EFFICIENCY OF FECAL COLIFORM, PHOSPHOROUS AND SUSPENDED SOLIDS REMOVAL IN SUBURBAN STORM WATER WETLANDS, ARCATA, CALIFORNIA

by

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ABSTRACT

EFFICIENCY OF FECAL COLIFORM, PHOSPHOROUS AND SUSPENDED SOLIDS REMOVAL IN SUBURBAN STORM WATER WETLANDS, ARCATA, CALIFORNIA

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The city of Arcata, California has identified bacteria, nutrients and suspended solids as pollutants of concern in the city's waterways. Suburban areas are known sources of fecal contamination, nutrients and suspended solids. Suburban areas increase the amount of impervious surfaces in watersheds causing peak flow and volume of storm water runoff to significantly increase. As runoff and overland flow increase so does the ability of water to entrain and carry a higher pollutant load. Wetlands have been increasingly used and found effective in reducing many of the water quality concerns associated with suburban runoff. Arcata has four wetlands located on three streams receiving suburban storm water through storm water infrastructure. Two of the wetlands are depressional and two are free water surface. Each stream was sampled during the 2010-2011 hydrologic year upstream and downstream of the wetlands during both storm and base flow events to determine reduction of total suspended solids (TSS), organic suspended solids (OSS), inorganic suspended solids (ISS), fecal coliforms, turbidity, and phosphorous. Of the metrics tested only suspended solids showed significant reductions. The highest mean TSS, ISS, OSS and fecal coliform concentrations came from Campbell Creek, which had the highest percent impervious surfaces (23%) comprised primarily of suburban housing. Suspended solids were about 22% organic by weight during storm and base flows making organic matter a significant portion of the suspended load.

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INTRODUCTION

The Clean Water Act (CWA) of 1972 was established to monitor and set standards for ambient water quality in the United States. Section 303(d) of the CWA requires states, territories and tribes to list all impaired waters that do not meet the standards set for their designated uses. Since the implementation of the CWA, the Environmental Protection Agency (EPA) has identified pathogens, metals, nutrients, sediment and organic enrichment as the top five water quality impairments under section 303(d) (Scott et al. 2006).

Suburban areas are significant sources of pathogens, nutrients, suspended sediments and organic matter (Scott et al. 2006). Suburban areas have high percentages of impervious surfaces that result in an increase in the volume and rate of storm water runoff and ability to entrain and transport such pollutants. It is common practice in many cities to route this storm water runoff and its concentrated pollutant load into nearby streams to reduce flooding.

The EPA has identified urban storm water runoff as one of the top four anthropogenic water quality impairments to lakes and reservoirs in the United States (United States Environmental Protection Agency 2002). Storm water runoff is the main mechanism by which pollutants gain entrance into water ways and during storms pollutants can reach their highest concentrations (Oberts and Osgood 1991, Kantrowitz and Woodham 1995) and thus have their highest ability to impact the aquatic environment and human health (Rose et al. 2001).

Wetlands have been used extensively around the world to mitigate suburban pollution and have been shown to be effective at reducing total suspended solids (TSS), organic suspended solids (OSS), inorganic suspended solids (ISS), turbidity, nutrients and pathogen loading (Scott et al. 2006, Kadlec and Wallace 2009). While none of Arcata's streams are listed as impaired under section 303(d), the city has identified pathogens, sediment and nutrients as pollutants of concern (City of Arcata 2004). Along each of the streams in this study storm water wetlands were constructed to help mitigate suburban runoff pollution, reduce flooding, provide recreational opportunities and increase wildlife habitat (City of Arcata 2004).

Suspended solid (SS) concentrations in streams have been thoroughly studied due to their effects on stream biota (Cordone and Kelley 1961) and chemistry (Houser et al. 2006). In 2000 the EPA identified total suspended solids (TSS) as one of the leading causes of river impairment in the United States (United States Environmental Protection Agency 2000). TSS impairs roughly 15% of U.S. streams (United States Environmental Protection Agency 2004). Although sediments have large effects on aquatic ecosystems, little is known or reported on the ratios of organic particles to inorganic particles that make up the complexity of suspended materials. It has been thought for some time that organics make up such a small percentage of suspended load weight that they are insignificant in most watersheds (Guy 1969). However, most suspended solid research is performed on higher order streams where riparian zone organic input and in-stream retention is reduced leading to the conclusion of the insignificance of organic suspended solids (OSS) (Webster et al. 1990). In forested low order streams, especially in coniferous forest (Benfield 1997) and areas with high precipitation (Jones 1997), terrestrial organic input can be substantial and exceed the metabolic potential of the streams (Golladay 1997) allowing OSS to make up greater than 40% of the total suspended solid weight (Kantrowitz and Woodham 1995, Madej 2005, Galloway 2008).

Organic matter in headwater streams is largely the result of litterfall and lateral movement of allochtonous materials from the riparian forests (Fisher and Likens 1973). Once in the stream or on the floodplain, storm events can transport a majority of the available organic material (Fisher and Likens 1973, Wallace et al. 1995, Golladay 1997, Madej 2005) to downstream reaches making storm flows the ideal time to test for organic suspended solids.

Knowing the organic portion of suspended solids can give valuable information as to the possible effects the SS will have. Allochtonous organic materials make up the majority of the food supply within headwaters streams (Fisher and Likens 1973, Jones et al. 1991) and are essential for the maintenance of diverse aquatic food webs (Wallace et al. 1997). Organic constituents also have a larger effect on light attenuation during low flows due to their smaller mass and longer entrainment times (Madej 2005). Lowering the light availability can lower phytoplankton biomass (Sobolev et al. 2009) and hinder visual fish feeding ability (Madej et al. 2007). With the ability of organics to be decomposed, the impact of organics as a suspended or sedimented solid is much different than inorganic suspended solids due to their ephemeral nature in aquatic ecosystems. ISS are recalcitrant and can fill in spawning grounds, smother microinvertebrates, abrade fish gills and reduce the heterogeneity of streambeds (Perry and Vanderklein 1996).

Fecal contamination is cited as the most prevalent stressor to water quality in the United States (Scott et al. 2006). A common method of determining fecal matter and subsequent pathogen risk to human populations is through enumeration of fecal coliforms. It would be extremely time consuming and expensive to test water for all known pathogens. Instead, the assumption is made that because enteric pathogens are ill adapted to living outside the intestinal environment they had to have been recently introduced by feces, accompanied by fecal coliforms. In order to evaluate potential pathogen removal efficiencies of the wetlands, fecal coliforms were enumerated in water samples upstream and downstream of each wetland during both storm and base flow events.

Macrophyte vegetation in wetlands slows incoming water and helps facilitate sedimentation of pathogens (Davies et al. 2000). Sedimentation is the main mechanism of pathogen removal in wetlands (Kantrowitz and Woodham 1995, Knox et al. 2008). Wetland plants also act to reduce the resuspension of sedimented bacteria which aids in bacterial die off (Brix 1997).

The United Sates Environmental Protection Agency (Scott et al. 2006) studied factors that may affect the die off rate of pathogens in constructed wetlands. These include pH, temperature, light, time, predation, adsorption and turbidity (Scott et al. 2006). However, light and time were the only factors found to be significant in reducing microbial loads (Scott et al. 2006). The EPA found that in the presence of light, bacterial concentrations were reduced twenty times faster than they were when light was absent (Scott et al. 2006). During high flows with cloud cover and a high turbidity it is unlikely that light will significantly affect fecal coliform concentrations. In low flows, however, light can play a significant role as cloud cover and turbidity are reduced.

Phosphorous is a limiting nutrient in many freshwater aquatic ecosystems. Increases in phosphorus can cause algal blooms, excessive growth (Davis and Masten 2004) and result in dissolved oxygen reduction. Wetlands have the ability to reduce phosphorous loading as a result of sedimentation (Nahlik and Mitsch 2008), chemical precipitation (Kantroitz and Woodham 1995) and biological uptake (Bitton 1994). During high flows only sedimentation and chemical precipitation are likely to affect phosphorous loading. During low flows biological uptake can have a larger effect although there are limits to the amount of uptake in any system.

Turbidity is a measure of light attenuation caused by suspended particles in aquatic environments. High turbidity has been shown to hinder visual predator feeding (Madej et al. 2007). Measuring turbidity during both high and low flows gives insight into the ability of wetlands to reduce turbidity during high flows and keep low flow levels under what would harm the coastal cutthroat trout (*O. clarki clarki*), coho salmon *(O. kisutch*), chinook salmon (*O. tshawytscha)* and steelhead trout (*O. mykiss)* currently living in these streams (City of Arcata 2004).

Based on available wetland research I hypothesized that TSS, OSS, ISS turbidity, phosphorous and fecal coliforms would be reduced as a result of the wetlands. The objectives of this study were to quantify the influent and effluent loading of the aforementioned variables and assess statistically whether or not any of the potential pollutants were reduced by the wetlands, and if so, to what degree. Another important aspect of this study was to quantify the percentages of TSS made up of organics to show that organics can be a significant portion of the suspended load in small streams.

MATERIALS AND METHODS

Site Description

The City of Arcata, located in northern California, extends over 28 square kilometers and encompasses 8 creeks used for suburban storm water runoff removal (City of Arcata 2004). Each of these streams begins in second growth, predominantly redwood forest, before moving through flat low-lying suburban areas and eventually emptying into Humboldt Bay. Of the 8 streams only Jolly Giant, Janes and Campbell Creeks have constructed wetlands for water quality mitigation and were the subjects of this study (Figure 1).

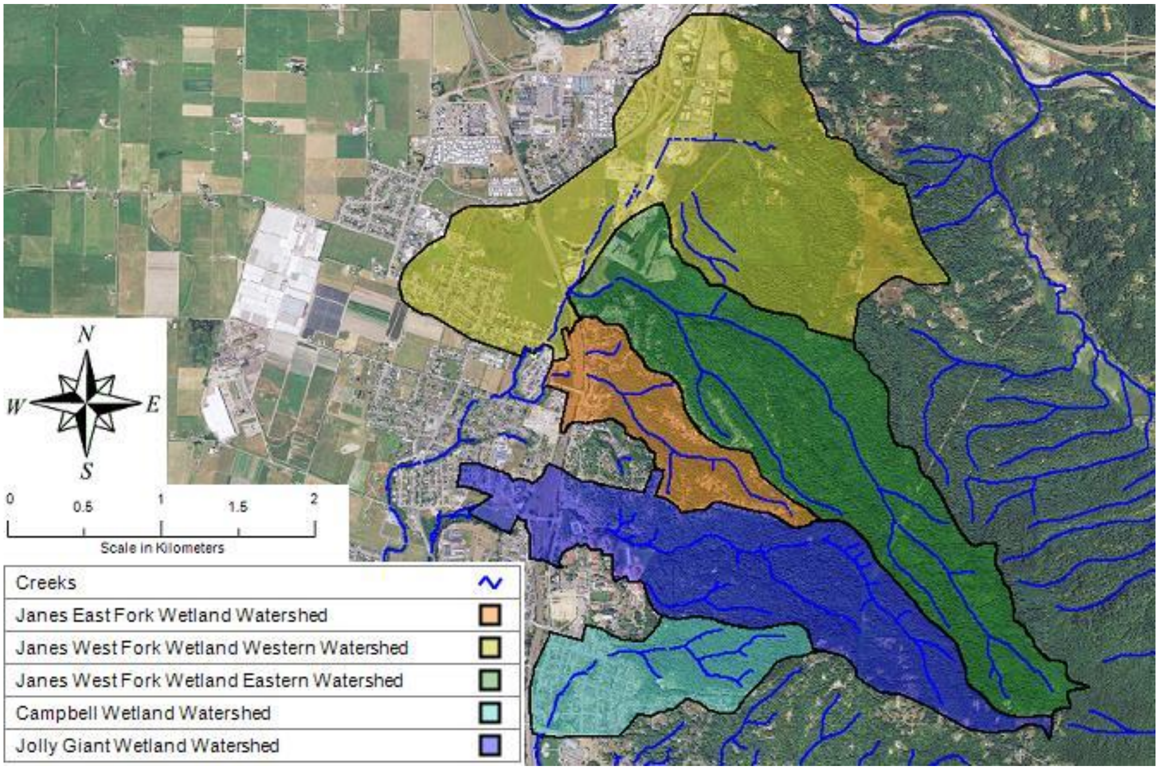

Figure 1. Arcata, California wetland watersheds aerial photo overlay 2010-2011.

