The Ecological Benefits of using Recycled Water for Streamflow Augmentation during the Dry Season in Marsh Creek, Brentwood, California

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ABSTRACT

While many studies have been done to assess the ecological degradation of streams due to human impact, the potential ecological recovery of highly degraded urban streams through augmentation using recycled water during the dry season has not been thoroughly examined. This case study of Marsh Creek in Brentwood, California, was designed to determine if adding recycled water from the Brentwood Wastewater Treatment Plant (BWTP) to a low-flow, urban stream during the dry season is ecologically beneficial. Habitat assessments and replicated benthic macroinvertebrate samples were taken at five sites along Marsh Creek, upstream and downstream of the recycled water effluent in September, 2012. Upstream and downstream water-quality data for the 2011-2012 water-year was provided by the BWTP. Improvements in habitat and water-quality parameters were observed, particularly increased flow velocity, less sediment deposition, and increased dissolved oxygen downstream. These improvements were likely due to the increase in streamflow provided by the added recycled water. The percent of pollution-sensitive benthic macroinvertebrates also increased downstream of the effluent compared to upstream. A decrease in benthic macroinvertebrate community richness was evident below the effluent compared to above, which can be explained by a reduction in the number of pollution-tolerant taxa. Moreover, the richness increases as one moves further downstream from the outlet, indicating ecological recovery to a more healthy benthic community overall after the recycled water and streamwater is fully mixed. These improvements indicate that adding recycled water from the BWTP to Marsh Creek during the dry season appears to be ecologically beneficial.

KEYWORDS

Benthic macroinvertebrates, water-quality, habitat assessment, urban stream, restoration

INTRODUCTION

As urban development has increased worldwide, the demand for water sources has also increased, especially in cities in regions that have an arid or semi-arid climate (Gasith and Resh 1999, Okun 2000). Water is typically either diverted within cities for human use or dammed upstream of cities, reducing downstream flows (Matlock et al. 2000, Okun 2000). The physical, chemical, and biological consequences of reduced stream flow can include: intermittency, higher concentrations of nutrients and contaminants, reduced biotic richness, and increased relative abundance of more tolerant species (Hart and Finelli 1999, Groffman et al. 2003, Walsh et al. 2005, Bernhardt and Palmer 2007). In urban streams in Mediterranean climate regions, these consequences can be intensified during the extreme low-flow conditions towards the end of the annual dry season (Gasith and Resh 1999, Brooks et al. 2006). One solution to the ecological dangers of anthropogenically induced low-flows in urban streams, especially during the dry season of drought years, is streamflow augmentation (Ponce and Lindquist 1990, Matlock 2000).

Streamflow augmentation can be implemented in many different ways, but in general, it refers to the practice of temporarily storing water in the wet seasons for later release into low-flow streams during the dry seasons (Ponce and Lindquist 1990). Some of the benefits of employing streamflow augmentation in streams include: healthier riparian areas, improved water-quality, enhanced fish and wildlife habitat, and improved stream aesthetics (Ponce and Lindquist 1990, Gasith and Resh 1999). One way to return low-flow urban streams back to their baseline conditions through streamflow augmentation is through the use of highly treated recycled water from wastewater treatment plants (WWTPs) (Okun 2000, Anderson 2003, Sala and Serra 2004, Latino and Haggerty 2007, Plumlee et al. 2012, US EPA 2012). Although recycled water has been used for environmental enhancement in several wetland restoration projects in Florida, California, and arid regions of Australia (Greenway 2005, Australia 2008) as well as for irrigation of agricultural fields and golf courses (US EPA 2012), rarely has it been used for urban stream restoration (Bischel et al. 2012, Plumlee et al. 2012). Reasons for this include state regulations of stream augmentation and wastewater discharge into public waters, competition with other users of recycled water, and a lack of indicators for monitoring recycled water-quality and resultant habitat conditions (Okun 2000, Miller et al. 2003, Latino and Haggerty 2007, Bischel et al. 2012, Plumlee et al. 2012). However, one of the most widely used biological health indicators in previous urban-stream ecosystem studies are benthic macroinvertebrates because of their relatively quick response to environmental change compared to fish, as well as their ease of identification compared to algae and diatoms (Gasith and Resh 1999, Walsh et al. 2005).

Research on the relationship between the effects of increased urbanization on stream and responding benthic macroinvertebrate assemblages has predominantly assessed how human alterations to the land surface at the catchment scale affect the ecology of streams (Jones and Clark 1987, Roy et al. 2003, Walsh 2004). These types of urban stream studies typically include the use of four benthic macroinvertebrate metrics for analyzing ecological health: (1) percent Ephemeroptera, Plecoptera, and Trichoptera (%EPT), which measures the percent of taxa most sensitive to environmental disturbances; (2) family biotic index (FBI), which measures the community's tolerance to pollution; (3) family richness, which measures the biodiversity of the community; (4) and functional feeding group (FFG) composition, which measures the community's balance of feeding strategies (Barbour et al. 1999). The biological characteristics that these metrics measure are closely related to physiochemical and biological qualities of the stream (Kauffman et al. 1997), which can be measured using habitat assessment rubrics (Barbour et al. 1999). Although many studies have been done to assess the ecological degradation of streams due to human impact, the potential ecological recovery of highly degraded urban streams through augmentation using recycled water during the dry season has not been thoroughly examined (Sala and Serra 2004, Walsh et al. 2005).

Consequently, this thesis examines a small low-flow urban stream during the dry season to determine if adding recycled water is ecologically beneficial. I hypothesize that there will be an observable improvement in velocity, pool substrate characterization, and pool-riffle variability in the stream, as well as improvements in water-quality parameters to support a healthier aquatic community. I also hypothesize that if adding recycled water to a low-flow, urban stream is ecologically beneficial, then I will observe a significant increase in %EPT and family richness downstream of the effluent, a decrease in FBI, and more appropriate FFG proportions for the site's location along the river continuum (Vannote et al. 1980).

METHODS

Study Site

The study was conducted at Marsh Creek in Brentwood, California (Contra Costa County). The Marsh Creek watershed drains about 250 square kilometers of the eastern slopes of Mount Diablo. Its headwaters flow continuously year round into Marsh Creek Reservoir. Downstream of the reservoir, Marsh Creek flows northward through the cities of Brentwood, Knightsen, and Oakley, and then into the Sacramento-San Joaquin Delta. These cities primarily consist of suburban development and agricultural land-use. Similar to many other small streams in Mediterranean climate regions, Marsh Creek had historically intermittent flows, but now the flows are perennial due to a combination of urban and agricultural runoff. As Marsh Creek reaches the northeastern city limits of Brentwood, the BWTP continuously adds highly treated recycled water to the stream. Within only a few meters downstream of the recycled water effluent, a stormwater effluent also continuously supplements the water in the stream. Approximately 300 meters upstream of the recycled water effluent is a USGS stream gage that was installed into a constructed 2 meter drop-structure and connected fish ladder.

