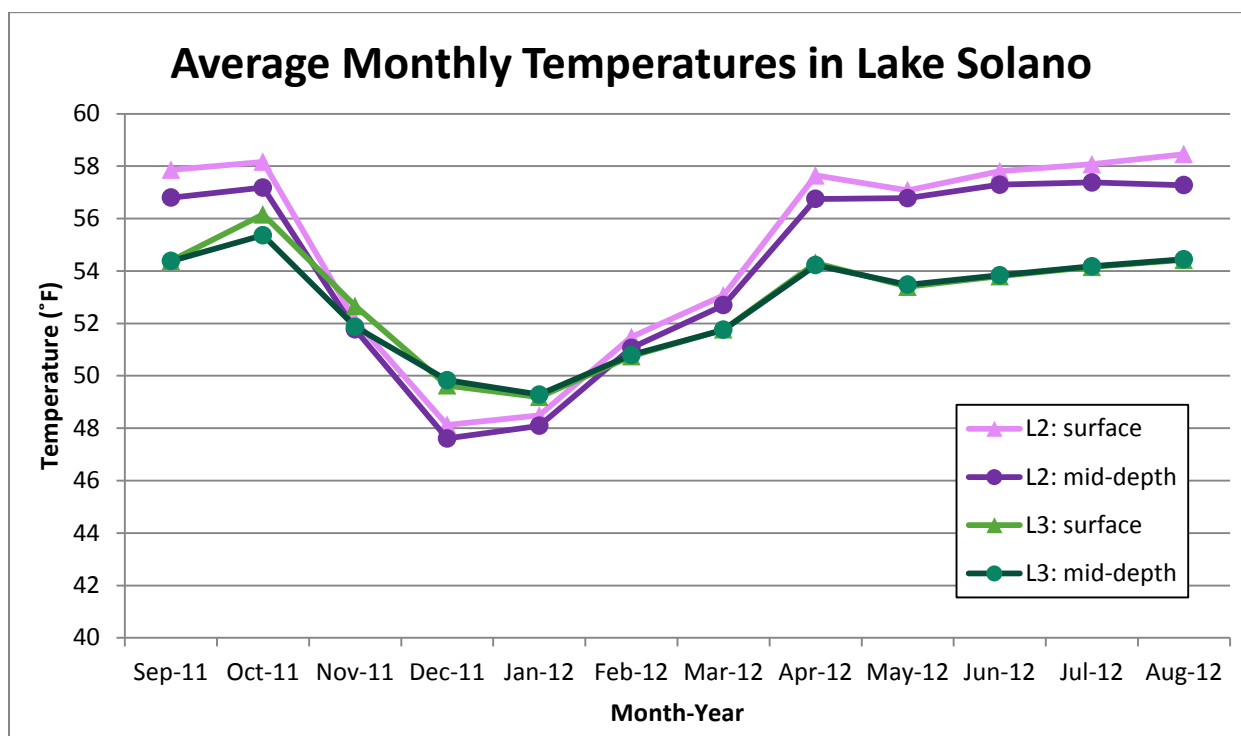


Figure 3.31. Average monthly temperatures at two locations (L3 and L2) in Lake Solano. L3 is upstream of L2.

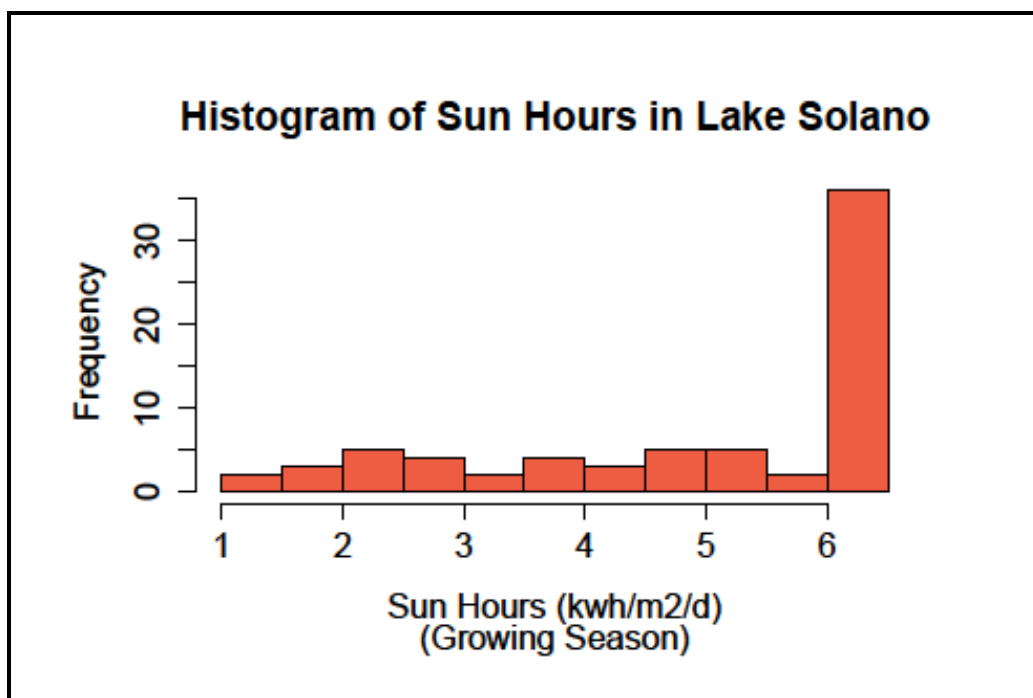
### 3.3.1 Light

Vertical extinction coefficients (" $k_d$ "), measurements of light attenuation with depth, averaged  $0.46 \text{ m}^{-1}$  in the summer,  $0.67 \text{ m}^{-1}$  in the fall,  $0.36 \text{ m}^{-1}$  in the winter, and  $0.33 \text{ m}^{-1}$  in the spring, and did not vary greatly or show a clear spatial pattern throughout the lake. These  $k_d$  values are in the low-middle range for freshwater lakes (Kirk 1994) (higher values indicate less light penetration through the water column). Vertical extinction coefficients are influenced by dissolved and suspended substances in the water column, and can vary on a short time scale (along with turbidity) due to activity by humans, wildlife, etc.

Given the average  $k_d$  of  $0.46 \text{ m}^{-1}$  in the summer, and an average PAR of  $1710 \mu\text{E}/\text{m}^2/\text{s}$  at the surface of the water in the middle of the lake (minimal shade), the amount of PAR reaching the bottom of the lake would be  $1075 \mu\text{E}/\text{m}^2/\text{s}$  at 1 m depth,  $676 \mu\text{E}/\text{m}^2/\text{s}$  at 2 m depth, and  $425 \mu\text{E}/\text{m}^2/\text{s}$  at 3 m depth. Most submersed plants, including those found in Lake Solano, reach light saturation (the point where light availability is optimal for photosynthesis) at around  $600\text{--}700 \mu\text{E}/\text{m}^2/\text{s}$ , and can grow in just over 15-

35  $\mu\text{E}/\text{m}^2/\text{s}$  (Van, Haller, and Bowes 1976). Given this, photosynthesis of macrophytes would be possible down to 7-13 meters in open (non-shaded) conditions. Because Lake Solano is, on average, only about 1 m deep, and never greater than 7 m, water clarity is sufficient, and in most cases, near optimal, throughout the lake.

Sun hours are a measure of how much solar radiation reaches a given location, and are measured in average kilowatt hours per meter squared per day. These values reflect how much canopy cover (shade) is present at a sampling point. Because the macrophyte growing season is usually March-October, the average sun hours during this time period was calculated. [There was a tight correlation between the sun hours calculated over the whole year and from March-October only (Pearson's correlation coefficient= 0.989).] Solar radiation was generally highest in the middle of the channel and in the downstream area of Lake Solano, near the PDD. As shown in Figure 3.32, the majority of sampling points were very sunny, with over 6 kWh/m<sup>2</sup>/d of solar radiation, but some points had greater amounts of shade, down to a minimum of 1.35 kWh/m<sup>2</sup>/d.



*Figure 3.32. Histogram showing average amount of solar radiation reaching sampling points in Lake Solano in the macrophyte growing season (March-October). Most points had little canopy cover and received a large amount of sunlight.*

## 3.4 Putah Creek (IDR)

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### 3.4.1 Macrophytes

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#### *Fall 2011*

Elodea was the most common and abundant macrophyte in Putah Creek, present in over 50% of the sampled points (Figure 3.33). Elodea was followed by Eurasian watermilfoil, which was present at almost one third of the sites. Horned pondweed, curly-leaf pondweed, and moss were all found at around 20% of the sites. Other species found included water speedwell, duckweed, and mosquito fern.

The average total percent cover of macrophytes in Putah Creek in the fall was 61.4%, but this varied widely depending on location. Out of 31 total sampling points on 13 transects, 5 points had 0% cover, and 12 had 100% cover. A map of macrophyte density by sampling point is shown in Figure 3.34.

#### *Winter 2012*

In winter, each macrophyte taxon had lower average percent cover and was found in fewer sampling points compared to fall (Figure 3.35), but the relative abundances were similar. Elodea was still the most abundant taxon, followed by Eurasian watermilfoil, but moss was more abundant than horned pondweed or curly-leaf pondweed. This is probably because moss, a non-vascular plant, does not senesce in the winter, while the other macrophyte taxa, all vascular plants, do (Glime 2007). Water speedwell, duckweed, and mosquito fern were not found in the winter.

The average macrophyte percent cover in the winter was 35.7%. Six points out of 28 had 0% cover, and no points had 100% cover.



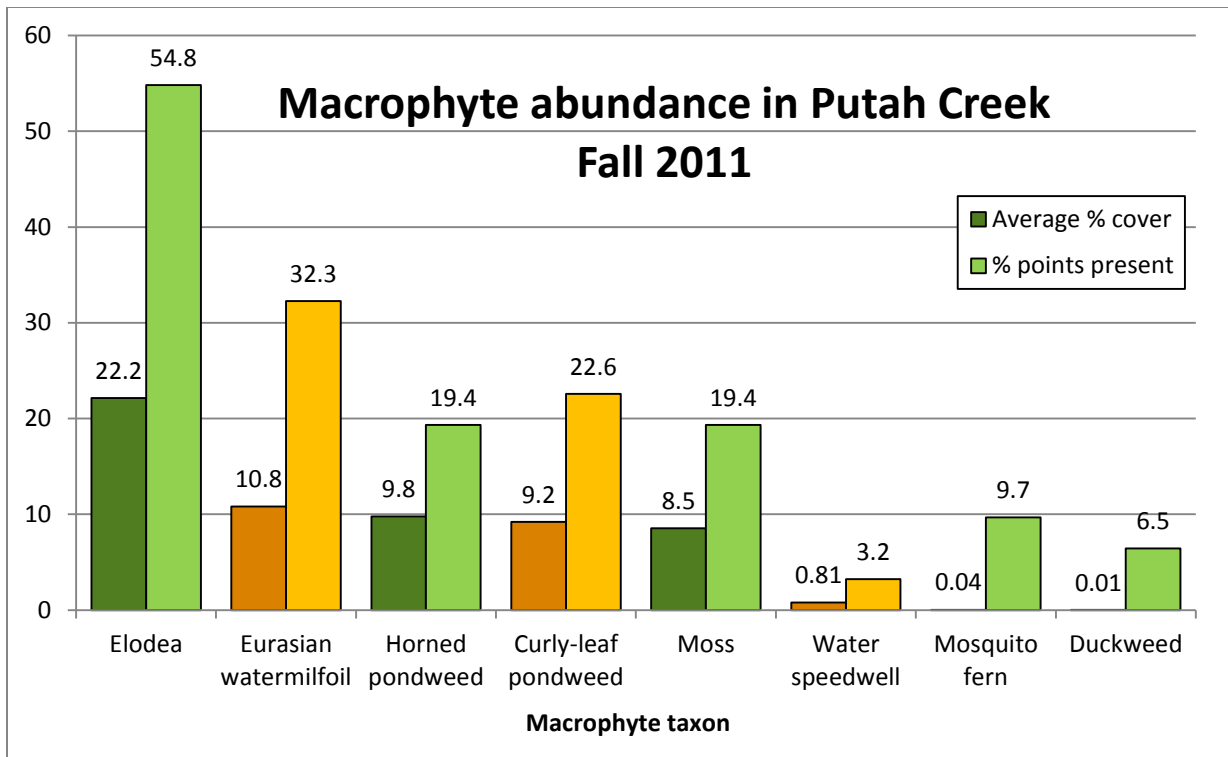


Figure 3.33. Dark bars show the average percent cover of each macrophyte taxon across 31 sampling points in Putah Creek in fall 2011. Light bars show the percent of points sampled in which the macrophyte taxon was present. Non-native species are indicated with orange bars, while native species are indicated with green bars.

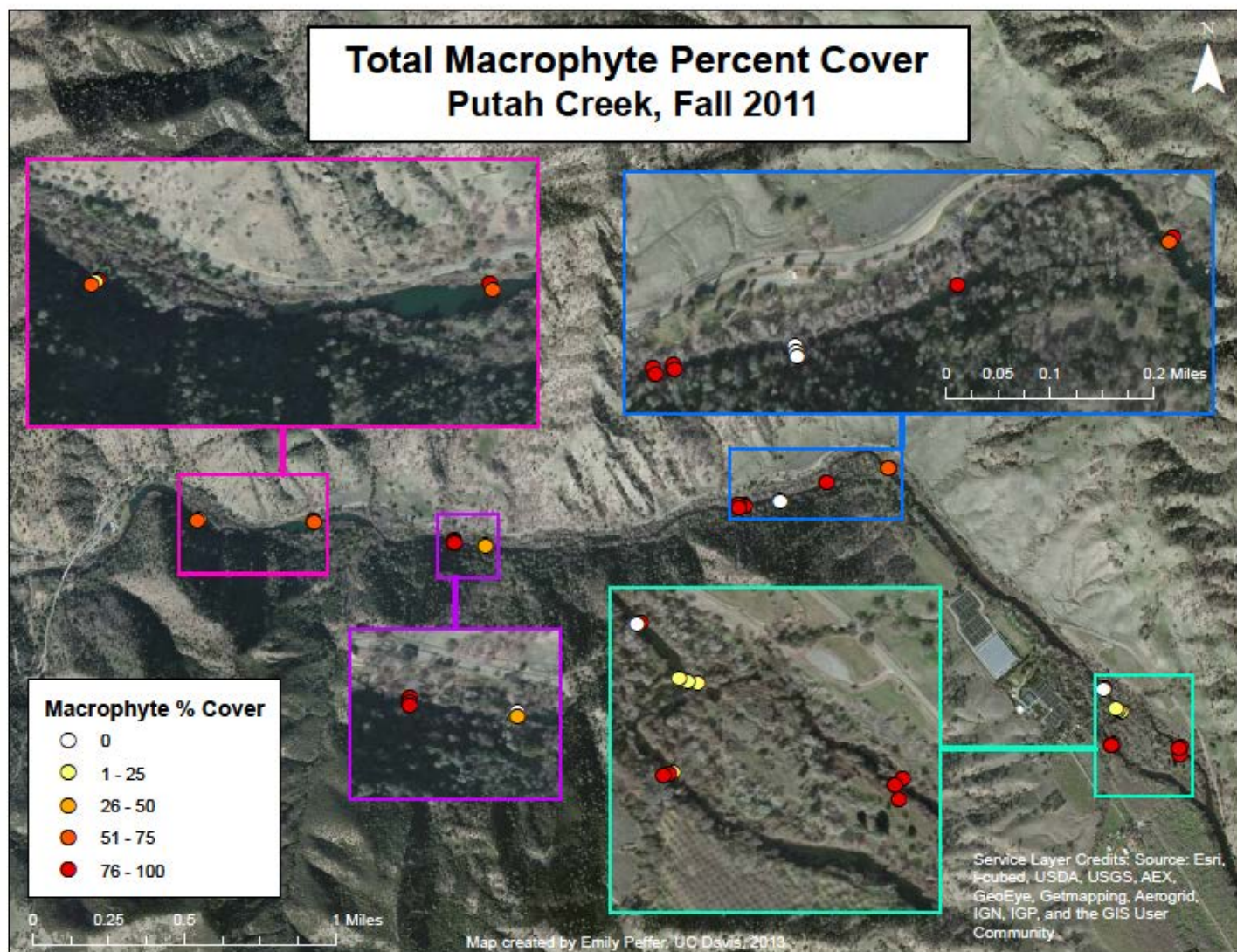


Figure 3.34. Total macrophyte density in the sampled locations of Putah Creek in fall 2011. Multiple insets are shown to better display the individual points on a transect.