Arcata has a Mediterranean climate as a result of its proximity to the Pacific Ocean (~ 6 km). Most precipitation falls between October and April with very little precipitation occurring during summer. The 2011 hydrologic year (October, 2010 to September, 2011) occurred during a multi decadal cooling of the equatorial Pacific Ocean. Rainfall during this period totaled 46.05 inches which is only slightly above the 41 inch average for the area. However, the number of storms totaling over one inch (n=18) of precipitation was greater than the average of 12.6 since 2005.

This study includes two depressional and two free water surface wetlands (Table 1). Depressional wetlands result from a depression in the ground allowing the soil to retain enough water for wetland adapted macrophytes to thrive. Depressional wetlands are characterized in this study by the presence of emergent wetland macrophytes and the absence of submerged or floating macrophytes.

Table 1. Arcata California watershed and wetland attributes.

Site	Stream Distance (km)	Slope (m/km)	Wetland Type	Wetland Size (ha)	Watershed Area (ha)[1]	Impervious Surface Area[1]
Janes West Fork East	4.89	68			293	15%
Janes West Fork West	2.41	7.9	Ephemeral Depressional	0.59	361	22%
Janes East Fork	2.06	65	Depressional	0.16	81	18%
Jolly Giant	3.78	69	Free Water Surface	0.041	216	12%
Campbell	1.98	83	Free Water Surface	0.071	95	23%

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[1] Data obtained from http://www.cityofarcata.org/departments/environmental-services/maps-gis.

[2] All other data obtained from http://datagateway.nrcs.usda.gov/ and processed using BASINS 4 (Better Assessment Science Integrating point & Non-point Sources).

Free water surface wetlands are characterized by having open standing water year-round and, as a result, contain floating and submerged macyophytes in the open water areas with emergent macrophytes in shallower areas.

The Jolly Giant wetland (Figure 2) was constructed over a previous dump in 1991. It was created to provide not only water quality enhancement but also act as an outdoor ecology laboratory for Arcata High School (Pinkham 2000). Jolly Giant Creek wetland receives runoff from a 216 ha watershed consisting of 12.2% impervious surfaces. The creek travels 2.6 km through a redwood forest before entering a heavily urbanized area where it receives runoff for 1.2 kilometers prior to entering the wetland. Jolly Giant wetland is a free water surface wetland designed with sloping sides for emergent vegetation and a deep center for year-round aquatic habitat. The wetland is ~23 meters long, holds 3,000 m^3 (Pinkham 2000) and is ~ 0.039 ha in size.

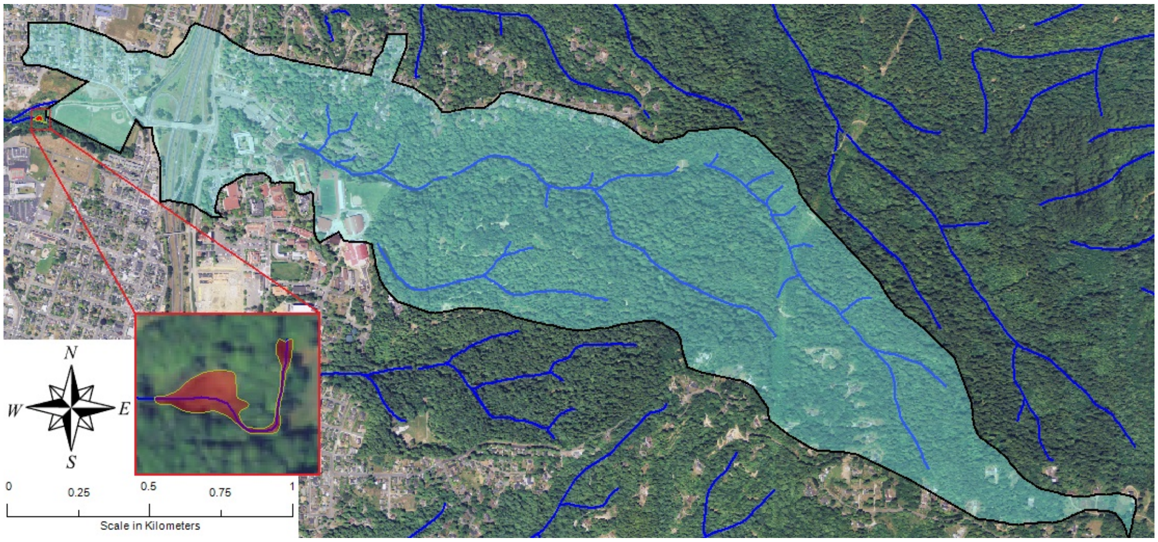

Figure 2. Jolly Giant Creek wetland watershed aerial photo overlay, Arcata California 2010-2011. Inset: free water surface wetland.

Vegetation consists of mostly cattails (*Typha latifolia*) and *Hydrocotyle sibthorpioides* around the wetted outer edge with sparse growth of skunk cabbage (*Lysichiton americanum*) near the entrance and exit of the wetland. The majority of the wetland is dominated by floating pond leaf (*Potamogeton natans*). Pacific water parsley (*Oenanthe sarmentosa*), creeping buttercup (*Ranunculus repens*), and Himilayan blackberry (*Rubus discolor*) dominate the outside perimeter of the wetland where freestanding water occurs only during storms.

Janes Creek west fork wetland (Figure 3) is a depressional ephemeral wetland covered with dense vegetation for its entire length. This wetland receives runoff from two watersheds. The western watershed is 361 ha, 22.3% impervious and made up mainly of industrial development. The eastern fork receives runoff from a 293 ha watershed that is 14.8% impervious and made up of mostly suburban development. Approximately one third of the effluent of Janes Creek west fork is the effluent from Janes Creek east fork due to an inability to accurately sample upstream of the confluence of Janes Creek east and west fork.

Prior to the 2003 housing development located on the confluence of the east and west fork, Janes Creek followed an incised channel through farmland. After the development, Janes Creek was dredged and widened into a shallow floodplain which became the Janes Creek west fork wetland. During storms the floodplain fills and acts as a wetland for suburban runoff treatment.

Vegetation consists mostly of canary grass (*Phalaris spp.*) with sparsely located red alder (*Alnus rubra*) and coastal willow (*Salix hookeriana*) over the majority of the wetland. Pacific water parsley (*Oenanthe sarmentosa*) and creeping buttercup (*Ranunculus repens*) dominate the outer edges. During drier periods and between storms standing water is reduced to a very small portion of the wetland.

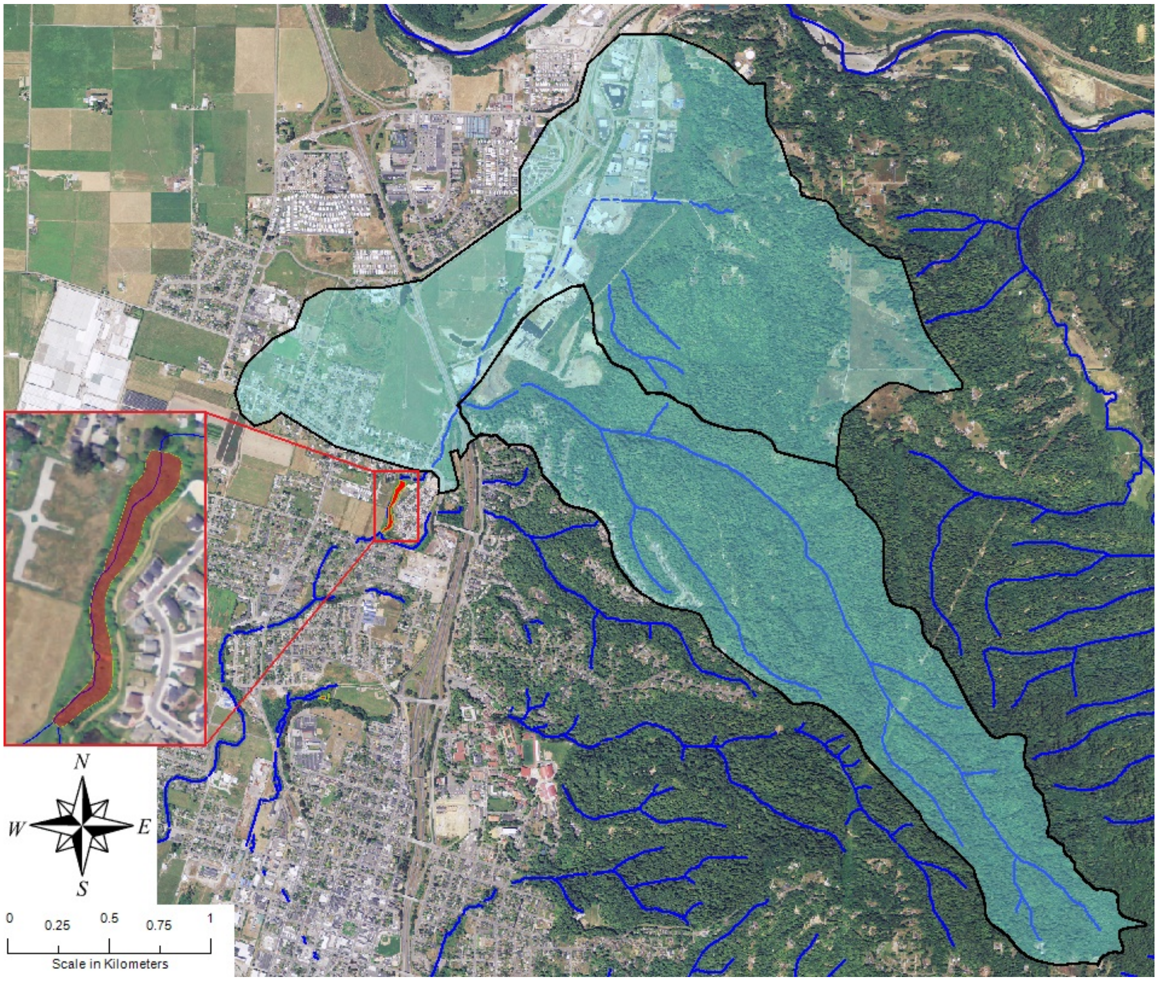

Figure 3. Janes Creek west fork wetland watersheds aerial photo overlay, Arcata California 2010-2011. Inset: depressional wetland.

