RECOVERY OF MACROINVERTEBRATE COMMUNTIES FOLLOWING FLOOD DISTURBANCE IN URBAN RESTORED STREAMS, MECKLENBURG COUNTY, NORTH CAROLINA

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
In partial fulfillment of the requirements
For the degree of Master of Science in
Earth Sciences

Charlotte

2015

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ABSTRACT

SARA EILEEN HENDERSON: Recovery of macroinvertebrate communities following
flood disturbance in urban restored streams, Mecklenburg County, North Carolina.
(Under the direction of DR. SANDRA CLINTON)

Flooding is an important disturbance structuring stream communities. Understanding macroinvertebrate post flood dynamics is critical for informing key ecosystem processes such as food web dynamics and organic matter processing in these systems. While flooding has been investigated in a diversity of freshwater ecosystems, there are fewer studies focused on urban streams. The overall objective of this research is to quantify changes in macroinvertebrate populations in urban restored streams following flood events.

I studied 4 streams in the Charlotte, NC region and monitored macroinvertebrate response to flooding in each stream for 6 storms during 2014-2015. I specifically asked whether macroinvertebrate community metrics are resistant or resilient to flood disturbance. Overall the studied sites were composed of Chironomids, Hydropsychids, Baetidae, and Oligochetes. I found that no sites were resistant to flooding and that the most urban site was the most impacted with a pre/post decrease in abundance of 63%. I also found that the oldest restored site and the forested reference showed similar resilience patterns as determined by how quickly they returned to pre-flood conditions. Similarly, the two younger restored sites had comparable resilience patterns. These data indicate that macroinvertebrate communities in urban streams are highly susceptible to flooding; however, they have the capacity to return to pre-flood conditions. Restored streams have the capacity to develop into communities more similar to urban forested

reference sites if given enough time. Understanding these macroinvertebrate dynamics important in creating management schemes for urban restored ecosystems.

DEDICATION

This thesis is dedicated to my mother, Brenda Eileen Henderson. For being there always and loving us no matter how annoying we are or how tired you feel.

ACKNOWLEDGEMENTS

Thank you to the Ecology and Biogeochemistry of Watersheds Laboratory at the University of North Carolina at Charlotte. Thank you to all lab members who assisted with all field work including Nicole Ng, Xueying Wang, Tiara Dienes and to Erin Turner for being part of the most efficient field team that has ever been. Thank you to my research advisor Dr. Sandra Clinton and my other committee members Dr. Sara Gagne and Dr. Amy Ringwood for all of their insight and advice. This work was supported by funds from the City of Charlotte Storm Water Services.

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CHAPTER 1: INTRODUCTION

1.1 Background

Macroinvertebrates are critical components of healthy stream ecosystems that 1) provide a significant source of production and 2) represent an important food chain link between organic matter and higher trophic levels (Huryn, 2000). Due to their importance in stream ecosystems macoinvertebrates are often used as indicators of water quality health. Macroinvertebrates are good indicators since they are easy and relatively inexpensive to sample while also integrating long term water quality changes occurring in the system (Goodnight, 1973; Rogers et al., 2002; Tullos, Penrose, & Jennings, 2006)

Urban streams have a consistent set of conditions, termed the “urban stream syndrome”- that includes altered hydrology, increased nutrient and metal contaminant loading, and a predictable decrease in biotic richness in both algae and macroinvertebrates (Paul & Meyer, 2008). This degradation results in stream ecosystem that do not function in similar ways to their forested counterparts. For example, urban streams may not process nutrients as efficiently and have lower rates of primary production, although these effects can vary with site specific variables (Sudduth et al., 2011). Most of this degradation is caused by increased runoff from increased impervious surfaces within cities (Walsh et al., 2005). Higher impervious surface coverage increases the amount of water that is quickly introduced into a stream resulting in bank erosion and channel incision. These events can exacerbate pollution effects by adding large quantities of sediment to the channel. Urbanization is altering the composition of the organisms that exist in these stream ecosystems. In urban streams macroinvertebrates are often less abundant, less diverse, and consist of more pollution tolerant taxa than their non urbanized counterparts leading to statistically distinct populations in urban and non urbanized areas (Cuffney et al., 2010; Morley & Karr, 2002; Walsh et al., 2001; Walsh et al., 2005). For example, Walsh et al. (2001) found that in degraded streams macroinvertebrate richness was highly correlated with impervious surface cover, and that the amount of impervious surface cover needed to decrease richness was as little as 12%. This relationship between impervious surface cover and macroinvertebrate diversity is common and has been documented by many researchers (Robinson et al., 2014; Roy et al., 2003; Walsh et al., 2001). Urban drainage systems are also a significant factor in explaining macroinvertebrate diversity patterns. For example, watersheds with improved storm water drainage systems with stream-wetland complexes had improved water quality that was quantified as the diversity and abundance of insects found in the urban watershed (Walsh et al., 2001).

Maintaining the health of freshwater systems is critical so they continue to provide the valuable ecosystem services of regulation, habitat, production, and information that are so vitally important to society (de Groot et al., 2002).In an effort to mitigate the negative effects of urbanization on stream health, many agencies have introduced the process of stream restoration. Restoration is defined by many government agencies as the manipulation of the physical, chemical, or biological characteristics of the site with the goal of returning natural functions to former or degraded streams (Environmental Protection Agency, 2012). Restoration often involves clearing the banks of a stream, raising the channel back up to an even level, and the installation of in-stream structures (Doll et al., 2003). In stream structures include large boulders to stabilize banks, cross vanes, riffle creations, or log jams. Overall urban stream restoration has not resulted in an increase in macroinvertebrate diversity or an increase in the occurrence of sensitive species (Bernhardt & Palmer, 2011; Violin et al., 2011). Bernhardt and Palmer (2011) proposed two reasons why few restoration projects meet with biological success---:1) the communities will simply never recover because there has been no meaningful improvement in habitat quality or 2) there has not been enough time for a measureable difference in community structure to be assessed (Bernhardt & Palmer, 2011). The restoration process may also act as a disturbance filter so that only disturbance tolerant species, such as Chironomids and Oligochetes, will be present in the post-restoration measurements (Bernhardt & Palmer, 2011). Thus restoration age becomes an important variable in understanding the recovery and stability of macroinvertebrates following restoration. The longer a site has to recover after restoration, the more complex the present communities will appear (Winking, Lorenz, Sures, & Hering, 2014) and may explain why restored systems require a long time to recover sensitive communities.

Flooding is a key component structuring stream ecosystems. The impacts of flooding are determined by the magnitude, frequency, duration, timing, and flashiness of the event (Poff et al., 1997). These factors influence local streamflow and therefore influence the water quality, water supply, and ecological integrity. In some ecosystems flooding is a natural part of the regime and is in fact necessary for appropriate organic matter flows and food web interactions to proceed (Junk, Bayley, & Sparks, 1986). Low order streams experience short and unpredictable flood pulses, so the stream organisms do not adapt to utilize this to their benefit but only to resist high flows. High order streams often experience longer seasonal floods that allow communities to adapt and be able to actually use the flood disturbance to their advantage (Junk, Bayley, & Sparks, 1989). It is therefore important not to establish either a flooding regime or a non-flooding regime in any certain area, but instead to re-establish the natural flooding regime of each particular system.

In urban streams, floods are the focus of many studies because urbanization has disconnected many streams from their natural floodplains and built upon this naturally flooded land. Furthermore, to exacerbate this problem many storm water systems route runoff directly into creeks and streams which only increases flooding danger and causes the degradation of macroinvertebrate populations and channel geomorphology (Roy et al., 2008). As these ecosystems change a frequent, flashy flooding regime is being experienced by the organisms living there. One way of studying the impacts of flooding in urban streams is quantifying resistance and resilience. Resistance can be defined as how a community immediately responds to a flood event, such as ability to dig down into sediment to escape high flows. Resilience can be defined as the rate of recovery following a flood event (Fritz & Dodds, 2004). An example of resilience would be the ability to rapidly reproduce with lots of young so that an area quickly becomes repopulated. Resistance and resilience adaptations combine together so that populations recover from disturbance.

Macroinvertebrate response to flooding has a long rich history in stream ecological studies (Resh et al., 1988; Stanley, Powers, & Lottig, 2010). The same idea of low resistance and high resilience has been found in other research studies. Hax and Golliday (1998) found that macroinvertebrates in general displayed very little resistance to flood disturbance, but they excelled in resilience and communities recovered within 2 months. Greenwood & Booker (2014) found that sites that were frequently flooded recovered much more quickly from disturbances than sites that were rarely flooded. They also found that sites with similar hydrologic regimes recovered in similar ways, including similar rates and directions. Another study done in a high disturbance stream found that macroinvertebrates were highly evolved for escaping high flows and that abundance recovered in as little as eight days and richness recovered in as little as three days (Matthei et al., 1997).

This study lies at the intersection of all three of these concepts: urban systems, flooding, and macroinvertebrate responses. The study focused on three sites that were previously typical impaired urban streams, but have been recently restored to improve stream health (Muddy Creek, Dairy Branch to Briar Creek (location in Sedgefield Park), and Torrence Creek) and an unrestored urban stream in a forested watershed (Reedy Creek). This study links these highly stressed urban areas with flood recovery response in an effort to understand how the recovery rate has been compromised by degradation. This research will examine changes in macroinvertebrate assemblages in urban restored streams after flooding.

