MACROINVERTEBRATE RECOLONIZATION DYNAMICS IN RESPONSE TO THE LEVEL OF URBANIZATION, DROUGHT AND FLOOD IN THREE AUSTIN, TEXAS, STREAMS.

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ABSTRACT

MACROINVERTEBRATE RECOLONIZATION DYNAMICS IN RESPONSE TO THE LEVEL OF URBANIZATION, DROUGHT AND FLOOD IN THREE AUSTIN, TEXAS, STREAMS

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Impervious cover of urbanized areas exaggerates the hydrologic disturbance (intensity of spates and duration of dry periods) common in central Texas. The objective of this study was to determine how benthic macroinvertebrate community composition, diversity, resilience, and recolonization in three Austin, Texas, streams that vary in degree of impervious cover are affected by drought and flood. The least urbanized watershed (Onion Creek, 1.6% impervious cover) was used as reference. Walnut Creek is in the most urbanized with 30% impervious cover followed by Barton Creek at 7%. Benthic macroinvertebrates were quantified in three riffles in each of the three streams. Recovery from drought and flood were determined by: 1) Two bi-weekly samples after flow resumed in September 2001, and monthly sampling thereafter until flood disturbance; 2) Two bi-weekly samples after flows receded in November 2001, and monthly sampling thereafter for three months. Among the three streams, Walnut Creek had the greatest overall abundance with 41% of the total organisms; Barton Creek had 30% and Onion

Creek 29%. Walnut Creek had the maximum abundance (3,774 individuals/m^2) and Barton Creek had the least abundance (1,914 individuals/m^2) during the post-drought. During post-flood, the greatest abundance occurred at Barton Creek (1,410 individuals/m^2) and Onion Creek had the least abundance (527 individuals/m^2). Overall, Chironomidae made up the bulk of the total organisms at all sites comprising 33.7% followed by *Simulium* (19%) and *Baetis* (17.1%). Chironomidae and *Baetis* were the dominants at all study streams.

Relative abundance of macroinvertebrate was 2 times greater during the post-drought than during post-flood. Greatest species richness occurred at the moderately disturbed stream where *Baetis, Caenis, Stenelmis* and Chironomidae were dominant. Results indicated that rate of recolonization following disturbance was inversely related to degree of impervious cover. Impervious cover appears to interact with natural hydrologic disturbances in determining structure and function of the benthic community in urbanized streams.

INTRODUCTION

Only recently have macroinvertebrates received attention in assessing surface water quality. With increasing anthropogenic disturbance, water is increasingly contaminated from agricultural, industrial and urban organic compounds which are persistent and mobile in surface and groundwater (Stauffer 1998). One economical and efficient way of detecting effects of contaminants is through the use of macroinvertebrates (Karr 1987, Karr and Chu 1999). Rapid Biological Assessments (RBAs) are used to evaluate the "health" of the stream and to assess effects of non-point source pollution which may not be apparent in traditional water chemistry analysis (Barbour et al. 1999, Karr and Chu 1999, Plafkin et al. 1989, Resh and McElravy 1993). Macroinvertebrate assemblages are good indicators of localized conditions because their sessile nature allows determination of spatial extent of impacts and their relatively long life cycles (± 1 year) allow assessment of temporal pollution impacts (Rosenberg and Resh 1993).

Stream macroinvertebrates also are periodically decimated by natural disturbances, such as floods and droughts (Resh et al. 1988). Recovery after disturbance is achieved through recolonization (Gray and Fisher 1981). Hynes (1970) identified the principal recolonization pathways for the benthos as eggs from aerial adults or downstream drift, upstream migration and vertical movements from below the substrate by immatures. Fisher et al. (1982) found that most aquatic insects recolonized through aerial pathways after a spate in a desert mountain stream. Many of the early colonizers, such as mayflies and midges are considered opportunistic species with multivoltine life histories believed to be disturbance coping strategies (Poff & Ward 1989, Rabeni and Minshall 1977, Williams 1996). Disturbances influence life histories and community dynamics of aquatic biota (Stanley et al. 1994). More is known on invertebrate response to flooding (Gray and Fisher 1981), than drought and intermittency.

In central Texas, the weather is characterized by flashy spates and long dry periods creating hydrologic conditions that are dramatically more variable than in most temperate regions (Baker 1977). Since bioassessment protocols were developed in temperate regions, understanding the effects of hydrology on the biological communities of streams in central Texas is crucial to the interpretation of bioassessment data. The biological response to hydrologic disturbance is well documented in studies of relatively pristine systems (Angradi 1997, Dole-Olivier et al. 1997, Scrimgeour and Winterbourn 1989), as is the biological, physical and chemical response of streams to urbanization (Britton et al. 1993, Pratt et al. 1981, Tikkanen et al. 1994). However, the effects of hydrologic variability on biological assessments and their interpretation in monitoring programs are not well understood.

Urban streams in Austin, Texas, have the same hydrological problems encountered in densely developed areas all over the world. Urbanization accompanied by impervious cover exaggerates stream flow patterns, producing greater runoff volumes, higher peak flows and reduced baseflow (Elliot et al. 1997, Schueler 1994, Scoggins 2001, Sponseller et al. 2001). This creates a very unstable system ranging from destructive floods to total dewatering in very short time intervals and subject the biological communities to frequent disturbance and adjustment. Macroinvertebrate community composition, resilience, and recolonization may be negatively affected by such conditions (Angradi 1997, Clausen and Biggs 1997, Death and Winterbourn 1995, Poff and Ward 1989). Thus, the effect of hydrologic conditions on metric scores from biological assessments (Barbour et al. 1999) should be greatest in more urbanized watersheds, due to impervious cover altering natural runoff patterns.

Stability of a community is measured by its resistance, resilience or both. Resistance is ability to resist change and resilience is the rate of recovery following disturbance (Miller and Golladay 1996). Recovery is defined as the re-establishment of community structure and function to pre-disturbance conditions which is accomplished through the pathways of recolonization, viz. drift, oviposition by aerial adults and instream refugia (Miller and Golladay 1996). The time required for recolonization varies depending upon stream type and the severity of disturbance (Lake et al. 1989). Fisher et al. (1982) noted that the physical and morphometric conditions typical of the pre-disturbance levels were restored quickly. Additionally, several studies of benthic macroinvertebrate communities in areas of naturally high disturbance show that they also recover quickly from disturbance events due to evolutionary adaptations (Lake et al. 1989, Poff & Ward 1989).

