Addressing Tuolumne River pulse flow impacts on macroinvertebrate community composition

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Abstract:

The Tuolumne river watershed is a highly managed aquatic system with a variety of anthropogenic alterations that in locations severely limit the continuity of habitat types and create an unnatural daily pulse flow regime. In the early summer of 2014 from June 14th – 23rd, we sampled portions of the Tuolumne river watershed for benthic macroinvertebrates and their microhabitat conditions with the goal of understanding the effects of flow management practices on the benthic macroinvertebrate community composition. We found that the main stem Tuolumne had the lowest diversity when compared to the other sampling sites. Differences in diversity may be due to the impacts of daily pulse flows in some river sections as well as fundamental differences in habitat structure from localized variables.

Introduction:

In 1811, an ill equipped and ambitious group of adventurers attempted a first descent down the Snake River in Wyoming. Lacking in experience, proper equipment, and the advanced boating techniques of today, they unfortunately failed to complete their trip, labeling the river too treacherous to descend (Cassidy 1981). Trailblazers, mapmakers, and adrenaline seekers of the 1800s are to thank for pioneering the sports of whitewater rafting, canoeing and kayaking. Since then, this outdoor activity's reputation has soared throughout North America and much of the world, giving thousands of people the opportunity to explore remote and beautiful natural spaces that would otherwise be inaccessible. Much of rafting and kayaking's popularity is due to the presence of dams that control river flows and allow for navigation year-round. For instance, with the multiple modifications to the Snake River, it is no longer a wild and formidable river, but one of the many recreationally boated rivers in the Pacific Northwest (Calhoun 1984). Dams can contribute to the regulation of water for agricultural, hydroelectric and recreational purposes. Boaters in particular advocate for ideally timed pulse flows or artificial water releases to create ideal white water conditions.

There are considerable impacts on watershed function from the presence of dams and releases of water for hydroelectric generation and whitewater recreation. This creates a discontinuity in the watershed with anthropogenic lentic reservoir habitats and an altered downstream lotic habitat that is highly influenced by the operational regime of the dam releases. These large pulses of water alter both the physical and chemical habitat components of aquatic ecosystems through variable transport magnitudes and rates (Feld & Hering 2007). These changes result in alterations to the preferred microhabitats of various aquatic invertebrates by generating adverse water column conditions and inopportune daily sediment transport, creating an overall change in the complex energy dynamics of aquatic ecosystems (Tupinambas *et. al.* 2014).

We assessed the potential impacts of flow variability below dams in the Tuolumne River watershed by sampling benthic macroinvertebrate communities as bioindicators of stream health. Sample reaches were located upstream of Hetch

Hetchy reservoir in the unregulated river through Tuolumne Meadows, in the regulated mainstem Tuolumne River below Hetch Hetchy and Holm powerhouse at the confluence of the unregulated Clavey River, and in the regulated lower Tuolumne river below New Don Pedro reservoir. At each study location, we also sampled the substrate size distribution as an indicator of physical habitat conditions.

From the basis of the River Continuum Concept (Vannote *et. al.* 1980), we hypothesized that the mainstem of the Tuolumne river below Hetch Hetchy Reservoir contained a greater variety of invertebrate species than upstream reaches in Tuolumne Meadows due to increased water temperature and greater organic material input from upstream and the stream banks. We expected the change in temperature and available nutrients in the middle portion of the watershed to support more tolerant species and functional feeding groups dominated by grazers. We hypothesized that the lower Tuolumne River below New Don Pedro reservoir would support the most tolerant species and functional feeding groups dominated by collectors due to the prevalence of warm, slow moving water.

Tuolumne River Management Background:

The climate in California is classified as Mediterranean, meaning that it receives the majority of its precipitation in the winter and little to no precipitation in the summer months. Watersheds throughout the Sierra Nevada mountains are governed primarily by this cycle of snow accumulation in the winter and melting in the summer. The montane snow pack is the primary source of water for these watersheds throughout the summer. Spring and summer flows consist of a relatively large spring- snowmelt pulse that slowly tapers off through the summer as the snowpack melts. In the Tuolumne river, water is channeled through steep narrow valleys alternating between bedrock chutes and pools above New Don Pedro reservoir. Once the river reaches New Don Pedro reservoir, the channel bed slope decreases from approximately 4% to less than 1%. Below the reservoir, the river is wide with a relatively low gradient, and the channel bed slope decreases to less than 0.03% near the confluence with the San Joaquin River.