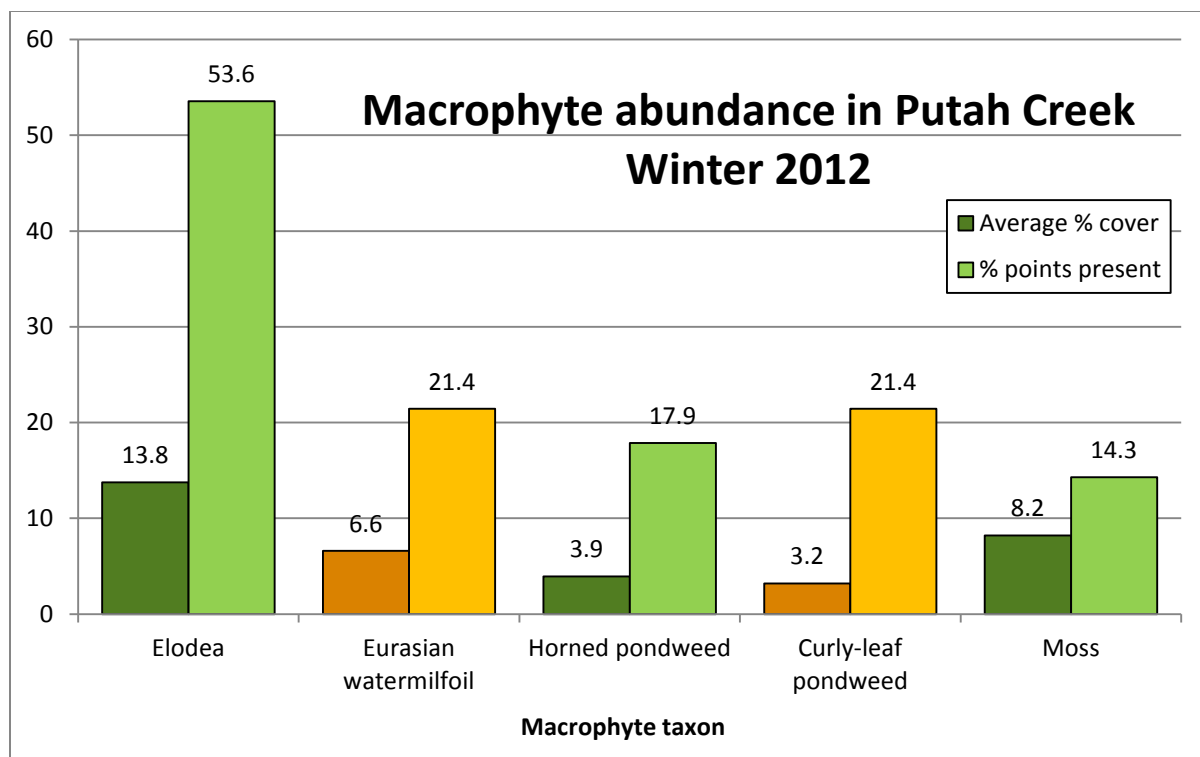


Figure 3.35. Dark bars show the average percent cover of each macrophyte taxon across 28 sampling points in Putah Creek in winter 2012. Light bars show the percent of points sampled in which the macrophyte taxon was present. Non-native species are indicated with orange bars, while native species are indicated with green bars.

### 3.4.2 Sediment

#### Fall 2011

The substrate type (clay and silt, sand, gravel, rock, and boulders, see Table 2.1) was diverse in Putah Creek, with most sampling points containing more than one type of substrate. Out of 31 sampling points, 11 had clay and silt, 13 had sand, 11 had gravel, 7 had rocks, and 13 had boulders.

Sediment samples were taken in five locations (sampling was not possible in rocky or deep locations) (Table 3.12). The total nitrogen in the samples averaged 0.14%, and total carbon averaged 1.71%. The carbon-to-nitrogen ratio averaged 14.0. The higher ratio in Putah Creek than in Lake Solano may indicate a higher percentage of organic material coming from terrestrial sources (Meyers and Ishiwatari 1993).

Nitrate was below detection limits in all samples. Ammonium averaged 55.4  $\mu\text{g/g}$ , but ranged widely, from 0.9-191.0  $\mu\text{g/g}$ . Soluble phosphorus values had a mean of 6.2  $\mu\text{g/g}$ .

The percentage of sand in the samples was high (84-85%) in transects 2, 7, and 13. In transects 5 and 11, silt had the highest percentage (49% and 44%, respectively).

No trends in sediment nutrient levels or particle size from upstream to downstream were observed. Values are probably more representative of the channel morphology at each particular location, which varies in a nonlinear way.

### *Winter 2012*

Average values for sediment nutrients and particle size in winter 2012 were similar to values in fall 2011 (Table 3.12). However, values for individual sampling points were not well correlated between the seasons. This could be due to the dynamic nature of Putah Creek- sediments are scoured, deposited, and transported over time, particularly with winter storms creating high flow events. This suggests that there may be more local variability than seasonal system-wide variability, at least from late fall to late winter.

Putah Creek Sediment Samples										
	Transect	Total N (%)	Total C (%)	C/N ratio	Nitrate (µg/g)	Ammonium (µg/g)	Soluble P (µg/g)	Sand (%)	Silt (%)	Clay (%)
Fall 2011	2	0.073	1.04	14.2	bdl	0.9	3.8	85	8	7
	5	0.134	1.39	10.4	bdl	191.0	4.8	21	49	30
	7	0.083	1.58	19.0	bdl	28.9	8.7	84	10	6
	11	0.347	3.50	10.1	bdl	33.5	8.6	39	44	17
	13	0.065	1.05	16.1	bdl	22.8	5.1	85	9	6
	Average	0.140	1.71	14.0	bdl	55.4	6.2	63	24	13
Winter 2012	2	0.158	2.48	15.7	0.21	38.2	2.0	36	28	36
	5	0.058	0.63	10.9	0.22	13.8	6.5	25	29	46
	7	0.053	1.06	20.0	bdl	22.8	8.2	80	8	12
	11	0.037	0.93	25.1	0.14	6.0	5.6	84	7	9
	13	0.247	2.83	11.5	bdl	88.7	17.6	49	35	16
	Average	0.111	1.59	16.6	–	33.9	8.0	55	21	24

Table 3.12. Results from sediment samples taken from Putah Creek in fall 2011 and winter 2012. Transects are shown in order from downstream (top) to upstream (bottom). Bdl= below detection limit. All samples were taken from the right (when facing upstream) edge of the channel. Unlisted transects were too rocky or too deep to sample.

### 3.4.3 Water samples

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#### *Fall 2011*

Two water samples were taken in Putah Creek in the fall, at transects 1 and 10 (see Fig 2.8 for transect locations). Both samples were below detection limits (0.05 mg/L) for ammonium and soluble phosphorus. Nitrate values were 0.09 mg/L and 0.12 mg/L for transects 1 and 10, respectively. This difference could be spatial and/or temporal, since transect 1 was sampled on 11/12/2011 and transect 10 on 11/21/2011.

#### *Winter 2012*

Two water samples were taken from transects 1 and 5 in winter 2012. Both samples were below detection limits (0.05 mg/L) for ammonium and soluble phosphorus. Nitrate values were below detection limits (0.05 mg/L) for transect 1, and 0.07 mg/L for transect 5.

### 3.4.4 Physical/chemical parameters

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Water velocities in Putah Creek varied greatly by location, ranging from not detectable (<0.16 ft/s) to 5.94 ft/s in the fall and 4.49 ft/s in the winter. Water velocities were similar in fall and winter (Table 3.13).

The amount of solar radiation reaching the sampling points in Putah Creek was generally lower than in Lake Solano, due to the narrower channel and greater amount of riparian vegetation. Sun hours for the growing season (March-October) averaged 3.70 kWh/m<sup>2</sup>/d for the edge points and 4.39 kWh/m<sup>2</sup>/d for the middle points. (For reference, 6.10 kWh/m<sup>2</sup>/d is the maximum possible value for this area.)

Water chemistry was measured at one location (transect 8) during the winter only. Temperature was 50.9 °C, pH was 8.4, turbidity was 0.1 NTU, and dissolved oxygen saturation was 103.8%.



Water Velocity and PAR in Putah Creek					
Transect	Position	Fall 2011 Water Velocity (ft/s)	Winter 2012 Water Velocity (ft/s)	Sun Hours Mar-Oct (kWh/m <sup>2</sup> /d)	Sun Hours (kWh/m <sup>2</sup> /d)
1	R	ND	ND	4.26	3.49
	M	ND	1.00	4.47	3.70
	L	0.25	1.18	4.17	3.21
2	R	0.95	3.03	1.00	1.04
	M	1.63	4.49	3.75	3.12
	L	1.23	1.41	3.59	2.42
3	R	ND	1.04	4.46	3.58
	M	0.30	–	5.55	4.43
	L	0.34	–	5.06	4.14
4	R	ND	–	3.43	2.45
	M	0.24	ND	3.55	2.78
5	R	ND	ND	4.55	3.60
	M	0.28	1.50	4.41	3.45
6	R	ND	ND	4.66	3.66
7	R	0.33	0.39	3.08	2.15
	M	0.28	1.02	2.67	1.86
	L	0.72	–	1.48	1.00
8	R	0.70	0.93	4.97	3.56
	M	0.21	ND	5.16	3.96
9	R	2.45	2.01	3.23	2.28
	M	5.94	1.51	4.73	3.26
10	R	0.89	0.62	1.78	1.27
	M	3.08	2.63	1.83	1.37
11	R	1.03	1.56	4.88	3.68
	M	1.30	1.41	5.47	3.88
	L	0.29	–	1.73	1.15
12	R	ND	0.22	5.35	4.20
	M	0.52	0.39	5.97	4.54
13	R	ND	ND	5.00	3.70
	M	0.81	0.72	5.17	3.59
	L	1.53	–	3.56	2.38
Average		1.10	1.12	3.97	3.00

Table 3.13. Water velocity and solar radiation values for sampling points in Putah Creek, fall 2011 and winter 2012. “Position” indicates whether samples were taken from near the left bank (L), middle (M), or right bank (R) of the channel. “ND” means “not detectable”, i.e., less than 0.16 ft/s. \*Average water velocity was calculated using 0.16 for all NDs.

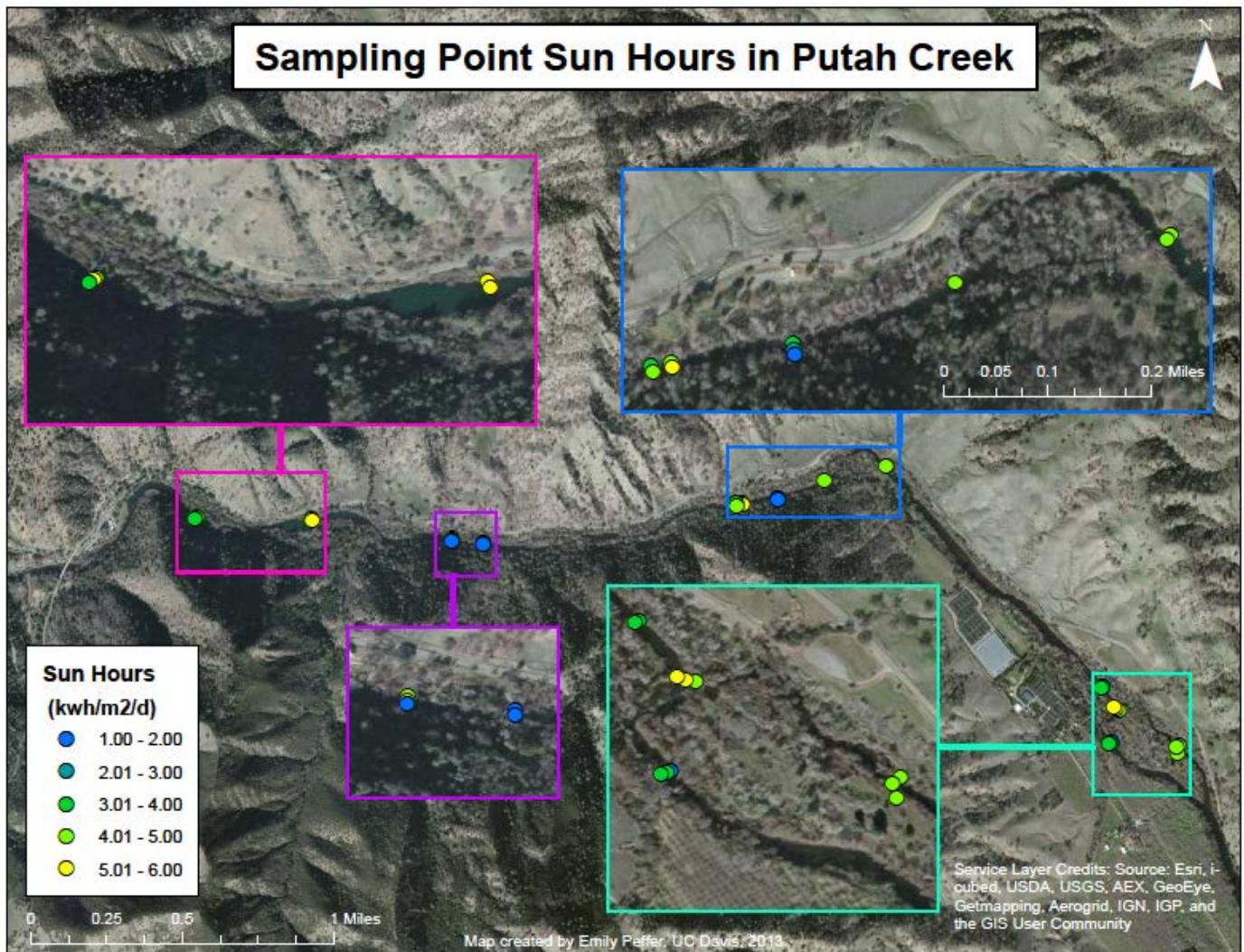


Figure 3.36. Map of sun hours in Putah Creek. Sun hours are kilowatt hours per meter squared per day, and data shown here are averages over the months of March-October (the macrophyte growing season).

## 4 Data Modeling

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### 4.1 Modeling approach

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To explore the relationships between environmental factors measured in this study and macrophyte abundance in the IDR, with a goal of understanding how manipulating these factors could potentially lessen the impact of excessive macrophyte growth, ecological models were created using 2011 survey data and a modeling approach called “boosted regression trees”.

Boosted regression trees (BRT) are a relatively new approach to modeling ecological data. The technique uses machine learning to combine multiple “decision trees” into a model with high predictive ability. Decision trees (also called classification and/or regression trees) are like flow charts that partition data with a series of binary splits. Each split partitions the data into two groups based on the value of a predictor variable (e.g., depth greater or less than 2.5 ft). This process continues by adding successive “branches” for different predictor variables, with each split attempting to explain the maximum amount of variation in the response variable (e.g., total macrophyte cover), to minimize residual error. “Boosting” refers to the process of creating many simple trees (few branches) in succession, with each tree built on the residual error of the previous tree. The trees are then combined into a single predictive model. To further increase predictive accuracy, multiple models are created from different bootstrapped samples of the full dataset. By combining the results of all these models, average predictions and confidence intervals can be obtained. BRT models are becoming increasingly recognized as one of the better available methods for modeling multivariate ecological data, due to their predictive accuracy and interpretability. For overviews of this technique, see Elith, Leathwick, and Hastie (2008) and De’ath (2007).