High resilience is crucial for recovery from drought since community composition is negatively affected due to reductions in habitat availability and increased intensity of biotic interactions with the decline in water level (Boulton et al. 1992 b, Miller and Golladay 1996). Greater resistance to drought than flooding is because flooding is less predictable and sudden in onset (Filho and Maltchik 2000). Although total macroinvertebrate density has low resistance and resilience to flooding, community composition has high resistance and resilience and this ability is an important mechanism of recovery to pre-disturbance conditions (Miller and Golladay 1996).

The objectives of this study are to: (1) determine patterns in the recolonization dynamics of benthic macroinvertebrates following a drought and a flood disturbance, (2) compare patterns of composition and recolonization of benthic macroinvertebrates among watersheds differing in degree of impervious cover and their corresponding levels of urbanization. (3) evaluate how the above factors influence water quality using rapid biological assessment determinations (Barbour et al. 1999) in central Texas urban streams.

In addition to the main objective, the following ecological principles were examined. MacArthur and Wilson (1967) recognized two groups of species that comprise a community and inferred that the predominance of one group over the other could be used to distinguish between community types. "Opportunistic" (nonequilibrium) communities should be largely r-strategists with high dispersal and reproductive potential that are more common in unstable, unpredictable environments. "Equilibrium" communities should consist mainly of K-strategists that predominate under more stable environmental conditions (Minshall et al. 1985). Based on r/K selection theory (MacArthur and Wilson 1967), the most urbanized watershed in this study (Walnut Creek, 30% impervious cover) will have higher population densities following recovery from disturbance as a result of the dominant organisms being r-strategists.

Based on the intermediate disturbance hypothesis (Connell 1978) which is widely applied in lotic studies (Resh et al. 1988, Ward and Stanford 1983), diversity will be greatest at intermediate levels of disturbance, with competitive exclusion and physical elimination leading to lower species richness at either end of the disturbance continuum (Russell and Winterbourn 1995). Therefore the moderately urbanized watershed (Barton Creek, 7% impervious cover) will have the highest species richness. At Walnut Creek (30% impervious cover) high levels of disturbance will reduce species richness and diversity and at Onion Creek (1.6% impervious cover) low levels of disturbance permits competition thus reducing richness and diversity. RBA metric scores will be higher and hydrologic variability and degree of impairment will be lowest in the least heavily urbanized watershed (Onion Creek, 1.6% impervious cover, Schueler 1994).

Effects of Drought on Stream Macroinvertebrates

The progressive effects of drying in both intermittent and permanent streams affect the systems in various physical and environmental ways. As stream water dwindles, flow is reduced. Reduced flow contributes to lower dissolved oxygen levels, making it harder for the fauna to persist (Closs and Lake 1994). As the amount of water continues to vanish, stream depth diminishes and the width recedes. The recession of stream width progressively dries the stream bank. However, the hyporheic zone (area >5 cm beneath the substratum) may retain moisture long after water loss, allowing organisms to withstand drought conditions (Firth and Fisher 1992).

The complete drying of the stream breaks the connectivity leaving the organisms concentrated in the remaining few pools (Fisher et al. 1982, Firth and Fisher 1992). The loss of connectivity also hinders organisms ability to obtain food. For instance, filter-feeding benthic organisms obtain food by filtering algae, bacteria, and zooplankton from the flowing water. Flow is crucial to their survival. Scrapers obtain nutrients by feeding on algal growth (Merritt and Cummins 1996), and flow is critical because in drought conditions the algae will dry out and perish. Fishes also obtain their benthic prey from flowing water, so reduced flow and connectivity inhibit their ability to survive. Stanley et al. (1994) observed high macroinvertebrate mortality after 10 days of drought conditions in desert streams.

Other studies reveal reduced taxonomic richness and diversity (Wiseman and Matthews 2000) following prolonged drought. Prolonged drought transforms the free-flowing rivers and streams into isolated stagnant pools.

Adaptations to Drought

Due to behavioral or physiological adaptations, some aquatic organisms can tolerate harsh environmental conditions better than others. Some of the tolerant organisms include Oligochaeta (roundworms), Ostracoda and Copepoda (crustaceans), Hydracarina (water mites), Coleoptera (beetles), and some Chironomidae (midges); while Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) have proven to be generally intolerant of extreme conditions (Hynes 1958). Consequently a water quality measure, the EPT index is based on the total number of species of these three orders. This index is one of the most widely used indicators of water quality. The smaller organisms within the tolerant groups (Oligochaetes, Chironomidae larvae) are known to survive the longest (Macan 1963). Many macroinvertebrates in egg stages can survive during drought, but few in active stages can persist (Macan 1963). In addition to life history adaptation, some benthic organisms exhibit physiological adaptations. Some Chironomidae, for example, are able to produce and store hemoglobin when oxygen is absent or depleted, a phenomenon often observed during drought (Macan 1963). Finally, some organisms can enter a dormancy period called diapause either in the egg or larval stages to escape from unfavorable conditions (Merritt and Cummins 1996).

Resilience of Stream Macroinvertebrate Community

The ability of organisms to re-establish following a disturbance is termed resilience. Williams and Hynes (1976) proposed four possible mechanisms of recolonization during stream recovery—aerial pathways, drift from upstream refugia, movements from downstream refugia, and vertical ascension from the subsurface (hyporheic) zone. Studies in deserts found that vertical movements from the hyporheic zone as recolonization routes were the least likely (Fisher et al. 1982, Gray and Fisher 1981), because of the complete drying of stream breaks the connectivity leaving the organisms in isolated pools (Firth and Fisher 1992) thus hindering acquisition of food for survival. Several studies show that aerial pathways predominate in intermittent streams due to the adaptations of these organisms to frequent drought (Crosskey 1990). For instance, during dry conditions eggs remain in dormant stage for several months and develop upon rewetting (Boulton et al. 1992 a). Drift from upstream and downstream refugia can provide colonists in permanent streams after major disturbances (Gray and Fisher 1981, Fisher et al. 1982, Stanley et al. 1994) but less so in intermittent streams. Flashy spates with increased intensity of flow wash away organisms (colonists) off the substrate. The inability to persist during flash flooding may result in further setback in community restoration (Brown 1971).