About 80% of the upper Janes Creek east fork receives indirect non-point source runoff from residential areas while the lower 20% receives direct storm water runoff from Arcata's storm water infrastructure (Figure 4).

Janes Creek east fork watershed covers 81 ha and consists of 17.9% impervious surfaces mainly from suburban development. In 2003 the west fork of Janes creek was converted from an incised channel to a heavily vegetated depressional wetland of approximately 0.16 ha.

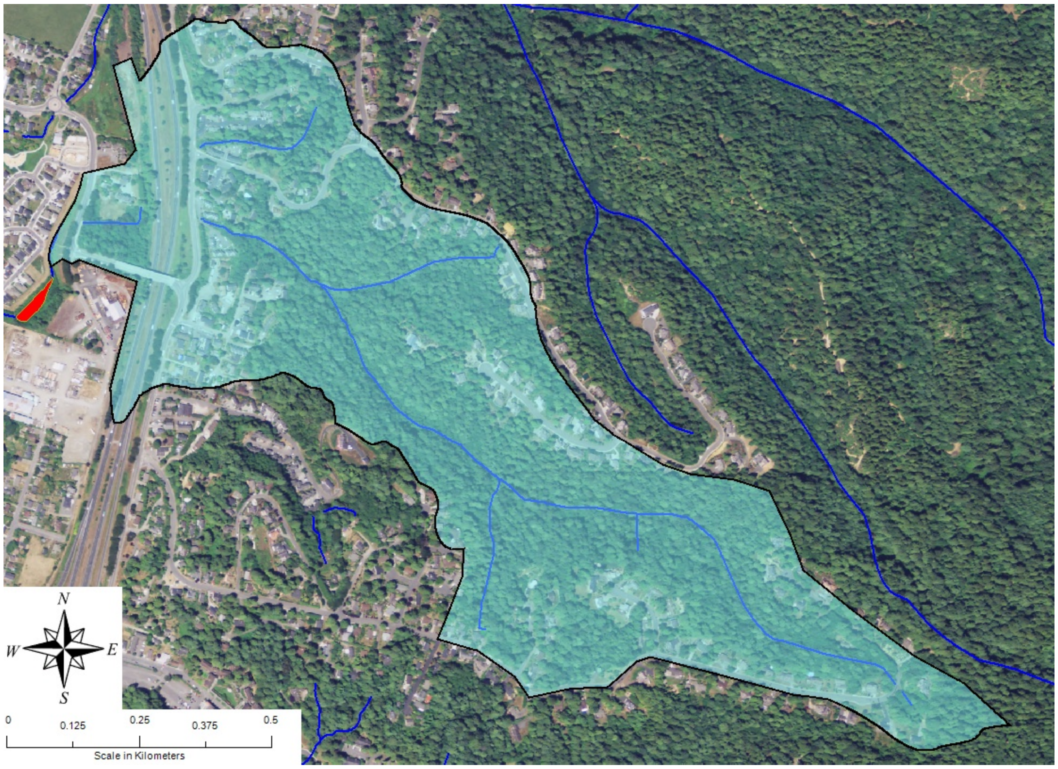

Figure 4. Janes Creek east fork wetland watershed aerial photo overlay, Arcata California 2010-2011. Wetland depicted in red.

The majority of the wetland is covered in cattails (*Typha latifolia*), canary grass (*Phalaris spp.*) and Pacific water parsley (*Oenanthe sarmentosa*). Creeping buttercup (*Ranunculus repens*) and coastal willow (*Salix hookeriana*) are located around the perimeter of the wetland.

The Campbell Creek wetland (Figure 5) was created as a community center mitigation project in 2000 (City of Arcata 2011). The wetland covers an area of 0.072 ha and can hold 3,028 m^3 of water (City of Arcata 2011). Campbell Creek wetland receives runoff from a 95 ha watershed that is 23.4% impervious.

Vegetation consists mostly of cattails (*Typha latifolia*), bull rush (*Scirpus* spp.), and *Hydrocotyle sibthorpioides* around the wetted outer edge with sparse growth of skunk cabbage (*Lysichiton americanum*) and arrowhead (*Sagittaria* *latifolia*) near the entrance and exit of the wetland. The majority of the wetland is dominated by floating pond weed (*Potamogeton natans*). Around the perimeter of the wetland, where freestanding water occurs only during storms, Pacific water parsley (*Oenanthe sarmentosa*), creeping buttercup (*Ranunculus repens*), and Himalayan blackberry (*Rubus discolor*) dominate.

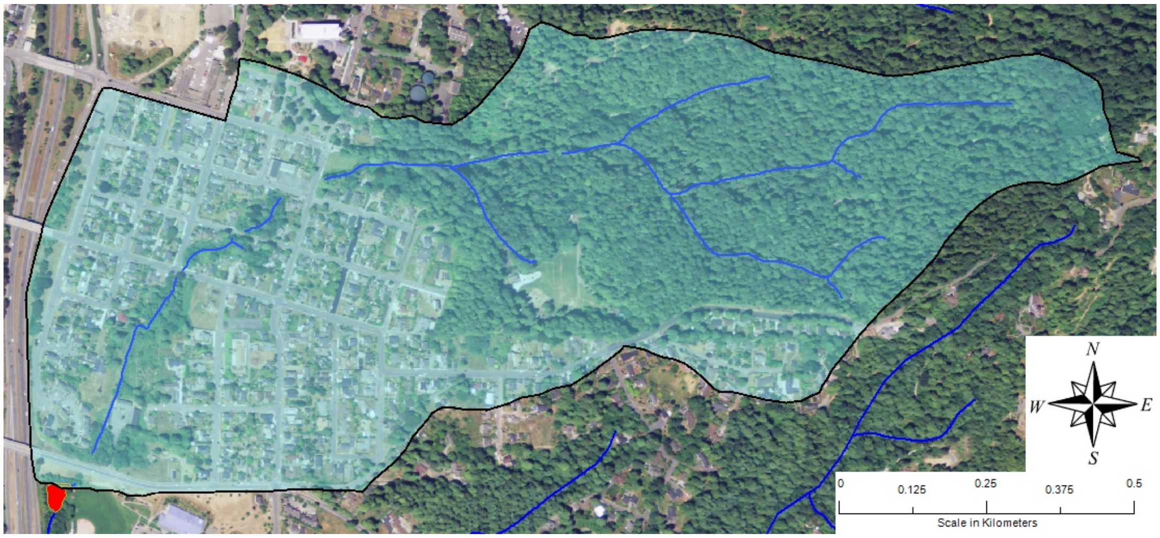

Figure 5. Campbell Creek wetland watershed aerial photo overlay, Arcata California 2010-2011. Wetland depicted in red.

Data Collection

Each water quality parameter was measured as water entered the wetland and immediately upon exiting. All grab samples were taken in the average flow velocity about 6/10 of the depth of the water column and processed at the Wastewater Laboratory at Humboldt State University. All field samples were collected and processed in accordance with the “Field Guide for Collecting and Processing Stream-Water Samples for the National Water-Quality Assessment Program” (Shelton 1994).

Grab samples were taken in autoclaved sterilized (150°C) 500 mL HDPE plastic Nalgene bottles. Fecal coliforms were filtered using Millipore 0.45 μm sterile filters (cat no: HAWG047S6). After filtration each filter was placed on Difco brand mFC agar and transferred to a water bath incubator (Isotemp 220) within 6 hours of being sampled. Incubation took place at 44.5°C for 24 hours. Fecal coliform enumeration was conducted in accordance with the membrane filtration technique as described in the Standard Methods for the Examination of Water and Wastewater method 9222 D (Eaton 2005).

Turbidity was measured using a Hach La Motte 2020e portable turbidimeter at the same time and location as grab samples from September 18, 2010 to November 22, 2010. All *in situ* samples were taken at ~6/10 the depth of flow to get a good representation of the sediment being transported downstream. Due to equipment failure, turbidity measurements were taken from grab samples in the laboratory using a Hach 2100Q turbidimeter from February 17, 2011 to May 13, 2011. Both meters were calibrated according to manufacturer's instructions using the factory supplied calibration solutions.

Temperature measurements were collected *in situ* in accordance with Shelton (1994). All temperature measurements were taken using a Hanna portable pH/Temperature handheld meter and tested against laboratory thermometers to ensure consistency throughout the study. After each use the Hanna meter was rinsed with distilled water to prevent contamination of subsequent samples.

Discharge was measured by Global water flow probe (model FP101). Flow was calculated by multiplying velocity (ms^{-1}) of each sub section in a cross section by the area of that subsection (m^2). The flows for each subsection were then summed to obtain the total flow (m^3/sec) for each stream.

Suspended solids were measured using the TSS method. All laboratory TSS quality assurance measures for equipment, handling, storage, processing, data entry, logbooks and data management came from the "Quality-Assurance plan for the Analysis of Fluvial Sediments by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory" manual (Shreve and Downs 2005).

Filter preparation, weighing and drying was conducted in accordance with the United States Department of Agriculture sediment laboratory procedures (2006). All filters were washed three times with 25mL of distilled water, heated to 450°C for four hours and then weighed before samples were passed through them to remove any affinity the filter may have for certain particles, to ensure the filter pulls evenly and to remove anything that may influence filter weights. All filters were weighed on an analytical balance (±0.0001g).

TSS was performed using approximately 100-400 mL of sample passed through the prewashed and combusted filters. Filters and suspended solids were then dried at 105 °C for at least 12 hours to remove any water not trapped in inorganic materials. After drying and cooling in a desiccator for thirty minutes, samples were weighed on an analytical balance (±0.0001g) and compared to the original weight of the filter to determine total suspended solids. Samples were then combusted at 450°C for four hours to burn off organic materials. Immediately after ashing, samples were placed in a desiccator for 30 minutes to cool to room temperature. Samples were then weighed on an analytical balance (±0.0001g) to determine weight of the remaining inorganic suspended solids. Organic suspend solids were determined using the equation:

OSS (mg/l)=TSS (mg/l)-ISS (mg/l)

The standard methods for the examination of water and wastewater (Eaton 2005) suggests 550°C as the temperature used to determine organic matter in wastewater, activated sludge and industrial wastes. This is typically the method used in studies utilizing loss-on-ignition (LOI) to find organic matter in aquatic environments. It has been shown to be highly correlated to organic matter content (Konen et al. 2002). However, when samples contain clay and other minerals, the water contained within the minerals (known as structural water) can be retained at 100°C and then released at higher temperatures which will increase OSS estimates as a result of water loss. While each mineral has a different water retention temperature, clays have been shown to have the most effect on overestimation of organics due to structural water loss at 550°C (Jackson 1969, Frangipane et al. 2008, Sun et al. 2009). Frangipane suggests using temperatures less than 500°C (2009) for LOI analysis and Lal et al. suggested using 450°C for 4 hours based on their own weight loss on ignition (WLOI) research (1998). In order to reduce water loss and sufficiently burn off carbon (Jackson 1969, Lal et al. 1998, Frangipane et al. 2009, Sun et al. 2009) I used 450°C for four hours to determine OSS.