Native flora and fauna in the Tuolumne watershed are highly adapted to California's Mediterranean climate of wet winters and dry summers. Two examples of these well-adapted species are the Foothill yellow-legged frog and the cottonwood tree. In order to protect their egg clutches, Foothill yellow-legged frogs synchronize their egg lying with the end of the spring snowmelt. This allows their eggs to remain relatively undisturbed through the early summer until they hatch. (Yarnell *et al.* 2010) Similarly, cottonwood trees release their seeds following the peak spring flows on the falling limb of the hydrograph since the receding waters provide moist soil appropriate for seedling establishment.

The Tuolumne River flow regime has been altered by dams and diversions to maximize anthropogenic benefits, including water supply for agricultural and municipal use, flood control, hydroelectric power generation, and recreation to a lesser extent. Management of the Tuolumne River Watershed stems from the Raker's Act of 1913. The act granted the San Francisco Public Utilities Commission (SFPUC) rights to the use of the water draining from the Tuolumne watershed and to construct O'Shaugnessey Dam along the mainstem of the Tuolumne River. Water behind O'Shaugnessey Dam, which forms Hetch Hetchy Reservoir, is used to supply water to SFPUC. Associated dams and hydroelectric powerhouses were later constructed on adjacent forks of the Tuolumne to complement SFPUC's activity within the watershed.

The dams placed on the Tuolumne River change the hydrology of the system dramatically. In general they reduce the magnitude of the spring snowmelt, homogenize the flow through the summer, and extend moderate flows past the normal low-water period. In addition, dam managers artificially create daily pulse flows in some river locations to produce hydroelectric power and to satisfy recreational boaters. These pulse flows increase the discharge of the river in a small window of time and then reduce it just as quickly (Robyn *et. al.* 2009).

Control structures placed on a river and their associated releases can have adverse effects on the geography of the stream and the species within it. Daily pulse flows affect the streambed by rapidly changing the amount of energy flowing through the system (Robyn *et. al.* 2009). Dams also alter the spring snowmelt regime and in turn disrupt the reproductive cycles of Foothill yellow-legged frogs, cottonwoods and other native aquatic organisms (Yarnell et. al. 2010)

Significance of Biodiversity:

Potential effects of dams and water management on the Tuolumne River were quantified by observed differences in invertebrate species composition and richness between the upper, middle and lower reaches of the Tuolumne. Biodiversity was quantified primarily by the Shannon-Weiner diversity index. This metric takes into account the number of different species present at a particular site and calculates the proportion they represent of the entire sample. (Magurran pg. 107) The highest diversity will come from a site which contains many different species as well as an even spread of individuals amongst all species present (Rhen & Ellenrieder 2008, Magurran pg. 107).

Metrics of biodiversity, such as the Shannon-Weiner Index, are commonly used as an indicator of overall stream health due to their link to physicochemical factors (Stranko *et. al*. 2012). When a stream becomes too polluted or homogeneous, it will no longer be able to support a large variety of species. In order for the stream to be utilized to its fullest potential, it must have a wide variety of microhabitats present within the reach. Sites with only a single habitat type will support fewer species because their niche utilizations will overlap. A well-developed stream will have multiple habitats such as riffles, pools, runs, and glides for different species to utilize. For example, Trichoptera will utilize runs and glides efficiently by capturing organic material from the water as it moves past them, whereas predators might prefer pools or riffles to hunt their prey (Vannote *et. al.* 1980).

Bioassessment of Macroinvertebrate Communities:

Bioassessment evaluates the health of aquatic ecosystems by comparing the community compositions of certain guilds of organisms along various habitat gradients (Cairns & Pratt 1993). The ratio of intolerant or sensitive species to more tolerant taxa is an indicator of particular desired habitat qualities. Benthic macroinvertebrates are considered ideal organisms to be used as indicators of habitat quality due to their limited mobility and exposure to local and physical habitat conditions for the majority of their lifetime. The cumulative effects of environmental disturbances can be quantified based on the presence or absence of certain indicator species (Rhen & Ellenrieder 2008, Tupinambas *et. al.* 2014).