Effects of Urbanization

With increase in urbanization the percentage of impervious surface (roads, buildings and parking lots) also increases. This exaggerates the stream flow patterns, producing greater runoff volumes, higher peak flows and reduced baseflow (Elliot et al. 1997, Schueler 1994, Scoggins 2001, Sponseller et al. 2001), creating a very unstable system ranging from destructive floods to total dewatering in very short time intervals and subject the biological communities to frequent disturbance and adjustment. High amounts of impervious surface are also directly related to high amounts of pollution of urban streams (Lenat and Crawford 1994). Urban runoff may contain metal, organic, and nutrient contaminants, much more so than in forested and undeveloped areas (Lenat 1988, Sponseller et al. 2001), and threaten the ability of the organisms to survive (Lenat 1988). Another negative effect of development is increased sediment deposition (Lemly 1982, Lenat and Crawford 1994, Sponseller et al. 2001, Reice and Carmin 2000). Introducing large amounts of sediments into the stream limits many organisms such as filter-feeders whose filtering apparatus gets clogged up with silt, preventing them from feeding. This leads to local extinction, reduced species richness, diversity, and biomass (Lemly 1982). The accumulation of sediment particles on respiratory structures (gills) may also contribute to this effect (Lemly 1982). Other effects of sedimentation such as increased turbidity have also been found to reduce aquatic insect community diversity and richness (Lemly 1982).

Finally, increased temperature also occurs in urban streams due to the progressive removal of corridor vegetation (Sponseller et al. 2001) and the heat trapping ability of concrete, glass, and steel. Higher temperatures may negatively affect organisms that require colder or variable temperature patterns in their life history or reproduction mechanisms. Urban streams often have reduced diversity and species richness, lower overall abundance, and fewer intolerant taxa (EPT). Dominance may shift from intolerant to tolerant taxa (Lemly 1982, Lenat 1988, Sponseller et al. 2001), such as Oligochaeta or Chironomidae (Lenat and Crawford 1994). Decreased taxa richness often reduces a stream's efficiency in energy processing and ability of larval insects to consume detritus. Fewer detritivores means less food for higher trophic groups (Lemly 1982) thus affecting the overall food chain of the community in that stream.

STUDY SITES

The study streams were selected based on their degree of impervious cover in the watershed corresponding to their level of urbanization. Examples of impervious cover are anything that has a concrete base such as buildings, parking lots and roads. Streams were selected after consulting City of Austin staff and examining data on degree of impervious cover within the watersheds. Impervious cover was estimated based on aerial photography and historic land use mapping data using geographic information system (GIS) by the city of Austin. Sampling sites on each stream were selected near United States Geological Survey (USGS) gauging stations.

Walnut Creek (30°16'59"N, 97°39'17"W) is located on Webberville road half a kilometer west of the Walnut Waste Water Treatment Plant (Figure 2). Walnut Creek has a drainage area of 132.9 km^2 and represents the most urbanized (30% impervious cover) watershed among my study sites. Barton Creek (30°04'58"N, 98°00'27"W) represents the moderately urbanized (7% impervious cover) watershed and has a drainage area of 321.2 km^2 and lies off of Capitol of Texas Highway on Lost Creek Boulevard (Figure 1). Onion Creek (30°16'26"N, 97°50'40"W) is in the least urbanized (1.6% impervious cover) watershed and has a drainage area of 277.1 km^2 and lies northwest of San Marcos off of FM 1826 at Driftwood (Figure 1). Onion Creek was used as the reference stream because it is least influenced by anthropogenic activities.

MATERIALS AND METHODS

Three Hess samples in each of three riffles in each of three streams were collected. The August 26th rain event rewetted the stream. The first sample was collected on September 15th 2001. The Hess sampler had a cylindrical diameter of 0.34 m and samples an area 0.09 m^2 ; a bag with mesh of 500 μm connects from the main drum and tapers to a small collecting container. Samples were sorted using a 200 μm mesh sieve. Each sample was sorted in its entirety and preserved in the laboratory in 70% ethanol. Macoinvertebrates were processed and identified to the lowest possible taxonomic unit, usually genus, using a 40X dissecting scope and dichotomous keys (Merrit & Cummins 1996, Thorp and Covich 1991). Physicochemical parameters (pH, conductivity, dissolved oxygen, temperature) were measured at each site using a Hydrolab Minisonde 4a. Photos were taken of the study riffles to document variation in flow and substrate conditions. Data on discharge were obtained from USGS gauging stations on the streams. Hydrologic parameters were used to determine if there is a relationship between hydrologic variability and benthic macroinvertebrate community structure.

Head capsule width was measured using a 100X stereo-microscope with an ocular micrometer. To determine life history characteristics, plots of size-abundance relationships using head capsule width against sample times were used to determine growth and size class structure.

RESULTS

Physicochemical Variation

Specific conductance was generally higher for Barton Creek than Walnut and Onion creeks. Barton Creek showed a general decline in conductance after flows resumed, whereas Onion Creek remained relatively low during the course of the study and Walnut Creek was intermediate (Figure 3). There was a general decline in dissolved oxygen (DO) on September 22 on all streams, and a subsequent alternating increase and decrease in the following three successive sampling dates. After December 15, DO at Walnut Creek showed little changes, DO at Barton Creek increased steadily thereafter and DO at Onion Creek showed a steady decrease until December 26 and increased again (Figure 3). pH was similar at all sites ranging from pH 4.6 to 8.0 (Table 1). Temperature steadily declined from September (≈ 26°C) through December (≈10°C) (Figure 3). Unfortunately, the temperature sensor broke and I did not take readings for next three sampling dates.

Stream Discharge

Data on discharge (Figure 4) were obtained from USGS gauging stations on the streams to determine the number of low or no flow days and the frequency and magnitude of floods. Walnut Creek had less than 0.5 cubic feet per second (cfs) for 27 days prior to rewetting, Onion Creek had 21 days of low flow and Barton Creek 19 days. During the November 15 flood event, Walnut Creek had high discharge over a four day period, Onion Creek for two days and Barton Creek for a single day (Table 3).

Comparisons of Taxonomic Richness During the Post-Drought and Post-Flood

A total of 58 macroinvertebrate taxa were collected from the three streams from September 15, 2001 through March 23, 2002. Taxonomic richness, as numbers of insect genera or families, was highest in Onion Creek (least urbanized) with a total of 50 taxa, lowest in Walnut Creek (highly urbanized) with 41 taxa and Barton Creek (moderately urbanized) had 49 taxa (Figures 5). Barton Creek had more taxa than either Onion or Walnut creeks during the post-flood period. During the post-drought period, Onion Creek had the greatest number of taxa followed by Barton and Walnut creeks, respectively (Figure 5).