To determine the structural water loss of samples in this study 72 samples were combusted at 450°C weighed, rewetted and placed back in the oven at 104°C to dry. The increase in weight between the combusted vs. rewetted and dried samples was considered to be the weight of water lost due to combustion. Forty of the samples used in the rewetting analysis were then placed in the furnace at 550°C to check for any additional weight loss due to water loss and (or) burn off of recalcitrant materials.

Hach method 8048 was used to determine the soluble reactive phosphorous (orthophosphate) content of water samples. Measurements were carried out using a Hach Colorimeter and Hach PhosphoVer®3 (ascorbic acid) reagents.

Storm flow is defined as the flow resulting from a storm accumulating at least one inch (25.4 mm). Base flows are defined as at least two days after peak discharge in stream flow due to a storm event.

Statistical Analysis

Most statistical tests require the random sampling of locations and times to get an accurate representation of the entire population. Neither the sites nor the sampling times in this study were random. Instead, they were chosen based on accessibility and timing of rain events and are therefore not representative of the entire population. Because the randomization assumption was not met and the data were not expected to have equal variance or normality, non-parametric statistics (bootstrap randomization) were used. It was expected that the data would be non-normal as a result of summer buildup and winter depletion of pollutants. Variances were expected to be different as a result of a decrease in concentrations downstream of the wetland resulting in reduced variation in the effluent as opposed to the influent. I hypothesized that fecal coliforms, phosphorous, organic suspended solids, inorganic suspended solids and total suspended solids would decrease after wetland treatment and therefore used a one-way randomization test for these factors.

Bootstrap Randomization assumes under the null hypothesis that if upstream and downstream values are not different then all combinations of these data are equally likely to occur. Under this assumption the actual difference found from the sampling data should not significantly differ from the means found from random reallocation (n=10,000). If the mean difference from sampling is greater than or equal to 95% of the mean differences from random reallocations it would be highly unlikely the data gathered was a result of chance (α=0.05). The number of mean differences that are equal to or greater than the mean difference found from the actual sample divided by the number of mean differences that are less than the actual sample (n=10,000) becomes the p-value for a one sided test. P-values less than α =0.05 result in a rejection of the null hypothesis. All statistical analyses were conducted using R software version 2.11.1.

RESULTS

Suspended Solids and Turbidity

Suspended solids and turbidity sampling took place during storm events from August 2010 to May 2011 on Jolly Giant and Campbell Creeks. Janes Creek was sampled from November 2010 to May 2011 and base flow sampling for all wetlands took place from January 25 to May 13, 2011. The first storm of the year occurred in August. Data show evidence of a first flush phenomenon for upstream sections of Jolly Giant but not Campbell Creek. Downstream data did not show evidence of a first flush for either stream. All wetlands show a significant ($\alpha=0.05$) reduction in TSS (Figure 6) and OSS. Only Janes Creek east fork does not show a significant reduction in ISS ($\alpha=0.55$). Turbidity was reduced in all of the wetlands (Figure 7); however, none are significant. All low flow turbidity samples had values less than 25 NTU.

Percent reduction for this study is based on mean % or geometric mean % difference between upstream and downstream concentrations using the equation:

(1) Reduction %=(((inflow-outflow)/inflow)*100) (Pundsack et al. 2001)

Janes Creek West Fork and Campbell Creek wetlands showed the highest reductions in TSS, ISS and OSS. Their reduction was almost double the reductions of Janes Creek East Fork and Jolly Giant wetlands. It is important to note that Janes Creek West Fork and Campbell Creek also had significantly higher input concentrations of TSS, ISS and OSS along with the largest watersheds.

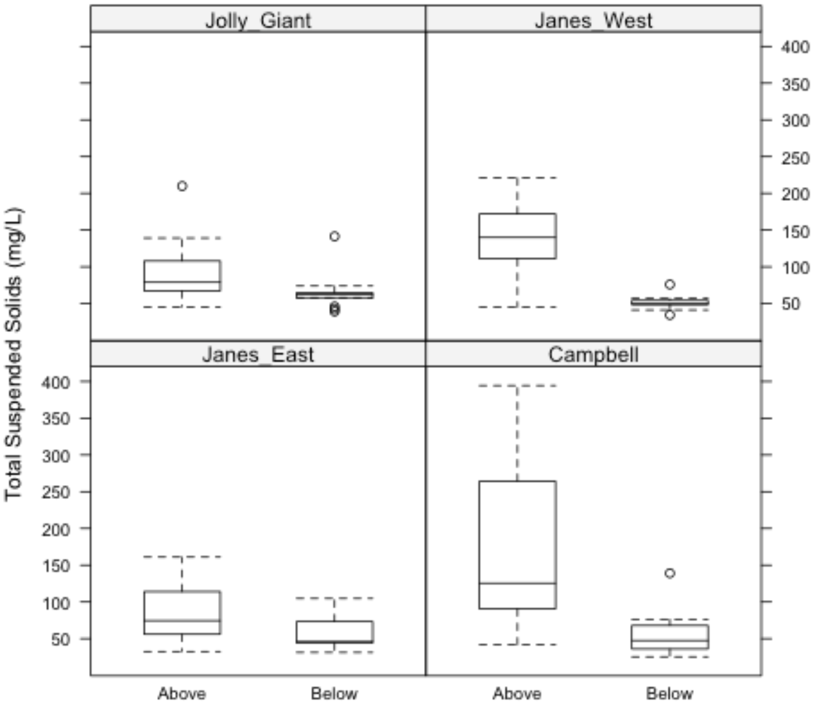

Figure 6. Storm flow TSS boxplot for all wetlands, Arcata California 2010-2011. Jolly Giant and Campbell (n=14); Janes Creek (n= 9).

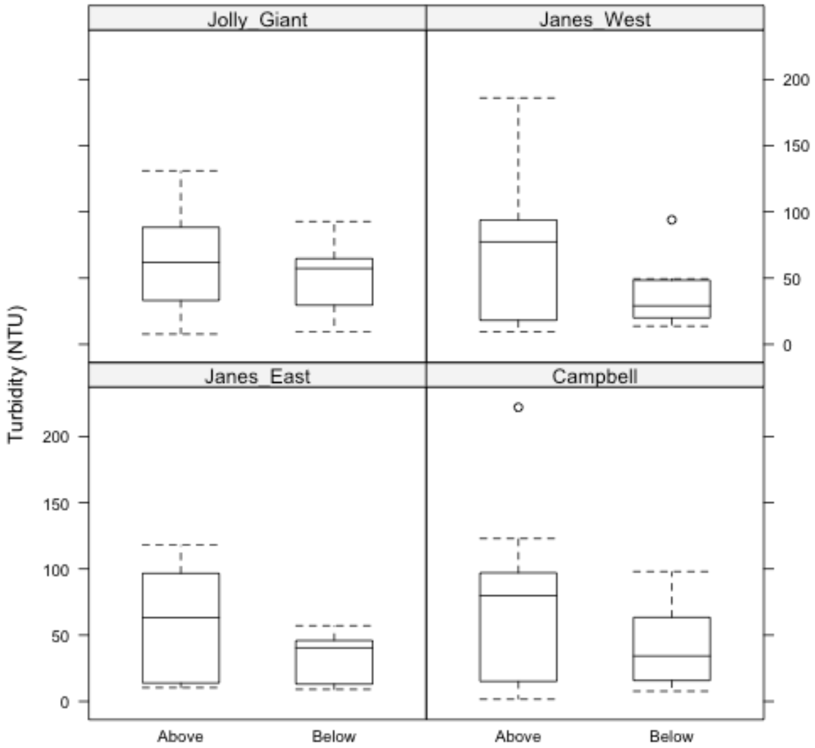

Figure 7. Storm flow turbidity boxplot for all wetlands, Arcata California 2010-2011. Jolly Giant and Campbell (n=12); Janes Creek (n=7).

Mean influent TSS concentrations differ by 94% (sd=77.7 mg/l) between the lowest and the highest TSS mean concentrations whereas effluent concentrations differ by 25% (sd=23.4 mg/l). If Jolly Giant was removed the difference between the highest and lowest mean TSS effluents would be 13%.

All wetlands removed both the OSS and ISS fraction of TSS (Table 2). OSS removal was higher than ISS for Janes Creek East Fork and Jolly Giant wetlands. However, ISS removal was higher for Janes Creek West Fork and Campbell wetlands. Janes Creek West Fork and Campbell Creek had mean influent ISS concentrations more than 4 times OSS while Janes Creek East Fork and Jolly Giant's ISS

Table 2. Suspended solids and turbidity reduction with p-values by wetland, 2011 hydrologic year.

Percent Reduction

Site	TSS	OSS	ISS	Turbidity
Janes Creek East Fork	33.3%	37.3%	32.1%	41.8%
Janes Creek West Fork	63.0%	56.8%	64.4%	46.3%
Jolly Giant	28.6%	30.6%	28.1%	20.0%
Campbell	67.6%	61.5%	69.1%	42.1%

Reduction p-value

Janes Creek East Fork	0.045	0.015	0.055	0.068
Janes Creek West Fork	0.000	0.000	0.000	0.065
Jolly Giant	0.024	0.009	0.036	0.192
Campbell	0.000	0.000	0.000	0.056

P-values based on one tailed randomization test on means of storm samples only. Percent reduction determined by percent reduction equation using means. Turbidity - Janes Creek wetlands (n=7), Jolly Giant & Campbell (n=12). SS - Janes Creek wetlands (n=9), Jolly Giant & [1]Campbell (n=14). TSS is total suspended solids, OSS is organic suspended solids and ISS is inorganic suspended solids.

concentrations were 3.4 times greater than OSS (Appendix A). Effluent mean OSS for all wetlands made up ~22% of the suspended load during storm and base flow events (Appendix A).

I hypothesized that ISS reduction would be greater than OSS reduction as a result of organics being lighter than inorganics. In addition, the high organic content of the wetlands would potentially add to the organic load in the effluent. This was seen in Janes Creek West Fork and Campbell but not Janes Creek East Fork and Jolly Giant.

Loss on ignition water loss at 450°C

The results of water loss from minerals using the 450°C loss on ignition (LOI) method show a logarithmic decrease in water for storm flow samples as TSS increased (Figure 8). In high flow TSS samples weighing less than 50 mg/l, the mean percent water loss by weight compared to TSS mean weight was 5.7%. For high flow TSS samples greater than 50 mg/l, mean water loss was 1.7% of TSS. Low flows had a larger range for percent water loss, which is attributed to an increase in measurement error as sample weights decreased. When combusted samples were placed back in the furnace at 550°C to check for additional weight loss no significant decrease was found indicating that 550°C is an adequate temperature and does not result in water or organic material loss greater than what was observed in samples combusted at 450°C.