On September 14, 2012, I collected three benthic macroinvertebrate samples at five sites (Fig. 1, Table 1) at Marsh Creek, totaling 15 samples in all. The five chosen sites were situated at every other riffle above and below the effluent, except for site A, which situated further apart because there was not enough flow in several riffles to allow sampling. The three sample spots chosen within each of the five sites were selected based on both the ability to position a D-frame net flush with the stream bed and the presence of sufficiently high current to force organisms to drift into the net. On September 28th, 2012, I performed a habitat assessment at the same five sites. There was no precipitation or other significant changes in weather during this two-week period between benthic macroinvertebrate sampling and habitat assessments.

Fig. 1. Aerial map of sample locations and BWTP. The yellow arrow indicates where the recycled water enters Marsh Creek. Sites A and B are located upstream of the recycled water effluent. Sites C, D, and E are located downstream of the recycled water effluent. The constructed drop-structure and fish ladder with an installed USGS stream gage is located between sites A and B.

Table 1. **Distance from effluent and geographic coordinates of sites.** The distances of each site upstream or downstream of the recycled water effluent and the latitudes and longitudes of each site are provided.

Site	Meters from Effluent	Latitude	Longitude
A	420 upstream	37°57’43” N	121°41’20” W
B	100 upstream	37°57’45” N	121°41’6” W
C	N/A	37°57’46” N	121°41’2” W
D	130 downstream	37°57’50” N	121°41’2” W
E	250 downstream	37°57’54” N	121°41’4” W

Physical and Chemical Assessment

Habitat Assessment

I conducted one physicochemical and biological habitat assessment at each of the five sites along the creek. This involved scoring habitat parameters on a scale of 0-20, where 0-5 represents a poor habitat condition, 6-10 represents marginal, 11-15 represents suboptimal, and 16-20 represents optimal. Each of these condition classifications consisted of a detailed description of what visually based qualities of the creek were necessary to warrant placement into a particular category (Appendix A) (Barbour et al. 1999). I then calculated the total scores of all the parameters for each of the five sites. I used a Wilcoxon signed-rank test to test for significant differences between the habitat parameter scores of the upstream and downstream sites.

Flow

I downloaded the average daily flows for each month of the October 1, 2011 to September 30, 2012 water-year from the USGS website (http://water.usgs.gov/), which had data collected from the flow gage upstream of the recycled water effluent. I also received average daily flow data from the BWTP of the recycled water effluent for each month of the October 1, 2011 to September 30, 2012 water-year. To find an approximate percentage of the downstream flow that was made up of recycled water for each month, I used the following equation:

$$\text{Percentage} = \frac{\text{RW}}{\text{RW+FG}} \text{ x } 100 \qquad (1)$$

where:

RW = Average daily flow (cfs) of recycled water for a particular month,

FG = Average daily flow (cfs) of at USGS flow gage for a particular month.

Water-Quality

I received a dataset of water-quality measurements taken by the BWTP for the October 1, 2011 to September 30, 2012 water-year. These measurements were taken once a week consistently at one upstream location and one downstream location. These water-quality measurements included dissolved oxygen, temperature, turbidity, conductivity, and pH. Using the monthly averages for the 2011-2012 water-year, and the weekly averages for the month of September, I tested for significant differences in the upstream and downstream measurements using a Wilcoxon signed-rank test.

Biological Assessment

At each of the five sites, I took three benthic macroinvertebrate samples, all within 50 meters of each other. To gather these samples, I disturbed the streambed with my foot for one minute while the current forced the benthic macroinvertebrates to drift into a D-frame mesh net that I was holding flush with the stream bed just downstream of my foot. I then put the sediment and benthic macroinvertebrates that I gathered in the D-frame net into a 10 inch sediment sifter, washed off all of the larger rocks with water, and put the sediment with the macroinvertebrates into a Ziploc bag filled with 75% ethyl alcohol. In the lab, I put the samples into trays filled with tap water, sorted through the substrate for the benthic macroinvertebrates, and placed individuals into glass vials labeled by site and sample number. Using a dissecting scope (Nikon SMZ800), I identified and counted each macroinvertebrate collected. All insect larvae were identified to Family level, whereas all other specimens were identified to Class, Sub-Class, or Order. Pupae, non-Hemiptera adults, and Mullusca specimens were not counted.

To test for differences in benthic macroinvertebrate metrics between the upstream and downstream sites, I compiled the three samples collected from each site into a single sample and then treated the different sites as replicates. I used a Wilcoxon signed-rank test to test for significant differences in %EPT, FBI, richness, and FFGs between the upstream and downstream sites. To examine general trends in the bioassessment metrics between each site, I created a boxplot using the original non-compiled samples.

RESULTS

Physical and Chemical Assessment

Habitat Assessment

Upstream and downstream physical habitat assessments revealed that the downstream sites had a higher median total score ($W_{2,3}$ = 0, p = 0.200) than the upstream sites (Table 4). The downstream sites had higher median scores in several habitat parameters, including epifaunal substrate/available cover ($W_{2,3}$ = 0, p = 0.139), pool substrate characterization ($W_{2,3}$ = 0, p = 0.139), pool variability ($W_{2,3}$ = 0, p = 0.200), sediment deposition ($W_{2,3}$ = 0, p = 0.128), and streamflow velocity ($W_{2,3}$ = 0, p = 0.139) (Table 2). The scores for pool substrate characterizations, pool variable, sediment deposition, and velocity gradually increased downstream of site B (Fig. 2).

Table 2. Comparison of habitat assessment mean scores for upstream and downstream sites. Qualitative score of 0–20 (poor to optimal). The upstream values are the median of the two sites scored separately and the downstream values are the median of three sites scored separately.

Habitat Parameter	**Marsh Creek, Upstream**	**Marsh Creek, Downstream**	**p-value**
Epifaunal Substrate/ Available Cover	11.5 (11-12)	15.0 (14-15)	0.139
Pool Substrate Characterizations	12 (11-13)	19.0 (16-19)	0.139
Pool Variability	8.5 (8-9)	14.0 (10-15)	0.200
Sediment Deposition	16 (16)	19.0 (18-19)	0.128
Velocity	11.5 (11-12)	19.0 (18.5-19)	0.139
Channel Alteration	7.0 (7)	7.0 (7)	NA
Channel Sinuosity	4.5 (2-7)	6.0 (5-6)	1.000
Bank Stability	9 (8-10)	10 (10)	0.414
Vegetative Protection	7 (7)	8 (8-9)	0.128
Width of Riparian Vegetation Zone	0 (0)	0 (0)	NA
Total Score	87 (83-91)	116 (107.5 -119)	0.200