Variation in EPT Taxa

The most urbanized of the creeks (Walnut Creek, 30% impervious cover) had the least number of EPT (Ephemeroptera, Plecoptera, Trichoptera) taxa , moderately urbanized (Barton Creek, 7% impervious cover) the highest and the least urbanized (Onion Creek, 1.6%) had intermediate EPT taxonomic richness during the post flood recovery (Figure 5). Walnut Creek also had the lowest EPT taxa during the post-drought period while Onion and Barton creeks were greater (Figure 5). Overall, Ephemeroptera constituted 22%, Plecoptera 2 % and Trichoptera 5% of all organisms collected at the three streams.

Comparison of Macroinvertebrate Abundance

Total invertebrate density was at least 2 times higher at Walnut Creek relative to Barton Creek, and Onion Creek was intermediate in density during the post-drought period (Figure 6). The post-drought period spans from September 15 to November 3. A spate occurred on November 15 that ended the post-drought and began the post-flood recovery. Consequently, the post-flood spans from December 1, the day of the first sampling after the flows receded to March 23, 2002. During the post-flood, total invertebrate density at Barton and Walnut creeks were 3 and 2 times greater than Onion Creek, respectively (Figure 6).

Abundance of macroinvertebrate during the post-drought period is consistently greater than that of post-flood period at all of the streams. At Onion Creek, the post-drought macroinvertebrate abundance was 6 times greater relative to post-flood. Walnut Creek had 4 times and Barton Creek had 1.5 times greater macroinvertebrate abundance during the post-drought relative to their post-flood periods. (Figure 6).

Post-Drought and Post-Flood Comparisons

Recolonization of macroinvertebrates after rewetting was more rapid and was at least 2 times greater relative to post-flood abundance at Walnut and Onion creeks (Figures 7). At Barton Creek, the post-drought macroinvertebrate abundance was 1.5 times greater relative to post-flood (Figure 7). The higher rate of macroinvertebrate recovery during the post-drought period relative to post-flood was largely associated with the abundance of a few dominant taxa.

Comparison of Dominant Taxa Among Streams

Walnut Creek had 2.5 times and Barton Creek 2 times greater abundance of chironomids relative to Onion Creek. (Figures 7, Table 4). Abundance of *Simulium* was 14 and 2 times greater at Walnut Creek and Barton Creek respectively relative to Onion Creek (Table 4). *Baetis* abundance was 1.5 times greater at Barton and Onion creeks relative to Walnut Creek. Abundance of *Caenis* was 5 and 1.5 times greater at Barton Creek and Walnut Creek respectively relative to Onion Creek. *Chimarra* was 16 and 5 times greater at Onion Creek and Barton Creek relative to Walnut Creek (Figure 7, Table 4). Overall Chironomidae made up the bulk of the organisms at all sites comprising one-third of the total invertebrates and *Simulium* and *Baetis* combined made up another one-third of the total invertebrates collected.

Comparison of Dominant Taxa During Post-Drought and Post-Flood Periods

Walnut Creek had 13 times greater abundance of *Simulium* during the post-drought relative to post-flood abundance. Abundance of Chironomidae was 1.5 times greater during the post-drought relative to its post-flood, and abundance of *Baetis* during post-drought and post-flood periods were similar (Figure 7, Table 5). At Barton Creek, Chironomidae and *Caenis* were almost 2 times greater during the post-drought compared to post-flood abundance. In contrast, *Baetis* was almost 5 times greater in abundance during the post-flood relative to post-drought (Figure 7, Table 6). At Onion Creek, Chironomidae was 3 times, *Baetis* 4 times and *Chimarra* 7 times greater during the post-drought relative to post-flood abundances (Figure 7, Table 7).

Temporal Variation in Macroinvertebrate Abundance

During post-drought recovery, macroinvertebrate abundance increased over time until September 22 for Walnut and Barton creeks, whereas abundance at Onion Creek continued to increase until October 6 (Figure 8). Macroinvertebrate abundance at Walnut Creek decreased by 50% on October 6 and there was a subsequent increase until the November flood which reduced the abundance by 25 times. Macroinvertebrate abundance at Onion Creek also was reduced by more than 20 times after the flood. However, macroinvertebrate abundance at Barton Creek gradually declined following the September 22 peak and abundance was not affected by the flood.

During the post-flood recovery, macroinvertebrate abundance remained low for 69 days at all streams. Barton Creek had consistently higher macroinvertebrate abundance than the other streams following the flood event, with the exception of Walnut Creek on a single occasion on February 23, 2002. Onion Creek had consistently lower macroinvertebrate abundance relative to Walnut and Barton creeks (Figure 8).

Post-Flood Recovery of Macroinvertebrate Assemblages

High similarity between pre- and post-flood assemblages (Table 3) was evident in that the same major taxa, particularly Chironomidae, *Baetis*, *Caenis* and *Stenelmis* occurred following both disturbances (Figure 7).

Recovery of macroinvertebrate abundances reached 50% of pre-flood conditions 90 days after the November 15th flooding at Walnut and Onion creeks. Abundance remained low at Walnut Creek following flooding in contrast to Barton and Onion creeks. Abundance at Barton Creek reached 50% of the pre-flood conditions 45 days following flooding. Following flood disturbance, the number of taxa were reduced by nearly 50% for Walnut and Onion creeks whereas Barton Creek showed little change in taxonomic richness (Figure 8).

Post-Drought Recovery of Macroinvertebrate Assemblages

Because the intermittent riffles were dry prior to rewetting in August 26, recovery rate or stability could not be assessed. However, 19 days after flow resumed, the largest number of taxa were collected from Onion Creek > Barton Creek > Walnut Creek (Figure 9). This trend continued through out the post-drought with the exception on a single occasion on September 22 where Barton Creek had the highest number of taxa.

Community Similarity Index

Sorenson's coefficient, an index of community similarity, ranges from 0 to 1 with higher values indicating a higher degree of similarity. A coefficient of 1 means complete overlap of species between two communities. In this study, similarity was determined among Walnut, Barton and Onion creeks and for each creek between post-drought and post-flood disturbances. The community similarity at each creek between the post-drought and post-flood disturbances are high and community similarity among creeks are lower (Table 2).