1.2 Research Questions

The objective of this study is to determine the response in macroinvertebrate communities to flooding in urban restored systems by quantifying two key aspects of disturbance response:- resistance and resilience. Specifically I ask the following question: How do macroinvertebrate community metrics vary in response to flood disturbance? This question is further divided into:

1. What is the community resistance to flood disturbance?
2. What is the community resilience to flood disturbance?

1.3 Hypotheses

1. Community resistance

   Null hypothesis*:* There will be no difference in macroinvertebrate community metrics before and after flood events. They will be resistant to flood disturbance.

   Alternate Hypothesis*:* Macroinvertebrate community metrics will differ before and after flood events. Communities will not be resistant to flood disturbances.

2. Community resilience

   Null hypothesis*:* Macroinvertebrate community metrics will show no development with time after a flood disturbance. They will not recover to pre-flood condition and will be considered non-resilient.

CHAPTER 2: METHODS

2.1 Study Area

Four low order streams in Mecklenburg County were selected for study (Figure 1; Table 1). Three sites were restored during the past ten years and the fourth site is an urban forested unrestored site that is considered a preservation subwatershed in the Reedy Creek watershed.. All sites are close enough geographically that they exist within the same soil type, either Cecil or Cecil-Urban. (CharMeck Water and Land Resources, 1978) and have the same climatic influences.

Table 2: Summary of site characteristics for each study site. ISC is impervious surface cover. Canopy cover is percent covered over the stream.

SITE	**YEAR COMPLETE**	**RESTORATION STRATEGY**	**ISC %**	**CANOPY COVER%**	**WATERSHED AREA (KM^2)**	**DOMINANT LAND USE**
Reedy Creek	n/a	n/a	3.6	95	6.8	forest
Muddy Creek	2010	Natural channel design	18	40	1.38	Urban residential
Torrence Creek	2010	Natural channel design	19	6	10.6	Suburban residential
Sedgefield Park	2006	Re-meander and floodplain access	38	70	0.79	Urban

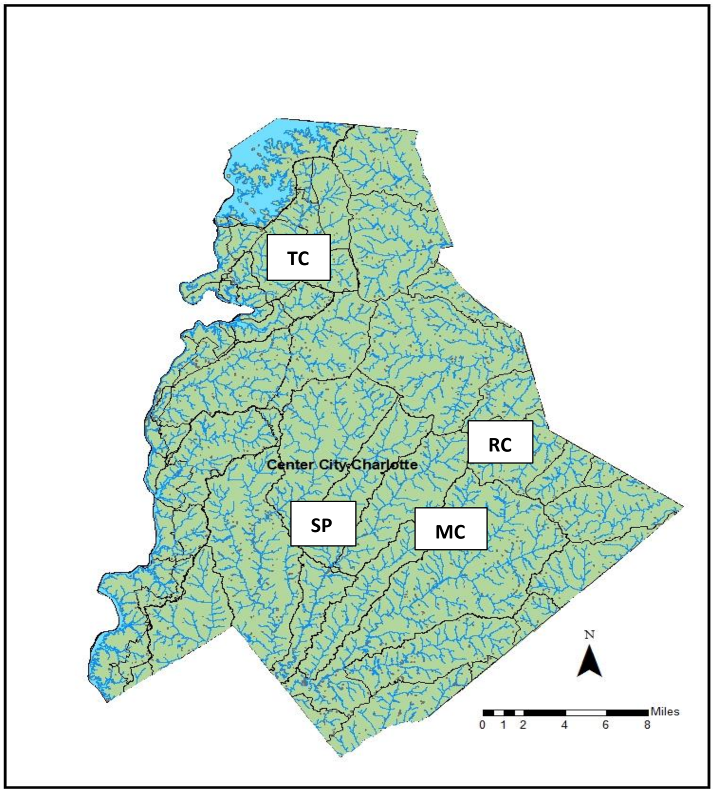

Figure 1 : Map of Mecklenburg County showing location of field sites.
RC=Reedy Creek, SP= Sedgefield Park, TC= Torrence Creek, MC=Muddy Creek

Torrence Creek (TC; Figure 2) has a watershed area of 26.5 km^2. The dominant land use in this area is suburban residential and the impervious surface cover is 19%. The impervious cover is evenly divided among roadways, residential, and commercial use. The average stream canopy cover is 6% represented by a few large trees that were left standing through the restoration process. The banks are covered by small saplings and thick riparian grasses. This stream was restored in 2010 using natural channel design

(Charlotte Mecklenburg Storm Water Services) including installed cross vanes to create riffle-pool sequences, regraded banks, and replanted the riparian zone.

Muddy Creek (MC; Figure 3) has a drainage area of 1.38 km^2. The dominant land use is urban residential. The average canopy cover is 40% and this is predominantly large trees that were left through the restoration and medium sized saplings that have started to hang over the stream. The impervious surface cover for this reach is 19% (McMillan et al., 2014). This reach is the youngest restoration completed in 2011 using natural channel design (Charlotte Mecklenburg Storm Water Services) with crossvanes creating riffle-pool sequences. The riparian zone was replanted with small tree saplings and riparian shrubs.

Dairy Branch at Sedgefield Park (SP; Figure 4) is the oldest of the study sites and has a 0.79 km^2 watershed area. The average stream canopy cover is 70%. The reach was restored in 2006 with the main restoration goals as increased flood plain access and re-meandering the stream. The impervious surface cover for this watershed is 38% and the predominant land use in this area is urban and a small recreational park constructed on one side of the restored stream.

Reedy Creek (RC; Figure 5) is an unrestored forested watershed located in a 6.8 km^2 nature preserve within the city of Charlotte in Mecklenburg County. This site has 3.6% impervious surface cover attributed to the roadways entering the park, the parking lots, and a small nature center. The watershed is forested by large mature trees and has an average stream canopy cover of 95%. The substrate is dominated by medium to coarse sand. The study site has very good floodplain access on one side of the stream and an average bank height of 4 feet on the other side.

Figure 2: Torrence Creek study site

Figure 3: Muddy Creek study site

Figure 4: Dairy Branch at Sedgefield Park study site

Figure 5: Reedy Creek unrestored study site.

At each site three consecutive riffle-run sequences were chosen as the sampling locations. These normally encompassed 30 meters of the stream length except in Torrence Creek where they were 50 meters in total length. These locations were sampled from October 2013 until December 2014. The sampling dates of the 5 storms sampled were November 2013, February and March 2014, May 2014, August 2014, and December 2014. The rainfall for all storms studied ranged 0.5-2.55 inches for a single storm event (Table 2). All sites received approximately the same amount of rain for each studied storm; thus, any differences in response will be attributed to differing land use and local stream community diversity.

Table 2: Rainfall Data (inches) summary for each storm. Winter(1) = November 2013; Spring (2) = February 2014; Summer (3)= May 2014; Fall(4)= August 2014; Winter (5)= December 2014.

RAINFALL DATA	RC	TC	MC	SP
STORM 1	0.6	0.6	0.6	0.6
STORM 2	1.9	2.3	2.2	2.2
STORM 3	1.8	2.2	2	1.9
STORM 4	1.23	2.55	1.24	1.14
STORM 5	1.1	1.05	1.01	0.97

2.2. Hydrology

The hydrology of individual storm events was monitored with a combination of USGS rainfall and discharge data and installed crest gages. USGS rainfall data is available from gauges in multiple locations (CRN-16 (gage #351540080430045), CRN-47 (gage# 351229080460245), CRN-60 (gage# 351104080521845), and CRN-62 (gage# 352523080535545)) within the city and one exists within 2 miles to every site. USGS discharge data is available for Torrence Creek from a gage immediately upstream of the most upstream riffle (USGS# 0214265808). Crest gauges were installed during May 2014 at each site in the middle riffle in each location. A crest gage is a device to measure the flood peak in a stream. The design includes a hollow tube with a wooden dowel in the center. Granulated cork is poured around the dowel and during high flow events it sits on top of the water and sticks to the wooden dowel at the flood crest and remains there when the water recedes. This height can then be measured to ascertain maximum flood height (USGS Streamgage definitions http://water.usgs.gov/nsip/definition9.html). Crest gage calibration curves are summarized in Appendix 1. The crest gages did not work as expected and flood peaks were not able to be calculated with the data collected. Following rainfall events, stream gage was recorded and later correlated with amount of cumulative rainfall to back calculate flood peaks for previously monitored storms at each site.

Figure 6: Crest gage installation example

2.3 Environmental variables

A YSI 650 Datasonde was placed in the middle riffle of each site on each sampling date to measure temperature, pH, conductivity, and dissolved oxygen. At each site a 250 mL water sample was collected in a 250 mL Nalgene bottle and filtered through a Whatman GF/F filter prior to nutrient analysis.Water samples were analyzed for ammonium, nitrate/nitrite, and orthophosphate on a Lachat QuickChem 8500 series and dissolved organic carbon on a Shimadzu TOC analyzer. Water quality was sampled at the same frequency as macroinvertebrates. In order to measure chlorophyll-a, ten sediment cores will be collected from the top 2 cm of the stream bottom at each riffle from each site. All ten samples will be homogenized and analyzed for chlorophyll-a as a measure of algal biomass (EPA method 445.0). This will be done on a fluorometer. They will then be dried and burned at 550°C for three hours to burn off all organic carbon. The ashed weight will be subtracted from the dry weight to obtain an Ash Free Dry Mass of organic carbon.

2.4 Macroinvertebrates

A total of six macroinvertebrate samples (one each from 3 riffles and 3 runs) were collected from each site on each sampling date using a Surber sampler (225 cm^2). Sampling was done by inserting the sampler into the water and disturbing only the area outlined by the metal frame of the sampler. Water flowing through the net forces the disturbed organisms to flow downstream into the net and from here they were poured through a 250 μm sieve to facilitate transfers to whirlpacks. Samples were preserved with 85% ethanol and returned to the laboratory for identification. The three riffles and runs chosen were consecutive, and the same riffles and runs were used on each sample date; however, at a different location within the riffle/run. Organisms were identified down to the lowest possible taxonomic unit, usually either genus or species using a dissecting microscope and compound microscope when needed. The community recovery information was obtained by sampling on specific days post flood spanning two days through two weeks with weekly sampling until four weeks. After four weeks, monthly baseline sampling resumed.