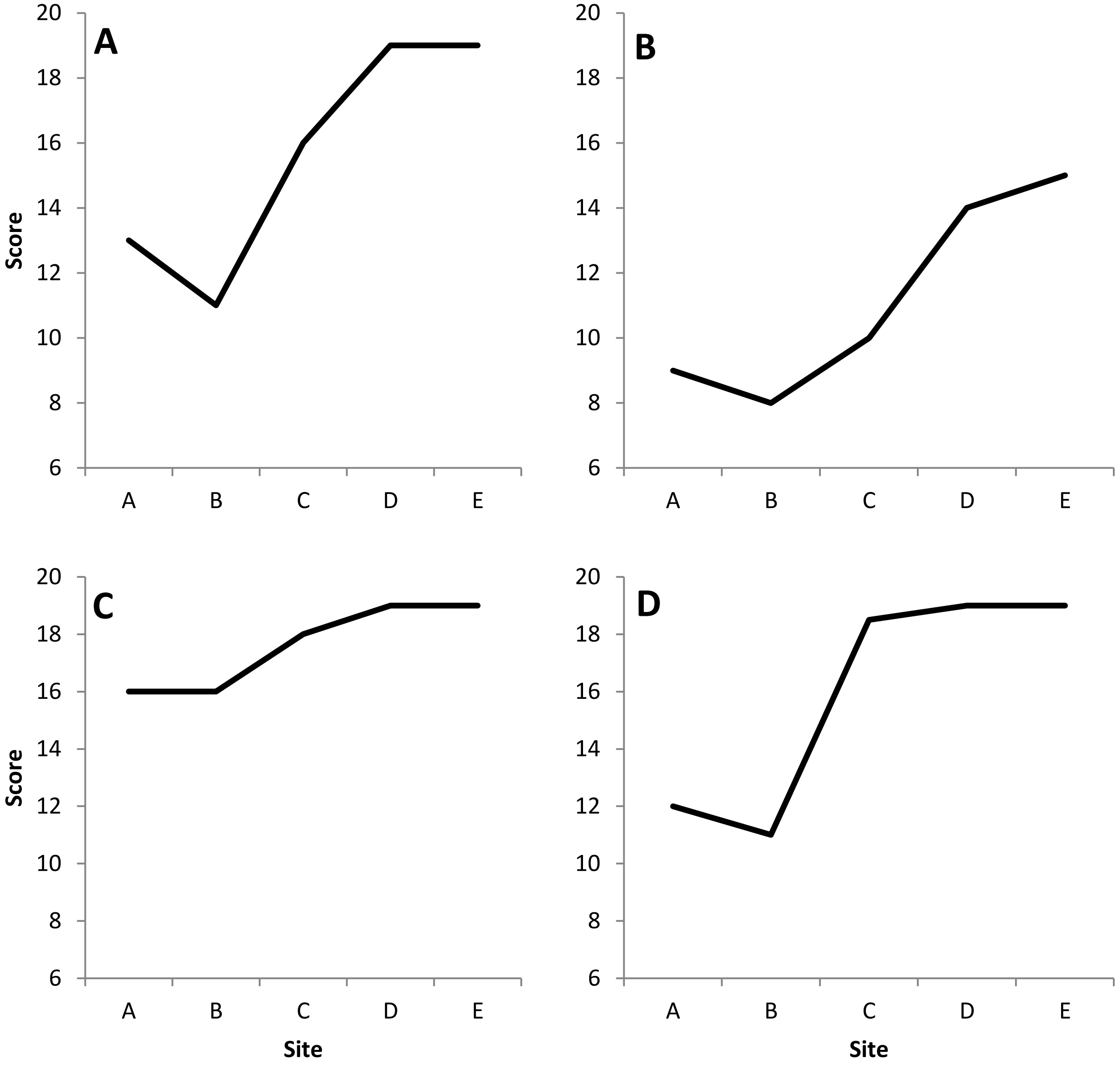

Fig. 2. Longitudinal trend in habitat parameters. Graphs show a general increasing trend downstream of site B in (A) pool a substrate characterizations, (B) pool variable, (C) sediment deposition, and (D) velocity.

Flow

During the October 1, 2011 to September 30, 2012 water-year, the monthly daily average flow downstream of the effluent ranged from approximately 37% recycled water in April, to nearly 94% in December (Fig. 3). During May through September, the typical dry months in California, the flow downstream was made up of approximately 84% to 92% recycled water. In September, the downstream flow was made up of approximately 91% recycled water.

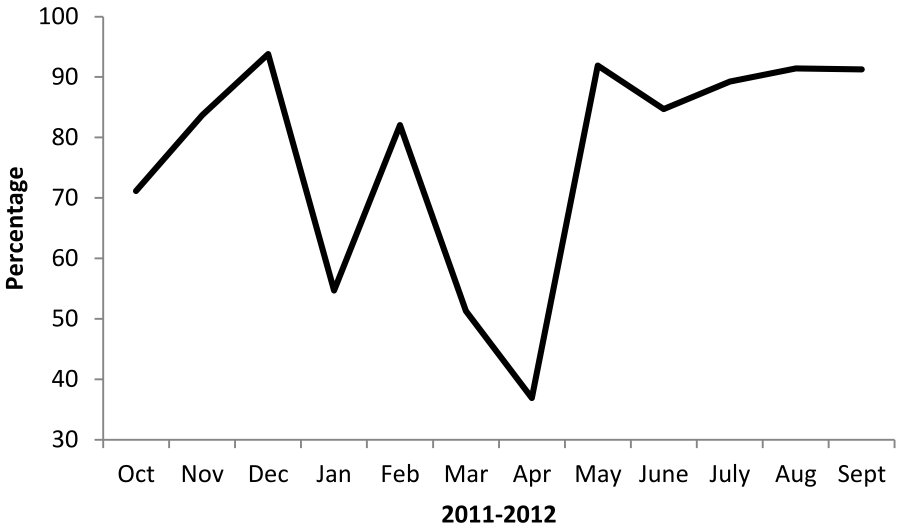

Fig. 3. Longitudinal graph of month-to-month recycled water dominance downstream of the effluent.

Water-Quality

The BWTP took dissolved oxygen, temperature, turbidity, conductivity, and pH measures upstream and downstream of the effluent 52 times during the October 1, 2011 to September 30, 2012 water-year. There were several statistically significant differences between the annual median upstream and downstream water-quality measurements, including temperature ($W_{12,12} = 36.5$, $p = 0.043$), turbidity ($W_{12,12} = 127.5$, $p = 0.001$), and conductivity ($W_{12,12} = 11$, $p < 0.001$) (Table 3). There was a larger upstream-to-downstream difference in dissolved oxygen and pH during the dry season, in temperature and turbidity during the wet season, and a consistent difference in conductivity year-round (Fig. 4). When comparing the differences between the median upstream and downstream water-quality measurements for the month of September, 2012 alone, there were statistically significant differences in dissolved oxygen ($W_{4,4} = 0$, $p = 0.029$), temperature ($W_{4,4} = 0$, $p = 0.028$), and conductivity ($W_{4,4} = 0$, $p = 0.029$) (Table 4).

Table 3. Differences in water-quality measurements during the 2011-2012 water-year. The upstream and downstream values are the median of the monthly averages from October, 2011 to September, 2012. Original data was provided by the BWTP.