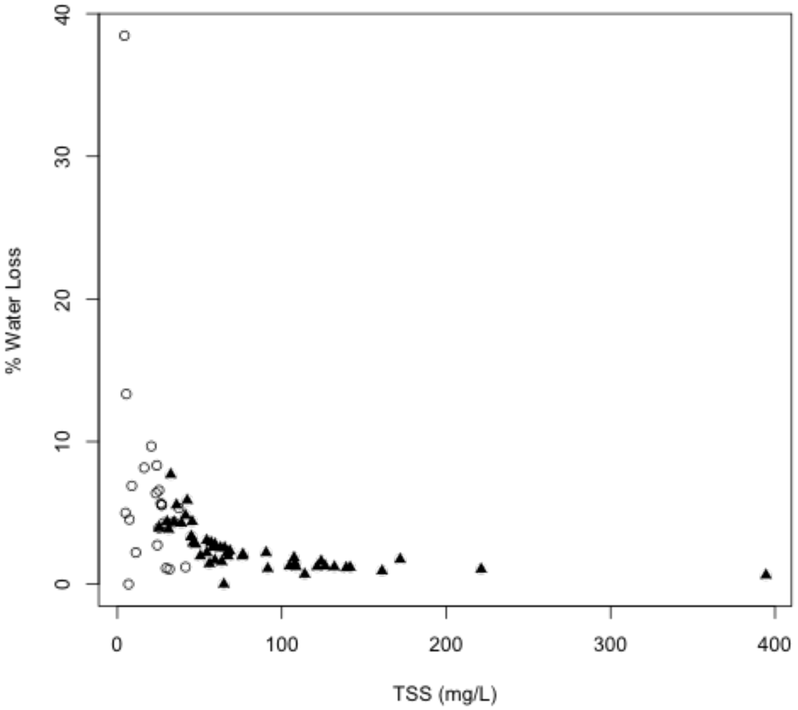

Figure 8. Water loss from clay as a result of ashing SS samples at 450°C. Percent water loss determined by water loss weight to TSS weight (n=72). ○ =low flow samples and ▲=high flow samples.

Fecal Coliforms

Fecal coliforms were measured above and below each wetland to obtain measurements of the effectiveness of storm water wetlands on reduction of pathogen loading (Figure 9). Reductions were found to be insignificant ($\alpha=0.05$) for all wetlands. Janes Creek West Fork had the lowest influent fecal coliform concentrations (geometric mean= 273 CFU/100 mL) along with the lowest percentage of impervious surfaces (13%) made up of primarily industrial areas. Campbell Creek had the highest influent coliform concentrations (geometric mean= 1,881 CFU/100mL) and the highest % impervious area (23%), which was primarily suburban housing. Janes Creek east fork (1182 CFU/100mL) and Jolly Giant (1249

CFU/100mL) had similar influent fecal coliform geometric mean concentrations and similar percent impervious surfaces, 18% and 12% respectively.

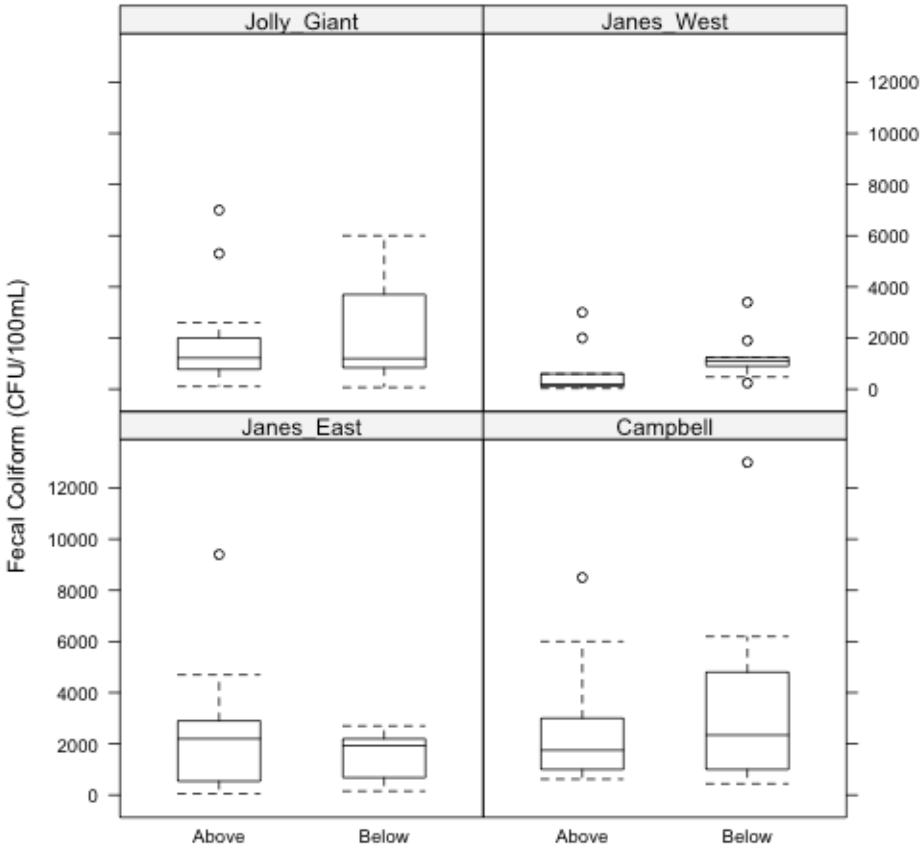

Figure 9. Storm flow boxplot of fecal coliform concentrations for all wetlands, Arcata California 2010-2011. Jolly Giant and Campbell (n=14); Janes Creek (n=9).

Current EPA regulations recommend fecal coliform geometric mean concentrations of less than 200 CFU/100mL for a 30-day period and no more than 10% of samples greater than 400 CFU/100mL (United States Environmental Protection Agency 1976). All sites during storm flows had geometric means above 200 CFU/100mL and only Janes Creek west fork had an influent geometric mean below 400 CFU/100mL.

During low flows none of the wetlands had influent or effluent geometric means above 200 CFU/100mL and none showed significant reductions. Campbell Creek had the highest concentrations entering and leaving the wetland and Janes Creek West fork had the lowest for low flow samples.

Phosphorous

Variability in soluble reactive phosphorous measurements among wetlands was high. However, no patterns were seen. There were no significant differences found between upstream and downstream concentrations using a one way randomization test of geometric means (α=0.05) although all wetlands show some reduction in phosphorous except for Jolly Giant (Table 3). Janes West Fork had the highest influent and effluent concentrations of phosphorous while Jolly Giant, Janes East Fork and Campbell showed similar concentrations in both the influent and effluent (Figure 10). As a result of skewness in the data, the geometric mean was used to identify the central tendencies of phosphorous concentrations.

Table 3. Phosphorous geometric means upstream and downstream of treatment wetland with geometric mean percent reduction and p-values for high flows, 2011 hydrologic year, Arcata California. Jolly Giant & Campbell (n=14), Janes Creeks (n=9)

Site	Upstream (mg/L)	Downstream (mg/L)	Reduction	p-value
Janes Creek East Fork	0.24	0.18	27%	0.084
Janes Creek West Fork	0.30	0.26	14%	0.341
Jolly Giant	0.21	0.22	-7.1%	0.606
Campbell	0.18	0.16	13%	0.316

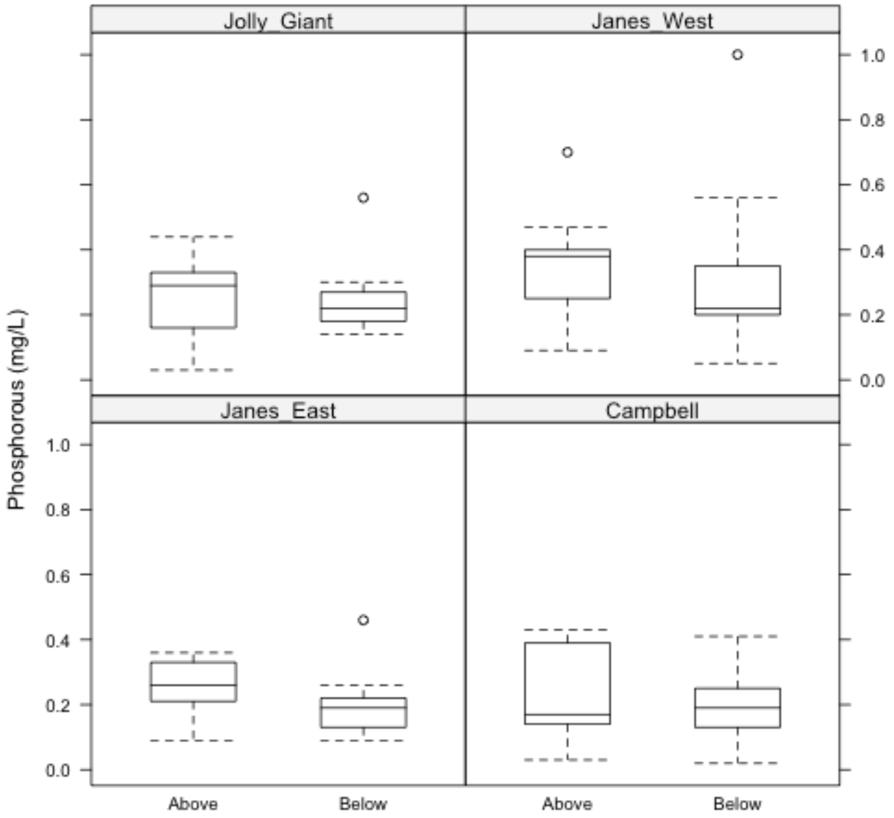

Figure 10. Storm flow boxplot of phosphorus concentrations for all wetlands, Arcata California 2010-2011.
Jolly Giant & Campbell (n=14), Janes Creek (n=9).

Temperature and Flow

Temperatures entering and leaving the wetlands were not significantly different for any of the wetlands (α=0.05). Jolly Giant and Campbell wetlands had the highest temperature means and the highest temperature ranges (Figure 11). This was likely a result of sampling early in the year when the weather was warmer. Janes West Fork and Janes East Fork had similar temperature ranges.

Campbell wetland had the lowest flows and Jolly Giant wetland had the highest even though Janes West Fork had the largest watershed and Janes East Fork the smallest (Figure 12).