2.5 Statistical Methods

2.5.1 Hypothesis 1

To test community resistance, a general linear model using a negative binomial regression was constructed using the statistical software "R" using the MASS package. This model tested the total abundance of macroinvertebrates before and after flood events while taking into account natural abundance fluctuations and is described as:

```
> summary(m1 <- glm.nb(abundance ~ flood + site1 + site2 + site3 + site4, data=nbr)
```

A total of 343 samples were included in the model. In this model pre-flood dates are any sampling dates that preceded a rainfall event or seasonal sampling events. Post flood dates are defined as the first and second sampling date after a rainfall event. For each storm, macroinvertebrate samples were collected for 3-4 weeks depending on when the next rainstorm occurred. This amounted to 4-6 samples for each storm.

2.5.2 Hypothesis 2

To test community resilience non-metric dimensional scaling was conducted with statistical software "R" using the vegan package targeted toward ecological data. The macroinvertebrate diversity data will be used in this portion of the analysis to see how the changing community develops after a disturbance. Abundance values were divided into six different diversity groups: Oligochetes, Diptera, EPT, Gastropods, Odonates, and Other. Results were based on the way the abundances of each of these groups changes with time. A bray-curtis distance measurement was used to calculate distance between points and results were displayed using a 2 axis system. A Wisconsin double transformation combined with a square root transformation was performed on all data.

CHAPTER 3: RESULTS

3.1 Hydrology

Storms were sampled over a 1 year period. Average cumulative rainfall for each event ranged from 0.6 inches to 2.2 inches (Table 1). The first sampled storm (November 2013) was the smallest disturbance with only 0.6 inches of rain. The largest storms were 2 and 3 and occurred in the spring.

3.2 Environmental Variables

The average concentrations of nutrients are summarized in Tables 3-5. The range for the orthophosphate concentrations was nondetectable - 0.096 mg/L, and the range for nitrate/nitrite was nondetectable - 2.68 mg/L. The range for ammonium was nondetectable - 0.05 mg/L. These ranges are well within other published values and those reported by the USGS (Dubrovsky and Hamilton, 2010). The general linear model performed on all of the environmental data yielded no significant differences in pre and post flood data (Table 6).

Table 3: Average Orthophosphate concentrations for each site by season. Number in parentheses is number of samples collected.

	PO_4 mg P/L			
	RC	TC	SP	MC
SUMMER (40)	0.052	0.03	0.059	0.036
FALL (40)	0.015	5.60E-03	0.028	6.42E-03
WINTER (32)	0.003	1.14E-02	0.023	0.014
SPRING (51)	0.038	0.034	0.056	0.039

Table 4: Average Nitrate/Nitrite concentrations for each site by season. Number is parentheses is number of samples collected.

	No_x mg/L			
	RC	TC	SP	MC
SUMMER (40)	0.187	0.312	0.778	0.255
FALL (40)	0.045	ND	0.469	ND
WINTER (32)	0.169	0.434	1.06	0.361
SPRING (51)	0.105	0.266	0.499	0.304

Table 5: Average Ammonium concentrations for each site by season. Number in parentheses is number of samples collected.

	NH_4 mg/L			
	RC	TC	SP	MC
SUMMER (56)	0.013	0.019	0.035	0.033
FALL (40)	5.76E-03	3.25E-03	1.96E-03	0.016
WINTER (40)	9.79E-03	7.13E-03	0.274	0.075
SPRING (32)	0.004	0.026	0.314	0.096

Table 6: General linear model results for environmental variables. No environmental variables were determined to have significant pre to post flood differences.

	P VALUE	**STD ERROR**	**Z SCORE**
NO4	0.2139	0.4691	0.456
POX	0.3262	1.2951	0.252
CHL A	-1.492	0.2313	-6.45
AFDM	-1.1358	0.4878	-2.328

3.2 Overall Diversity

A total of 11,896 organisms which included 65 taxa in 15 orders were collected and identified. The majority of organisms were collected during the summer (30% of total organisms) and fall (23% of total organisms) with communities being the least abundant in late winter (9% and 14% for 2 separate storms). The annual variability in total abundance for each site issummarized in Appendix B (Figures B-1 through B-4).

The most common organisms collected at all sites were the Chironomids, encompassing 44% of the communities with the Hydropsychids (21%) the next prevalent family. Table 7 summarizes the percent community composition of all sites. At the Reedy Creek forested site the most common organisms were Chironomids (60% of total abundance) followed by Hydropsychids (18% of the total abundance). This site also consisted of 6% Oligochetes, 4% clams, and 3% Baetidae mayflies. Torrence Creek was also dominated by Chironomids with 35% followed by the Hydropsychids. This site also harbored 9.4% Baetidae mayflies, 7.8% clams, and 3.8% Oligochetes. Dairy Branch at Sedgefield Park was also dominated by the Chironomids, but was followed more closely by Hydropsychids with 38% and 33% respectively. This site also had 25% Oligochetes and 4% Baetidae mayflies. The Muddy Creek site was the only site not dominated by Chironomids with only a 25% composition, and was instead dominated Oligochetes with 31% composition. Muddy Creek also had 20% Hydropsychids, 5% clams, and 1% Baetidae Mayflies.

Table 7: Percent Community composition of dominant groups of each site.

	RC (%)	**TC (%)**	**SP (%)**	**MC (%)**
HYDROPSYCHIDS	18	18.7	33.4	20
CHIRONOMIDS	60	35	38	25
BAETIDS	2.9	9.4	4.1	1
OLIGOCHETES	6	3.8	25.2	31.4
CLAMS	3.9	7.8	0	5.2

The dominant Hydropsychid in this research was the *Hydropsyche* genus. This is a net spinning Trichoptera that is a filter feeder. These are common organisms that are more tolerant of negative water quality than many other Trichoptera. The dominant Ephemeroptera was family Baetidae and genus *Baetis*. These are small swimming mayflies that feed primarily on algae. The dominant Diptera is the family Chironomidae.

These are small larvae that often feed on decaying organic matter. They are often found in urban streams and are highly resistant to anoxic or polluted conditions. Oligochetes are also often noted for their prevalence in polluted waters (Merritt and Cummins, 2008)

3.3 Hypothesis 1: Community Resistance

The negative binomial regression showed a statistical difference between the pre- and post flood macroinvertebrate abundance (Table 8). Figure 7 shows the change in abundance in total macroinvertebrates from pre to post flood measurements for all storms monitored. A multivariate regression was also performed with macroinvertebrate abundance and all environmental variables (NOx, PO4, Chlorophyll a, AFDM). This regression showed that macroinvertebrate abundance and chlorophyll a concentration within the sediments were statistically related (Table 9). Chlorophyll a was the only environmental variable measured that was statistically related to macroinvertebrate abundance.

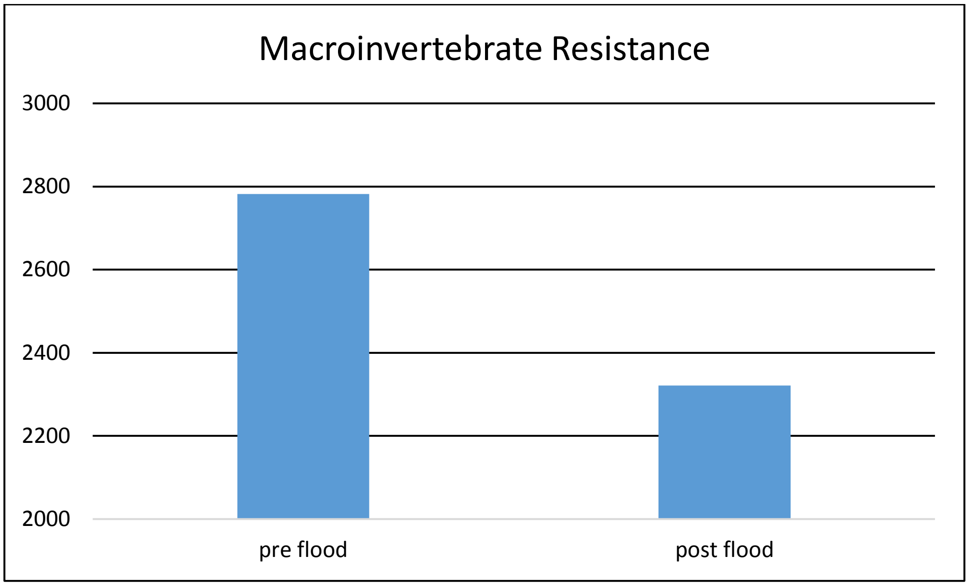

Figure 7: Change in macroinvertebrate total abundance from pre flood to post flood for all storms combined (n=114)

Table 8: Negative Binomial Regression model results from all sites combined showing that flood had a significant effect on abundance.

VARIABLE	**P VALUE**	**STANDARD ERROR**	**Z SCORE**
FLOOD	0.007	0.069	0.110
SITE1	0.247	0.164	1.505
SITE2	0.522	0.163	3.185
SITE3	0.644	0.166	-3.882

Table 9: Multivariate regression results from environmental data with abundance showing that chlorophyll was the only variable associated with macroinvertebrate abundance.