Water-Quality Parameter	Marsh Creek, Upstream	Marsh Creek, Downstream	p-value
Dissolved Oxygen (mg/L)	6.16 (3.01-23.33)	7.68 (5.99-9.66)	0.204
Temperature (C°)	17.01 (10.33-23.33)	20.97 (16.78-24.78)	0.043
Turbidity (NTU)	8.13 (1.8-55.8)	1.25 (1-22.5)	0.001
Conductivity (µmhos/cm)	1261 (674-1483)	1638 (1033-1895)	0.0001
pH	7.64 (7.45-7.84)	7.73 (7.42-7.84)	0.101

Table 4. Differences in water-quality in the month of September, 2012. The upstream and downstream values are the median of the weekly measurements taken in September, 2012. Original data was provided by the BWTP.

Water-Quality Parameter	Marsh Creek, Upstream	Marsh Creek, Downstream	p-value
Dissolved Oxygen (mg/L)	3.03 (2.82-3.16)	6.96 (5.76-8.77)	0.029
Temperature (C°)	20.00 (19.44-20.56)	23.61 (22.22-25.0)	0.028
Turbidity (NTU)	1.5 (1.0-18.0)	1.0 (1.0)	0.186
Conductivity (µmhos/cm)	1320 (1290-1440)	1789 (1640-1900)	0.029
pH	7.44 (7.40-7.67)	7.78 (7.55-7.83)	0.057

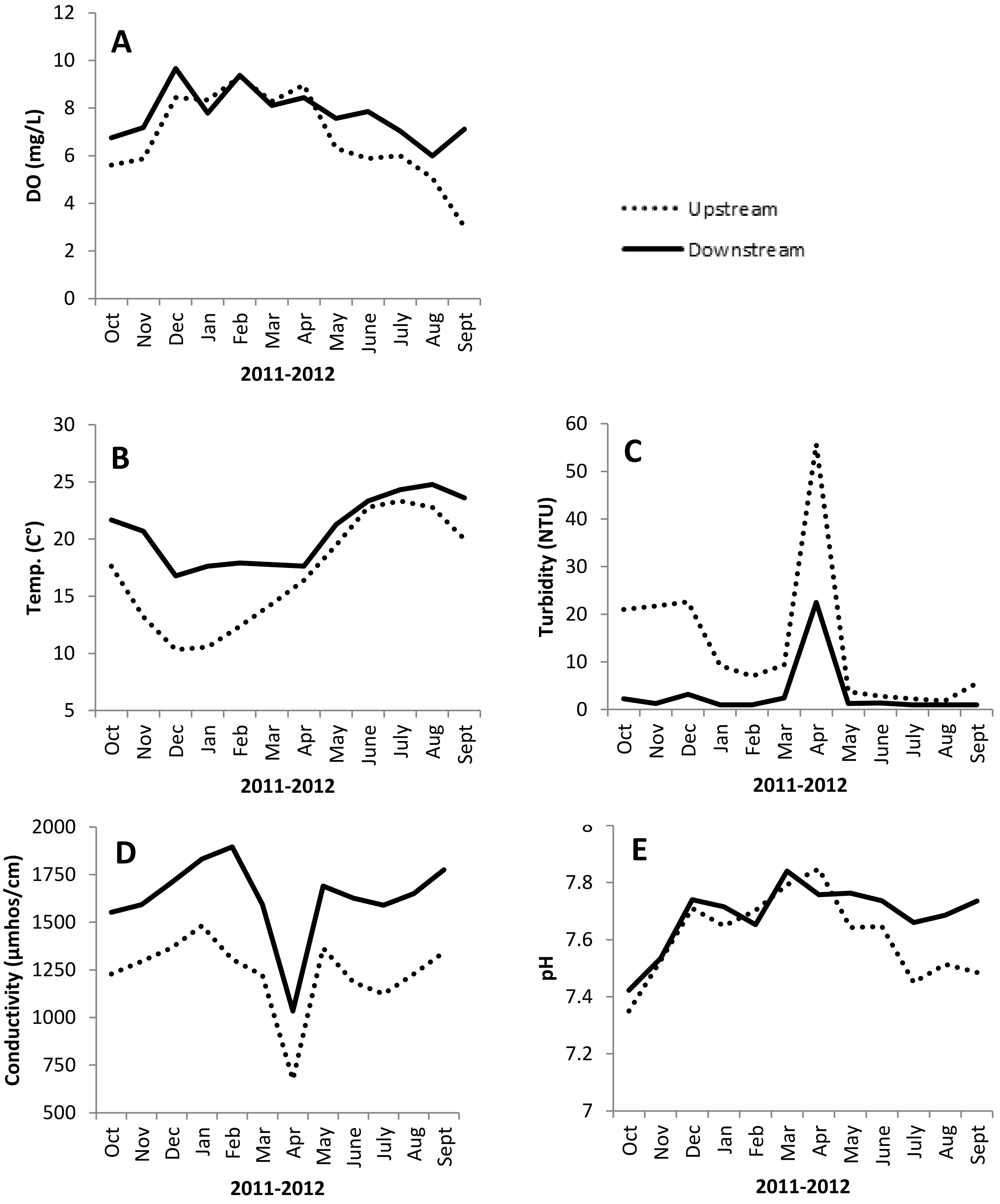

Fig. 4. Longitudinal graphs of month-to-month upstream and downstream water-quality measurements. Upstream (dotted line) and downstream (solid line) monthly average measurements are shown for (A) dissolved oxygen, (B) temperature, (C) turbidity, (D) conductivity, and (E) pH. Measurements were taken during the October 1, 2011 to September 30, 2012 water-year. Original data was provided by the BWTP.

Biological Assessment

A total of 4,800 benthic macroinvertebrates were identified and counted in this study, representing 28 different taxonomic groups. In the upstream sites, the most common taxonomic groups identified were Chironomidae, Hydroptilidae, and Oligochaeta (in order of decreasing abundance). In the downstream sites, the most common taxonomic groups identified were Amphipoda, Baetidae, and Hydropsychidae. The dominant FFGs were collector-gatherers (81%, 67%) and filter-collectors (1%, 18%) in both the upstream and downstream sites, respectively.

None of the bioassessment metrics showed statistically significant differences when comparing the medians of the upstream and downstream sites. However, the downstream sites had a higher median %EPT ($W_{2,3} = 0$, $p = 0.200$), and a lower median FBI score ($W_{2,3} = 6$, $p = 0.200$), and lower median richness ($W_{2,3} = 6$, $p = 0.139$) (Table 5). An increase in %EPT, a decrease in FBI, and a decrease followed by a rebound in richness was evident below the effluent (Fig. 5).

The filter-collectors and collector gatherers made up the largest percentage of FFGs within the samples collected upstream and downstream. The upstream sites had a higher median percentage of collector-gatherers ($W_{2,3} = 5$, $p = 0.400$), while the downstream sites had a higher median percentage of filter-collectors ($W_{2,3} = 0$, $p = 0.200$) (Table 5). While the percent collectors remains relatively constant in the upstream and downstream sites, the percent collector-gathers decreases and the percent filter-collectors increases downstream of the effluent (Fig. 6).

Table 5. Median values of bioassessment metrics from upstream and downstream sites.