Number of Larval Instars in Baetis species

Baetis species was the dominant taxa found consistently at all streams throughout the study. *Baetis* had eleven instars (Figure 10). There is a greater number of later instars

(X and XI) during the post-flood than during post-drought suggesting that relatively few individuals would have emerged between the time of rewetting in August and the November spate.

DISCUSSION

Effects of Urbanization

Disturbances on macroinvertebrates in streams addressed in this study are hydrologic variability associated with drought and flooding exaggerated by impervious cover (level of urbanization). With a higher percentage of impervious cover in a watershed the number of low flow days increases as does discharge during flooding (Finkenbine et al. 2000, Scoggins 2001). The number of low flow days is a measure of how often a stream has minimum flow (<0.5 cfs) at the gage station and should be positively correlated to impervious cover (Klein 1979, USEPA 1997). As percentage of impervious cover (level of urbanization) increases, amount of water infiltrating into ground decreases due to decreased porosity of the ground, consequently increasing the number of low flow days (Klein 1979) in that watershed. That higher urbanization will lead to more low flow days is consistent with my findings where the number of low flow days at the urbanized Walnut Creek was higher than Onion and Barton creeks. Walnut Creek with less than half the drainage area had comparable discharges to the less urbanized streams and the lowest taxonomic richness and is consistent with hydrologic disturbances having greater effects on macroinvertebrate community in more urbanized watersheds (Finkenbine et al. 2000, USEPA 1997).

Variation in specific conductivity and dissolved oxygen (DO) is usually attributed to the level of urbanization in the watershed (Hynes 1970, Klein 1979, Lenat and Crawford 1994). Dissolved oxygen is the amount of gaseous oxygen dissolved in an aqueous solution. Oxygen gets into water by diffusion from the surrounding air, by aeration (turbulence), and as a waste product of photosynthesis and is freely available to aquatic organisms. The major causes of low DO are increases in water temperature, algal blooms, human waste, and animal waste (Warren 1971). Lower DO at Onion Creek may be due to the pollution from human and dogs at the sampling site (personal observation) during weekend (i.e sampling) as it is adjacent to a park frequented by weekend picnickers. Specific conductance is a measure of the ability of water to conduct an electrical current and increases with the decrease in water quality. It is surprising that Barton Creek had consistently higher conductance with higher DO. Normally conductance and DO are inversely related (Warren 1971), i.e. if a stream has higher DO (more pristine or lower pollution) it will have lower conductance and vice versa. Adequate DO is necessary for the life of fish and other aquatic organisms. About 3 to 5 mg/L or ppm is the lowest limit for support of fish life over a long period of time. The dearth of DO is not a concern since all study streams had DO well above 6 mg/L. The effect of temperature on DO shows a normal trend, i.e. with gradual decrease in temperature there is a steady increase in DO.

Impacts of the Flood on Stream Biota

Declines in macroinvertebrate density and diversity (measured as number of taxa) following the flood in Austin, Texas streams are frequently observed in studies on the effects of hydrological disturbances on stream ecosystems (Scrimgeour and Winterbourne 1989). Following flood disturbance, the number of taxa for Walnut and Onion creeks decreased almost by half relative to the pre-flood number of taxa. Such impacts are typically caused by combinations of high shear stress leading to dislodgement, scouring and abrasion from high sediment loads and substrate mobilization (Collier and Quinn 2003).

Impacts of Drought on Stream Biota

Droughts can have direct and indirect impacts on stream biota. Direct impacts are those caused by loss of water and flow, and habitat reduction and reconfiguration, whereas indirect impacts are those associated with changes in phenomena such as interspecific interactions, especially predation and competition, and the nature of food resources (Lake 2003). Mortality after water loss should be severe as only few macroinvertebrate taxa can survive longer than 10 days (Stanley et al. 1994). The abundance of *Caenis* at all my sites during the post-drought exceeded that of the post-flood. The ability of *Caenis* to persist during the period of drought may be due to diapausing eggs and also to morphological adaptations such as specialized gills, thickened opercula and interlacing fringes (Miller and Golladay 1996), which protect underlying gills from siltation and improve oxygen uptake in stagnant water and isolated pools. Similar persistence by *Caenis*, *Baetis* and chironomids was reported in a study by Stanley et al. (1994) in an intermittent Sonoran Desert stream in Arizona.

Resistance and Resilience

Resistance and resilience were evaluated using invertebrate density and indices of community structure. Resistance was quantified as the percent reduction relative to predisturbance densities of the entire invertebrate assemblage as well for the individual taxa. Resistance was considered to be higher for a population in which percent reduction was relatively low. Resilience was measured by time to recover to predisturbance density, a method used by Grimm and Fisher (1989) and also by monitoring density over time.

More taxa were collected during post-drought (20 days after rewetting) at all streams relative to the post-flood (28 days after the flood event) recovery. Relative abundance of macroinvertebrate was also at least 2 times greater during the post-drought than during post-flood. Greater resistance to drought than flooding may be because flooding is less predictable and sudden in onset (Filho and Maltchik 2000). Another key component of resistance and resilience, and hence overall survival of fauna in a drought, is the use of refugia (Lake 2003). This may be passive, such as retreat downstream as the headwaters dry, or active such as the possession of desiccation-resistant life stages. Greater abundance of macroinvertebrates during the post-drought relative to post-flood may be the result of more taxa able to use refugia or diapause stages during the drought period. The fauna of intermittent streams with seasonal droughts have acquired, through evolution, a range of adaptations, such as life-history schedules, physiological mechanisms and behaviors that provide refugia (Williams 1996). Thus, the fauna of intermittent streams would be expected to be both resistant and resilient.

Resilience following flood was slow, however, Barton Creek showed a greater resilience by recovering faster to the pre-flood conditions compared to the other two creeks. Greater abundance of spate-resistant taxa at Barton Creek viz. *Baetis* and *Caenis* which preceded the flood disturbance, may have helped Barton Creek to exhibit greater resilience following flood.