VARIABLE	P VALUE	STANDARD ERROR	Z SCORE
CHLOROPHYLL	0.0023	0.0037	0.603
AFDM	6.5222	12.1733	0.536
NOX	14.6017	10.2347	1.427
PO4	31.5011	71.9667	0.438
NH3	46.7055	26.8659	1.738

When each site was separated and run in its own regression, the effect of flood on abundance of organisms was most strongly significant ($p<0.01$) in the most urban site, SP. Muddy Creek had the highest estimate and flood did not have a significant effect on it. RC and TC were also both significant (Table 10). When each storm was run separately, storms 1 and 5 had significant effects on community abundance. This is likely because these storms occurred in the winter season and the macroinvertebrate abundance was already at a low point. Storms 2 and 3 had insignificant effects on community abundance even though they had large amounts of rainfall (Table 11).

Table 10: Negative Binomial Regression from each site showing that MC organism abundance was the only site that was not significantly affected by flood events.

	P VALUE	STD ERROR	T VALUE
RC			
FLOOD	0.0496	0.676	0.499
SITE1	0.17444	1.284	0.199
TC			
FLOOD	0.04838	0.675	0.499
SITE2	0.59378	4.493	7.03E-06
SP			
FLOOD	0.002522	-0.036	0.971
SITE3	0.943903	-7.189	6.54E-13
MC			
FLOOD	0.05604	0.763	0.445
SITE4	0.15951	-1.083	0.279

Table 11: Negative binomial regression results showing flood effects on abundance for each storm separately. Storms 1 and 5 had significant effect of flood on abundance.

FLOOD ESTIMATES	P VALUE	STD ERROR	T VALUE
STORM NUMBER			
1	0.01163	-0.081	0.936
2	0.750506	-3.329	0.000871
3	0.2452	1.322	0.18618
4	0.09842	-0.384	0.7011
5	0.01735	0.064	0.9491

3.4 Hypothesis 2: Community Resilience

Non metric dimensional scaling analysis was performed on community data. To investigate the specific impact of storms each site was run in its own model. Then to investigate how an individual storm influenced multiple sites each storm was run in its own model.

Results show that the forested reference (RC) returns to a point closer to the origin than any of the other sites (Figure 8). Following the trajectory of the diversity changes after each storm shows that this site is resilient because the community eventually develops back to a similar state as it began in (Figure 8).

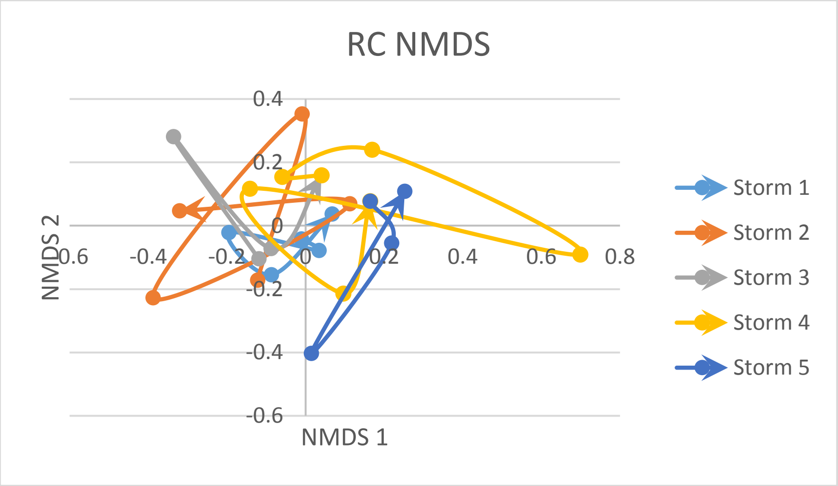

Figure 8: Reedy Creek combined NMDS plot showing recovery paths of each storm. The pre flood point is the round dot and flows in the direction of the arrows.

The two youngest sites (TC and MC) show no similar evolution. Both of these sites seem to have a one way trajectory and each successive storm begins where the previous storm left off (Figure 9 and Figure 10).

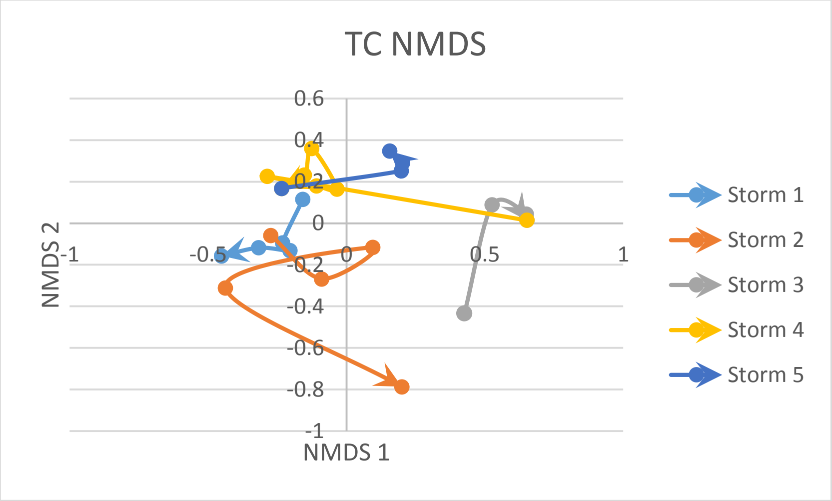

Figure 9: Torrence Creek combined NMDS plot showing recovery paths for each storm.

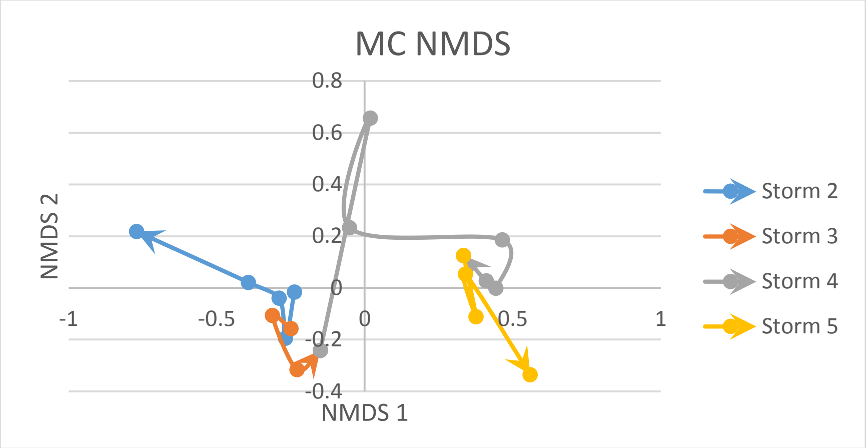

Figure 10: Muddy Creek combined NMDS plot showing recovery paths for each storm.

The oldest restored site (SP) shows a more complex pattern after flood disturbances, but still does not appear to recover as quickly as the forested reference (Figure 11).

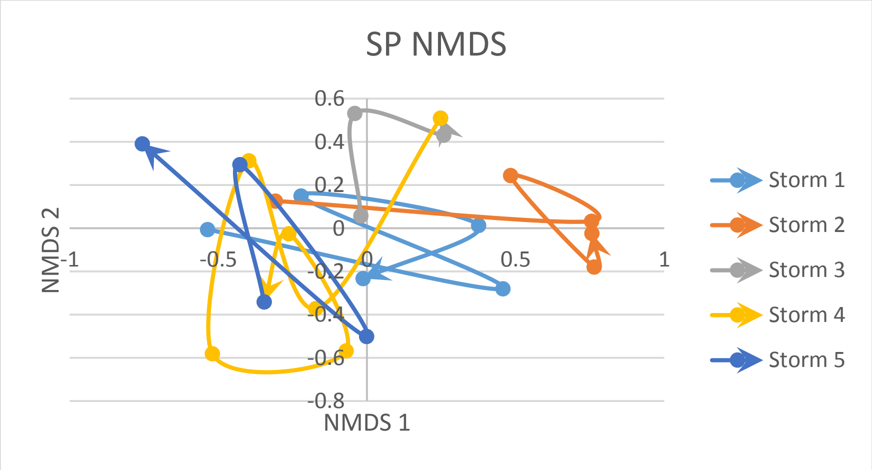

Figure 11: Sedgefield Park combined NMDS plot showing recovery paths for each storm.

The axis loadings for each sites (Table 12) indicate which diversity group had the most influence separating the communities on different days. The Reedy Creek site is controlled mostly by Odonates and Gastropods in both directions. Torrence Creek is controlled by Oligochetes along the NMDS 1 axis and by Odonates and EPT along the NMDS 2 axis. Sedgefield Park in comparison is controlled by Oligochetes and Diptera on the NMDS 1 axis and Gastropods and Odonates on the NMDS 2 axis. Muddy Creek is strongly controlled by the EPT on the NMDS 1 axis and by the Oligochetes on the NMDS 2 axis.

Table 12: Table showing axis loadings for each site model.

DIVERSITY GROUP	**RC**		**TC**		**SP**		**MC**	
	MDS1	MDS2	MDS1	MDS2	MDS1	MDS2	MDS1	MDS2
DIPTERA	-0.0545	-0.1382	0.1971	0.0515	0.3189	-0.1083	0.0218	-0.0909
EPT	0.1704	-0.1512	-0.1438	0.4553	-0.4960	-0.4765	0.7747	0.0390
GASTROPODS	-0.2390	0.2126	-0.2027	-0.2818	-0.4233	0.6550	0.0462	-0.1584
ODONATES	0.6131	0.3372	-0.5932	-0.0935	-1.5005	0.9341	0.0394	1.5457
OLIGOCHETES	-0.1734	-0.1525	0.4306	0.1225	0.4224	0.0781	-0.4316	-0.0843
OTHER	0.0582	0.0945	0.1735	-0.4060	-0.2922	0.0524	-0.1379	0.1370

Each storm was also run in a model with all sites’ trajectories. Storms 1 and 5 (Figures 12 and 16) showed simpler trajectories because these were smaller winter storms as shown by the rainfall data. Storms 2, 3, and 4 showed more dramatic shifts in community diversity because the storms were much larger and the communities were more strongly affected (Figure 12, 13, and 14). The axis loadings for the storm models are summarized in Table 8.