Bioassessment Metrics	Marsh Creek, Upstream	Marsh Creek, Downstream	p-value
Diversity & Composition			
Total Abundance	927(657-1197)	699 (604-1643)	1.000
Total Richness	18.5 (17-20)	13.0 (13-15)	0.139
% Chironomidae	49.59 (36.5-62.7)	9.37 (8.30-17.1)	0.200
% Baetidae	9.86 (1.75-18.0)	27.39 (15.9-47.1)	0.400
% Hydropsychidae	1.14 (0-2.28)	16.72 (7.36-21.7)	0.200
Water-Quality			
EPT Abundance	204 (179-229)	531 (215-628)	0.400
% EPT	24.95 (15.0-34.9)	38.22 (35.6-76.0)	0.200
Family Biotic Index	5.83 (5.67-5.99)	5.14 (4.29-5.15)	0.200
Function Feeding Groups			
% Shredder	2.18 (1.17-3.20)	0.00 (0-0.18)	0.139
% Filter-Collector	1.29 (0-2.59)	18.21 (7.49-21.7)	0.200
% Collector-Gatherer	80.68 (76.6-84.8)	67.22 (60.1-82.0)	0.400
% Scraper	13.61 (12.6-14.6)	9.16 (3.83-10.1)	0.200
% Predator	2.23 (1.42-3.04)	6.45 (4.47-9.01)	0.200

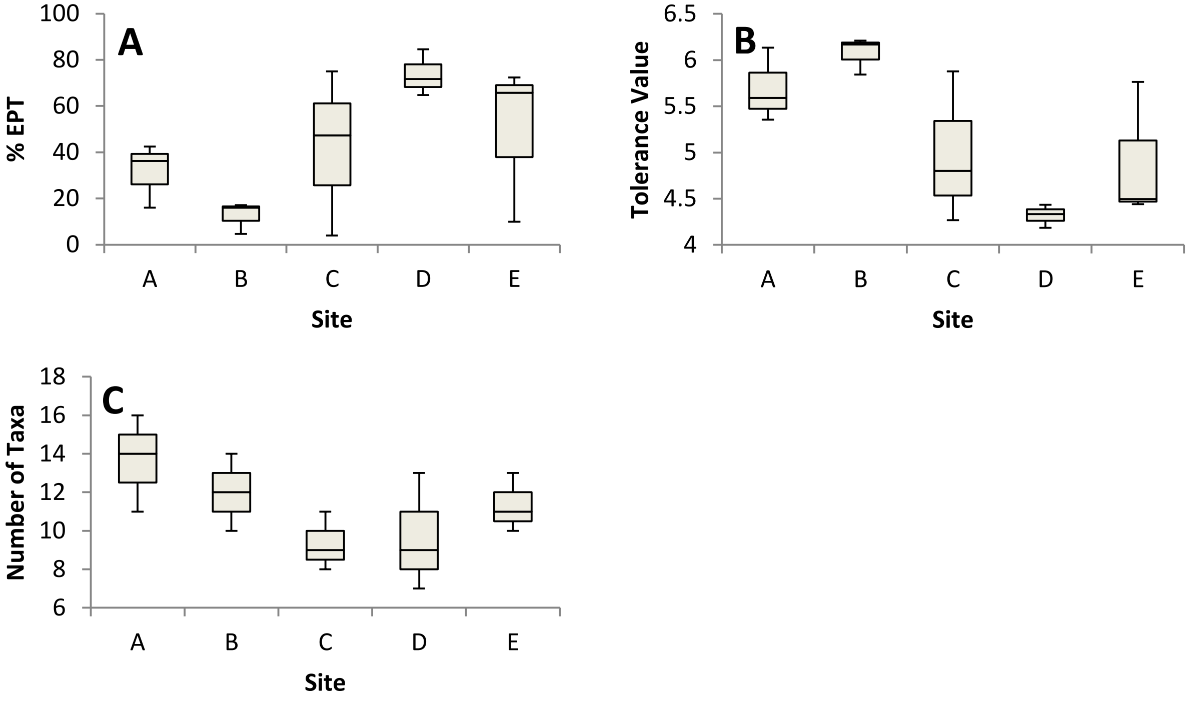

Fig. 5. Boxplot of bioassessment metrics. Boxplots of (A) %EPT, (B) FBI, and (C) richness are shown for each site. Sites A and B are upstream and sites C, D, and E are downstream.

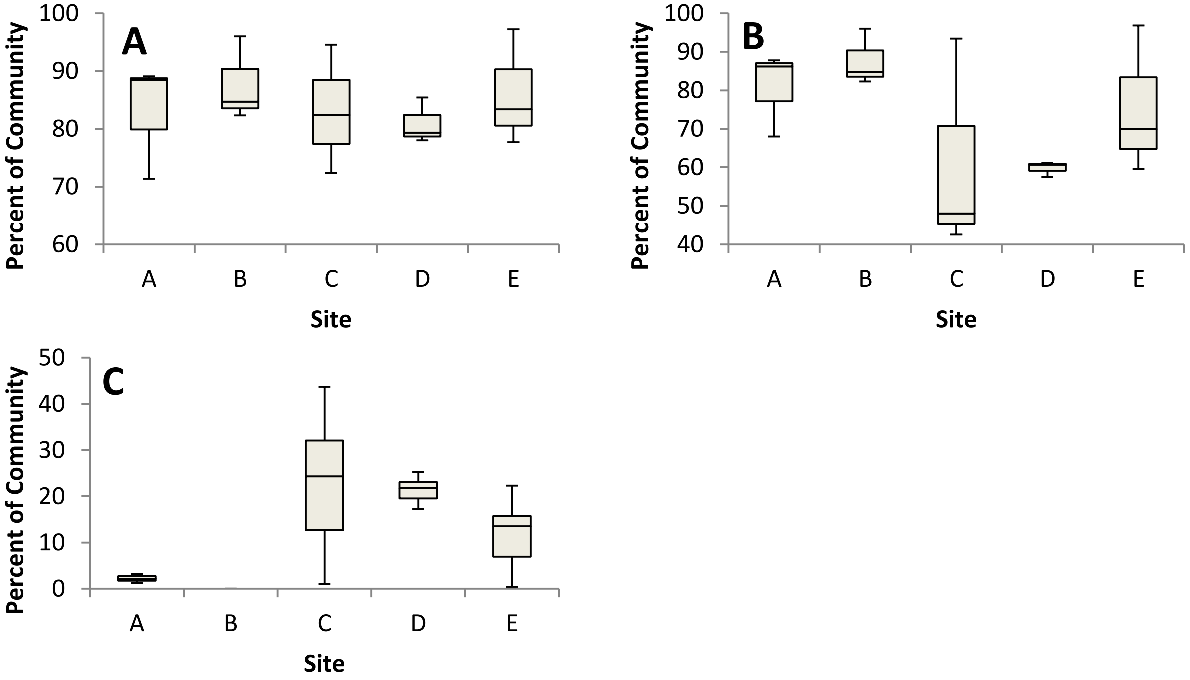

Fig. 6. Boxplot of dominant functional feeding groups. A boxplot of (A) percent collectors, (B) percent collector-gatherers, and (C) percent filter-collectors are shown for each site. Sites A and B are upstream and sites C, D, and E are downstream.