Bioassessment provides a basis for estimating environmental health as well as a technique for monitoring alterations to stream quality over time. There are many species within the orders Ephemeroptera, Plecoptera and Trichoptera that are considered indicators of good habitat quality because of their low physiological tolerance to insufficient dissolved oxygen content and chemical pollutants. However, these species are also capable of withstanding high flow rates, giving them potential to be more abundant within high flow areas like the mainstem Tuolumne than other taxa that are less tolerant (e.g. Odonates and other large poor swimmers). Because the overall habitat structure may cater to certain feeding guilds or niches of insects, it is important to assess both physical habitat components as well as water quality parameters (Tupinambas *et. al.* 2014)

Methods:

In order to assess biodiversity within the watershed, quantitative data was collected from benthic macroinvertebrate sampling and channel substrate sampling, and qualitative evaluations were determined from field sketches and photographs of the study area.

Within each study reach, the largest riffle was chosen for macroinvertebrate sampling. Samples were collected following standard kick-net procedures (Barbour et. al. 1999). Three cross-sections were randomly selected along the length of the riffle, and five kicks were completed in equi-distance locations along each cross-section. Each kick was completed for 30-seconds and covered approximately $0.09m^2$ upstream of the kick-net. The five samples from each cross-section were composited into a single bucket, and then sorted and identified in the field to family. Data was recorded separately for each of the three cross-sections in each study reach in order to determine potential variability within each study site.

Bed substrate composition was collected at the invertebrate sampling sites to determine potential physical habitat differences between samples. Following the standard Wolman Pebble Count method (Wolman 1954), two surveyors randomly selected and measured a minimum of 100 substrate particles to determine the grain size distribution of the sample area. Substrate size was measured along the median axis of each particle using a gravelometer. The substrate size distribution was compared to the macroinvertebrate diversity to assess potential correlations with local physical habitat conditions.

Algae samples from substrate surfaces were also collected at each sampling site to determine potential differences in biotic condition that might contribute to observed differences in macroinvertebrate diversity. Five substrate particles were randomly selected in each study reach. One square inch was sampled from each particle and collated into a single sealable bag. The algae samples were then placed in cold storage until processing. In the lab, the samples were filtered using Whatman™ 47 mm glass microfiber filters and dried for 24 hours. Total dry mass and ash-free dry mass (AFDM) (mg/cm2) were calculated to measure total biomass (total dry mass – AFDM) within each sample.

At each sampling location, field sketches and photographs were completed to record key habitat features. For each field sketch, the following basic information was included: stream name, sampling locations, surrounding landmarks, vegetation type and extent, large sediment locations, pools, riffles, gravel and sand bars.

Results:

Benthic macroinvertebrate community compositions within Tuolumne Meadows in reach A (most upstream near head of meadow) and reach B (middle portion of meadow) were fairly similar. Both locations had an EPT percentage over 76% and Shannon's Diversity Index values over 1.133 (Figure 1 and Figure 2, respectively). Plecoptera were the dominant EPT order in comparison to Trichoptera and Ephemeroptera (Appendix A, Macroinvertebrate Index Table). The substrate size distribution for both sample sites was 22.6mm-64mm (Figure 3). In comparison, Tuolumne Meadows reach C (most downstream near base of meadow) had an EPT percentage of 50% (Figure 1), and more Chironomids than the other two Meadow sites (Appendix A). Reach C also had finer sediment, with a majority falling between 8 and 32mm in size (Figure 3).

The mainstem of the Tuolumne River below Hetch Hetchy reservoir and Holm Powerhouse, referred to as Tuolomne Main, had the lowest biodiversity of the sampled reaches. The Tuolumne Main sites upstream and downstream of the Clavey River confluence had EPT percentages below 20% and a Shannon's Diversity Index less than 0.70 (Figure 1 and Figure 2, respectively). Mites comprised the majority of invertebrates found in the two mainstem sample sites (Appendix A). The majority of the substrate in the Tuolumne Main upstream of the Clavey River was larger than 64mm, while the Tuolumne Main downstream of the Clavey River had a more evenly sample substrate size distribution (Figure 3). The Tuolumne Main upstream of the Clavey River also had the highest algae levels with 8.62 mg/cm^2 of biomass (Figure 5).