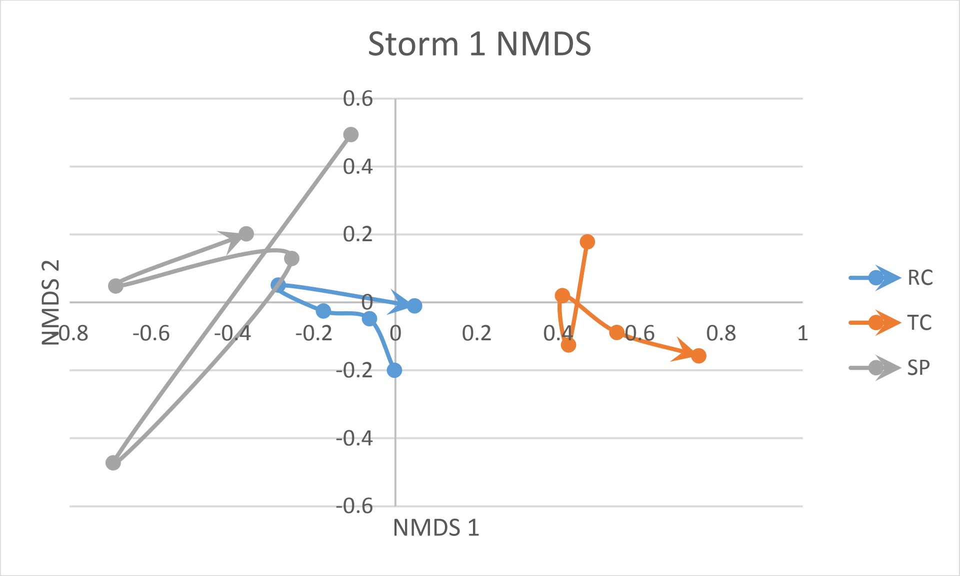

Figure 12: Storm 1 combined NMDS plot showing site recovery paths

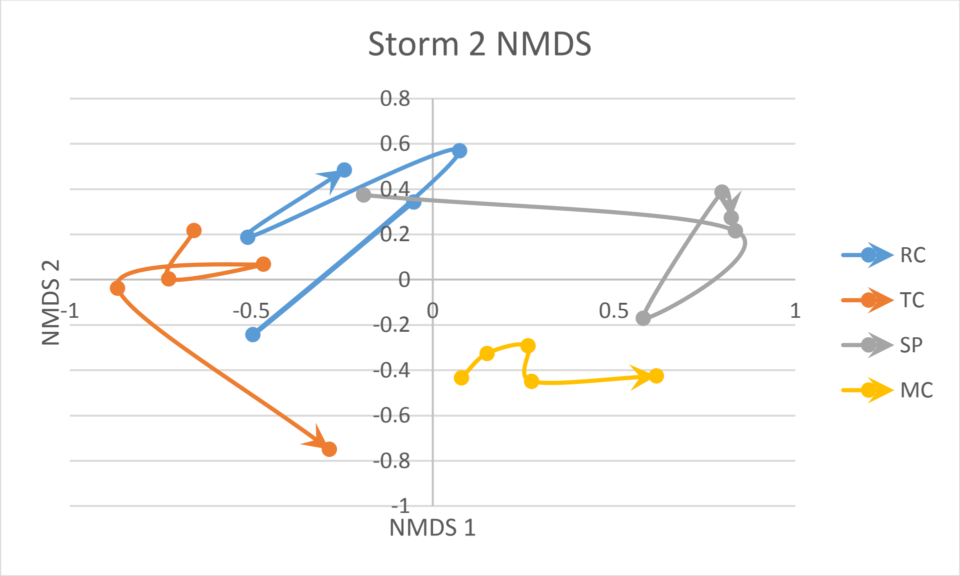

Figure 13: Storm 2 combined NMDS showing site recovery paths.

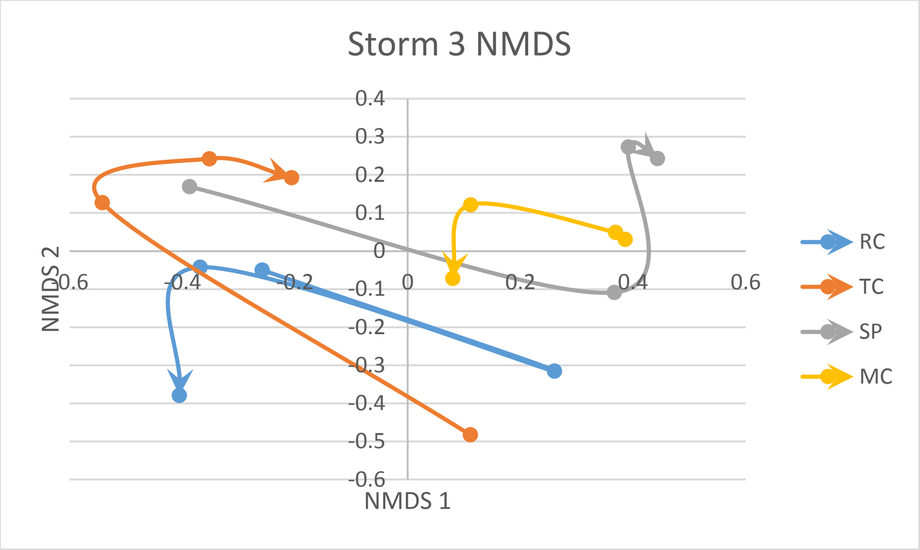

Figure 14: Storm 3 combined NMDS plot showing site recovery paths.

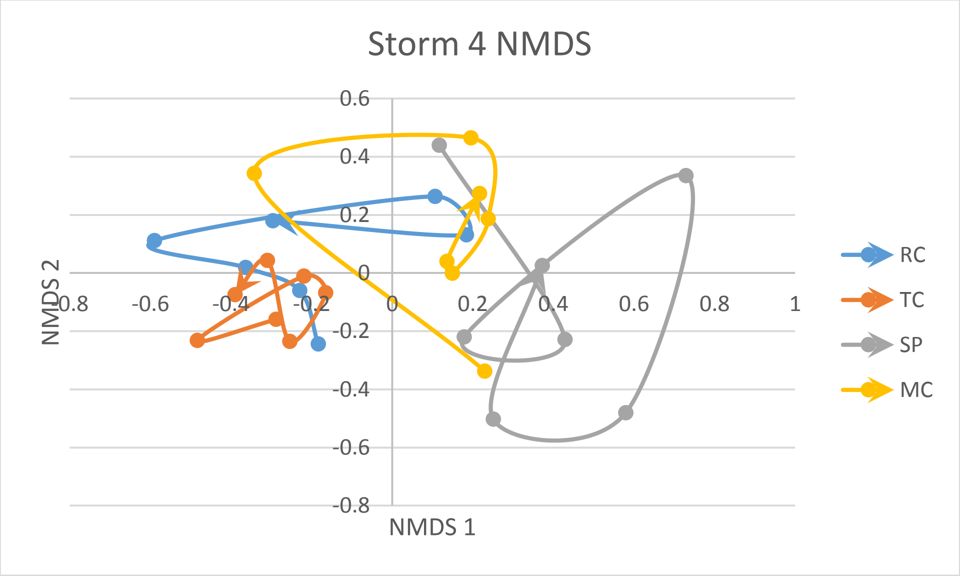

Figure 15: Storm 4 combined NMDS plot showing site recovery paths

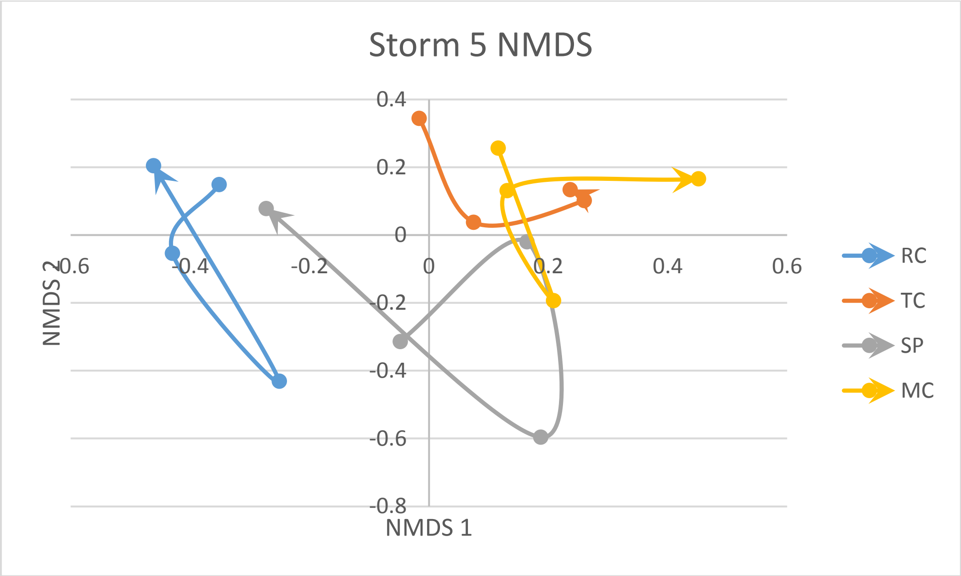

Figure 16: Storm 5 combined NMDS plot showing site recovery paths

The axis loadings for the storm models are summarized in Table 13.