DISCUSSION

The improvements in physical habitat parameters and benthic macroinvertebrate community metrics below the recycled water effluent compared to above were not statistically significant because the measurements had high variability. In contrast, I was able to detect significant differences in several water-quality parameters between the upstream and downstream sites because these parameters were less variable within sites. Although only one of my hypotheses was statistically supported, general ecological improvements were suggested downstream of the effluent compared to upstream, which could prove significant if subjected to a more extensive sampling protocol. However, such a protocol was beyond the resources of this study. These ecological improvements are likely due to the increase in the flow of the stream as a result of the recycled water effluent. Because of these suggestive directional changes, adding recycled water from the BWTP to Marsh Creek during the dry season appears to be ecologically beneficial.

Physical and Chemical Assessment

Habitat Assessment

Overall, this reach of Marsh Creek is highly urbanized. High channelization is present, sinuosity is low, and riparian vegetation has been removed both above and below the effluent. These are common signs of urbanized streams which have been engineered to allow stormwater to move quickly through the channel, thereby reducing flood hazards (Walsh 2005, Bernhardt and Palmer 2007). However, a comparison of overall habitat assessment scores between the upstream and downstream sites indicates that the downstream site’s habitats improved relative to the upstream habitats, which is primarily the result of the increase in water volume downstream. With the additional flow, less channel substrate is exposed, sediment deposition is reduced, and the amount of large-deep pools found within the channel is higher. Moreover, these relatively deep portions of the channel are important to fish for rearing habitat during low-flows, when much of the stream's total water volume may reside in pools (Beschta and Platts 1986). The observations thus suggest that additional instream habitat for fish may have been created by the effluent through the addition of larger, deeper pools downstream compared to upstream.

Flow

The average of 4.77 cubic feet/second of recycled water supplied to Marsh Creek during the month of September, 2012 was approximately 91% of downstream total volume. Such flow domination has become increasingly prevalent in urbanized streams that historically had ephemeral flow, but are now perennial due to a combination of urban runoff (e.g. from lawns and car washing) and municipal and/or industrial effluent discharges from WWTPs (Brooks et al. 2006). Continuous flow augmentation to these streams by effluent discharges have been theorized to modify temperature, dissolved oxygen regimes, nutrients and chemical constituent loadings, water-quality, and instream toxicity (Brooks et al. 2006). However, increases in discharge have been associated with higher water-quality through the dilution of pollutants (Gasith and Resh 1999), thus in some cases, like Marsh Creek, the benefits outweigh the harms.

Water-Quality

The increase in the stream’s temperature downstream of the effluent compared to below is likely due to the addition of recycled water from the BWTP. It is common for streams receiving recycled water to be warmer downstream of the effluent compared to upstream, largely because of residential use of heated water that passes through the treatment plant (Kinouchi 2007). Water temperature is considered the most fundamental and significant water-quality variable and has a large effect on aquatic ecosystems and recreation (Kinouchi 2007). Although a rise in annual median temperature is observed in this study, the change is much lower than what has been found at other streams augmented with recycled water (Kinouchi 2007, Hsiao, unpublished).

Typically, dissolved oxygen is lower in streams receiving recycled water (Ortiz et al. 2005, Grantham 2012), which is related to the water’s temperature because warm water has less capacity to retain oxygen. In this study, the increase in dissolved oxygen downstream of the effluent is likely due to both the cascading aerator that the recycled water falls through before entering the stream, and the increase in turbulent flow downstream of the effluent from the increase in velocity (Matlock et al. 2000). Generally, an increase in dissolved oxygen is beneficial to aquatic ecosystems.

Biological Assessment

Although not significantly different, a general increase in %EPT and decrease in FBI were observed in the downstream benthic macroinvertebrate communities compared to the upstream communities, which indicates an increase in water-quality (Barbour et al. 1999). This is a promising observation because most benthic communities exposed to recycled water have shown a decrease in sensitive taxa (Ortiz et al. 2005, Grantham 2012, Hsiao, unpublished). However, the increase in sensitive taxa observed downstream of the effluent is primarily due to the decrease in Chironomidae (i.e. the median percentage of Chironomidae in the upstream sites was 50%, while the upstream percentage was 9%), which are highly tolerant of polluted and stagnant streams (Barbour et al. 1999). Increases in the percentages of Ephemeroptera and Trichoptera downstream of the effluent were primarily due to the relative increase in Baetidae and Hydropsychidae families, respectively. Both of these families are only slightly less tolerant of polluted and stagnant streams than Chironomidae (Barbour et al. 1999). The order Plecoptera are highly sensitive to warm temperatures (Hamilton et al. 2010), and are completely absent in all of the sites sampled in this study. This absence indicates that neither the upstream nor downstream sites are in pristine ecological condition.

The River Continuum Concept is a model developed in 1980 that attempts to explain both the balance between physical and biological factors in a flowing water system, and where and why certain stream communities, or FFGs, are found at certain locations in a catchment (Vannote et al. 1980). According the model, instream communities found in larger rivers will be made up of approximately 90% collectors and 10% predators, where middle reaches will have more scrapers, and headwaters will have more shredders.

Collectors were the dominant FFG found in this study, making up nearly 70-100% of the sampled communities. These collectors can be broken down into two subgroups called gatherers and filterers, based on their collecting strategies. There was a higher percentage of gatherers upstream of the effluent compared to downstream, which is likely due to the stagnant, algae filled water found at these reaches that makes gathering organic matter easier. Furthermore, there were a higher percentage of filterers found downstream of the effluent compared to upstream, which is likely due to the increase in suspended organic matter as a result of the additional flow (Ponce and Lindquist 1990).

Limitations

The general trends observed in this study would likely have had more significance if the study design had more replicate sites above and below the wastewater effluent, (i.e. higher statistical power), and if a reference stream of similar urbanization and elevation was used as a control. Furthermore, as physical and water-quality parameter measurements and benthic macroinvertebrate samples were only collected once for this case study, it only describes a brief snapshot of the ecological impacts of adding recycled water to Marsh Creek during the dry season. Although this snapshot appears to signify an improvement in water-quality below the recycled water effluent during the dry season, as indicated by a suggestive increase in more sensitive taxa, it is important to understand how and why these impacts might change seasonally.

Future directions

In order for environmental scientists to gain a better understanding of how and why this increase in water-quality was observed, more in depth ecological studies should be done at Marsh Creek and other urban stream sites that receive recycled water additions. A study done for several years with water-quality measurements and benthic macroinvertebrate samples collected during both the wet and dry seasons would give a more complete indication of the relative ecological benefits or harm of adding recycled water to an urbanized stream. With more information gathered from these various studies, potential metrics for identifying project opportunities and evaluating project success could then be selected and established. The use of recycled water for streamflow augmentation will be appropriate at some sites and inappropriate at others.