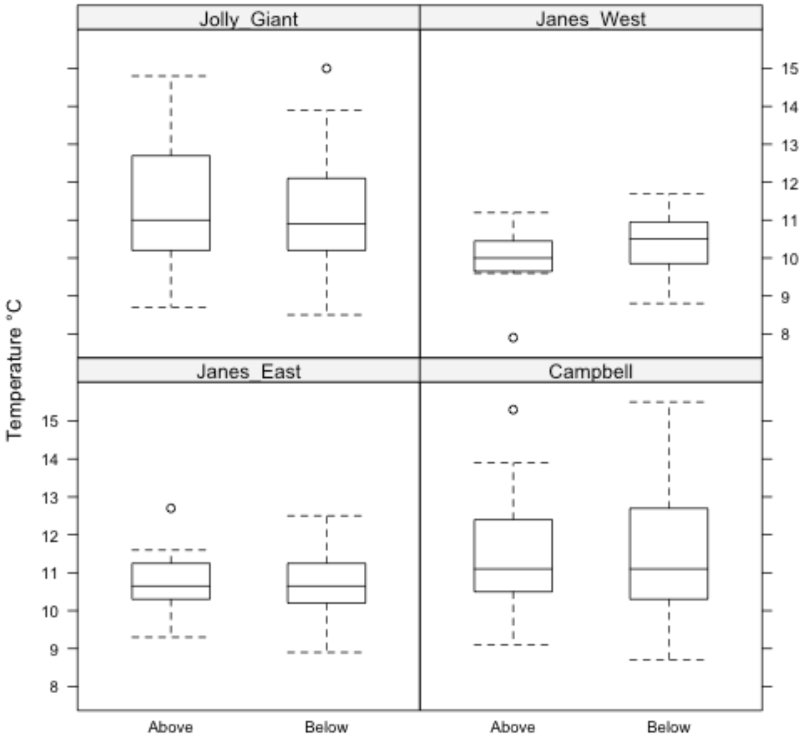

Figure 11. Storm flow boxplot of temperatures for all wetlands, Arcata California 2010-2011. Jolly Giant & Campbell (n=14), Janes Creek (n=9).

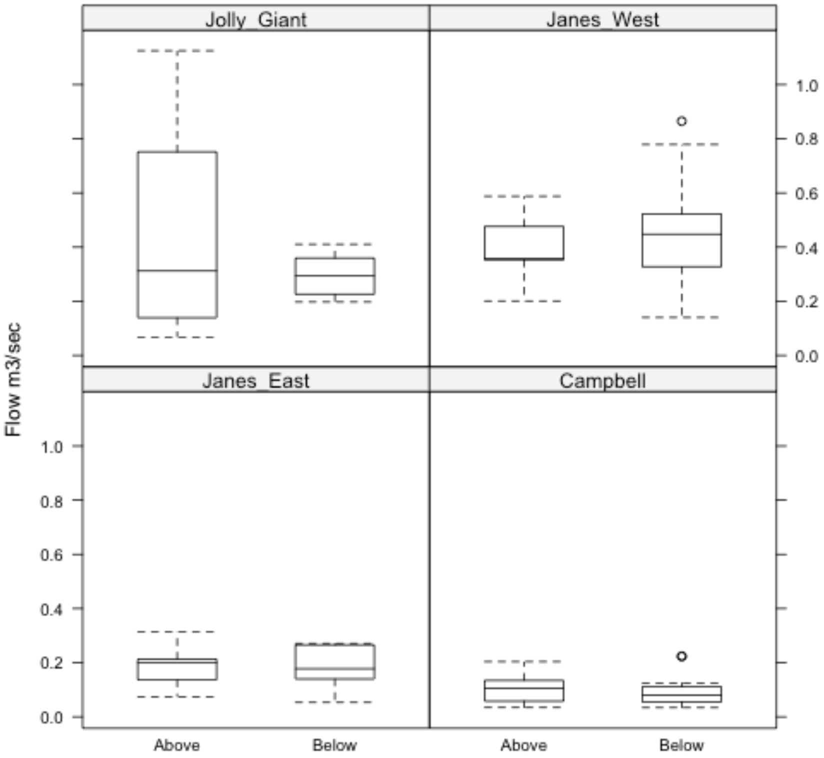

Figure 12. Storm flow boxplot of flow for all wetlands, Arcata California 2010-2011. Jolly Giant and Campbell (n=14), Janes Creek (n=9).

DISCUSSION

Total suspended solids, inorganic suspended solids and organic suspended solids showed significant reductions as a result of Arcata's in-stream wetlands. Total suspended solids reduction ranged from 28-67%. The median reduction for suburban runoff wetland treatment in the U.S. is roughly 68% (Kadlec and Wallace 2009). Organic suspended solids had mean reduction efficiencies of 31-62% and inorganic suspended solids had mean reduction efficiencies of 28-69%. Mean organic suspended solids from the Campbell Creek and two Janes Creek wetlands had effluent concentrations from ~11.2-12.4 mg/l whereas Jolly Giant wetland had a mean concentration of 14.3 mg/l. Mean inorganic effluent concentrations show a similar trend with values from 40.6-46.5 mg/l for Campbell and the two Janes Creek wetlands and 50.5 mg/l for Jolly Giant wetland.

Jolly Giant wetland is the least efficient at removing suspended solids of all of the wetlands in this study. Part of the reason for this is that samples were taken as the water entered the wetland directly downstream of a settling basin. This settling basin was designed to settle out larger particles before entering the wetland allowing the wetland to last longer and the City to easily remove excess sediment. Even though the settling basin lowered Jolly Giant's reduction values by removing easily settled particles, Jolly Giant also had the highest effluent suspended solids concentrations. Jolly Giant wetland had mean organic and inorganic effluent concentrations that were 16% and 17% higher than the other wetlands. The reasons Jolly Giant has the highest effluent concentrations is because it is the smallest wetland by surface area relative to the size of the watershed. In addition, the angle of entry for the influent is aimed almost directly at the outlet. As the influent enters Jolly Giant wetland the water is not forced into the outer reaches of the wetland where denser vegetation and a longer flow path would aid in the removal of suspended material. Water moves quickly to the outflow reducing residence time and lowering its settling effectiveness.

The most efficient wetland for suspended solids removal was Campbell Creek which reduced total suspended solids by 68%, organic suspended solids by 62% and inorganic suspended solids by 69%. Campbell Creek had the lowest flows of all of the wetlands and higher concentrations of suspended solids. The low flows increased retention time allowing suspended solids to be removed more efficiently than the other wetlands. Campbell Creek wetland also had about a 90^{o} angle of entry and a shore design that forces the water to zigzag across the wetland and into the denser emergent vegetation where residence time and settling increased. Also, the entrance to the wetland contained a vegetated strip rather than a channel. This acts to spread out the incoming water into different directions effectively reducing its velocity and ability to take on a preferential flow path.

Organic suspended solids concentrations across this study were found to make up ~22% of the total suspended solids during high and low flows. This is consistent with other findings (Kantrowitz and Woodham 1995, Madej 2005, Galloway 2008). It has been commonly believed that organics in the suspended load are insignificant by weight (Guy 1969) and are therefore rarely taken into account.

This study along with others provide evidence that this is not always the case. Organic suspended solids can make up a significant portion of the suspended load during both high and low flows and therefore should not be overlooked when determining suspended solids concentrations or impact.

Organic suspended solids in headwaters streams are the result of litter fall and lateral movement of allochtonous riparian materials (Fisher and Likens 1973). Organic suspended solids are the basis of the aquatic food web (Fisher and Likens 1973, Jones et al. 1991) and essential for aquatic life and diversity (Wallace et al. 1997). However, current suspended solids regulations only take into account the total amount of suspended materials when determining their potential deleterious impact. To fully understand the impacts of suspended solids it will be essential that future suspended solids research also take into account the organic portion of the suspended load as it can be significant and constitute a benefit rather than a detriment to the aquatic environment.

I had hypothesized that inorganic suspended solids reduction in wetlands would be greater than organic suspended solids reduction as a result of organics being lighter coupled with the high organic contents of wetlands. Overall this trend was not seen and it is not understood why.

Turbidity was reduced in all of the wetlands though none of the reductions were statistically significant. It was hypothesized that the depressional wetlands would show higher reductions in turbidity and suspended solids because particle settling is inversely proportional to depth (Kadlec and Wallace 2009). The depressional wetlands are about 0.3-1 meter deep during high flows whereas the free water surface wetlands are about 1-3 meters deep. With the depressional wetlands being shallower, particles would need less time to settle out than they would in the deeper free water surface wetlands. However, residence time during high flows was estimated to be less than 24 hours making the wetlands unable to reduce the finest particles (Ministry of Environment and Energy 1994) that likely caused much of the high turbidity even with shallower depths. All low flow turbidity samples were less than 25 NTU.

Janes West, Janes East, Jolly Giant and Campbell wetlands showed no significant reduction in fecal coliforms. Fecal coliform removal in storm water wetlands has been found to be associated with the settling of finer (<5μm) particles (Davies and Bavor 2000, Characklis 2005), which can take weeks to months to achieve (Ministry of Environment and Energy 1994). Arcata's wetlands held storm water for less than 24 hours during peak storm flows making them unreliable in retaining the sediment size needed to reduce bacterial loading during the 2010-2011 hydrologic year.

Reduced efficiency of fecal coliform removal could also be caused by reintroduction and regrowth (Karim et al. 2004). Reintroduction is the result of defecation directly into and around the wetland from animals and homeless people commonly seen near wetlands. In wetlands with warmer temperatures and high concentrations of organic matter, fecal coliforms have the ability to reproduce, also known as regrowth, resulting in higher fecal coliform effluent concentrations. In wetlands receiving lower CFU values ($<10^4$/100mL), FWS wetland performance is reduced because regrowth and reintroduction can be on the order of about 0-10^3

CFU/100mL (Kadlec and Wallace 2009). Median effluent CFU values from Arcata's wetlands during storm flows are close to 1,500 CFU/100mL making reintroduction and regrowth potentially significant factors in determining efficiencies. While reintroduction by wildlife is problematic, these wetlands provide essential habitat to local wildlife, fish and migratory birds traveling along the Pacific flyway.

Wetland studies from other regions show decreases in fecal indicator bacteria of up to 90% (Kadlec and Wallace 2009). However, wetland research focuses on municipal and industrial wastewater treatment where sedimentation, natural die off, filtration, predation, heat and UV radiation have weeks to months to act on bacterial loading. During storm events only sedimentation and filtration of the finest particles are likely to reduce bacterial loading and residence time was not long enough to accomplish this.

Rewetting and drying of suspended solids samples after ashing at 450°C (n=72) showed that water loss from clays as a result of ashing can be as high as 1.7-5.7% of the total suspended solids weight. When samples from the rewetting analysis were re-combusted at 550°C no significant ($\alpha=0.05$) decrease in weight was found. This indicates that four hours at 450°C or 550°C will give the same results when determining organic content of suspended solids samples in Arcata's streams.

The principle issue that needs to be addressed in order to increase the efficiency of Arcata's wetlands in removing storm water pollution is retention time. One way to increase retention time is to increase the area of the wetlands so water has farther to travel and the wetlands can hold a larger portion of a storm for a longer amount of time. Due to land and topographic constraints this is not currently possible for the Janes Creek wetlands. However, it is possible for the Campbell Creek wetland which can be extended south towards Samoa road and the Jolly Giant wetland which could be extended west within Shay park. By increasing the size of the wetlands and the distance from the inlet and outlet, retention time and contact with vegetation will increase and lead to higher retention rates of suspended solids, turbidity and potentially bacterial loading. This extension would also increase wildlife and fish habitat.

Jolly Giant wetland could be made more efficient with a few design changes. The most important change is the angle of the incoming water relative to the effluent water. By moving the inlet to enter the wetland from a 90° angle more water will be forced into the out edges of the wetland where denser vegetation and a longer treatment path will help facilitate further reductions in suspended solids, turbidity and potentially bacterial loading. Adding a wide opening to the influent and a vegetated strip, similar to Campbell Creek's, along the entire length of this opening will spread the water out evenly into the wetland, reduce its velocity and reduce the ability of the water to take a direct flow path to the outlet. Currently Jolly Giant wetland is having water draw-down issues that can significantly affect established wetland vegetation and future treatment. Just before the log at the effluent a hole is causing the water levels to be much lower than the established height designated by the log. By filling in this hole the water will rise and provide wetland plants a larger area to grow which will aid in future wetland pollution removal and increase wildlife habitat.