Recovery from Flood Disturbance

Recovery of macroinvertebrate abundances to the pre-flood conditions was 2 times faster at Barton Creek (reached 50% of pre-flood abundance in 45 days) than at Walnut and Onion creeks (reached 50% of pre-flood abundance in 90 days). Recovery was associated with the reestablishment of dominant taxa Chironomidae, *Caenis* and especially *Baetis*. *Baetis* abundance during the post-flood was more than 4 times greater relative to post-drought which largely contributed to the higher recovery of the community following spate at Barton Creek. *Baetis* abundance during the post-flood at Walnut Creek was 2 times relative to post-drought and Onion Creek had a slight decrease in *Baetis* abundance during the post-flood. The recovery at Barton Creek following spate is faster than that of an intermittent stream in southern Oklahoma (Miller and Golladay 1996) which took 126 days for invertebrates to recover to 67% of pre-spate density. Chironomidae, *Caenis* and *Baetis,* which are more resistant to spate, were the dominants at Barton Creek as well as in the southern Oklahoma intermittent stream. Similarly, Collier and Quinn (2003) found that 90% of the density and 80% of taxa richness recovered to pre-disturbance levels within 12 months following a pulse disturbance in a hill-country stream in northern New Zealand. Chironomids were the dominant taxa in the hill-country stream of New Zealand as well.

The post-drought recovery period lasted for 69 days and there may have been adult macroinvertebrate emergence for certain taxa preceding the flood event. The presence of aerial adult macroinvertebrates (such as dipterans, mayflies and caddisflies) would mean they would be available to oviposit following disturbance. Macroinvertebrates in larval stage may exhibit persistence in response to disturbance through: (i) morphological or physiological adaptations (e.g. hooks, claws and body shape) that enable individuals to withstand flood flows, (ii) behavioral changes that lead to changes in habitat and avoidance of high flows, (iii) the ability to utilize within habitat refugia and (iv) the ability to persist in spatial refugia such as unaffected tributaries or adjacent catchments (Lancaster and Belyea 1997). Despite these adaptations, recovery following flood was much slower compared to the recovery after rewetting, which was at least 2 times faster. The flood may have drastically eliminated algae and invertebrate standing crop and reduced its overall abundance. Algae and invertebrate standing crop was reduced by 98% in Sycamore Creek, Arizona (Fisher et al. 1982) following a flood event. Such an enormous reduction in standing crop may be due to the sandy substrate of the Sycamore desert stream that tends to be washed away more easily. Elimination of algae may have been accompanied by reduction in food quantity that may have accelerated mortality (Fisher 1983). On the other hand, there was a lower reduction in invertebrate density following a flood in an Australian stream which could be due to the more stable cobble substrate and dense algal mats that are known to harbor many invertebrates and are highly resistant to spates (Boulton et al. 1992 a).

Recovery During Post-Drought Period

Recolonization commenced rapidly after flow resumed at all study streams. Recolonization of disturbed reaches by stream macroinvertebrates took anywhere from a few days to about 2 months in experimental studies (Reice 1985, Robinson and Minshall 1986) and from months to several years following natural disturbances (Fisher et al. 1982). Simuliids were the most abundant macroinvertebrate at Walnut Creek where they constituted 70% of the insects after flows resumed. Simuliids and chironomids can be considered r strategists (MacArthur and Wilson 1967) due to their rapid life cycle and high dispersal capability. These taxa are found to be among the first to colonize rewetted areas of intermittent streams in Australia (Boulton 1989), Arizona (Boulton et al. 1992 a), New York (Delucchi 1998), and Scotland (Morrison 1990). Simuliids can survive during dry conditions for several months by remaining in a dormant egg stage and develop rapidly upon rewetting (Crosskey 1990). With the resumption of flow upon rewetting, fine particulate organic matter (FPOM) transport increases (Ward 1992). Also, food quantity increased as the stream recovered, as algal mats grow (personal observation) and diatoms and FPOM increased. Greater availability of food could be part of the explanation for why Walnut Creek had higher abundance of macroinvertebrates relative to Barton and Onion creeks. On all creeks, collector/ gatherer Chironomidae were abundant. The abundance of chironomids may be indicative of the abundance of FPOM available to this functional feeding group. Small and fine gravel substrate (≈ 1 cm diameter) rather than large cobble substrate (≈8.5 cm diameter), maintain the highest densities of macroinvertebrates (Minshall 1984, Reice 1980), as small particles of detritus do not accumulate in large substrates where interstices are larger and current velocities higher. Walnut Creek had fine gravel substrate (personal observation) that could harbor more FPOM and subsequently be able to support higher abundance of macroinvertebrates relative to Onion or Barton creeks.

Recolonization Processes

Chironomidae and *Simulium* were the first to colonize at my study streams following disturbances and is consistent with Collier and Quinn's (2003) conclusion that recolonization times for major lotic groups generally following the order Diptera<Ephemeroptera<Trichoptera<Plecoptera. This pattern is apparently related to generation times and life history variability (Collier and Quinn 2003).

My study streams are located in the Edwards Plateau region of central Texas where a hyporheic refugia and source of recolonization is unlikely because of the karst geomorphology (Omernick 1987), which is either exposed or close to the surface thereby severely limiting the depth of hyporheic development. Colonization by aerial pathways is the principal recolonization mechanism for the majority of insect taxa, and sole pathway for some groups (Benzie 1984, Gray and Fisher 1981, Townsend and Hildrew 1976). Aerial colonization may occur from oviposition by terrestrial adults or from immigration by aquatic adults capable of flight (i.e. some Coleoptera and Hemiptera). Ovipositing by aerial adults could be the principal source of colonization in my study streams because the ovipositing adults may have persisted through the drought period (Gray and Fisher 1981) as the adult insects are capable of flight during disturbances. Aquatic adults are also known to exhibit behavioral avoidance of floods and therefore suffer few losses. Isolated floods have relatively little effect on all populations, despite high losses of immatures, because adults that left the stream prior to flooding are present to rapidly recolonize. Gray and Fisher (1981) tested the hypothesis that aerial pathways are used by most macroinvertebrate taxa to recolonize after flooding (summer and winter flood) in Sycamore Creek, a desert mountain stream in Arizona. They found that two-thirds of the macroinvertebrate taxa recolonized by aerial pathways in both seasons of study thus supporting the hypothesis.

Drift is the primary recolonization process for stream reaches connected to undisturbed sites upstream (Smock 1998). Since the entire watershed at all the stream sites was affected by flooding, it is unlikely that downstream drift played a major role in recolonization of the my study reaches.