Broader implications

Despite the temporal and spatial limitations of this seven month-long study, it indicated that adding recycled water to a low-flow stream during the dry season can improve both physical instream habitat and water-quality. As the demand for freshwater continues to grow with its increased use in cities, agriculture, and industry, the ability to reuse water of high quality will become increasingly invaluable (Okun 2000, Anderson 2003). Through additional research on streamflow augmentation using recycled water, scientists will be able to develop more economically and environmentally sustainable approaches to improving water-quality for both aquatic habitats and humans alike (Hart and Finelli 1999, Purcell et al. 2002, US EPA 2012). These sustainable approaches to water management will become increasingly important as the world's urban populations and their need for water continue to grow while global climate change makes historically predicable water supply less reliable.

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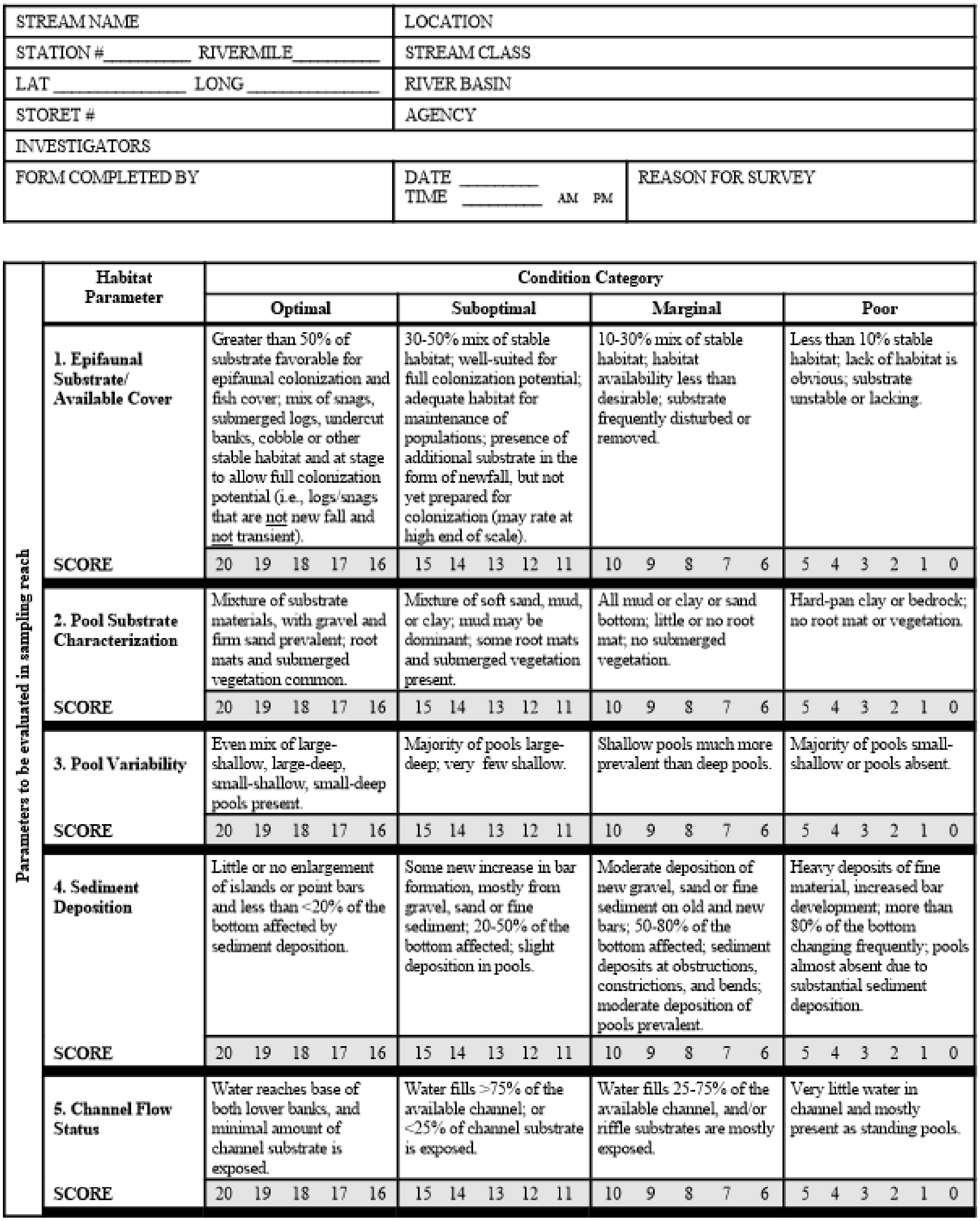
APPENDIX A: Habitat Assessment Rubric