Within the Clavey River, biodiversity was high with a Shannon's Diversity Index and EPT percentage at the upper Clavey site of 1.37 and 64.81%, respectively, and 1.38 and 62%, respectively, at the lower Clavey site (Figures 1 and 2, respectively). Among the consolidated kicks, there were 9 new families of invertebrates that were not sampled in the Tuolumne Meadows or Tuolumne Main sites. The families included: Perlidae, Pteronarcyidae, Tabanidae, Coleoptera, Hydropsycidae, and Racaphylidae. A majority of the substrate within the Upper Clavey site was comprised of bedrock, while the substrate within the Lower Clavey was skewed towards the mid-sized substrate (Figure 4).

On the lowest section of the Tuolumne River below New Don Pedro, there was also high biodiversity. Ephemeroptera, Trichoptera, and Plecoptera invertebrate orders accounted for 62.1% of the total sample (Figure 1), while Shannon's Diversity Index was 1.65 (Figure 2). A majority of sediment sizes within the reach were between 22.6mm and 64mm (Figure 4).

Discussion:

Tuolumne Meadows had substantially different habitat conditions than the downstream locations due to colder water temperatures (8-14 °C) and finer substrate sizes (Figure 3), which may have contributed to higher EPT percentages in the upper Meadow sampling sites (Reach A and B) (Figure 1). In support of the study hypothesis, lower water temperatures may have contributed to a greater abundance of Plecoptera within those samples (Appendix A).

The lower biodiversity observed along the mainstem Tuolumne River during the sampling period may have been due to impacts from pulsed flows released for hydropower and recreation. Higher velocities from daily pulse flows are known to flush individuals downstream (Rhen & Ellenrieder 2008), decreasing the likelihood of finding larger-bodied sensitive species within the sample areas. While the larger particle sizes observed in the mainstem Tuolumne is a preferred substrate for some sensitive species, the biodiversity of invertebrates in the Tuolumne Main sample sites was far lower than in the unregulated Tuolumne Meadows or unregulated Clavey River sample sites.

The low diversity of invertebrates in the mainstem Tuolumne River may also have been related to impacts from the Rim Fire of August 2013. The effects of the fire were still present within the river during sampling, as evidenced by the large volume of silt observed within the kick locations and along the channel margins. Large deposits of silt within the river can decrease the survival rates for many invertebrate families with open gills if the silt were to become trapped within or cover the gills (Tupinambas *et. al.* 2014).

The diversity of invertebrates within the Clavey River was significantly higher than in the adjacent mainstem Tuolumne River. The increased biodiversity may be due to warmer water temperatures, moderate-sized sediments, higher algal biomass, and the unregulated nature of the river. The natural stream flow likely allowed invertebrates to adhere to a more natural and seasonally stable habitat structure. Additionally, high algal densities found within the Clavey River may explain the high density of Ephemeropterans, which are grazers (Tupinambas *et. al.* 2014).

The data support a positive relationship between biodiversity and moderate substrate sizes between 22.6mm and 64mm. EPT percentages and Shannon's Diversity Index values were lowest in the Tuolumne mainstem near the Clavey confluence where the majority of the substrate was greater than 64mm and silt was prevalent throughout, while diversities were higher in the Clavey River and Tuolumne Meadows reaches where median grain sizes were 23mm – 32mm. While there appeared to be a relationship between substrate size and biodiversity, additional research is needed to determine any statistical correlations. Based on the data presented here, future studies attempting to discern the impacts of flow regime on aquatic diversity should more closely examine the relationships between biodiversity, sediment size, and algal resources.

Potential Sources of Error:

There are several potential sources of error within this study. Limiting the sampling location to riffles may lend bias as there are many other microhabitat types that benthic macroinvertebrates use. If additional microhabitats such as backwater eddies or large pools were sampled, there would likely be different species present resulting in differing EPT percentages. Potential inconsistencies among team members in sampling techniques may also have occurred. There was potential bias in invertebrate samples based on how aggressively each person disturbed the substrate while doing an invertebrate kick, and whether the substrate was disturbed by feet only, hands only or both. When sampling in Tuolumne Meadows reach C, the team observed that the invertebrate samples had fewer large particles disturbed when using only their hands. During field identification, differences in the ability of individual team members to sort out invertebrates and determine which families were included for identification (e.g. the identification of mites was omitted in a few samples) may have contributed to error between samples.