The BRT model was built using R software (R version 2.15.2, R Development Core Team, Vienna, AT), with the gbm package (Ridgeway 2013). Model specifications are listed in Table 5.1. The dataset used in this analysis included data from the sampling done in Lake Solano in late August 2011 (72 sampling points), and in Putah Creek in mid-November 2011 (31 sampling points). Predictor variables used in the models are presented in Table 5.2 with summary statistics. The modeled response variable was the combined percent cover of the following subset of macrophyte species: *Myriophyllum spicatum*, *Potamogeton foliosus*, *Stuckenia pectinata*, *Zannichellia palustris*, *Elodea spp.*, *Potamogeton crispus*, and *Ceratophyllum demersum*. These are species judged to be the most problematic to SCWA, either because of their extensive growth within the PSC (first four), or because they produce a significant

amount of floating vegetative material that can clog screens at the Headworks and in the canal (last three), as determined by the PSC vegetation monitoring study conducted by Northwest Hydraulic Consultants (2010a).

For the modeling exercise, the response variable of percent cover was converted to a discrete (rather than continuous) variable composed of 20 “spaces” that could each be either occupied or not occupied by macrophytes. Whether or not a space was occupied was treated as a binomial process. This process is analogous to flipping biased coins, with the bias being driven by the predictor variables. In other words, to determine the percent cover rounded to the nearest 5%, the model would flip 20 biased coins, and the graphs for each predictor variable show the bias of those coins.

It should be noted that the results shown in the section below are based on correlations between environmental variables and macrophyte cover, and do not prove causation. For example, macrophyte cover is predicted to be lower where there is lower sediment nitrogen; however, this does not necessarily mean that reducing sediment nitrogen will result in reduced macrophyte growth. It may be that macrophyte presence increases nitrogen in the sediment, for instance, or that both macrophyte cover and sediment nitrogen are linked to an unmeasured variable. Before taking management action on any of these findings, greater investigation of causal mechanisms through experiments and/or literature review should be conducted.

Additionally, models tend to improve in predictive accuracy as sample size increases. The dataset used in this analysis was relatively small, and a larger or different set of sampled points probably would have resulted in different model predictions. Therefore, patterns in the model predictions for predictor variables should be taken as informative trends, and not treated as absolute fact.

<b>Model Parameters</b>
Number of models = 150
Number of trees per model = 4100
Number of branches per tree = 2
Shrinkage* = 0.001

*Table 4.1. Parameter specifications used in the BRT model. \*Shrinkage, or learning rate, refers to the amount each individual tree contributes to the overall model (Elith, Leathwick, and Hastie 2008).*

Summary Statistics for Predictor Variables					
Predictor Variable	Variable type	Average	Standard Deviation	Range	N
Water velocity (m/s)	Continuous	0.17	0.22	0.05 - 1.81	103
Depth (m)	Continuous	1.04	0.74	0.15 - 3.8	103
Sun Hours-Yearly (kWh/m <sup>2</sup> /d)	Continuous	3.58	1.27	0.95 - 4.87	102
Sand (%)	Continuous	58	23	15 - 88	24
Silt (%)	Continuous	28	18	5 - 64	24
Clay (%)	Continuous	15	6	6 - 30	24
Sediment N (Total %)	Continuous	0.097	0.064	0.023 - 0.347	26
Sediment C (Total %)	Continuous	1.13	0.64	0.21 - 3.5	26
Sediment Nitrate (µg/g)	Continuous	0.15	0.15	0.07 - 0.80	26
Sediment Ammonium (µg/g)	Continuous	37.4	42.9	0.9 - 191	26
Sediment Soluble P (µg/g)	Continuous	6.8	3.12	1.4 - 15.5	23
Substrate (qualitative scale)	Ordinal	1	-	1 - 5	87
Position	Categorical	-	-	R, M, L	103
System	Categorical	-	-	Lake Solano, Putah Creek	103

*Table 4.2. Summary statistics of predictor variables used in the models described in this section. Averages are arithmetic means, except for “substrate”, which is the modal value.*

## 4.2 Modeling results

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The relative importance of variables in the BRT models is shown in Figure 4.1. The importance of a variable describes the amount of variation in the data explained by that variable relative to all the other variables. In these models, variables with greater importance are stronger predictors of macrophyte cover. Yearly average sun hours was the most important variable, with almost 25% of the explanatory power in the models. The proportion of soft substrate and boulders were the second and third most important variables, with 21% and 19% of the importance, respectively. Depth had a relative importance of 15%, followed by total sediment nitrogen with 7%, and water velocity with 4%. Each of the other variables had less than 2% relative importance.

Graphs showing model predictions of the total cover of nuisance macrophytes along the ranges of each of the six most important predictor variables are shown in Figures 5.2-5.7. The mean predicted response (nuisance macrophyte cover) is shown, along with the 50<sup>th</sup> and 95<sup>th</sup> percent confidence intervals around the prediction. Again, these values were generated from 150 models fitted to bootstrapped samples from the original data. Where present, tick marks along the top of the graphs show actual observed values of the predictor variables in the dataset, and are displayed to show the distribution of the data used for building the models. Confidence intervals tend to be wider (i.e., lower confidence) in the range of predictor values with fewer data points.

The predictor with the greatest influence in the models was total (yearly) sun hours- the average kWh/m<sup>2</sup>/d of solar radiation reaching the surface of the water at a sampling point. Differences in sun hours reflect differences in canopy cover (shade), and greater canopy cover is correlated with lower nuisance plant cover. At sampling points with sun hours of approximately 2.4 kWh/m<sup>2</sup>/d and higher, macrophyte cover is predicted to be around 80%. Below this, macrophyte cover is predicted to be around 65% or less (Figure 4.2). Of the sampled data points in the IDR dataset, 79 out of 102 (77%) were above this 2.4 kWh/m<sup>2</sup>/d threshold. Because the sampling strategy disproportionately sampled points close to the edge of the water, which are generally shadier than the middles, an even greater proportion of the IDR is likely to have shade levels that favor higher macrophyte growth.

The second and third most important predictor variables were two of the qualitatively defined substrate variables. For this analysis, substrate was treated as a categorical variable, and broken into the five classes (see Table 2.1). Each class was entered as a separate predictor variable in the models. Because some sampling points had more than one substrate class present, this variable was input as the proportion of a given substrate class at each sampling point, divided evenly between the number of



substrate types present. For example, if a point had both classes 1 and 4, the substrate for that point was assigned as 50% substrate 1 and 50% substrate 4. The substrate classes that had the most influence in the models were classes 1 and 5, soft substrate (silt and clay) and boulders, respectively. Greater proportions of soft substrate were correlated with higher nuisance macrophyte cover (Figure 4.3), while greater proportions of boulders at a sampling point were correlated with lower nuisance macrophyte cover (Figure 4.4).

Interestingly, the quantitative measures of particle size distribution in the sediment (% sand, silt, and clay) were not important predictors in the models, while two of the qualitative substrate variables were. This suggests that the major classes of substrate are more important in determining plant cover than the finer-scale measures of particle size. (The method for determining particle size only analyzes the fraction of the material consisting of sand, silt, and clay, and does not measure gravel, rock, or boulders.)

Depth is an important factor in determining macrophyte cover, according to the BRT models. At depths down to approximately 2.4 m (7.9 ft), there is relatively little difference in predicted macrophyte cover (Figure 4.5), and at depths greater than this, macrophyte cover is predicted to decline. Given a typical amount of light at the surface of unshaded water in the summer ( $1900 \mu\text{mol}/\text{m}^2/\text{s}$  PAR), and the average vertical extinction coefficient of  $0.46 \text{ m}^{-1}$  measured for Lake Solano in the summer, a depth of 2.4 m corresponds to around  $625 \mu\text{mol}/\text{m}^2/\text{s}$  PAR. The light saturation point of most macrophytes, measured as the light level above which photosynthesis does not increase, occurs around 600-700  $\mu\text{mol}/\text{m}^2/\text{s}$  PAR (Kirk 1983). Therefore, this threshold of 2.4 m may be reflecting the light saturation point of macrophytes. The models suggest that increasing the depth of Lake Solano to greater than 2.4 m, possibly through dredging, could potentially reduce the growth of problematic macrophytes.

A small reduction in macrophyte cover is also predicted at the shallowest depths, and this might be due to yearly water level fluctuations, which could cause the shallowest depths to dry out at certain times of the year. Greater impact from waves at the shallower depths may also play a role.

The response of nuisance macrophyte cover to sediment total nitrogen levels is relatively uniform, with a reduction in cover only predicted to occur below 0.05% (Figure 4.6). It may be that low sediment nitrogen values limit the growth of nuisance macrophytes. On the other hand, lack of macrophytes might result in lower sediment nitrogen. Only three data points out of 26 were equal to or below 0.05% N, so caution should be taken in assessing the importance of this result.

Macrophyte cover is predicted to be lower with higher water velocity (Figure 4.7), but the effect is very small (only a couple percentage points). Very high water velocity may remove fine sediments that

are favorable for macrophyte growth, physically remove macrophytes and their propagules, and/or create stressful conditions that certain macrophytes cannot tolerate. The water velocity data used to create the BRT models were collected at single time points, and do not reflect the full range of velocities that occur throughout the year (see Appendix C). Water velocity is probably most important to macrophytes in terms of its influence on substrate, and the effect of the finest and coarsest substrate classes (arguably a better long-term indicator of velocity) were shown to be more important than the water velocity measurements.

“System” (Lake Solano or Putah Creek) did not appear as an important predictor. This means that most differences between Lake Solano and Putah Creek could be accounted for by the other measured variables, and the fact that Putah Creek was sampled at a different time of year than Lake Solano was probably not very important. Transect position (left, right, or middle), had even less importance in the models. Apart from total nitrogen, the other sediment nutrient variables had little influence in the models.

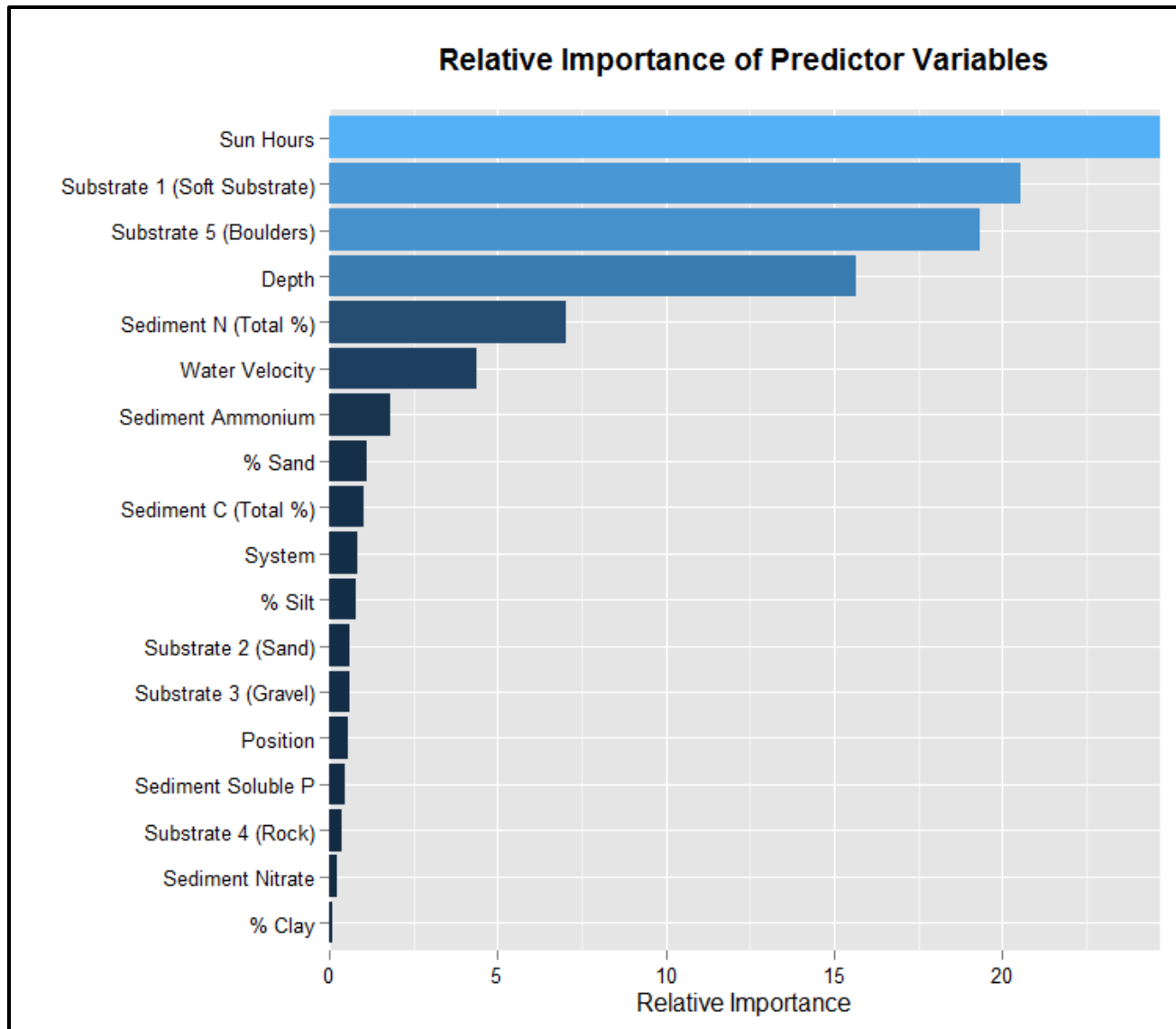


Figure 4.1. Relative importance of variables in predicting nuisance macrophyte cover in the BRT models. Eighteen total predictors were used in the models.

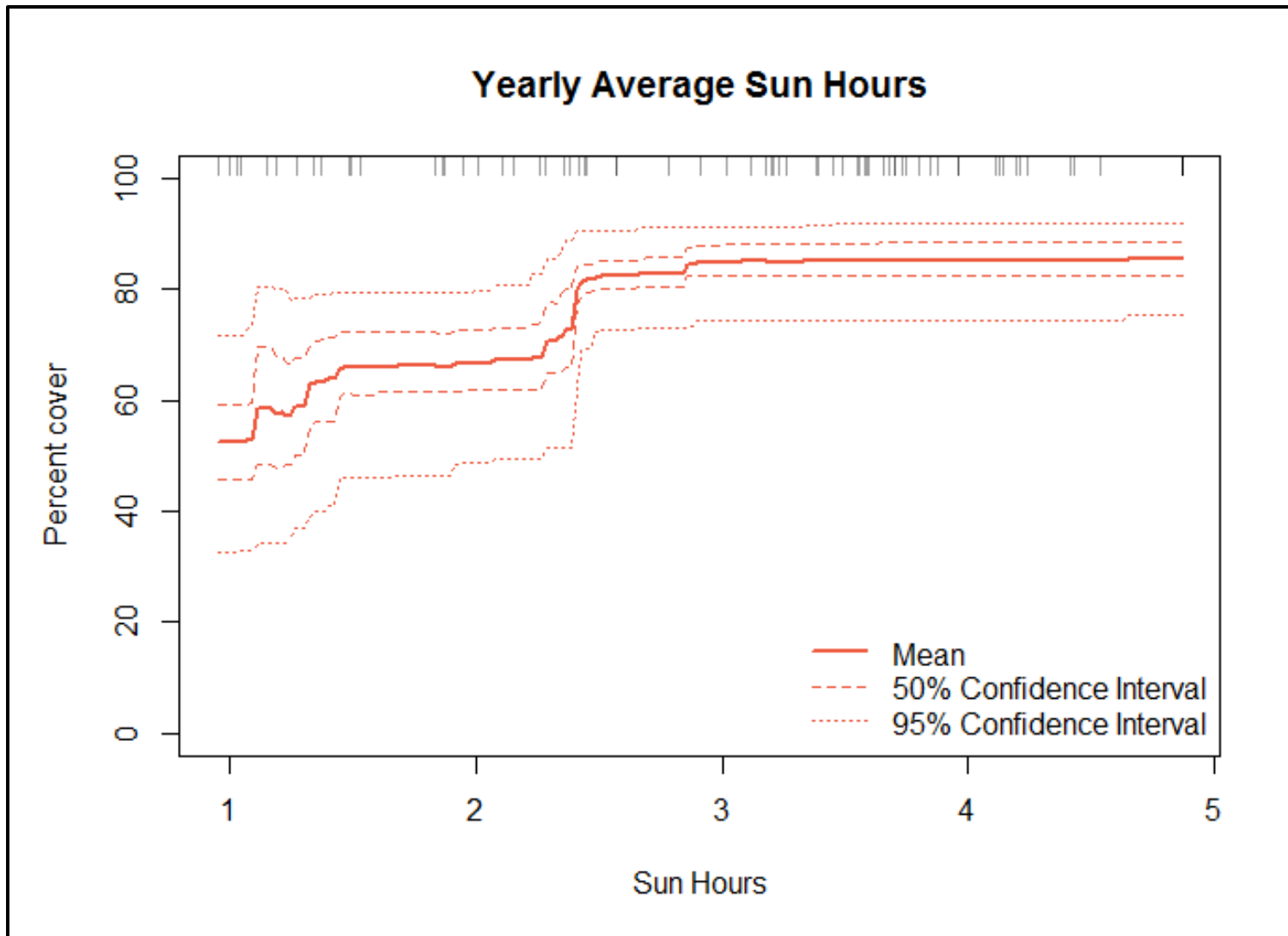


Figure 4.2. Modeled predictions of nuisance macrophyte cover given a range of yearly averaged sun hours in  $\text{kWh/m}^2/\text{d}$ . Tick marks at the top of the plot show the distribution of observed points. A large number of points (36 out of 102) had sun hour values of  $4.87 \text{ kWh/m}^2/\text{d}$ , which represents zero shade.