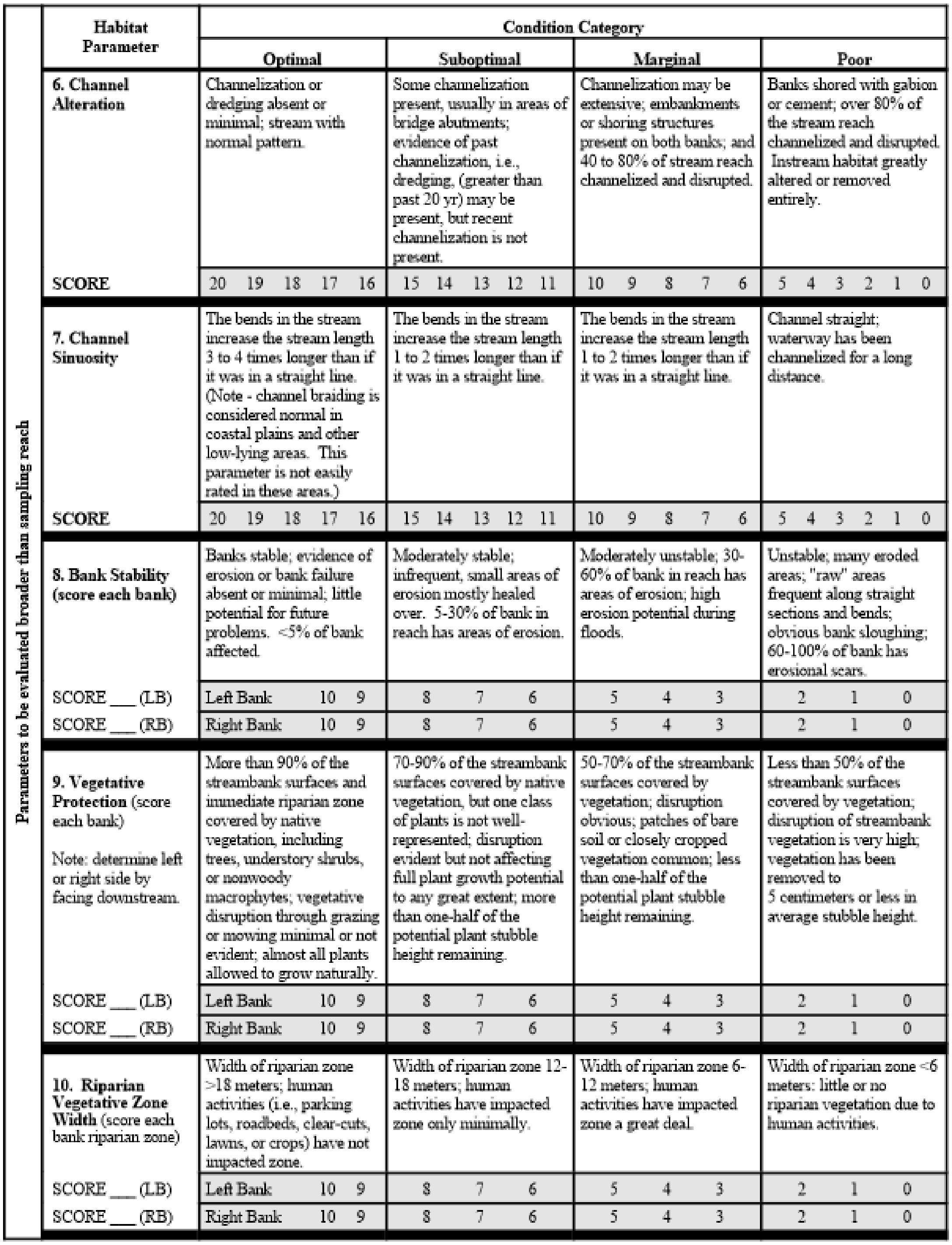


STREAM NAME	LOCATION	
STATION #_________ RIVERMILE_________	STREAM CLASS	
LAT ______________ LONG ______________	RIVER BASIN	
STORET #	AGENCY	
INVESTIGATORS		
FORM COMPLETED BY	DATE _________ TIME _________ AM PM	REASON FOR SURVEY

	Habitat Parameter	Condition Category			
		Optimal	**Suboptimal**	**Marginal**	**Poor**
Parameters to be evaluated in sampling reach	**1. Epifaunal Substrate/ Available Cover**	Greater than 50% of substrate favorable for epifaunal colonization and fish cover; mix of snags, submerged logs, undercut banks, cobble or other stable habitat and at stage to allow full colonization potential (i.e., logs/snags that are not new fall and not transient).	30-50% mix of stable habitat; well-suited for full colonization potential; adequate habitat for maintenance of populations; presence of additional substrate in the form of newfall, but not yet prepared for colonization (may rate at high end of scale).	10-30% mix of stable habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 10% stable habitat; lack of habitat is obvious; substrate unstable or lacking.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	2. Pool Substrate Characterization	Mixture of substrate materials, with gravel and firm sand prevalent; root mats and submerged vegetation common.	Mixture of soft sand, mud, or clay; mud may be dominant; some root mats and submerged vegetation present.	All mud or clay or sand bottom; little or no root mat; no submerged vegetation.	Hard-pan clay or bedrock; no root mat or vegetation.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	3. Pool Variability	Even mix of large-shallow, large-deep, small-shallow, small-deep pools present.	Majority of pools large-deep; very few shallow.	Shallow pools much more prevalent than deep pools.	Majority of pools small-shallow or pools absent.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	4. Sediment Deposition	Little or no enlargement of islands or point bars and less than <20% of the bottom affected by sediment deposition.	Some new increase in bar formation, mostly from gravel, sand or fine sediment; 20-50% of the bottom affected; slight deposition in pools.	Moderate deposition of new gravel, sand or fine sediment on old and new bars; 50-80% of the bottom affected; sediment deposits at obstructions, constrictions, and bends; moderate deposition of pools prevalent.	Heavy deposits of fine material, increased bar development; more than 80% of the bottom changing frequently; pools almost absent due to substantial sediment deposition.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	5. Channel Flow Status	Water reaches base of both lower banks, and minimal amount of channel substrate is exposed.	Water fills >75% of the available channel; or <25% of channel substrate is exposed.	Water fills 25-75% of the available channel, and/or riffle substrates are mostly exposed.	Very little water in channel and mostly present as standing pools.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Fig. A1. Habitat Assessment Field Data Sheet – Low Gradient Stream (Front). Each habitat assessment parameter is divided into four conditional categories: optimal, suboptimal, marginal, and poor. The conditional categories for each parameter are described and given a range of scores (Barbour et al. 1999).

APPENDIX A: Habitat Assessment Field Data Sheet – Low Gradient Stream (Back)



	Habitat Parameter	**Condition Category**			
		Optimal	**Suboptimal**	**Marginal**	**Poor**
Parameters to be evaluated broader than sampling reach	**6. Channel Alteration**	Channelization or dredging absent or minimal; stream with normal pattern.	Some channelization present, usually in areas of bridge abutments; evidence of past channelization, i.e., dredging, (greater than past 20 yr) may be present, but recent channelization is not present.	Channelization may be extensive; embankments or shoring structures present on both banks; and 40 to 80% of stream reach channelized and disrupted.	Banks shored with gabion or cement; over 80% of the stream reach channelized and disrupted. Instream habitat greatly altered or removed entirely.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	7. Channel Sinuosity	The bends in the stream increase the stream length 3 to 4 times longer than if it was in a straight line. (Note - channel braiding is considered normal in coastal plains and other low-lying areas. This parameter is not easily rated in these areas.)	The bends in the stream increase the stream length 1 to 2 times longer than if it was in a straight line.	The bends in the stream increase the stream length 1 to 2 times longer than if it was in a straight line.	Channel straight; waterway has been channelized for a long distance.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	8. Bank Stability (score each bank)	Banks stable; evidence of erosion or bank failure absent or minimal; little potential for future problems. <5% of bank affected.	Moderately stable; infrequent, small areas of erosion mostly healed over. 5-30% of bank in reach has areas of erosion.	Moderately unstable; 30-60% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "raw" areas frequent along straight sections and bends; obvious bank sloughing; 60-100% of bank has erosional scars.
	SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
	SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
	9. Vegetative Protection (score each bank) Note: determine left or right side by facing downstream.	More than 90% of the streambank surfaces and immediate riparian zone covered by native vegetation, including trees, understory shrubs, or nonwoody macrophytes; vegetative disruption through grazing or mowing minimal or not evident; almost all plants allowed to grow naturally.	70-90% of the streambank surfaces covered by native vegetation, but one class of plants is not well-represented; disruption evident but not affecting full plant growth potential to any great extent; more than one-half of the potential plant stubble height remaining.	50-70% of the streambank surfaces covered by vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of the potential plant stubble height remaining.	Less than 50% of the streambank surfaces covered by vegetation; disruption of streambank vegetation is very high; vegetation has been removed to 5 centimeters or less in average stubble height.
	SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
	SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
	10. Riparian Vegetative Zone Width (score each bank riparian zone)	Width of riparian zone >18 meters; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zone 12-18 meters; human activities have impacted zone only minimally.	Width of riparian zone 6-12 meters; human activities have impacted zone a great deal.	Width of riparian zone <6 meters: little or no riparian vegetation due to human activities.
	SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
	SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

Total Score __________

Fig. A2. Habitat Assessment Field Data Sheet – Low Gradient Stream (Back). Each habitat assessment parameter is divided into four conditional categories: optimal, suboptimal, marginal, and poor. The conditional categories for each parameter are described and given a range of scores. All of the scores are then added together and reported as the "Total Score" (Barbour et al. 1999).