Table 13: Table showing axis loadings for each storm model.

DIVERSITY GROUP	STORM 1		STORM 2		STORM 3		STORM 4		STORM 5	
	MDS1	MDS2	MDS1	MDS2	MDS1	MDS2	MDS1	MDS2	MDS1	MDS2
DIPTERA	-0.1447	-0.0178	0.2704	0.3781	-0.0878	0.1015	0.0283	-0.1760	-0.0950	-0.1453
EPT	0.2524	0.1289	-0.6084	0.6490	-0.6507	0.0638	0.1425	-0.1035	0.2098	-0.0115
GASTROPODS	0.6081	-0.0722	-0.4283	-0.2263	0.1781	-0.1697	-0.0944	-0.0698	0.2584	0.3851
ODONATES	0.7762	-0.2400	-1.0743	0.0514	-0.8638	-1.1781	-0.8069	-0.0518	-0.8497	0.4603
OLIGOCHETES	-0.4841	-0.2056	0.5998	-0.0892	0.3304	0.2056	0.3856	-0.2218	0.0471	-0.3125
OTHER	-0.1686	0.3472	-0.1188	-0.5106	0.1561	-0.2443	0.1467	0.4762	-0.2784	0.0709

CHAPTER 4: DISCUSSION

This study focused on community resistance and resilience in restored urban streams and an urban forested reference stream in Mecklenburg County, NC. While there are several studies investigating the relationship between urbanization and macroinvertebrate diversity (Walsh et al., 2001; Robinson et al., 2014), there are fewer studies focusing on the ecology of macroinvertebrates in urban streams (Wenger et al., 2009). This paper seeks to fill that gap by focusing on how macroinvertebrates respond to flooding, a key disturbance in stream ecosystems.

4.1 Overall Diversity

Taxa richness can be used as a measure of community health in some urban streams and can indicate different stressors influencing multiple organisms (Barton & Metcalfe-Smith, 1992). In this study there was a high percentage of Oligochetes at the two most urban sites, Sedgefield Park and Muddy Creek, indicating that these sites have poorer water quality than the forested reference site or the suburban residential site (Merrit and Cummins, 1996). Sedgefield Park and Muddy Creek also both had lower total abundance values throughout all seasons of the study. Overall urban streams have lower macroinvertebrate abundance compared to their forested counterparts (Walsh et al., 2001) and this lower abundance at the most urbanized sites is likely also correlated with water quality parameters not measured in the study such as metals or other chemical contaminants (Robinson et al., 2014). The Chironomids dominated at the forested reference site with 60% of the total abundance. This is because the high level of canopy cover gives the stream a very large amount of organic matter in the form of leaf litter input. Chironomids are a shredder species that will thrive in this environment and will be less adversely affected by any water quality issues that may arise than other species. This site also had some types of caddisflies such as Rhyacophilidae and Limnephilidae and stoneflies such as Perlidae and Chloroperlidae that were found nowhere else in the study. These organisms are indicative of improved water quality.

There was a shift in percent composition with a higher percentage of Trichoptera, Ephemeroptera, and Chironomid and a decrease in Oligochetes and clams over time across the restoration ages. The Hydropsychid population increased from 20% at Muddy Creek (the youngest site) to 33% at Sedgefield Park(the oldest site), and the Baetid population increased from 1% at Muddy Creek to 4.1% at Sedgefield Park. The Oligochetes dropped from 31.4% at Muddy Creek to 25.2% at Sedgefield Park. These patterns could reflect the fact that older communities have had time to develop specialist species niches whereas the younger site is still suffering from the disturbance that is restoration and have not had time to properly recover (Winking et al., 2014). There are no long term studies on macroinvertebrates and restoration for Piedmont streams so it is not clear whether these patterns occur across multiple sites. I recognize that the number of sites represented on my age gradient is low (1 per age) and other factors such as differences in watershed hydrology may also influence the change in community composition (Richards et al., 1997)

4.2 Community Resistance

Flooding is a common disturbance in stream ecosystems and investigating how communities respond can reveal important information about their stability and function. This study demonstrated that there was a significant decrease in macroinvertebrate total abundance following flood events and is consistent with other disturbance studies (Grimm and Fisher, 1989; Fritz & Dodds, 2004; Matthei, Uehlinger, & Frutiger, 1997). I also found a positive linear relationship between macroinvertebrate abundance and chlorophyll a which has also been described in previous studies (Fisher et al., 1982). This relationship is unsurprising as algal communities are also affected by flood disturbance and have life history patterns to reflect resiliency. As they are a main food source for some macroinvertebrates, it is logical that their recovery would be correlated (Huryn and Wallace, 2000).

Sedgefield Park macroinvertebrate abundance was the most strongly affected by flood disturbance throughout the course of this study. This can result from its high impervious surface cover, 38%, which is the highest of all the sites. High impervious surface cover will lead to more flashy floods that will more strongly affect the benthic community (Walsh et al., 2001). The resistance seen at the MC site is driven by the dominance of Oligochetes in this site (31.4% of total abundance). Oligochetes display high resistance to strong flows as deeper sediment acts as a refugia for them. Reedy Creek and Torrence Creek show similar initial responses to storm flows, but their recoveries look quite different.

When all storms were run separately in models, storms 1 and 5 showed a significant decrease on community abundances. Both of these storms were in early winter but were in successive years. Community abundance is already at a low point in the winter season, so organisms that possess strong resistance life history traits could be a lower portion of the community than in the summer seasons. Changes in abundance post storm were smaller for the late winter storm. This could be because the community is already at its lowest point in numbers and diversity that there is not much left to affect.

4.3 Community Resilience

As invertebrate communities often show little resistance to flood events, it becomes important to study their recovery from such disturbances (Hax & Golladay, 1998). This study found that the forested reference (RC) and the oldest restored site (SP) showed more complex responses to flood disturbances. These sites had a higher taxa richness that may reflect a greater diversity of response to disturbance than the other sites. Sedgefield Park was restored in 2008 and has had longer to develop specialist organisms. Even though Sedgefield Park often showed very little resistance after initial disturbance, the complex recovery pattern as measured by more movement through space on the NMDS axes shows that the community here has adapted well for their current disturbance regime as has been shown in other literature (Matthei et al., 1997). The community has shifted towards organisms that are able to more quickly recover from disturbances because they colonize quickly, reproduce quickly, or have any other resilience traits. This is supported by the community shifts in dominant organisms from clams and Oligochetes to the Trichoptera, Chironomids, and Ephemeroptera. Torrence Creek and Muddy Creek, the younger sites, show a much more unidirectional recovery pattern that does not return to pre flood composition indicating that these communities have not had time to develop any such characteristics. The axis loadings complement the diversity data because the most common organisms at each site controlled their axes. When each storm was run in its own model storms 1 and 5 showed the smallest pathways for all sites. This is because the storms were in the winter season and abundance was already compromised. It was shown in the resistance portion of analysis that storms 1 and 5 had the most significant effects on abundance. Storms 2,3, and 4 showed more dramatic shifts in community diversity because the communities had a stronger macroinvertebrate abundance initially.

4.4 Management implications

Restoration is often cited as a solution to the urban stream syndrome. However there has been little long term research into how these restored streams are actually responding to restoration practices and how communities change over long time periods. Several researchers have documented that urban stream restoration is unsuccessful in increasing macroinvertebrate diversity as compared to forested reference reaches or unrestored reaches (Bernhardt and Palmer, 2011; Violin et al., 2011). Most of these studies however, have only investigated patterns 1-5 years post restoration. This research found that older restored streams (9 years since restoration) are beginning to respond to flood events in a similar way as an unrestored reference site. This site has the highest impervious surface cover, so without restoration it likely would have had a simple recovery pattern indicative of a non-specialized community (Walsh et al., 2001). The youngest restored sites still had simpler recovery patterns and did not move through space like the unrestored reference. Using this data water managers can more accurately judge the recovery time to be greater than the common monitoring frame of 3-5 years and begin to prove that these ecosystems will need to be monitored for 5-10 years to capture the real response of stream to restoration as stated in Bernhardt and Palmer (2011).