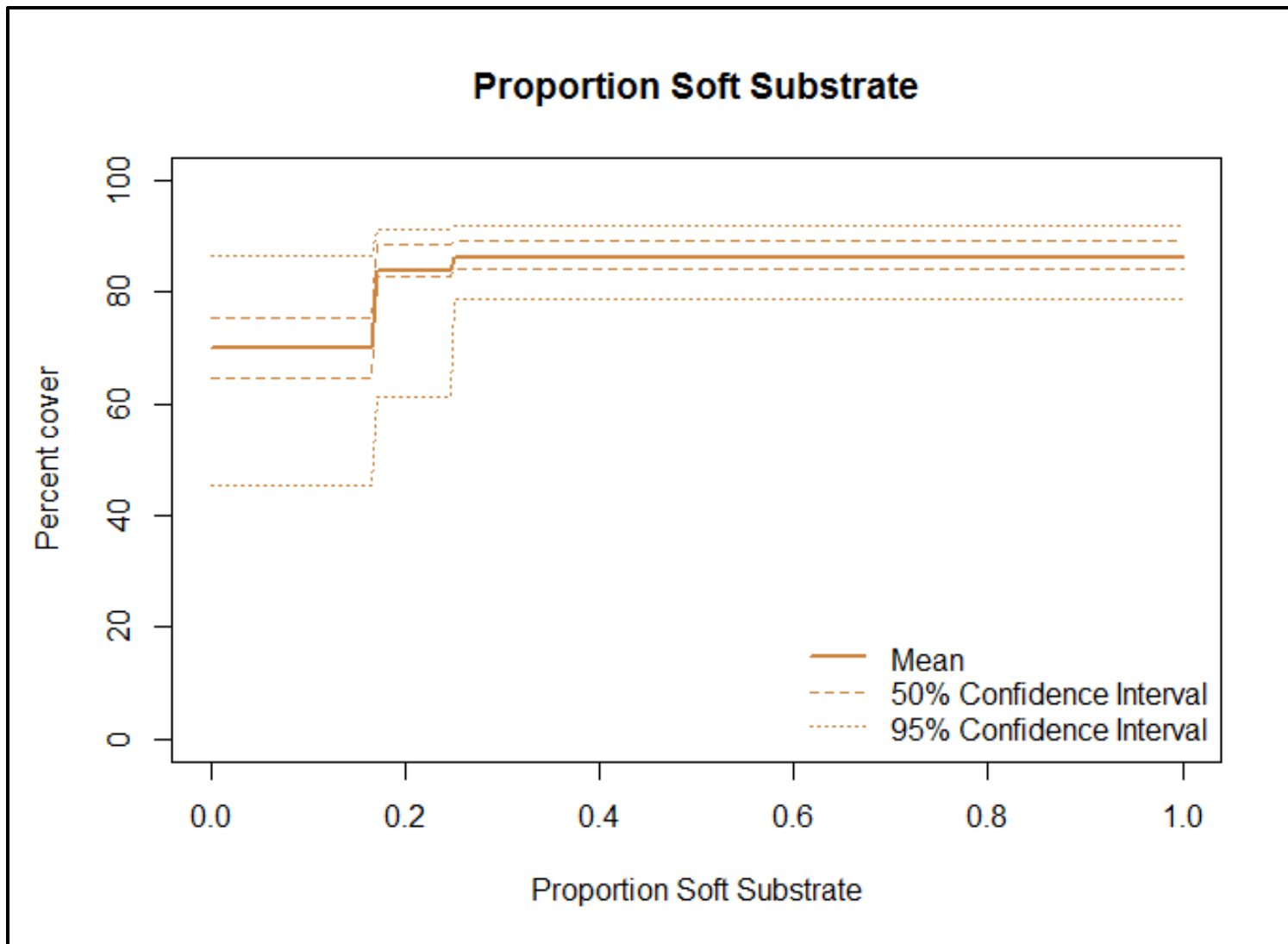


Figure 4.3. Predicted nuisance macrophyte cover over a range of proportions of soft substrate (class 1) relative to other types of substrate.

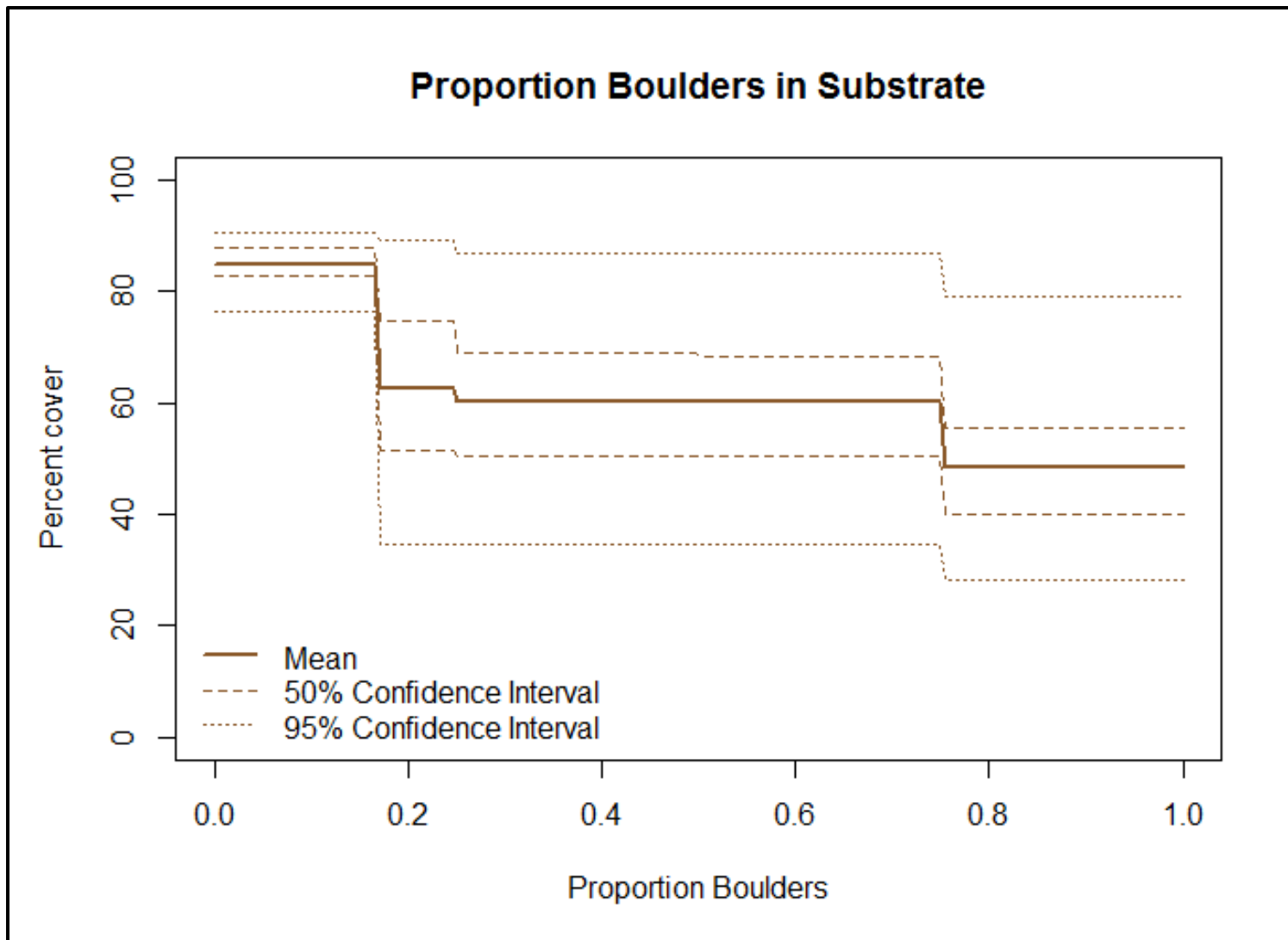


Figure 4.4. Predicted nuisance macrophyte cover over a range of proportions of boulders (class 5) relative to other types of substrate.



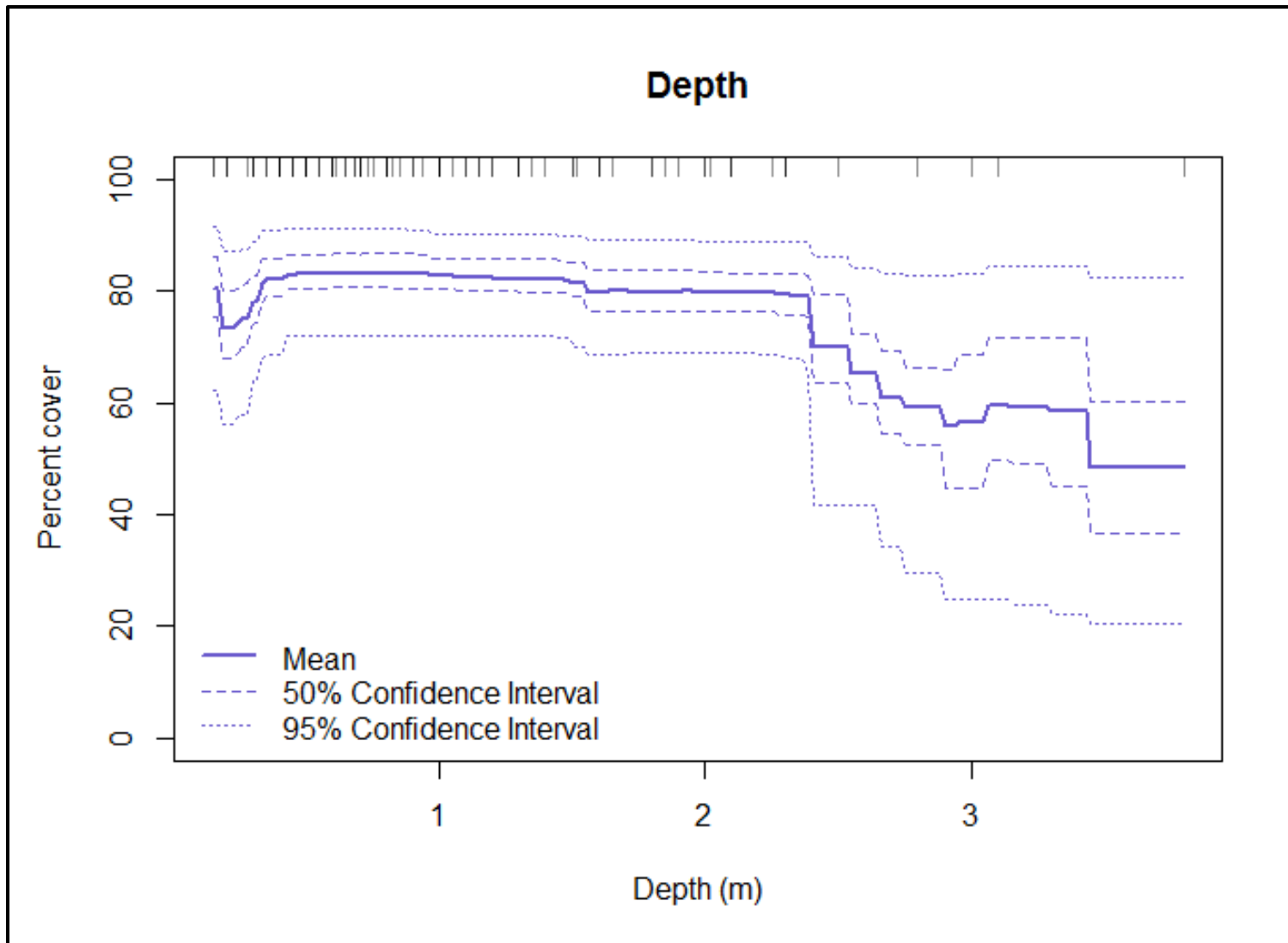


Figure 4.5. Predicted nuisance macrophyte cover over a range of depths in the IDR. Tick marks at the top of the plot show the distribution of observed points. Plant cover is generally predicted to decrease with depth. The dip in the shallow range may be due to water level fluctuations that could result in shallow areas drying out at certain times of the year.

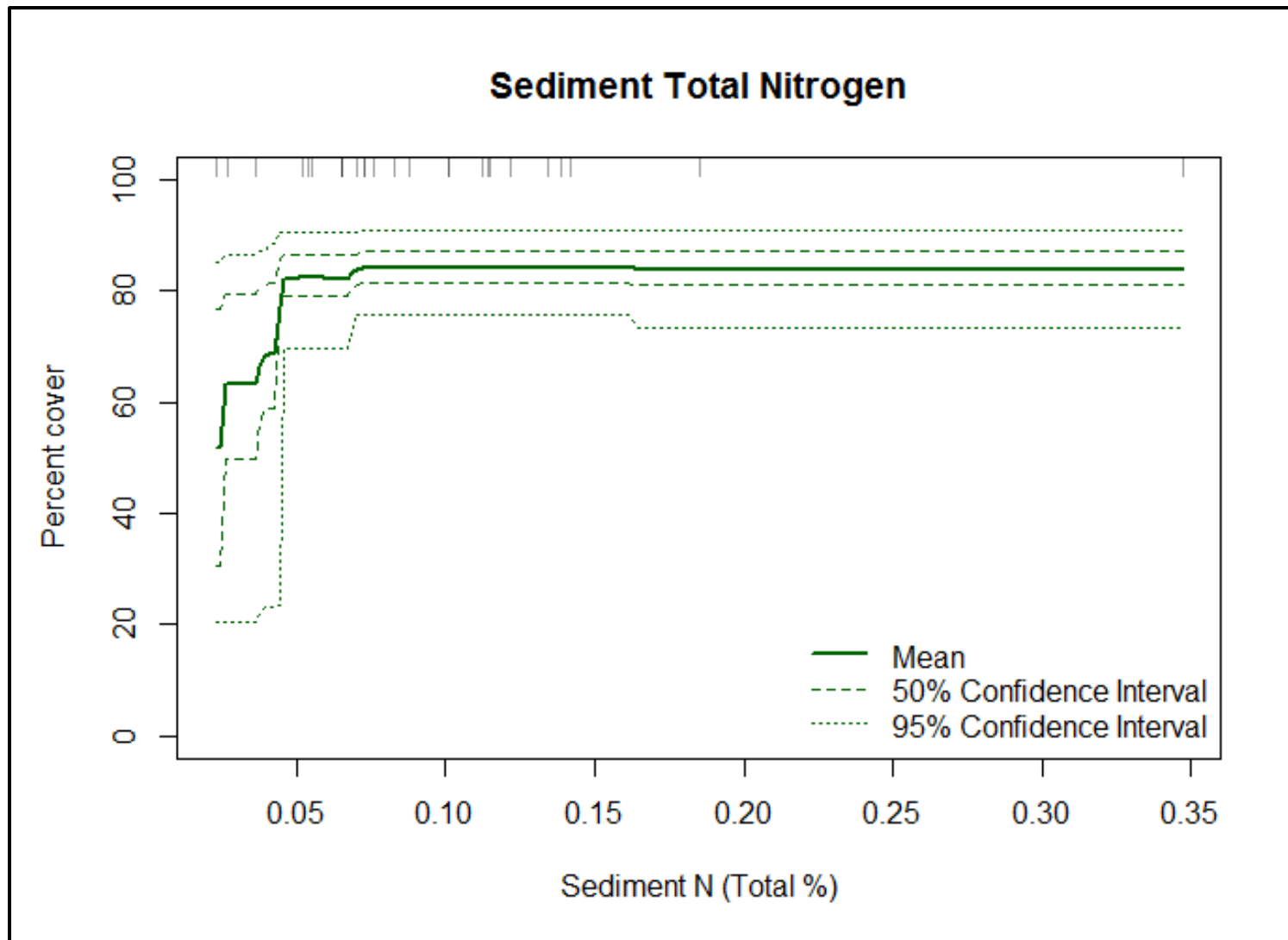


Figure 4.6. Predicted nuisance macrophyte cover, given a range of sediment nitrogen values (total percent). Tick marks at the top of the plot show the distribution of observed points. It should be noted that only a few data points are driving the response below 0.05%.