Conclusion:

Nearly all of California's watersheds are highly altered ecosystems with a variety of anthropogenic impacts. Though the Tuolumne river watershed is designated as a Wild and Scenic River, it is still a highly managed aquatic system with dams and powerhouses that severely limit the continuity of habitat types longitudinally and create an unnatural daily pulse flow regime in the mid-elevation sections of the river. This study sought to address the potential impacts of flow management practices on the benthic macroinvertebrate community composition by collecting benthic macroinvertebrate samples and quantifying associated microhabitat conditions. The study results indicate the most impacted section, the mainstem Tuolumne River below the flow inputs from Holm powerhouse, had the lowest biodiversity as quantified by Shannon's Diversity Index. These results are likely attributed to the impacts of daily pulse flows that potentially flush individuals downstream, as well as differences in habitat structure from localized variables within each sub-reach.

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Figures:

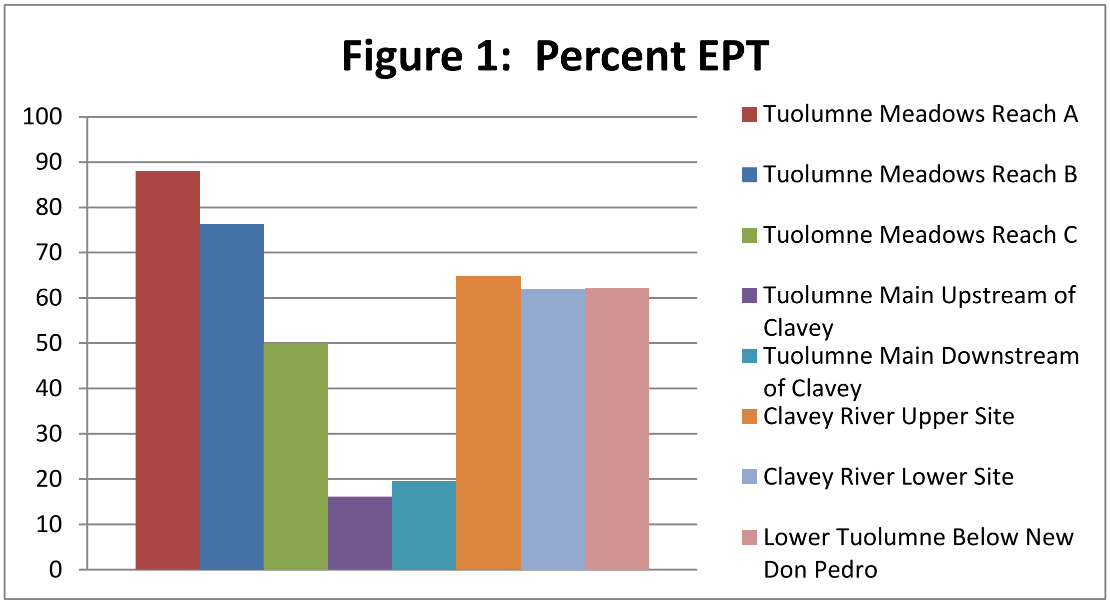

Figure (1): Calculated Ephemeroptera-Plecoptera-Trichoptera percentage relative to the total number of orders for each sample location