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APPENDIX A: HYDROLOGY

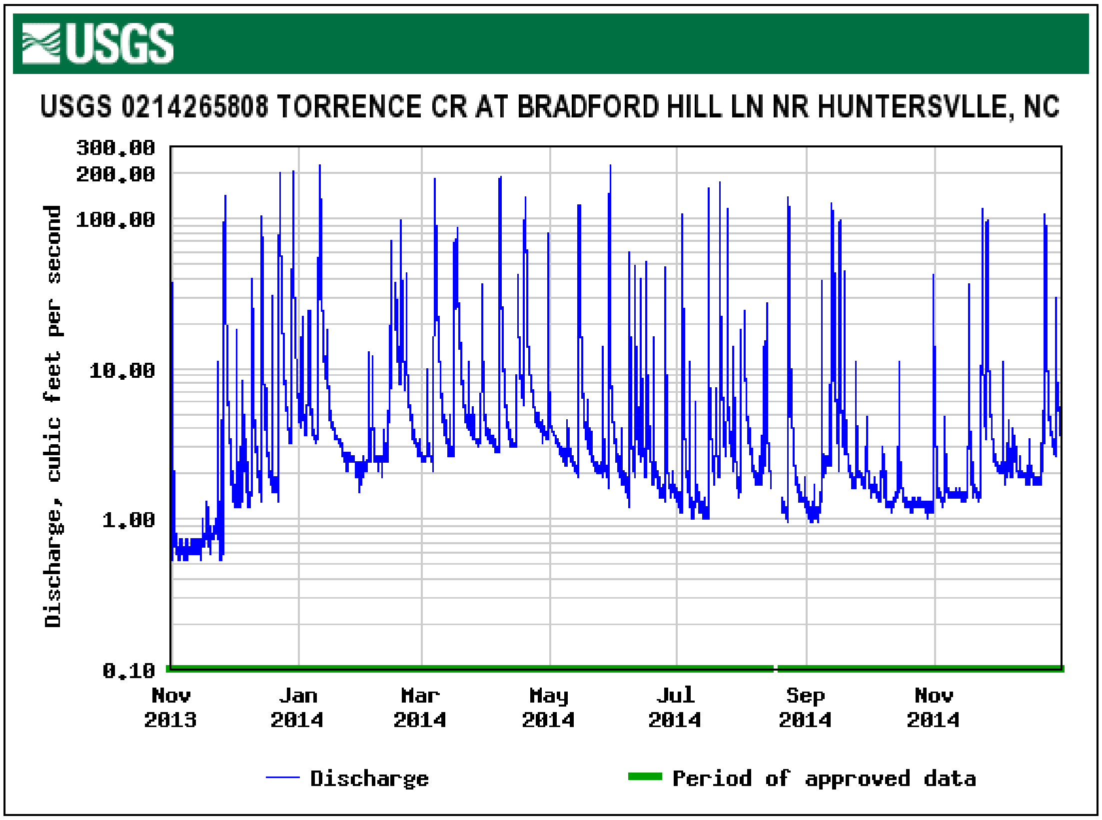

Figure A-1: Torrence Creek hydrograph for 2013-2014 sampling period. Red Dots Mark sampled storms.

Crest Gage Data:

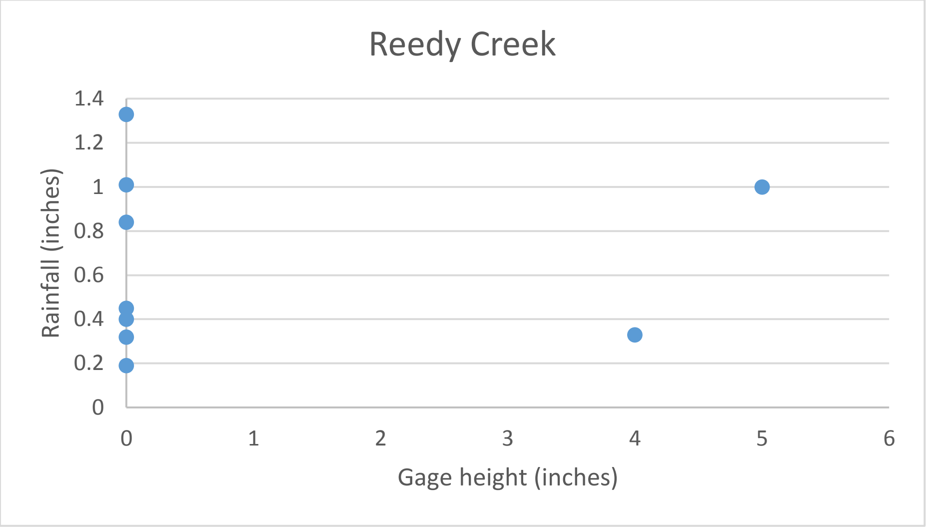

Figure A-2: Reedy Creek Crest gage calibration

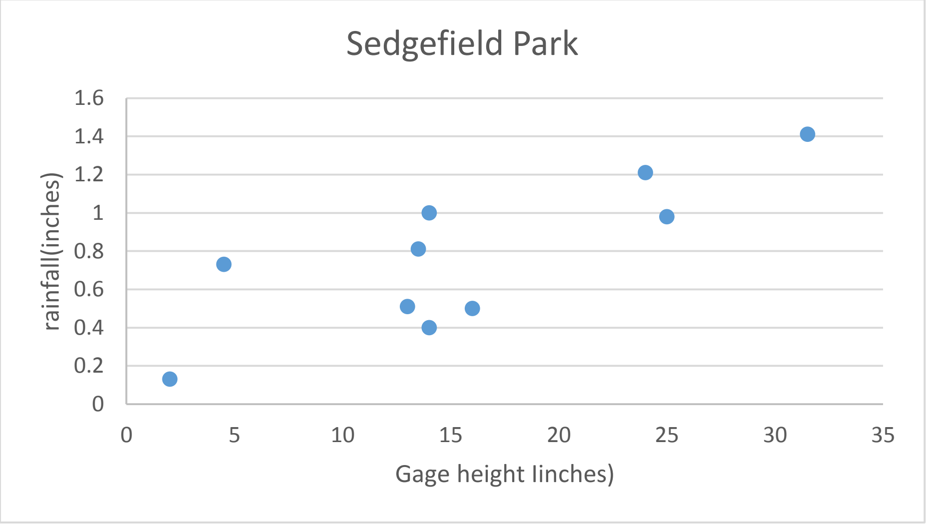

Figure A-3: Sedgefield Park Crest gage calibration

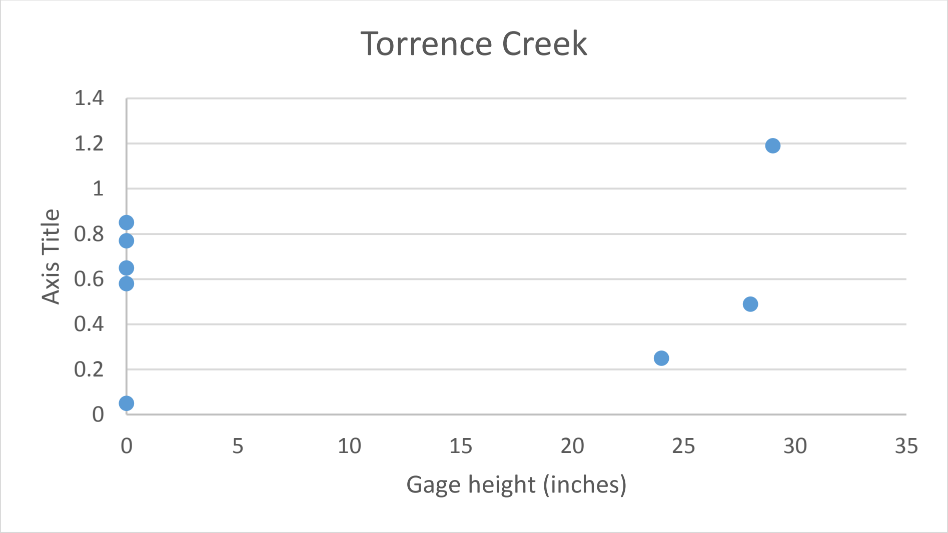

Figure A-4: Torrence Creek crest gage calibration

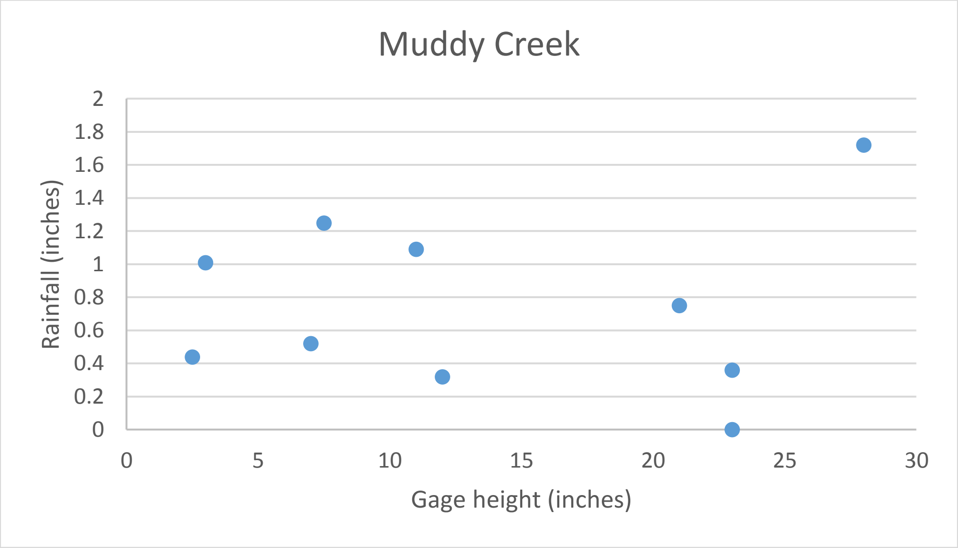

Figure A-5: Muddy Creek crest gage calibration

APPENDIX B: MACROINVERTEBRATE DATA

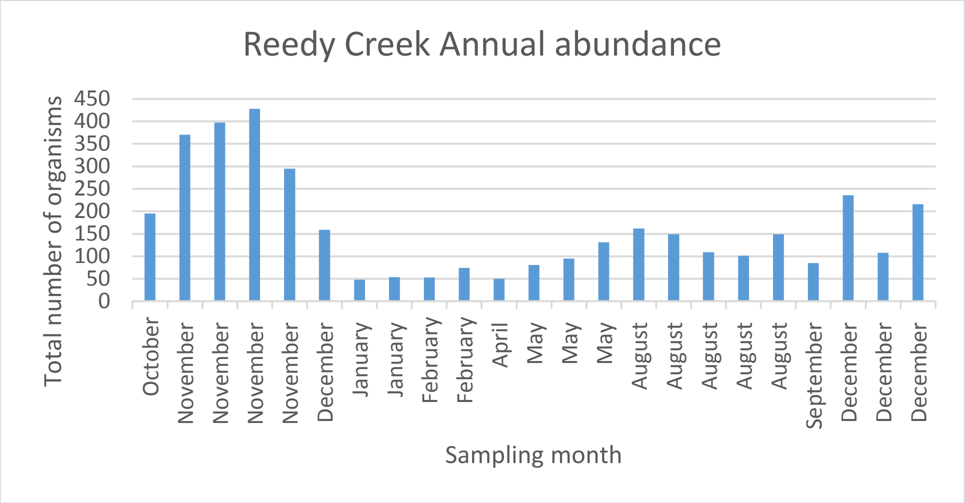

Figure B-1: Annual variability in total abundance of organisms for Reedy Creek.