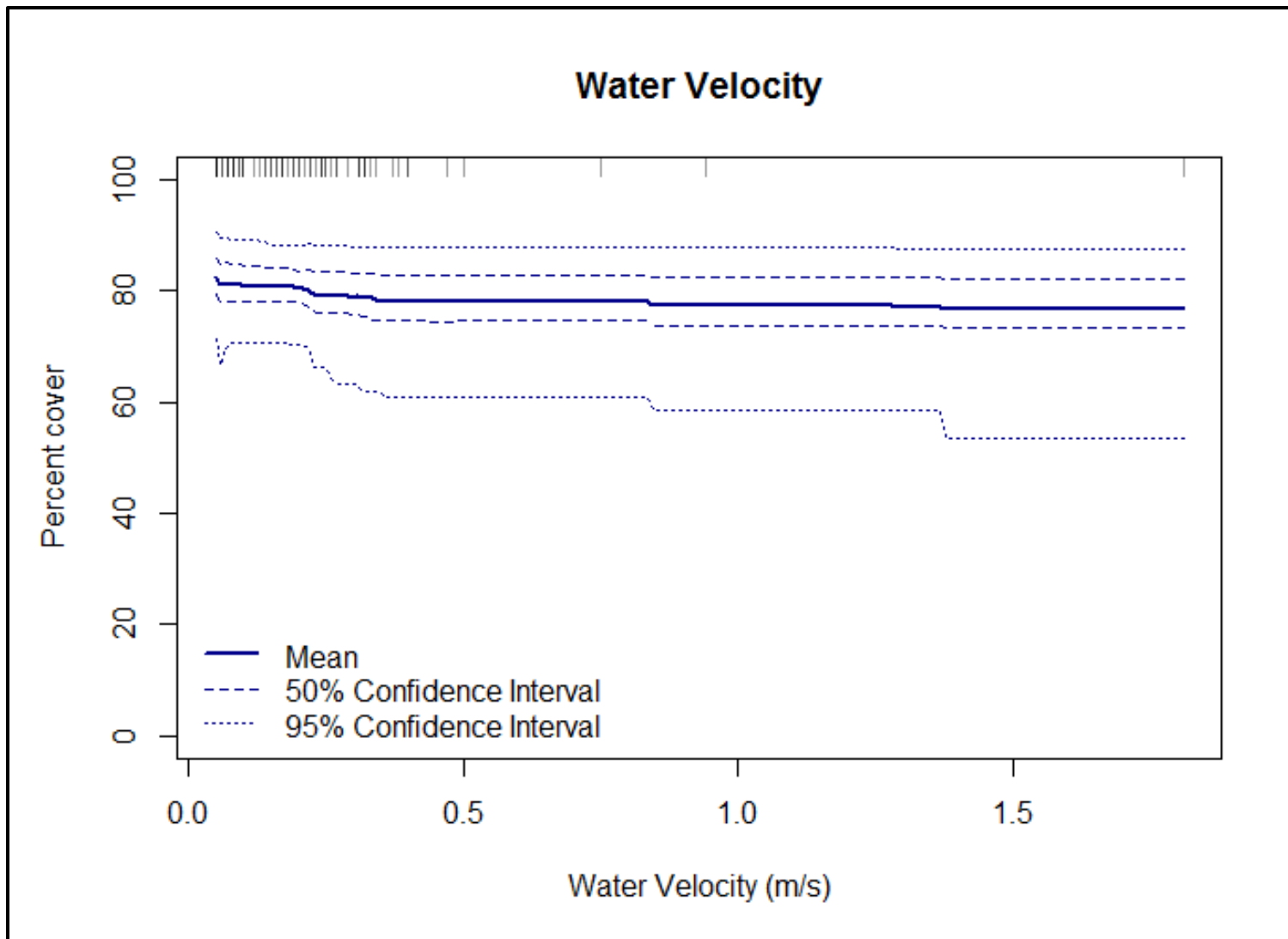


Figure 4.7. Plot of the predicted effect of water velocity on percent cover of nuisance macrophytes in the IDR. Tick marks at the top of the plot show the distribution of observed points.

### 4.3 Model performance

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If the BRT models (recall that 150 models were created from subsamples of the data) were able to perfectly predict the *exact* values of nuisance macrophyte cover at all sampling points, a plot of the average predicted (expected) values vs. the actual (observed) values would form a straight line with a slope of 1. The extent to which the predicted values differ from the observed values can provide information about the accuracy of the model predictions. A graph of the observed vs. predicted values for the BRT models was generated by plotting the average values predicted by the models against the actual observed data values of those sampling points. As you can see in Figure 4.8, the model predictions deviate somewhat from the actual values, with high observed values generally having lower predictions, and lower observed values generally having higher predictions. The  $R^2$  of this analysis is 0.72. (An  $R^2$  value of 1 would indicate a perfect match between predicted and observed values). This is actually quite good for this kind of ecological data, but because the  $R^2$  is based on predicting the macrophyte cover of sampling points that were used to create the models (“in-sample prediction”), this might be a bit overconfident.

An example depicting the predictive accuracy of the BRT models is shown in Figure 4.9, where average predicted values for the sampling points in the middle of the channel of Lake Solano are shown with their 95% confidence intervals. The observed values are shown for comparison. The models tend to predict values that are less extreme than the observations.

Because the BRT model predictions are imperfect, it is important to remember that while this modeling exercise can be used to guide management, it should mostly serve as a starting point for further exploration into how manipulating certain environmental factors could influence macrophyte cover. SCWA should not expect that altering conditions in a specific way suggested by the models will unquestionably result in the reduction in macrophyte cover predicted by the model.

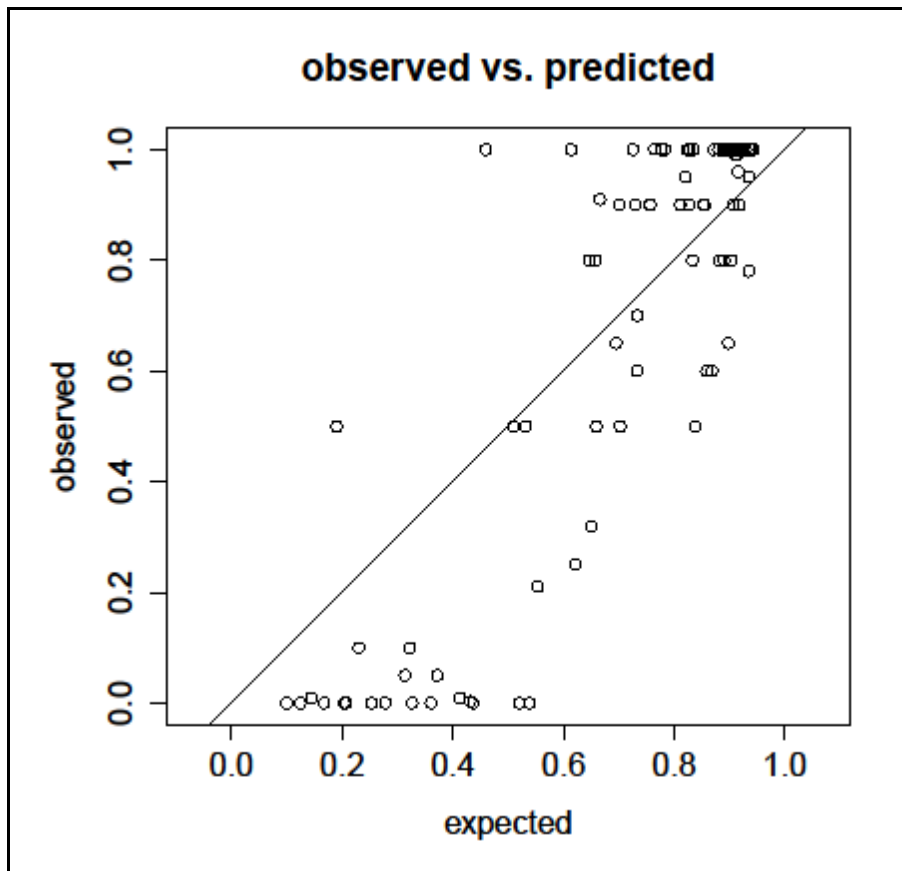


Figure 4.8. Plot of average model predictions (expected values) of nuisance macrophyte percent cover at a sampling point vs. observed values from field-collected data. Line shows an ideal 1:1 relationship between predicted and observed values. The model tends to predict values that are higher than the observed values when the observed values are low, and values that are lower than the observed values when observed values are high.

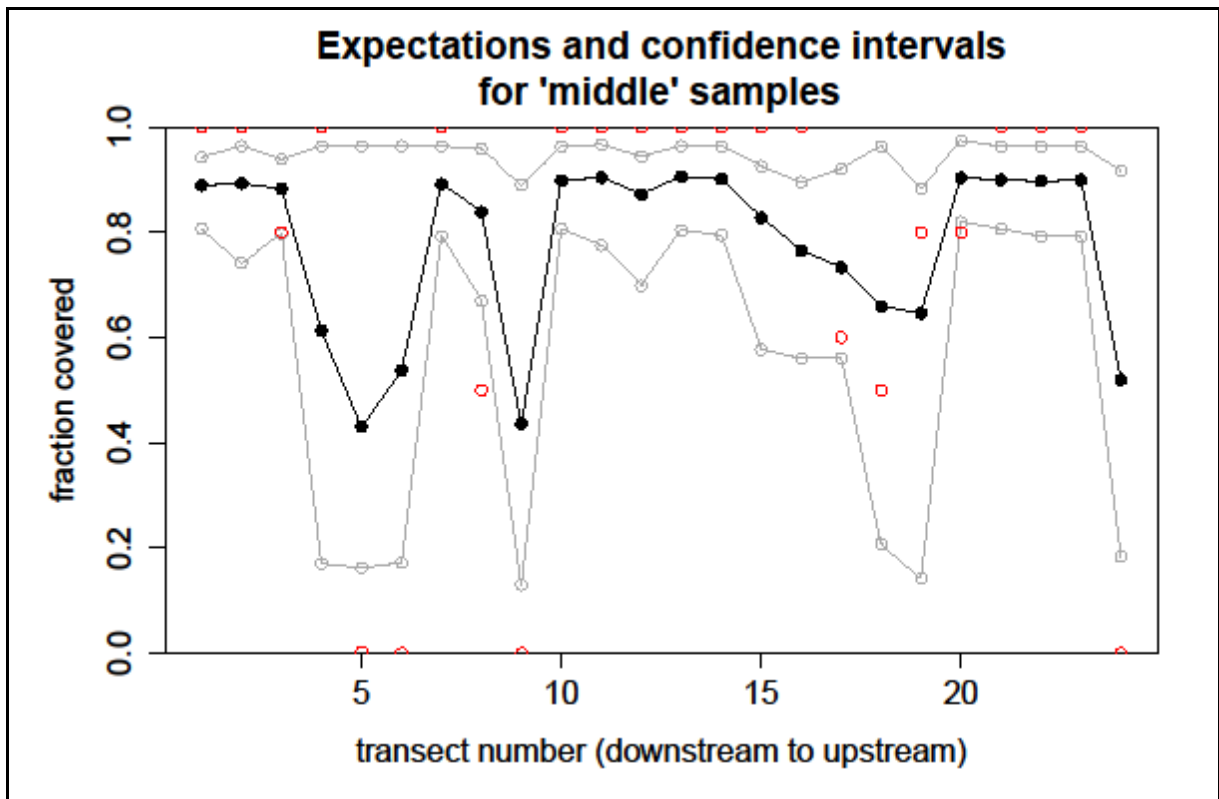


Figure 4.9. This graph is a demonstration of the predictive accuracy of the BRT models: Dark points and lines show average macrophyte cover values predicted by the BRT models for samples taken in the middle of the channel in Lake Solano, with 95% confidence intervals indicated in gray. Red circles are the observed values at the indicated transect locations from 1 (downstream) to 24 (upstream). The model tends to “underpredict” high values of macrophyte cover and “overpredict” low values.



## 5 Recommendations for Management

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In this section I discuss a variety of possible strategies for managing the vegetation in the Interdam Reach, the Putah South Canal, and the Terminal Reservoir, outlining what I perceive to be their pros and cons. I include in this section a discussion of some strategies that I do *not* recommend, but that have been suggested or brought up by others. The discussion here is intended to be a starting point for further exploration. Any of these strategies, if adopted, would require a much more detailed investigation.

### 5.1 Interdam Reach

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#### 5.1.1 Direct removal or reduction of macrophytes in the IDR

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**Mechanical removal**- Macrophytes can be cut and harvested using large machines designed for these purposes. Mechanical removal can result in dramatic reductions of macrophyte biomass, but this is typically only a short term solution, because weedy macrophyte species can regenerate from belowground structures and stem fragments. Mechanical harvesting usually results in the generation of large numbers of plant fragments, most of which can develop into new plants. Mechanical removal can also cause collateral damage to invertebrates and fish that live on and within macrophytes.

**Herbicides**- Several herbicides have been found to be effective at controlling weedy macrophytes, but these are not likely to be suitable for the IDR. Herbicides need to be applied at prescribed concentrations and contact times, which are difficult to achieve in large, flowing water bodies. It is also unlikely that herbicide in the IDR would be permitted given the uses, including downstream uses, of the waterway.

**Biological control** – Macrophytes can be effectively controlled with triploid grass carp, however, the California Fish and Game Code, Section 6440-6460, prohibits the use of triploid grass carp “in waters with an open fresh water connection to other waters of the state,” therefore, triploid grass carp are not a control option for the IDR. The “milfoil weevil”, *Euhrychiopsis lecontei*, has been shown to be effective in controlling Eurasian watermilfoil in eastern and midwestern regions of the United States (Reeves et al. 2008; Sheldon and Creed 1995). However, it is unclear whether *E. lecontei* could be used successfully in California (Spencer and Ksander 1999).

In their 2010 report, Northwest Hydraulic Consulting states, “The key to reducing vegetation-related problems in the PSC is to develop effective means for reducing or eliminating vegetation and sediment from entering the PSC from Lake Solano”(Northwest Hydraulic Consultants 2010b). However, I would advise against attempting to control the aquatic macrophytes in Lake Solano and the IDR through mechanical or chemical means, for several reasons. First, macrophytes are a natural and necessary component of the aquatic environment. Without macrophytes, Lake Solano and Putah Creek would not support the diversity of fish, birds, and other wildlife that make them such important ecological and recreational assets to the region. Second, the extent of macrophytes is so great that attempts at eradication would be extremely costly and difficult, if not impossible. Even targeting certain “problem” areas for macrophyte removal is unlikely to be effective in the long-term, because of the rapid rate at which macrophytes regenerate, spread, and recolonize (as is evident in the PSC, where tremendous macrophyte biomass is produced despite cleaning every year). Third, macrophytes stabilize sediments and absorb nutrients from the water column, and their removal may result in increased turbidity and algal blooms, and greater sediment loading into the PSC.