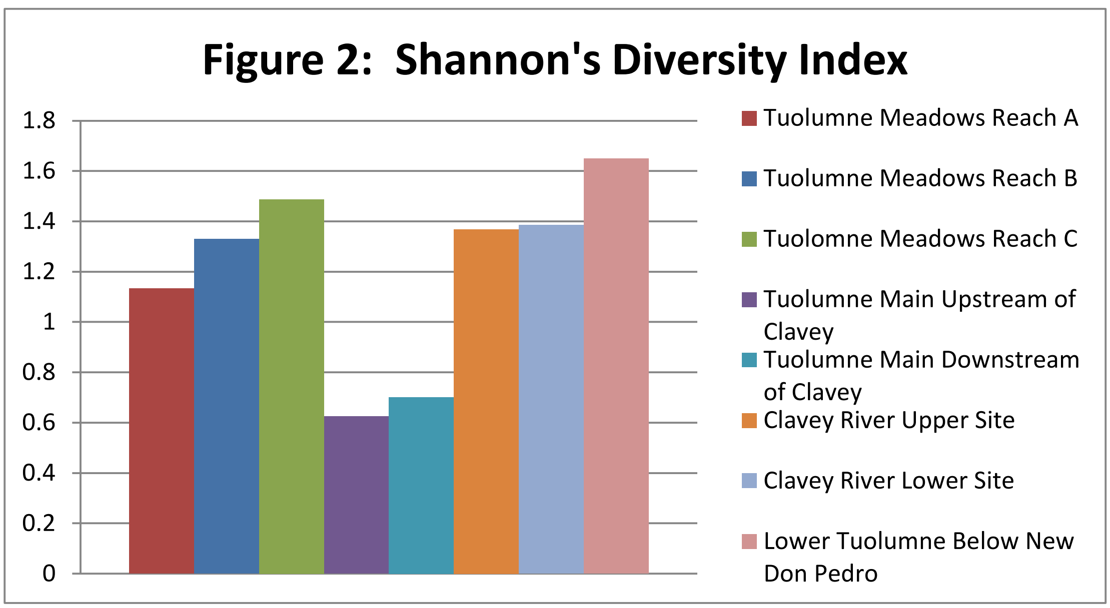

Figure (2): Calculated Shannon's Diversity Index for each sample location.

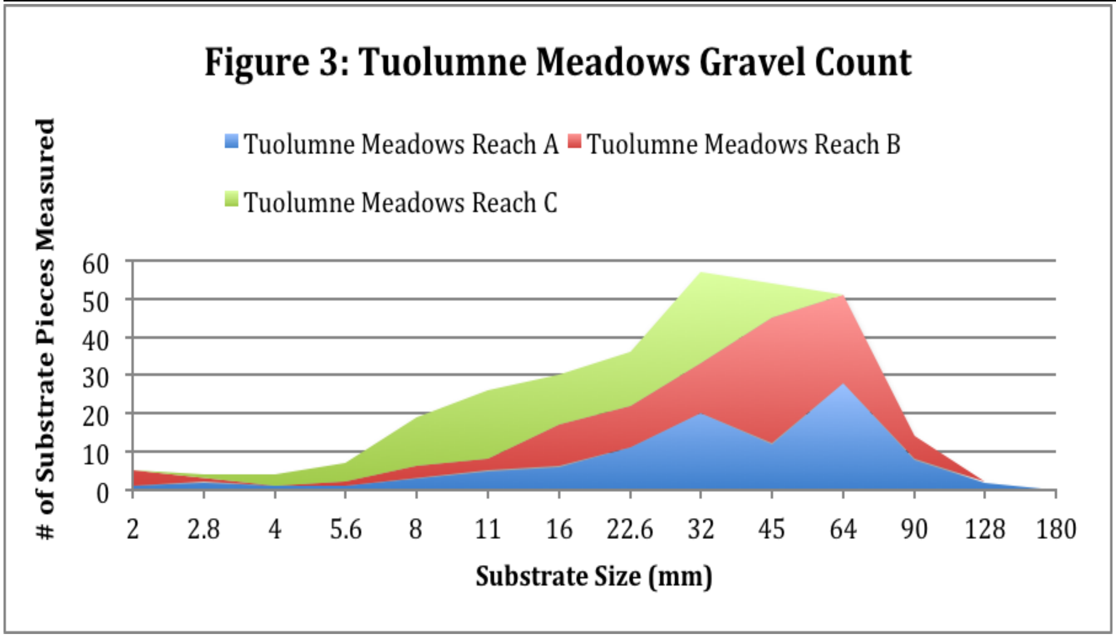

Figure (3): Distribution of substrate sizes at each sample location in Tuolumne Meadows. Reach A was the most upstream location with Reaches B and C downstream in sequential order.