Intermediate Disturbance Hypothesis

Use of the intermediate disturbance hypothesis (Connell 1978) has been advocated for stream ecosystems (Ward & Stanford 1983). The moderately urbanized stream, Barton Creek had more taxa than either Onion Creek or Walnut Creek during the post-flood, conforming to the bell-shaped intermediate disturbance hypothesis species richness curve. This result is similar to the finding of Townsend and Scarsbrook (1997) in their study in 54 stream sites in seven sub-catchments of the Taieri River in New Zealand that differed in the frequency and intensity of flood related episodes. Taxon richness was highest at intermediate intensities and frequencies of disturbance and conformed to the intermediate disturbance hypothesis. Other research that supported the intermediate disturbance hypothesis in streams was Robinson and Minshall's (1986) manipulation of disturbance frequency by turning over experimental brick substrates at various intervals. Invertebrate species richness and density declined as disturbance frequency was increased and maximum richness occurred at intermediate frequency of disturbance.

At low levels of disturbance, the species richness will be decreased due to competition. As resources became limiting and as population reach the carrying capacity, physical elimination and competitive exclusion will occur. However, 3 months recovery once flows resumed was likely insufficient for macroinvertebrates to reach carrying capacity and allow for competitive reduction in diversity to occur. Moreover, the difference in impervious cover between the least and the moderately urbanized sites are not large. Therefore, the taxonomic richness during the post-drought wherein Onion and Barton creeks had greater number of taxa than Walnut Creek are consistent with the Intermediate Disturbance Hypothesis (Connell 1978, Ward & Stanford 1983).

r/K Theory

Walnut Creek (most heavily urbanized) had greater overall abundance of macroinvertebrates than Barton and Onion creeks during post-drought and Barton Creek had greater abundance during the post-flood. Chironomidae and *Baetis* comprised the dominants at all creeks during both post-drought and post-flood. Walnut and Barton creeks also had the greatest abundance of r-strategists. More abundance of r-strategists in a given stream may mean that it will recover faster after a disturbance and reach the pre-disturbed conditions faster than streams with fewer r-strategists. Barton and Walnut creeks are consistent with my hypothesis that predicts that an increase in the disturbance (impervious cover) will favor taxa that are r strategists (MacArthur and Wilson 1967) and will result in faster recovery times abundance times and result in greater population densities.

Sorenson's Community Similarity

Sorenson's index showed that the composition of post-drought and post-flood assemblages were similar in all my study streams. This result was probably associated with the ability of the resistant taxa to persist during both post-drought and post-flood events in the respective streams. Even though Chironomids and *Baetis* were common at all three streams, the community similarity among creeks are not as high. The variation in the abundance of the other core taxa, especially *Chimarra*, Ceratopogonidae, *Stenelmis*, *Arctopsyche* and *Argia* at these three streams explains the lower coefficient.

Baetis Life Cycle

The presence of a greater number of later instars, particularly X and XI, during the post-flood suggests that fewer number of individuals would have emerged between the rewetting on 26 August and the flooding on 15 November. This also indicates that the 4 months following flooding was enough time for *Baetis* species to complete its aquatic stage or complete a generation. Recruitment was continuous since early instars were present throughout the study period. The fact that at least from the III instar on (Head capsule width 0.20 – 0.26 mm) were present through out the sampling period indicates that *Baetis* species is multivoltine in these streams, producing at least two generations a year.

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Table 1. Physicochemical characteristics of Walnut, Barton and Onion creeks during the study period. *n* represents the total number of samples.

	Depth (meter)	Temperature (°C)	Dissolved Oxygen (mg/L)	Specific Conductivity (μS/cm)	pH
Walnut Creek					
mean	0.10	18.7	9.1	592.1	7.8
min	0.06	10.2	7.5	548.9	6.95
max	0.14	25.4	10.9	637.3	8.0
n	10	6	10	10	9
Barton Creek					
mean	0.20	13.7	9.7	645.2	7.3
min	0.03	12.35	8.01	568.0	4.66
max	0.45	26.45	12.05	709.8	8.23
n	10	6	10	10	9
Onion Creek					
mean	0.10	13.6	8.4	526.7	7.4
min	0.02	13.4	6.56	510.0	6.12
max	0.15	25.31	10.2	565.0	7.88
n	10	6	10	10	9

Table 2. Comparison of taxonomic similarity among the three streams and for each stream between post-drought and post-flood.

Stream comparisons	**Sorenson Coefficient**
Walnut Creek and Barton Creek	0.672
Walnut Creek and Onion Creek	0.650
Barton Creek and Onion Creek	0.731

Post-drought versus post-flood	
Walnut Creek	0.887
Barton Creek	0.953
Onion Creek	0.901

Table 3. Overview of stream watershed characteristics, hydrology and macroinvertebrate taxonomic richness and abundance.

Creeks	Impervious Cover (%)	Days of flow < 0.5 cfs	Peak Discharge in cfs	Maximum abundance /m^2	Drainage Area (Km^2)	Taxonomic richness
Walnut	30	27	2,330 (11/15) 969 (11/16) 654 (12/15) 470 (11/28)	6,717 (11/03) 3,750 (2/23)	132.9	41
Barton	7	19	3550 (11/15)	2,640 (09/22) 2,830 (01/26)	321.2	49
Onion	1.6	21	1090 (11/15) 2930 (11/16)	5,197 (10/06) 1,340 (2/23)	277.1	50

Flow resumed on 8/26/2001
Flood event occurred on 11/15/2001

Table 4. Total abundance and relative abundance of macroinvertebrate taxa at Walnut, Barton and Onion creeks during the entire study.