These downsides to direct removal apply to both native and non-native macrophytes. Even if possible negative effects are ignored or deemed unlikely, it would be very difficult to selectively remove only non-natives because native and non-native macrophytes are generally found growing in close proximity, often intertwined (though large, relatively uniform patches of non-natives could potentially be targeted). Biological control with the milfoil weevil or other emerging biological control agents may be promising for targeting a single species, but again, efficacy and feasibility in California is unclear, though this may be a subject to look into.

Ultimately, I believe that attempts at directly removing, killing, or controlling macrophytes in the IDR, without changing the underlying conditions that support macrophyte growth, would be a losing battle, and not worth the cost.

### 5.1.2 Scouring flows

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Planned “flushing flows” have been used successfully to control macrophytes in flow-regulated rivers (Rorslett and Johansen 1996; Batalla and Vericat 2009; Merz and Setka 2004), and more commonly, to maintain channel form and remove fine sediments for fishery enhancement (Reiser, Ramey, and Wesche 1990). Planned, periodic high flow events within the IDR could uproot macrophytes, and also remove fine particles that macrophytes need in order to establish and grow. Soft substrate was the second most important predictor of nuisance macrophyte cover in the BRT models described in the

above section, suggesting that reducing fine sediments could lower the amount of macrophyte growth in the IDR.

Flushing flows could result in high macrophyte and sediment load to the PSC initially, but might ultimately decrease the total amount of macrophyte biomass transported into the canal for a few years, if a large amount of vegetation is removed throughout the IDR. I have heard from fishermen and others who are familiar with the IDR that the weed problem has increased in recent years, and this might be due to the lack of spill-over from the “Glory Hole” in Lake Berryessa, as these events create high flow, potentially “flushing” conditions. Intentional releases from the Monticello Dam to create short-term, high flow events during the winter or spring might help restore favorable macrophyte abundances.

Prescriptions for the magnitude, duration, and timing of effective dam releases are system-specific and difficult to predict, but could be investigated through modeling activities [see Reiser et al. (1990) for a good review, and Batalla and Vericat (2009) for an example]. In general, recommendations are for a rapid increase in flows for maximum scouring. In their “Lake Solano Sediment Removal and Management Study,” Northwest Hydraulic Consultants recommended a total flow of 4000 cubic feet per second to begin to flush sediments out of Lake Solano, or a velocity of 2-3 feet per second (Northwest Hydraulic Consultants 1998). An event of this magnitude could possibly be generated by coupling a large storm event to intentional high flow releases from the Monticello Dam. The Monticello Dam has two penstocks that can each release a maximum of 1100 cfs when the power plant is not operating. If the powerplant is operating, one of the penstocks can release only 650-700 cfs. Therefore, a storm event would have to generate runoff in the IDR exceeding 1800-2250 cfs, which may not occur every year (Alex Rabidoux, personal communication).

I recommend a more in-depth study on the potential effectiveness of this approach, which also takes into account possible impacts on or benefits to sensitive aquatic species, nearby landowners, and other stakeholders of the Putah Creek system.

### 5.1.3 Increasing the depth of Lake Solano

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The modeling exercise and light measurements in the field revealed that at depths greater than around 2.4 m (7.9 ft), macrophytes might be near their light saturation point (where photosynthesis is at its maximum rate and does not increase with greater light). In deeper waters than this, light becomes limiting. Therefore, increasing the depth of Lake Solano to greater than 8 ft through dredging may reduce nuisance macrophyte growth. Significantly, these findings also imply that increasing depth only a small amount may have no effect on macrophyte growth.

Because the relationships between depth and macrophyte cover described in the BRT models are based on correlative data only, SCWA may want to experiment with increasing the depth of the lake in a smaller section first and monitoring macrophyte response, before undertaking a larger scale dredging project. Note that a deeper lake may result in a slower growth rate for macrophytes due to lower light levels, but submersed macrophytes can still establish and grow in very low light levels, and would probably eventually reach the surface anyway.

There are a number of potential downsides to dredging that should be considered. First, there would likely be environmental impacts to wildlife, such as fish, amphibians, and benthic invertebrates. Second, creating a deeper system without narrowing the channel would result in lower water velocities, and this could increase the rate of sedimentation in the channel. Third, dealing with all the issues encompassing sediment disposal could become logistically prohibitive.

#### 5.1.4 Shading macrophytes with benthic barriers

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Securing tarps or fabric to the bottom of lakes to create “benthic barriers” can be effective in killing or suppressing macrophytes. For example, a recent paper by Laitala et al. (2012) found that placing synthetic weed fabric on top of macrophyte beds in two Idaho lakes eliminated Eurasian watermilfoil, a non-native macrophyte, after 8 weeks, while allowing native macrophytes to regenerate. (Allowing the barrier to remain longer had greater impact on native macrophytes.) This technique might be effective in Lake Solano, particularly in the shallow areas close to the PDD, for selectively reducing Eurasian watermilfoil. Recall that Eurasian watermilfoil was found in the majority of points sampled and had high average percent cover (Figure 3.16).

Benthic barriers, if left in place for a long time, can accumulate sediment and may require maintenance. Note that after removing barriers, macrophytes are likely to rapidly recolonize the bare area (Eichler et al. 1995).

#### 5.1.5 Converting wide, shallow areas of Lake Solano to marsh or floodplain

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A tremendous amount of submersed plant material is produced from the wide, shallow areas of Lake Solano, especially near the PDD. A deeper channel runs through the center of what is increasingly becoming marsh, and this shallow area will probably continue to fill up with emergent macrophytes and sediment over time, gradually closing in on the central channel. In shallow areas suitable for their growth, emergent macrophytes, such as bulrushes and cattails, can outcompete submersed macrophytes, such as Eurasian watermilfoil and pondweeds, by creating shade and competing for nutrients and space. Floating-leaved plants like water lilies generally grow in deeper areas than

emergent plants, and can create even more shade on the water's surface, reducing the growth of submersed plants underneath. The conversion of shallow lake to marsh may therefore decrease the amount of submersed plant material flowing into the Headworks. This is a natural process, but could possibly be accelerated through the addition of sediment to decrease the depth of shallow areas, with subsequent planting of emergent or floating-leaved vegetation.

To a more extreme degree, large portions of the channel could be filled in entirely and planted with riparian and floodplain vegetation, "restoring" Lake Solano to a riverine system. This could reduce nuisance macrophyte growth in several ways. First, the combination of faster transportation of cold water from Lake Berryessa and greater riparian shade would lead to cooler water temperatures, which would reduce the productivity of submersed macrophytes. Second, the modeling exercise (Section 4) showed a strong correlation between light levels (as measured by sun hours) and nuisance macrophyte growth; because mature, shade-providing vegetation already grows along the banks in the IDR, the only way to increase shade over the channel to reduce macrophyte growth would be to narrow the channel. Third, higher flows would prevent large amounts of fine sediment from settling, and coarser substrate may be less conducive to macrophyte growth. Finally, and probably most importantly, reducing the total habitat area for macrophytes by filling in large portions of the lake would result in far less area for macrophytes to grow. The recent channel-realignment restoration project at Winters Putah Creek Park could serve as an example for this type of floodplain creation.

It is important to note that even if Lake Solano were converted to a marsh or river, macrophyte growth will still occur within the system, and propagules will still be transported downstream to the Headworks, though probably to a lesser degree. The creation of marsh, and especially floodplain, could also have negative (though possibly only short-term) effects on wildlife and recreational users of the lake. Large amounts of "earth moving" to create a shallower marsh or floodplain could produce high levels of total suspended solids in the project area, which could increase turbidity and sedimentation downstream in lower Putah Creek during the restoration work. Best management practices would be required to minimize this disturbance.

## 5.2 Putah South Canal and Terminal Reservoir

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### 5.2.1 Scouring flows

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If logistically possible, creating scouring flows within the PSC during the early summer may help reduce macrophyte density by the end of summer. This could be done by lowering water levels in a check as much as possible, and then allowing water to rush in from the upstream check. The turbulence and water velocity could dislodge or break off much of the macrophyte biomass, and scour out sediment deposits. Because macrophytes are capable of exponential growth, I recommend early summer for the timing of these events in order to interrupt their growth at an early stage. Removing macrophytes before they achieve maximum biomass might help prevent and reduce problems caused by vegetation in the canal (clogging screens and lowering water quality) before they occur.

### 5.2.2 Physical dislodging of macrophytes

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Similar to the recommendation above, dragging a chain or other device through sections of the canal that experience high macrophyte growth during the early growing season could interrupt the exponential growth of the macrophytes, resulting in reduced biomass by the end of summer. It would be important to try to remove as much dislodged biomass as possible, as remaining vegetation would probably reestablish in the canal. Growth of new propagules might occur after this process, but they might not reach the densities that would occur without a physical disruption event.

### 5.2.3 Repairing, sealing, or covering cracks and seams in the PSC

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Macrophytes require sediment to anchor their roots and obtain most of their nutrients. It is likely that sediment and macrophyte propagules (fragments, seeds, tubers, turions) get caught in the cracks of the PSC, which facilitates their growth. I observed during my surveys that macrophytes often appeared to be concentrated around cracks or seams in the canal. Once macrophytes establish and begin to grow, their biomass can catch more propagules and sediment, creating a positive feedback. Sealing cracks and seams might help prevent initial establishment by macrophytes.

### 5.2.4 Reducing sediment input from upstream sources

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The presence of sediment in the PSC is necessary for macrophyte growth, therefore efforts should be taken to reduce the amount of eroded material coming in from any sources in the watershed, including around the canal itself. This may include reducing erosion-causing activities, employing best management practices to reduce the inputs of fine materials into upstream waterways and the canal,



restoring denuded riparian areas through vegetation planting, and using a pipeline to bypass Lake Solano during high flow/ high turbidity events in the winter months. The 2010 report by NHC covers this topic in great detail.

### 5.2.5 Improving canal cleaning methods

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Northwest Hydraulic Consultants reported that after the 2008 canal cleaning event, sediment deposits remained at depths of 2-12 inches in certain checks (Northwest Hydraulic Consultants 2010b). Macrophytes may start growing in the spring from seeds, tubers, turions, rhizomes, or root crowns that remain in this sediment from the previous year, even if this sediment dried out during cleaning. This sediment also provides a hospitable habitat for new macrophyte propagules entering the canal. Therefore, more thorough removal of sediment from the canal during cleaning may reduce macrophyte problems in the following year.

### 5.2.6 Installing better screens

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The quantity of vegetative fragments entering the PSC could be reduced by installing finer-mesh screens and/or improved screen cleaning devices. By reducing the input of vegetation into the canal, the establishment and growth of vegetative fragments in the canal may also be reduced.

However, I have a hypothesis that the initial source of vegetation in the canal in spring and early summer is *not* stem fragments, but seeds and tubers that either travel in through the Headworks or remain in the sediment left over after canal cleaning. I have two main reasons for this hypothesis. First, the macrophyte elodea (*Elodea* spp.) was found in abundance in Lake Solano and Putah Creek, upstream of the Headworks. Prior surveys by Lars Anderson and NHC found large numbers of elodea fragments coming into the canal (Northwest Hydraulic Consultants 2010a). Despite this, I did not find any rooted elodea in the PSC. Elodea primarily reproduces via vegetative fragmentation, and rarely produces seed. The species that I did find in greatest abundance were species that do produce seed or small tubers (pondweeds and milfoil). The lack of elodea and the presence of these other species lead me to hypothesize that vegetation in the canal is coming from seeds, not fragments (at least initially). Second, vegetation appears to be centered on the cracks and seams in the canal. Given the high flows in the canal, I think it is more likely that seeds get trapped in these crevices, and less likely that plant fragments get caught in or on them and begin to grow.

The screens currently in place at the Headworks are spaced at 3/4 inch, which is large enough to let in small seeds (the four main species found in the canal all have dispersing fruits or seeds that are less than 5 mm, or 0.2 inches, in length- see Appendix A). While finer mesh screens of down to 1/32 inch are

available, these screens are prone to clogging and require greater maintenance. If in fact macrophytes are regenerating in large part every year from a seed and tuber bank, installing finer screens may be relatively ineffective. (A study examining the seed and tuber bank left in the PSC after cleaning may be informative in this regard.) Therefore, better cleaning methods, reducing sediment input, or repairing cracks in the canal may be more effective solutions for preventing macrophyte establishment than installing finer screens.

### 5.2.7 Shading the PSC

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Without light, macrophytes and algae would not grow in the PSC. Currently, the channel is wide open, allowing ample light into the channel to encourage rapid plant growth. Decreasing light penetration into the canal could reduce or eliminate this problem. While this may be logistically difficult and expensive initially, permanent or long-term structures or mechanisms to lower light levels may result in much lower maintenance costs over an extended period of time.

Management techniques for shading macrophytes include applying dyes to the water to reduce light penetration, applying tarps or weed fabric directly on top of plants, planting tall vegetation on channel banks, erecting shade structures over waterbodies, and applying floating plastic “shade balls” or sheeting to the surface of the water. Of these options, only the last two are probably feasible for the PSC. Shade balls can block 90% of sunlight according to suppliers ECC, LLC., but it’s unclear how well they would work in a flowing system. Similarly, floating plastic sheets may be difficult to secure, but could be worth exploring. Erecting shade structures over the PSC may make some types of canal maintenance difficult, but could ultimately decrease maintenance related to weed growth.

### 5.2.8 Grass carp

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Grass carp are voracious herbivores, and have been used successfully in California to control macrophytes. For example, the Imperial Irrigation District has used them successfully in their irrigation canals to control hydrilla. I recommend that SCWA investigates the option of stocking triploid grass carp into the PSC and Terminal Reservoir. To use grass carp as a biological control agent, a permit must be obtained from the California Dept. of Fish and Game, per the California Fish and Game Code (sec. 6440–6460). Each individual introduced grass carp must be tested and certified as triploid, which ensures the fish’s sterility. To be issued a permit, SCWA would have to ensure that fish would not escape from the canal into other waters of the state, and would have to pay permitting fees to CDFG. The cost of these control efforts would depend on the number of fish stocked. Currently, fees to CDFG are \$15 per fish for initial stocking, plus an annual renewal fee of \$7.50 per fish (State of California Department of Fish and

Game). If stocked at a high enough rate, grass carp can eradicate macrophytes in a short amount of time (weeks to months).

It is important to note that stocking grass carp could increase the risk of planktonic algal blooms. By converting plant material to waste products, the fish can increase the concentration of nutrients in the water column, making them more available for algae. Given that the PSC is a flowing system, I would assume that this may be more of an issue in the more stagnant waters of the Terminal Reservoir.

#### 5.2.9 Dredging the Terminal Reservoir

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Removing all macrophytes and several feet of sediment may pose a temporary solution for the reduced capacity of the Terminal Reservoir. Innumerable propagules probably exist in the sediment, and simply removing the aboveground plant material is unlikely to have a lasting effect beyond the first year. Increasing the depth of the reservoir to below the light saturation point ( $\sim 650 \mu\text{mol}/\text{m}^2/\text{s}$  PAR) may slow the growth of reestablishing macrophytes, but eventually, they would reach the surface, again filling the lake. Combining dredging with the addition of rocky substrate might buy some additional time, but eventually propagules and sediment would probably enter from the PSC, and macrophytes would reestablish. If macrophytes are not posing much of a management problem in the Terminal Reservoir, it is probably best to leave things as they are.

## 5.3 Recommendations for further research

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### 5.3.1 Analysis of Union Check

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Union Check has unusually low densities of macrophytes compared to the other checks. Even the checks immediately upstream and downstream of Union Check (Alamo and McCoy Checks, respectively) have higher macrophyte densities, and Union Check seems to be an outlier in the canal (see Figure 3.5). The reasons for this are unclear from the data collected, but understanding why Union Check has relatively low macrophyte densities could potentially help SCWA understand how to reduce macrophyte densities in other checks. I recommend an exploration of this topic beginning with on-site visual observations, analysis of GIS layers, and a review of historical information about the construction and management of different checks.