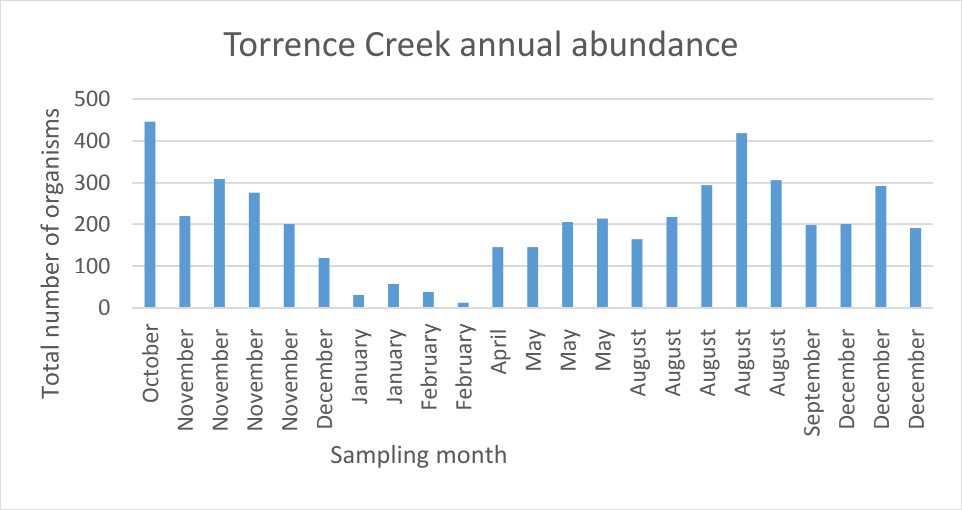

Figure B-2: Annual variability in total abundance of organisms for Torrence Creek.

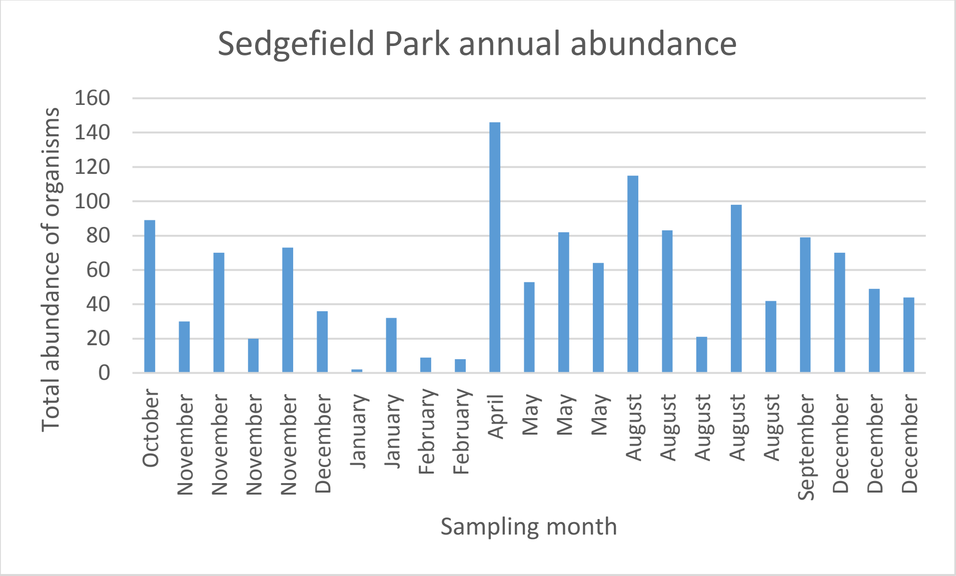

Figure B-3: Annual variability in total abundance of organisms for Sedgefield Park.

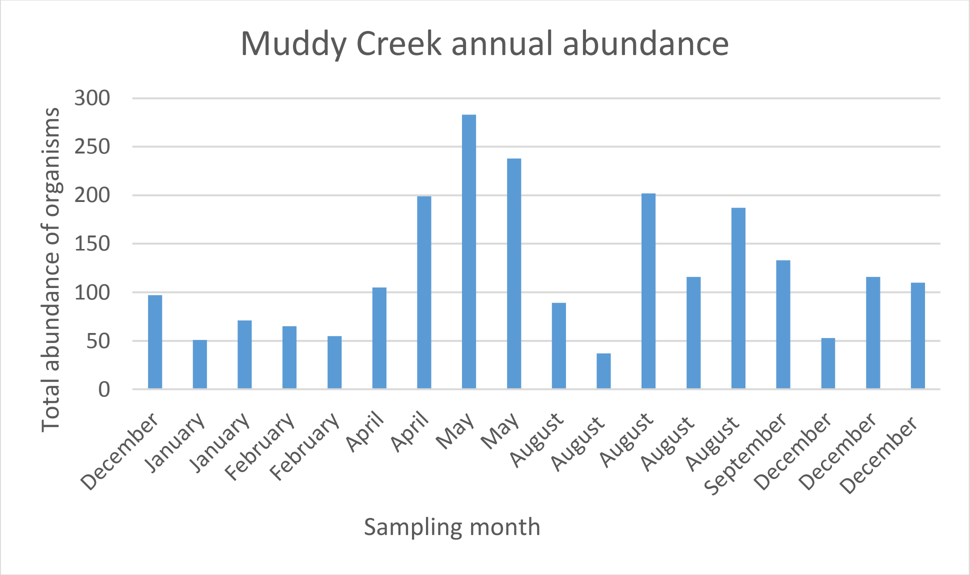

Figure B-4: Annual variability in total abundance of organisms for Muddy Creek.

Table B-1: Complete taxa list for all samples

TAXA LIST		
ORDER	Family	Genus
AMPHIPODA		
ANNELIDA	Hirudinae	
ANNELIDA	Oligochetes	
CLAMS		
COLEOPTERA	Carabidae	
COLEOPTERA	Dytiscidae	Neoclypeodytes
COLEOPTERA	Elmidae	
COLEOPTERA	Psephenidae	
COLEOPTERA	Ptilodactylidae	
COLLEMBOLA		
COPEPODA		
DECAPODA	Crawfish	
DIPTERA	Ceratopogonidae	
DIPTERA	Chironomids	
DIPTERA	Culicidae	
DIPTERA	Dixidae	
DIPTERA	Empididae	
DIPTERA	Limnophila	
DIPTERA	Sarcophagidae	
DIPTERA	Simuliidae	
DIPTERA	Tabanidae	
DIPTERA	Tipulidae	Pilaria
DIPTERA	Tipulidae	
EPHEMEROPTERA	Ameletidae	
EPHEMEROPTERA	Baetidae	Baetis
EPHEMEROPTERA	Ephemerellidae	Ephemeralla
EPHEMEROPTERA	Ephemerellidae	Eurylophella
EPHEMEROPTERA	Heptageniidae	Macaffertium
EPHEMEROPTERA	Leptophlebiidae	Paraleptophlebia
EPHEMEROPTERA	Neophemeridae	
GASTROPODA	Limpets	
GASTROPODA	Planorbella	
GASTROPODA	pomacea	
HEMIPTERA	Gerridae	
HEMIPTERA	veliidae	
ISOPODS		
LEPIDOPTERA	Crambidae	
NEMATODA		

ODONATA	Calopterygidae	Calopteryx
ODONATA	Coenagrionidae	Argia
ODONATA	Cordulegastridae	Cordulegaster
ODONATA	gomphidae	Stylogomphus
ODONATA	Lestidae	
PLECOPTERA	Capniidae	
PLECOPTERA	Chloroperlidae	Haploperla
PLECOPTERA	Nemouridae	
PLECOPTERA	Perlidae	Beloneuria
PLECOPTERA	Perlidae	Eccoptura
TRICHOPTERA	Glossosomatidae	Glossosoma
TRICHOPTERA	Hydropsichidae	Hydropsyche
TRICHOPTERA	Hydropsychidae	Cheumatopsyche
TRICHOPTERA	Hydroptilidae	Hydroptila
TRICHOPTERA	Hydropychidae	Diplectrona
TRICHOPTERA	Lepidostomatidae	Lepidostoma
TRICHOPTERA	Leptoceridae	Oecetis
TRICHOPTERA	Limnephilidae	Anabolia
TRICHOPTERA	Limnephilidae	Pycnopsyche
TRICHOPTERA	Molannidae	Molanna
TRICHOPTERA	Odonotceridae	
TRICHOPTERA	Oligonuridae	
TRICHOPTERA	Philopotamidae	Chimarra
TRICHOPTERA	Phryganeidae	
TRICHOPTERA	Polycentropodidae	Cyrnellus
TRICHOPTERA	Polycentropodidae	Nyctiophylax
TRICHOPTERA	Rhyacophilidae	Rhyacophila
TRICHOPTERA	Sericostomatidae	Agarodes