The Campbell Creek wetland could benefit from dredging the settling basin immediately upstream from the wetland entrance. Currently this basin is almost entirely full and its depths are the same as the incoming stream. During high flows the sediment basin becomes a channel that pushes materials once settled out in the basin into the wetland. As a result, the Campbell wetland is receiving all of the sediment from the watershed, effectively reducing its longevity and increasing future maintenance costs. I suggest making the settling basin larger and deeper so incoming particles can immediately settle out and be easily removed. Making a larger settling basin would increase sedimentation and reduce the number of times the basin would need to be dredged which would result in reduced maintenance costs and cleaner streams.

One likely significant source of bacterial loading to Arcata's streams and wetlands is the homeless populations who are often found camping for extended periods of time around Campbell and Jolly Giant wetlands. During this study human feces, toilet paper and camping equipment were found around both of these wetlands. Keeping these areas free of camping would likely reduce the bacterial load to Arcata's wetlands and streams.

My study has shown the potential significance of organics in suspended solids calculation and it is believed that future research should try to quantify the impacts of organic and inorganic suspended solids on ecosystems to help better understand each independently. To only identify the total amount of suspended material and not take into account the influence of organics is to leave out valuable information that could be used to make future restoration projects more successful.

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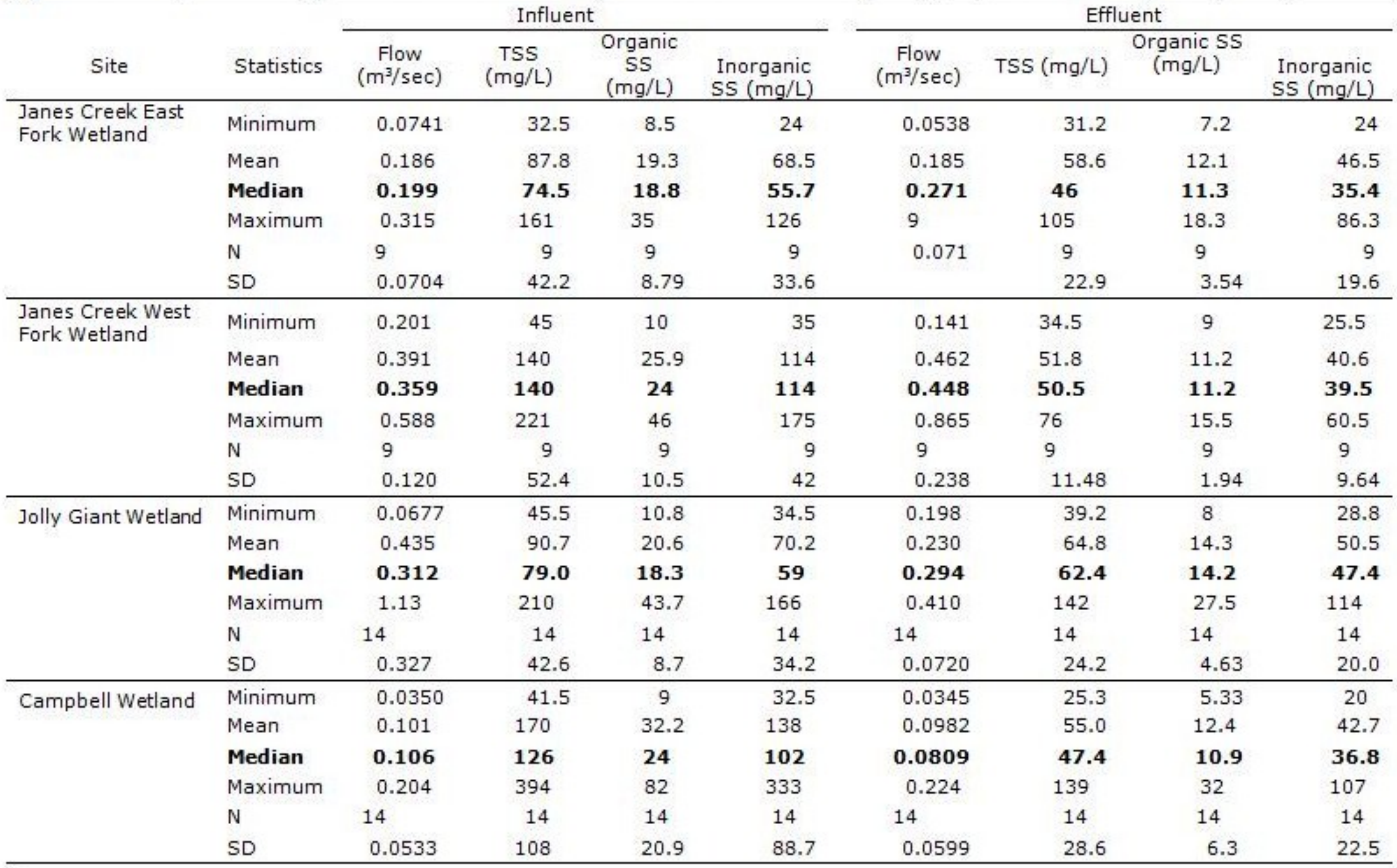
APPENDIX

Appendix A: High flow suspended solids statistics. Janes Creek wetlands (n=9), Jolly Giant & Campbell (n=14).

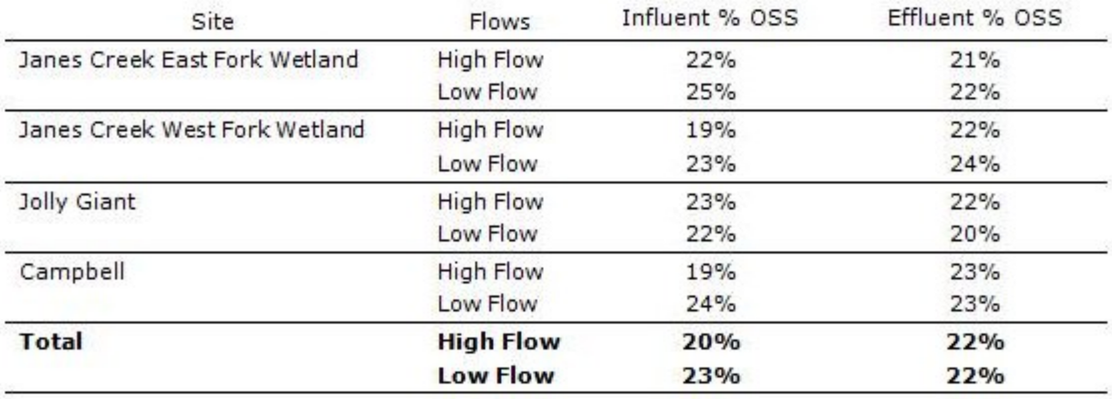


		Influent				Effluent			
Site	Statistics	Flow (m³/sec)	TSS (mg/L)	Organic SS (mg/L)	Inorganic SS (mg/L)	Flow (m³/sec)	TSS (mg/L)	Organic SS (mg/L)	Inorganic SS (mg/L)
Janes Creek East Fork Wetland	Minimum	0.0741	32.5	8.5	24	0.0538	31.2	7.2	24
	Mean	0.186	87.8	19.3	68.5	0.185	58.6	12.1	46.5
	Median	**0.199**	**74.5**	**18.8**	**55.7**	**0.271**	**46**	**11.3**	**35.4**
	Maximum	0.315	161	35	126	9	105	18.3	86.3
	N	9	9	9	9	0.071	9	9	9
	SD	0.0704	42.2	8.79	33.6		22.9	3.54	19.6
Janes Creek West Fork Wetland	Minimum	0.201	45	10	35	0.141	34.5	9	25.5
	Mean	0.391	140	25.9	114	0.462	51.8	11.2	40.6
	Median	**0.359**	**140**	**24**	**114**	**0.448**	**50.5**	**11.2**	**39.5**
	Maximum	0.588	221	46	175	0.865	76	15.5	60.5
	N	9	9	9	9	9	9	9	9
	SD	0.120	52.4	10.5	42	0.238	11.48	1.94	9.64
Jolly Giant Wetland	Minimum	0.0677	45.5	10.8	34.5	0.198	39.2	8	28.8
	Mean	0.435	90.7	20.6	70.2	0.230	64.8	14.3	50.5
	Median	**0.312**	**79.0**	**18.3**	**59**	**0.294**	**62.4**	**14.2**	**47.4**
	Maximum	1.13	210	43.7	166	0.410	142	27.5	114
	N	14	14	14	14	14	14	14	14
	SD	0.327	42.6	8.7	34.2	0.0720	24.2	4.63	20.0
Campbell Wetland	Minimum	0.0350	41.5	9	32.5	0.0345	25.3	5.33	20
	Mean	0.101	170	32.2	138	0.0982	55.0	12.4	42.7
	Median	**0.106**	**126**	**24**	**102**	**0.0809**	**47.4**	**10.9**	**36.8**
	Maximum	0.204	394	82	333	0.224	139	32	107
	N	14	14	14	14	14	14	14	14
	SD	0.0533	108	20.9	88.7	0.0599	28.6	6.3	22.5

Appendix B: Low flow suspended solids statistics (n=3)