### 5.3.2 Finer-scale velocity data in the PSC

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The velocity and flow rate data shown in Appendix B are useful for comparing water velocities between checks. However, no data are currently available for how velocity changes *within* each check, from upstream to downstream. Most checks show a pattern of increasing macrophyte density with distance downstream within a check (i.e., the closer the check structure downstream, the slower the velocities). It may be useful to have finer scale velocity data to see if these spatial correlations correspond to differences in water velocity.

### 5.3.3 Investigating nutrient contributions from Hines Growers nursery

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The section of highest algal growth in the PSC, near MP 3-5 in Sweeney check, is directly adjacent to Hines Growers nursery. Nutrients in fertilizers used at the nursery may be entering the canal, causing a local bloom of filamentous algae. It may benefit SCWA to investigate if and how this is occurring, so that efforts can be taken to prevent this from occurring in the future.

While previous water samples taken in this area have not shown noticeable increases in nutrient concentrations (Alex Rabidoux, personal communication), this could be due to a mismatch in the timing of sampling and fertilizer application. Also, since such a large volume of water is flowing by the canal walls, even a small increase in nutrient *concentration* in the water could greatly increase the total *amount* of nutrients that attached algae are exposed to over a period of time. If nutrients are being released from the nursery into the canal slowly, the high flow rate may dilute this signal. More sensitive tests of water nutrient concentrations with lower detection limits may be worth investigating.

Organisms that take up nutrients from different sources often have different isotope signatures that reflect their nutrient sources. For example, organic and synthetic fertilizers have different isotope ratios of  $^{15}\text{N}/^{14}\text{N}$  (Bateman and Kelly 2007). Therefore, another approach that could be useful in determining whether Hines Growers is the source of increased algal growth would be a comparison of stable isotope signatures between 1) the algae found in the canal near the nursery, 2) algae upstream of the nursery, 3) the irrigation water at the nursery, and 4) canal water upstream of the nursery. If nutrients from fertilizers applied at the nursery are the cause of increased algal growth, algae from the parts of the canal that are adjacent to the nursery may have a different isotopic signature than algae from upstream, and this signature may reflect that of the irrigation water used at the nursery.

Additional methods to explore might include sampling the air near the nursery for increased nutrients that could be a source of atmospheric deposition into the PSC (in conjunction with an examination of wind patterns in the area), or taking groundwater samples if high-nutrient groundwater leaching into the canal may play a role.

#### 5.3.4 Determine the source of macrophyte generation in the PSC

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Propagules from the IDR that enter the canal every year may be the cause of macrophyte growth in the PSC. However, it is also possible that the sources of macrophytes in the PSC are propagules that remain in the sediment, even after cleaning. If larger macrophyte stem fragments are not the true culprit, SCWA may want to focus management attention away from installing finer-mesh screens, and instead on better cleaning methods.

A first step may be to determine whether viable propagules are left over after cleaning, by collecting sediment from the bottom of the canal immediately after cleaning takes place (note that this would not be possible with suction dredging), putting that sediment into an environment hospitable for plant growth, and observing over time to see if any macrophytes germinate or grow.

#### 5.3.5 Research possible feasibility and impacts of flushing flows in the IDR and PSC

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As mentioned above, planned “flushing flows” in the IDR may pose a solution to excessive macrophyte growth in the IDR by removing plants and sediments. Investigation into the velocities needed to achieve a desired effect via literature review and system-specific modeling may be a good step in determining the feasibility and potential effectiveness of this approach. This could build on the work of Northwest Hydraulic Consultants in their report on sediment management in Lake Solano (Northwest Hydraulic Consultants 1998). The fate of the flushed sediment and vegetation, and the impacts this could have on downstream users and wildlife should also be explored.

Similarly, flushing the PSC could help remove sediment and vegetation, but research should first be done into the velocities required for adequate flushing and whether or not these velocities could be achieved.

### 5.3.6 Assess the possibility of using grass carp as biological control in the PSC

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Grass carp could be a solution to the aquatic vegetation problems in the PSC, however, these organisms are highly regulated. The first step would be to consult with the California Department of Fish and Wildlife to see whether grass carp would be permitted in the canal. An inquiry into appropriate stocking rates and associated costs could follow. I would also recommend a smaller scale trial, perhaps in one check only, to see if the carp can achieve the desired effect, or to experiment with stocking rates. Aquaculture researchers at the University of California, Davis in the Department of Animal Sciences may be able to assist with or conduct this research.

### 5.3.7 Research shading techniques for the PSC and Lake Solano

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Greatly limiting the amount of light in the PSC would undoubtedly slow, if not stop entirely, macrophyte and algae growth. Surface shading techniques are typically implemented in lakes and reservoirs, and therefore research into the practicality of applying these techniques (e.g., floating plastic sheets or balls) in a flowing canal system should be conducted. If a certain technique seems promising, I recommend conducting a trial run in one or two checks.

The vegetation in Lake Solano could possibly be managed by placing benthic barriers on the sediment surface. These barriers block light and have been shown to reduce or eliminate macrophyte growth, especially the growth of non-native species. Trials in smaller areas could be done to determine the effectiveness of this technique, and/or to experiment with materials or timing to achieve the most effective and/or inexpensive results.

## 6 Summary of Recommendations

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Based on the analysis of results from the surveys conducted in the IDR and the PSC, and the subsequent modeling exercise to identify important variables driving macrophyte cover, the two most important factors contributing to nuisance macrophyte growth in the PSC, IDR, and Terminal Reservoir are 1) the abundant sunlight for plant growth, caused by lack of shading, relatively clear water, and shallow depths, and 2) the abundance of soft substrate in the PSC, Lake Solano, and Terminal Reservoir. Because the clarity of the water would be difficult (and undesirable) to alter, reducing light availability to macrophytes could be achieved primarily by increasing shade or increasing depth. Removal of fine sediments could occur through either mechanical means (better canal cleaning) or through flushing flows.

The underlying conditions throughout most of the IDR, especially Lake Solano, are ideal for macrophyte growth, and are a product of the structures of the Solano Project. The Monticello Dam moderates flows, and prevents large, sudden flushing events that would remove fine sediments. In addition, the dam traps coarser materials, allowing only finer particles to move downstream. The PDD backs water up, slowing flows, and allowing greater sediment deposition in Lake Solano, particularly near the dam. The wide, shallow conditions create a high-light environment, ideal for photosynthesis. The most permanent solution to excessive macrophyte growth in the IDR is to address these underlying conditions. Increasing shade may be impossible without larger-scale restoration to narrow the main channel. Increasing depth may be easier, but this could be objectionable for other reasons (listed in section 5.1.3.). Placing “benthic barriers” on the sediment surface to shade macrophytes might be an effective strategy for reducing or temporarily eliminating macrophyte growth in certain areas. Removing sediment from the IDR may be possible with planned “flushing flows” from Lake Berryessa or through dredging. Addition of coarser materials to the substrate, such as rock and boulders, could help reduce plant growth in certain areas, but without changes to the flow regime, these would probably just get covered with sediment over time. Periodic macrophyte removal through mechanical means might improve conditions in the short term, but this would probably have no effect in the long term. In sum, finding sustainable ways of reducing fine sediments and light availability in the IDR will be the best ways to address nuisance macrophyte growth in the long term.

Preventing macrophyte propagules from entering the canal may be impossible due to their small size, and even then, enough propagules may be left behind in the sediments to reestablish and create problematic conditions. Therefore, I believe the primary focus for SCWA should be decreasing the amount of light and/or sediment in the canal. Light availability could potentially be reduced in the canal



through the placement of shade structures above the canal, or directly on the surface of the water. Periodic flushing or disturbance to reduce sediment accumulation may be helpful (if possible), but might not reduce sediment amounts enough to eliminate macrophyte growth. Improved cleaning methods may be the most efficient way to reduce sediments, and thus macrophytes, in the canal. In addition, grass carp have been found to be effective in other canal systems and this option is worth exploring.

For the Terminal Reservoir, dredging may be a temporary fix to increase water storage capacity, but is unlikely to be a permanent solution. Given the low management concerns regarding the reservoir, it may be best to leave it alone.

Any management actions should be preceded by more detailed investigations into the costs, benefits, and feasibility of the approach, including potential alternatives. Often, management aimed at solving or ameliorating one problem ends up creating another. Consultation with experts in relevant fields may help identify and mitigate some of these unforeseen problems before they arise.

Overall, the problems of nuisance aquatic vegetation in the PSC, IDR, and Terminal Reservoir have no straightforward or easy solutions. I believe that actions can be taken to reduce these problems, but it will be up to SCWA to determine which seem most appropriate based on their management objectives and limitations.

## Acknowledgements

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## APPENDIX A: Descriptions of the four most abundant macrophytes in the Putah South Canal

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Information in this appendix comes from *The Jepson Manual, second ed.* (Baldwin et al. 2012), *Aquatic and Riparian Weeds of the West* (DiTomaso and Healy 2003), and personal observations.

### Sago Pondweed *Stuckenia pectinata* L.



**Family:** Potamogetonaceae, Pondweed family

**Description:** Native perennial submersed plant. Stems up to 80 cm with many branches. Leaves alternate, with air channels along both sides of the midvein, up to 20 cm, and 0.2-1 mm wide. Flowers submersed or floating, small, on short flower stalk (4-12 cm). Fruits 2.5-5 mm long. Foliage dies back in winter.

**Reproduction:** Reproduces from seed, and vegetatively from stem fragments and tubers. Flowers May-July. Seeds may require scarification (ingestion by an animal) to germinate. Tubers germinate in the spring.

**Eurasian Watermilfoil**  
***Myriophyllum spicatum* L.**



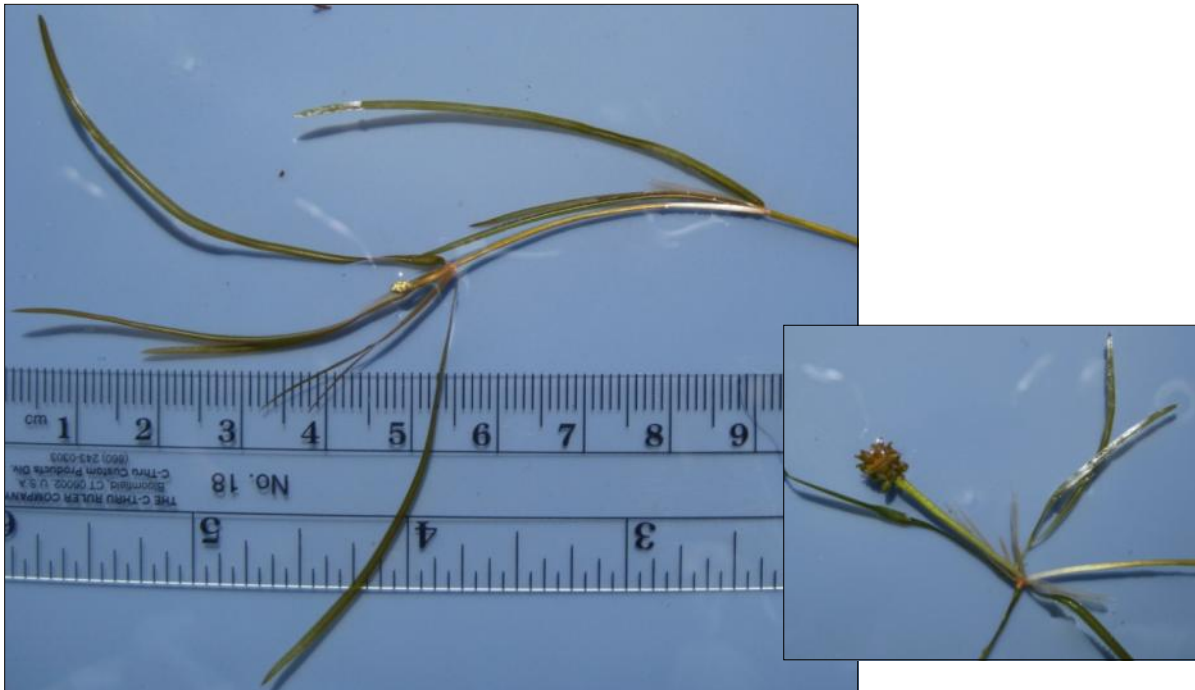
**Family:** Haloragaceae, Watermilfoil family

**Description:** Non-native, invasive perennial submersed plant. Stems up to 7 m long, green to reddish, branching. Stems can become emergent when flowering. Leaves in whorls of 4, < 3 cm, with over 14 pairs of thin linear segments per leaf. Flowers on a 4-8 cm spike above water. Fruits spherical, 2-3 mm long. Can senesce over winter or persist.

**Reproduction:** Reproduces primarily vegetatively from stem fragments and rhizomes. Reproduction from seed is possible, but thought to be rare. Flowers June-Sept.



**Leafy Pondweed**  
***Potamogeton foliosus* Raf.**



**Family:** Potamogetonaceae, Pondweed family

**Description:** Native submersed plant, generally annual but sometimes perennial. Stems up to 100 cm, with many branches. Leaves alternate, slender, often with obvious midvein, 3-10 cm long and 0.3-3 mm wide. Flowers small, often floating or emergent on the end of a short flower stalk (generally <3 cm). Fruits 2-3 mm long. Plant senesces in winter.

**Reproduction:** Reproduces primarily from seed but also from stem fragments and winter buds. Flowers from July to October. Seeds may require scarification to germinate.

**Horned Pondweed**  
***Zannichellia palustris* L.**



**Family:** Zannichelliaceae, Horned-pondweed family

**Description:** Native perennial submersed plant with creeping rhizomes. Forms dense turf-like mats.

Stems very thin, up to 0.5 m long, with few branches. Leaves mostly opposite, linear, 2-10 cm long and less than 1 mm wide. Flowers almost inconspicuous, in leaf axils. Fruits are banana-shaped, with several together in leaf axils, 2-4 mm long.

**Reproduction:** Reproduces from seed and rhizomes. Flowers from March-November. Seeds may require a period of stratification (exposure to cooler temperatures) before they can germinate.

## APPENDIX B: Putah South Canal Flow Rate and Velocity

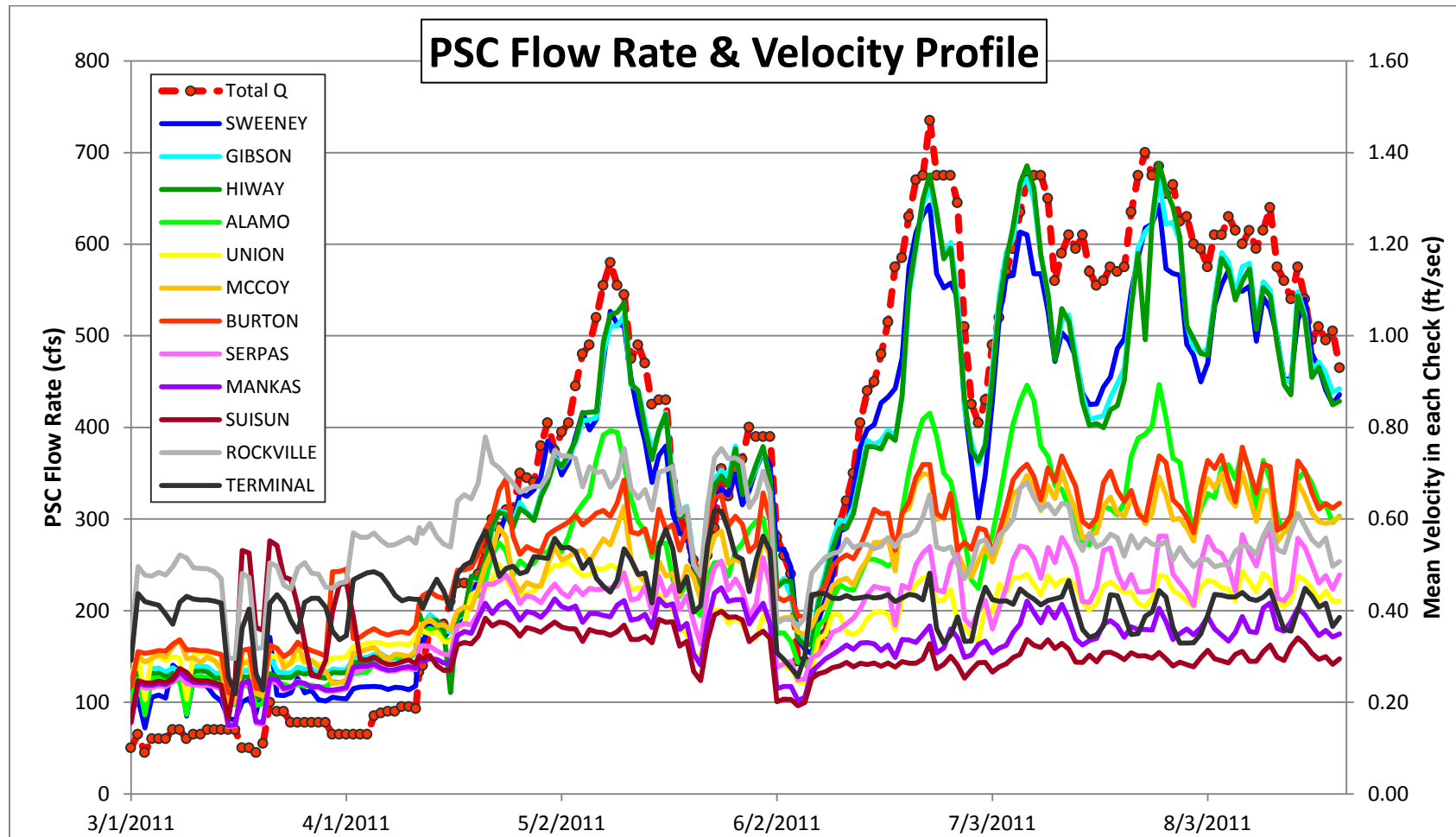


Figure B. Mean velocity by check in the Putah South Canal from March 1, 2011 to August 22, 2011. Red dashed line shows total flow rate for the canal.