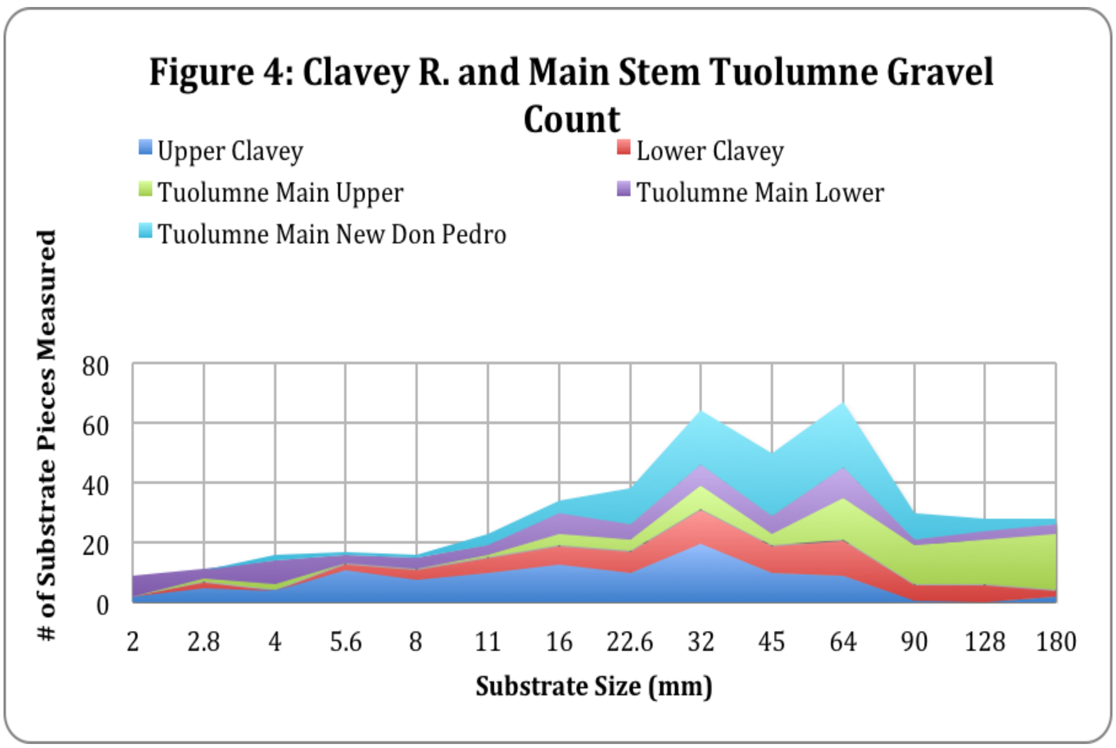

Figure (4): Distribution of substrate sizes at each sample location in the Clavey river and Tuolumne river mainstem. It is important to note that the Tuolumne Main Upper site was located upstream of the Clavey R. confluence, while the Tuolumne Main Lower site was downstream of the confluence.

Figure (3): Distribution of substrate sizes at each sample location in Tuolumne Meadows. Reach A was the most upstream location with Reaches B and C downstream in sequential order.

Figure (5): Estimated algae content extrapolated from samples collected from substrate.

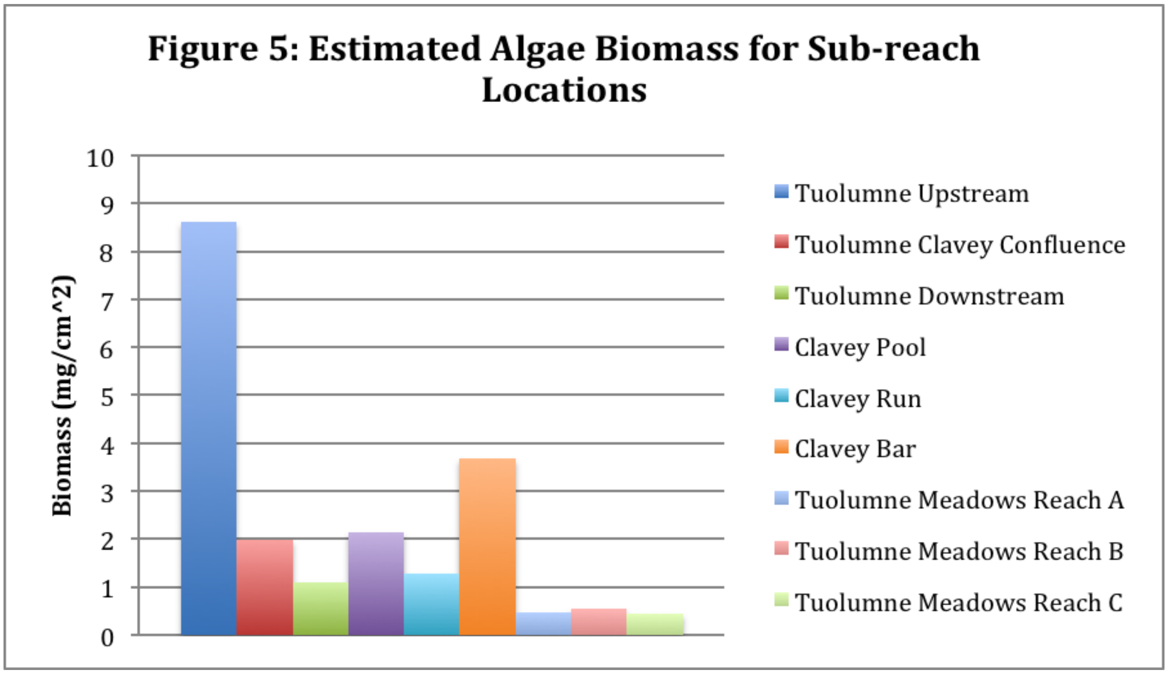

Figure (5): Estimated algae content extrapolated from samples collected from substrate.