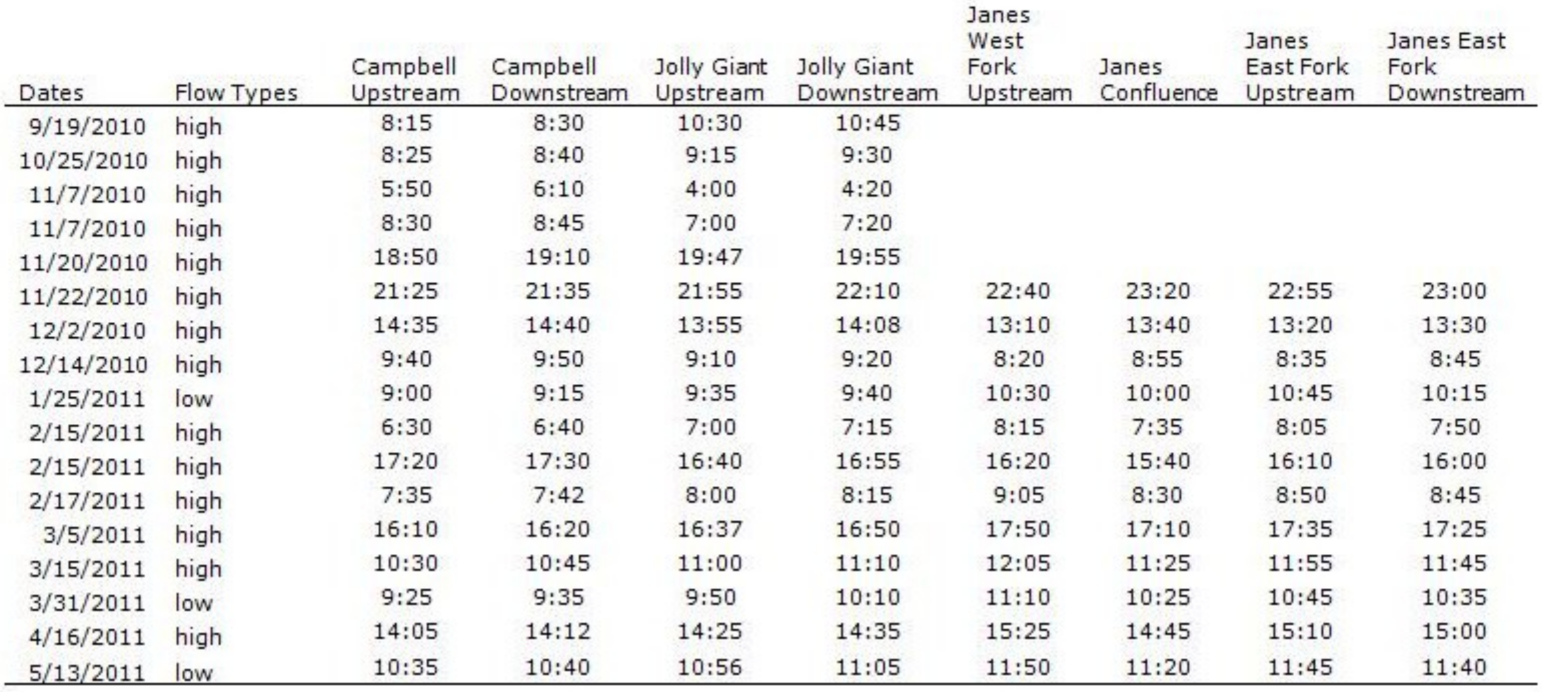
			Inflow			Outflow	
Site	Statistics	TSS (mg/L)	Organic SS (mg/L)	Inorganic SS (mg/L)	TSS (mg/L)	Organic SS (mg/L)	Inorganic SS (mg/L)
Janes Creek East Fork Wetland	Minimum	8.81	2.74	6.08	7.33	1.67	5.67
	Mean	**20.2**	**4.97**	**15.3**	**18.7**	**4.16**	**14.6**
	Median	25.3	5.67	19.7	23.5	5.33	18.0
	Maximum	26.5	6.5	20.0	25.3	5.5	20.0
	N	3	3	3	3	3	3
	SD	9.89	1.98	7.94	9.90	2.17	7.76
Janes Creek West Fork Wetland	Minimum	11.25	2.75	8.50	29.7	6.67	23.0
	Mean	**25.8**	**5.91**	**19.9**	**36.2**	**8.56**	**27.7**
	Median	31.7	7.00	24.7	37.5	9.00	27.5
	Maximum	34.5	8.00	26.5	41.5	10.0	32.5
	N	3	3	3	3	3	3
	SD	12.7	2.79	9.91	6.02	1.71	4.75
Jolly Giant Wetland	Minimum	5.49	1.47	4.03	6.82	1.77	5.05
	Mean	**19.2**	**4.22**	**14.9**	**20.1**	**4.03**	**16.1**
	Median	24.0	5.2	18.8	24.3	4.33	20.0
	Maximum	28.0	6.00	22.0	29.2	6.00	23.2
	N	3	3	3	3	3	3
	SD	12.0	2.42	9.59	11.8	2.13	9.69
Campbell Wetland	Minimum	4.33	1.67	2.67	5.00	1.25	3.75
	Mean	**15.9**	**3.78**	**12.1**	**17.6**	**3.97**	**13.6**
	Median	16.3	3.67	12.7	20.7	4.67	16.0
	Maximum	27.0	6.00	21.0	27.0	6.00	21.0
	N	3	3	3	3	3	3
	SD	11.34	2.17	9.18	11.32	2.45	8.88

Appendix C: Organic percent suspended solids for high and low flows.



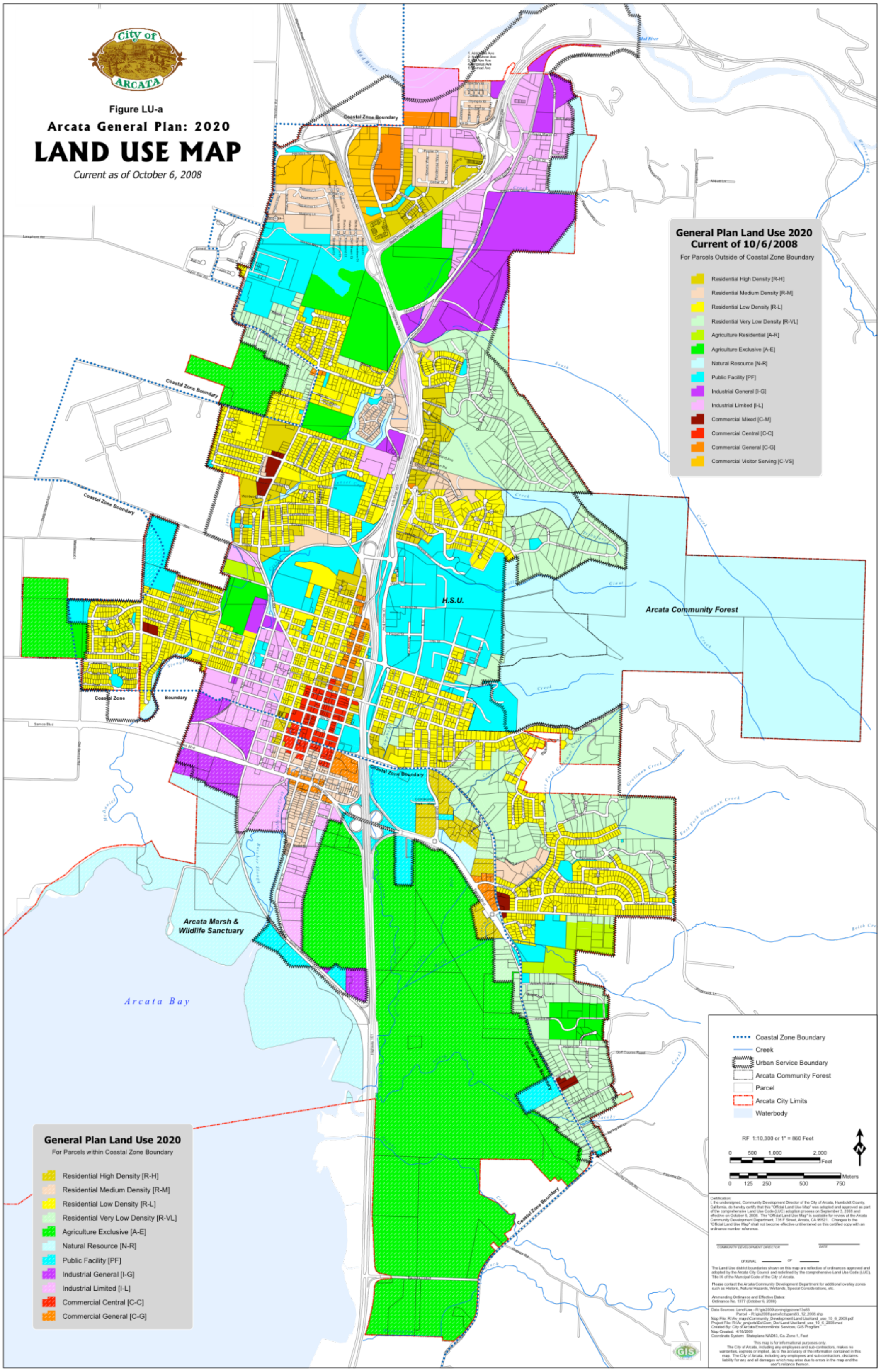
Site	Flows	Influent % OSS	Effluent % OSS
Janes Creek East Fork Wetland	High Flow	22%	21%
	Low Flow	25%	22%
Janes Creek West Fork Wetland	High Flow	19%	22%
	Low Flow	23%	24%
Jolly Giant	High Flow	23%	22%
	Low Flow	22%	20%
Campbell	High Flow	19%	23%
	Low Flow	24%	23%
Total	**High Flow**	**20%**	**22%**
	Low Flow	**23%**	**22%**

Appendix D: Sampling dates and times for the 2010-2011 hydrologic year (24 hour).



Dates	Flow Types	Campbell Upstream	Campbell Downstream	Jolly Giant Upstream	Jolly Giant Downstream	Janes West Fork Upstream	Janes Confluence	Janes East Fork Upstream	Janes East Fork Downstream
9/19/2010	high	8:15	8:30	10:30	10:45				
10/25/2010	high	8:25	8:40	9:15	9:30				
11/7/2010	high	5:50	6:10	4:00	4:20				
11/7/2010	high	8:30	8:45	7:00	7:20				
11/20/2010	high	18:50	19:10	19:47	19:55				
11/22/2010	high	21:25	21:35	21:55	22:10	22:40	23:20	22:55	23:00
12/2/2010	high	14:35	14:40	13:55	14:08	13:10	13:40	13:20	13:30
12/14/2010	high	9:40	9:50	9:10	9:20	8:20	8:55	8:35	8:45
1/25/2011	low	9:00	9:15	9:35	9:40	10:30	10:00	10:45	10:15
2/15/2011	high	6:30	6:40	7:00	7:15	8:15	7:35	8:05	7:50
2/15/2011	high	17:20	17:30	16:40	16:55	16:20	15:40	16:10	16:00
2/17/2011	high	7:35	7:42	8:00	8:15	9:05	8:30	8:50	8:45
3/5/2011	high	16:10	16:20	16:37	16:50	17:50	17:10	17:35	17:25
3/15/2011	high	10:30	10:45	11:00	11:10	12:05	11:25	11:55	11:45
3/31/2011	low	9:25	9:35	9:50	10:10	11:10	10:25	10:45	10:35
4/16/2011	high	14:05	14:12	14:25	14:35	15:25	14:45	15:10	15:00
5/13/2011	low	10:35	10:40	10:56	11:05	11:50	11:20	11:45	11:40

Appendix E: Arcata land use map.



Certification:
I, the undersigned, Community Development Director of the City of Arcata, Humboldt County, California, do hereby certify that this "Official Land Use Map" was adopted and approved as part of the comprehensive Land Use Code (LUC) adoption process on September 3, 2008 and effective on October 6, 2008. The "Official Land Use Map" is available for review at the Arcata Community Development Department, 736 F Street, Arcata, CA 95521. Changes to the "Official Land Use Map" shall not become effective until entered on this certified copy with an ordinance number reference.

The Land Use district boundaries shown on this map are reflective of ordinances approved and adopted by the Arcata City Council and redefined by the comprehensive Land Use Code (LUC), Title IX of the Municipal Code of the City of Arcata.

Appendix F: Arcata wetland photos.

From left to right Janes Creek East and West Fork 1989, 2003, 2009. Images taken from Google Earth.

Jolly Giant FWS Wetland

Campbell Creek FWS Wetland

Janes Creek West Fork Wetland

Janes Creek East Fork

Appendix G: Dehydration curves of minerals (from Jackson 1969).

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