## APPENDIX C: Lake Solano flow rate from October 2010-October 2011

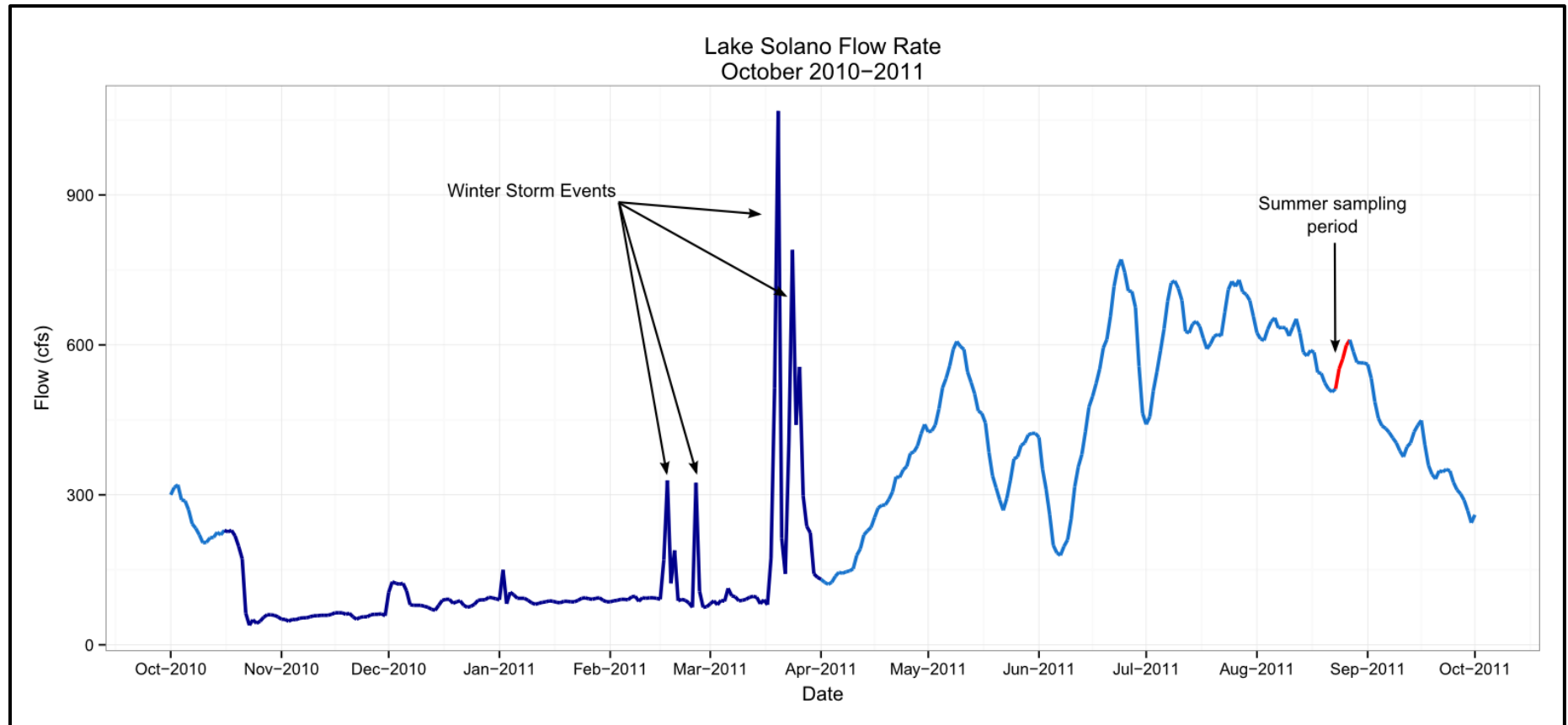


Figure C.1. Average daily flow rates in Lake Solano from October 2010-October 2011. The lighter blue line indicates the agricultural season (April 1-October 15), when flows in the lake are higher due to the release of water from Lake Berryessa for irrigation. The red line indicates the four days in August (23-26) in which sampling of Lake Solano for this study took place. The mean flow during this sampling period was 559 cfs, which is bit higher than the average 445 cfs during the agricultural season. Mean flow over the whole year was 296 cfs.

## APPENDIX D: Year-long data from temperature loggers

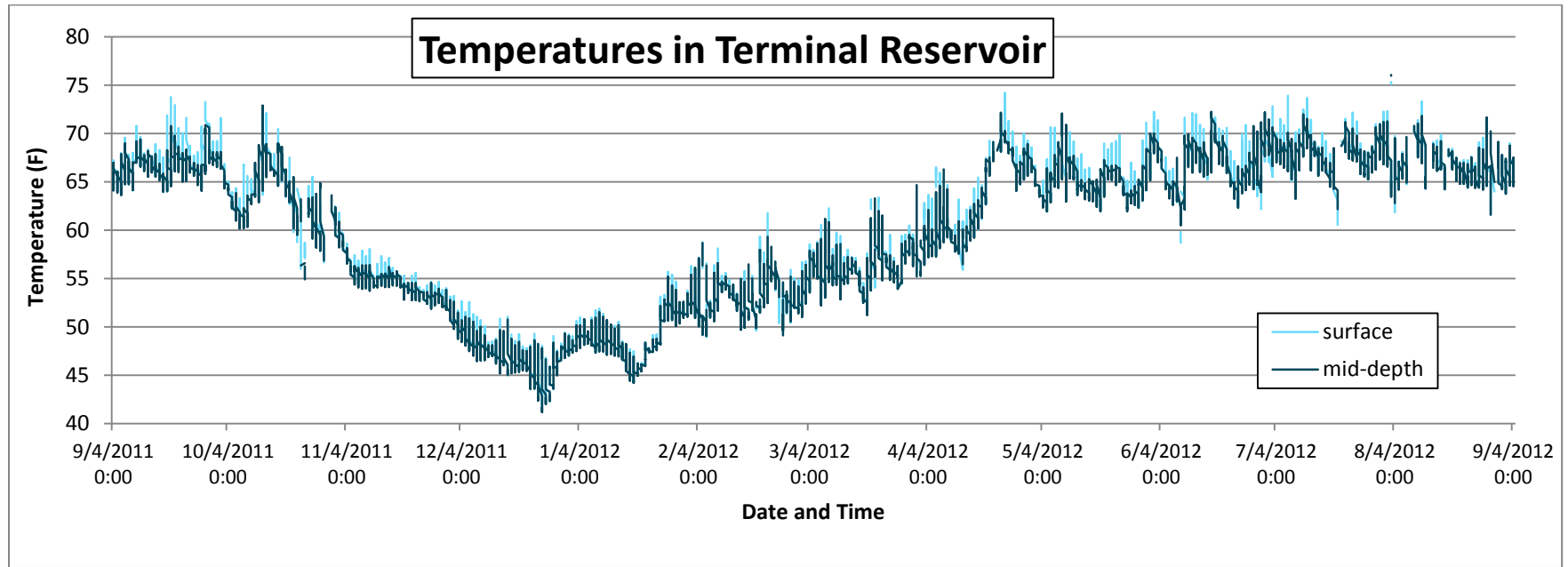
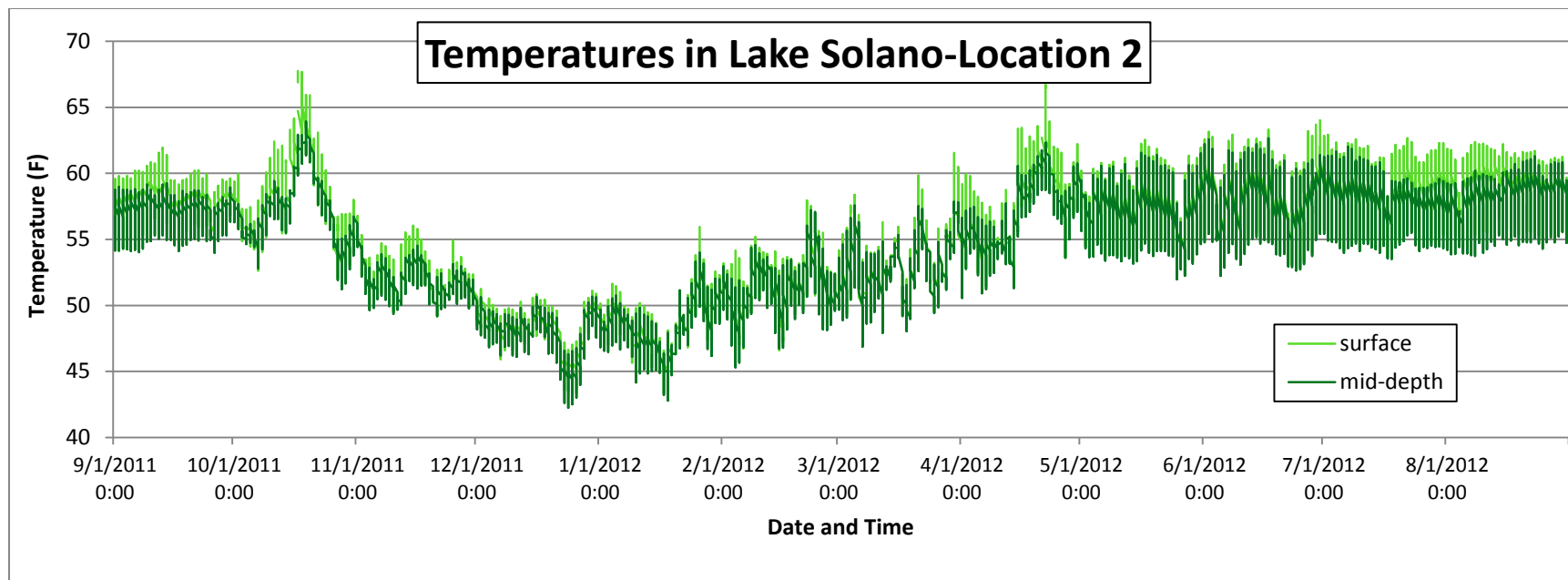


Figure D.1. Data from year-long deployment of temperature loggers in the Terminal Reservoir. One logger was placed near the surface of the water, and one at a depth of 0.6m (these depths may have fluctuated with water levels). Data points were logged every two hours. Large spikes in temperature may have been caused by exposure to air if water levels dropped. Outlying points, most likely caused by low water levels and exposure to air, were removed from the graph.



*Figure D.2. Data from year-long deployment of temperature loggers in Lake Solano. Two loggers were placed at the metal SCWA water quality station a short distance downstream from the Pleasants Creek inflow. One logger was placed near the surface of the water, and one at a depth of 0.65m (these depths may have fluctuated with water levels). Data points were logged every two hours. Outlying points, most likely caused by low water levels and exposure to air, were removed from the graph.*

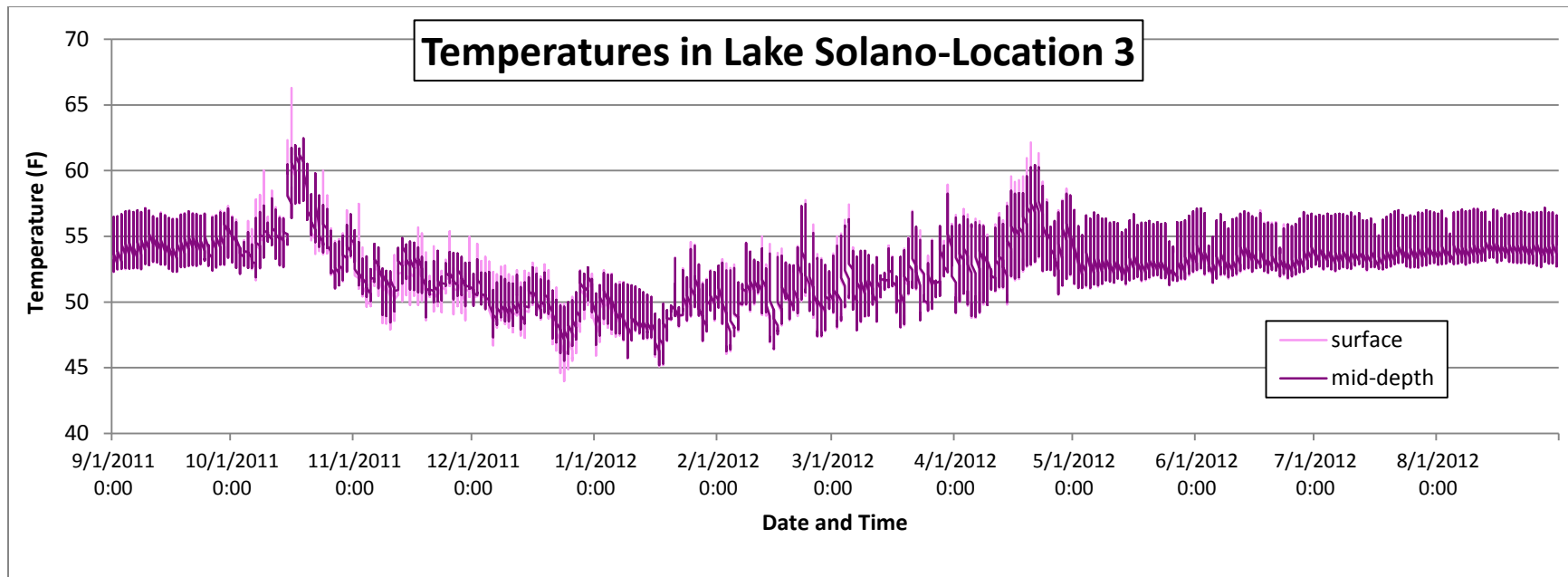


Figure D.3. Data from year-long deployment of temperature loggers in Lake Solano. Two loggers were placed just downstream of the island that creates the fork in the channel where Lake Solano becomes Putah Creek. One logger was placed near the surface of the water, and one at a depth of 0.6m (these depths may have fluctuated with water levels). At some point between June and September 2012, the loggers moved downstream, possibly pushed by high flows. The surface logger was retrieved at a depth of 0.5 m below the surface, and the mid-depth logger was 1.1 m below the surface. Data points were logged every two hours. Outlying points, most likely caused by low water levels and exposure to air, were removed from the graph.