Appendix A:
Macroinvertebrate Index Tables:

	Tuolumne Meadows			Tuolumne Meadows			Tuolumne Meadows		
	Reach A			Reach B			Reach C		
Family	Kick 1	Kick 2	Kick 3	Kick 1	Kick 2	Kick 3	Kick 1	Kick 2	Kick 3
T. Caddisfly	2		1		1		1		
P. Stoneflly	16	22	18	10	8	10		5	2
Dipteran	1			3		1	1	3	
E. Heptageniidae	15	6	1	6		4	3	5	3
E. Siphlonuridae	1								
Chronomidae	4	6			9	3	7	18	3
Baetidae Mayfly			6	3	6	7	4	4	9
Annelid			1	1					
Mite			3					6	
Simuliidae								1	3
Dragonfly									
Damselfly									
Pupae									
Beatle									
Caddisfly Pupae									
Racaphylidae (caddis)									
Coleoptera (dyticidae)									
Hydropsycid									
Planarian									
elmidea (beatles)									
Tabanidae (dipteran)									
Perlidae (stonefly)									
Pteronarcyidae									
Copepod									

Amphipod									
Bivalve									
Sum of Individuals	103			72			78		
Shannon Index	1.13			1.33			1.49		
EPT %	88			76			50		

	Tuolume Main Upstream of Clavey			**Tuolume Main Downstream of Clavey**		
Family	Kick 1	Kick 2	Kick 3	Kick 1	Kick 2	Kick 3
T. Caddisfly				2		1
P. Stonefly	1		4			
Dipteran						
E. Heptageniidae	1			12	2	4
E. Siphlonuridae						
Chronomidae	6	2		2	14	
Baetidae Mayfly	29	70	20	20	3	4
Annelid		2		1	1	
Mite	a lot			15	5	20
Simuliidae	1			4		
Dragonfly						
Damselfly	1	4	3			
Pupae						
Beatle		2	5		1	
Caddisfly Pupae	1	1				
Racaphylidae (caddis)	4					
Coleoptera (dyticidae)	7	1	2	1		
Hydropsycid	2	2	2	8	2	1
Planarian	1			4	1	
elmidea (beatles)		6				

Tabanidae (dipteran)		1				
Perlidae (stonefly)		1				
Pteronarcyidae			1			
Copepod				1		
Amphipod				3		2
Bivalve						1
Sum of Individuals	137			92		
Shannon Index	0.63			0.70		
EPT %	16			20		

	Clavey River			**Clavey R.**			**Lowest Tuolumne Main**		
	Upper Site			**Lower Site**			**Below New Don Pedro**		
Family	Kick 1	Kick 2	Kick 3	Kick 1	Kick 2	Kick 3	Kick 1	Kick 2	Kick 3
T. Caddisfly							2		1
P. Stoneflly		7	16	1		4			
Dipteran									
E. Heptageniidae		3	1	1			12	2	4
E. Siphlonuridae									
Chronomidae	1	2	5	6	2		2	14	
Baetidae Mayfly	5	2	1	29	70	20	20	3	4
Annelid		2	2		2		1	1	
Mite				a lot			15	5	20
Simuliidae				1			4		
Dragonfly									
Damselfly	1	3	1	1	4	3			
Pupae			1						
Beatle			1		2	5		1	
Caddisfly Pupae				1	1				
Racaphylidae (caddis)				4					

Coleoptera (dyticidae)				7	1	2	1		
Hydropsycid				2	2	2	8	2	1
Planarian				1			4	1	
elmidea (beatles)					6				
Tabanidae (dipteran)					1				
Perlidae (stonefly)					1				
Pteronarcyidae						1			
Copepod							1		
Amphipod							3		2
Bivalve									1
Sum of Individuals	54			183			135		
Shannon Index	1.39			1.38			1.65		
EPT %	65			62			62		