	WALNUT CREEK		BARTON CREEK		ONION CREEK		Total	
Taxa	**Abundance**	**Percent**	**Abundance**	**Percent**	**Abundance**	**Percent**	**abundance**	**Percent**
Ambrysus	0	0 0	4	0 2	1	0 1	5	0 1
Arctopsyche	47	2 2	70	4 3	198	13 1	315	6 0
Argia	23	1 1	64	3.9	92	6 1	178	3 4
Baetis	240	11 2	310	19 3	349	23 1	899	17 1
Berosus	5	0 2	59	3 7	21	1 4	85	1 6
Brechmorhoga	3	0 1	0	0 0	6	0 4	9	0 2
Caenis	24	1 1	82	5 1	16	1 0	121	2 3
Caloparyphus	1	0 0	2	0 1	1	0 1	4	0 1
Cambaridae	0	0 0	4	0 2	0	0 0	4	0 1
Camelobaetis	16	0 8	13	0 8	11	0 7	40	0 8
Ceratopogonidae	13	0 6	21	1 3	62	4 1	96	1 8
Chimarra	14	0 6	74	4.6	219	14 5	307	5 8
Chironomidae	844	39 6	591	36 7	336	22 3	1771	33 7
Claassenia	5	0 2	13	0.8	9	0 6	27	0 5
Cladocera	0	0.0	1	0 1	0	0 0	1	0 0
Copepoda	0	0 0	3	0 2	1	0 1	4	0 1
Corydalus	0	0 0	0	0.0	1	0 1	1	0 0
Curculionidae	0	0 0	0	0 0	1	0 1	1	0 0
Dugesia	10	0 4	29	1 8	32	2.1	70	1.3
Ephydridae	0	0 0	0	0.0	1	0 1	1	0 0
Farrodes	7	0 3	6	0 3	18	1 2	30	0.6
Glossosomatidae	1	0 0	2	0 1	2	0 1	5	0 1
Helicopsyche	0	0 0	10	0 6	1	0 1	11	0 2
Heterelmis	8	0 4	1	0 1	2	0 1	11	0 2
Heterosternuta	0	0 0	0	0 0	2	0 1	2	0 0
Hirudinea	3	0 1	6	0 4	0	0 0	9	0 2
Hyallela	9	0 4	24	1 5	8	0 5	40	0 8
Hydracarina	5	0 2	11	0 7	3	0 2	18	0 3
Hydroperla	0	0 0	2	0 1	0	0 0	2	0 0
Hydropsyche	22	1.0	0	0 0	11	0 7	32	0 6
Isonychia	4	0 2	2	0.1	15	1 0	21	0 4
Isopoda	3	0 1	3	0 2	1	0 1	7	0 1
Lutrochus	15	0 7	12	0 7	0	0 0	27	0 5
Macrelmis	12	0 5	5	0 3	2	0 1	18	0 3
Macromia	0	0 0	16	1 0	21	1 4	36	0.7
Odontomyia	1	0 0	18	1 1	11	0 7	30	0.6
Oecetis	0	0.0	6	0 4	0	0.0	6	0 1
Oligochaeta	12	0 5	41	2 5	67	4 5	120	2 3
Ostracoda	9	0 4	12	0 7	5	0 3	26	0.5
Peltodytes	3	0.1	0	0 0	0	0 0	3	0 0
Perlodidae	0	0 0	6	0 4	2	0 1	8	0 2
Perlomyia	22	1 0	20	1 2	38	2 5	79	1 5
Petrophila	5	0 2	3	0 2	23	1 5	31	0 6
Physa	12	0 5	26	1 6	8	0 5	45	0 8
Planorbidae	5	0 2	6	0 4	7	0 4	18	0 3
Planospiral	1	0 0	3	0 2	4	0 3	8	0 2
Polycentropodidae	15	0 7	5	0 3	102	6 7	122	2 3
Promogomphus	7	0 3	7	0 4	10	0 7	24	0 5
Psphenus	3	0 1	13	0 8	19	1 3	35	0 7
Rheumatobates	1	0.0	2	0 1	0	0.0	3	0 1
Scirtes	0	0 0	0	0 0	1	0 1	1	0 0
Simulium	838	39 3	102	6 3	60	4 0	999	19 0
Sphaeriidae	0	0 0	28	1 7	1	0 1	29	0 5
Stenelmis	89	4 2	65	4 0	38	2 5	192	3 7
Stenonema	8	0 4	61	3 8	32	2 1	101	1.9
Tabanus	0	0 0	0	0.0	2	0 1	2	0 0
Thraulodes	4	0 2	4	0 2	12	0 8	20	0 4
Tricorythodes	0	0 0	4	0.2	14	0 9	18	0 3
# Organisms	2132		1612		1509		5253	
# of Taxa	41		49		50		58	

Table 5. Total abundance and relative abundance of macroinvertebrate taxa in Walnut Creek during post-drought and post-flood periods.

Walnut Creek	Post-drought		Post-flood	
Taxa	**Abundance**	**percent**	**Abundance**	**percent**
Hirudinea	3	0 2	0	0 0
Oligochaeta	6	0 4	6	0 9
Chironomidae	504	33 4	339	54 6
Argia	21	1 4	2	0 3
Stenelmis	49	3 2	40	6 5
Macrelmis	9	0 6	3	0 5
Heterelmis	4	0 3	4	0 6
Lutrochus	15	1 0	0	0 0
Baetis	118	7 8	122	19 6
Camelobaetidius	9	0 6	8	1 2
Isonychia	2	0 1	2	0 3
Ceratopogonidae	12	0 8	2	0 2
Berosus	1	0 1	4	0 6
Simulium	776	51 4	61	9 9
Chimarra	8	0 6	6	0 9
Stenonema	7	0 5	1	0 2
Thraulodes	4	0 3	0	0 0
Farrodes	1	0 1	6	1 0
Helicopsyche	0	0 0	0	0 0
Caenis	21	1 4	3	0 5
Tricorythodes	0	0 0	0	0 0
Psphenus	0	0 0	3	0 4
Arctopsyche	30	2 0	17	2 7
Claassenia	0	0 0	5	0 8
Perlomyia	0	0 0	22	3 5
Hydroperla	0	0 0	0	0 0
Perlodidae	0	0 0	0	0 0
Odontomyia	0	0 0	1	0 2
Caloparyphus	0	0 0	1	0 2
Tabanus	0	0 0	0	0 0
Petrophila	3	0 2	2	0 2
Sphaeriidae	0	0 0	0	0 0
Hydropsyche	11	0 7	11	1 8
Hyallela	4	0 3	5	0 8
Hydracarina	4	0 2	1	0 2
Ostracoda	9	0 6	0	0 0
Copepoda	0	0 0	0	0 0
Cladocera	0	0 0	0	0 0
Cambaridae	0	0 0	0	0 0
Brechmorhoga	3	0 2	0	0 0
Promogomphus	6	0 4	1	0 2
Oecetis	0	0 0	0	0 0
Glossosomatidae	0	0 0	1	0 2
Corydalus	0	0 0	0	0 0
Rheumatobates	1	0 1	0	0 0
Isopoda	3	0 2	0	0 0
Scirtes	0	0 0	0	0 0
Ephydridae	0	0 0	0	0 0
Peltodytes	3	0 2	0	0 0
Heterosternuta	0	0 0	0	0 0
Macromia	0	0 0	0	0 0
Curculionidae	0	0 0	0	0 0
Ambrysus	0	0 0	0	0 0
Polycentropodidae	15	1 0	0	0 0
Physa	6	0 4	6	1 0
Planorbidae	0	0 0	5	0 8
Planospiral	1	0 1	0	0 0
Dugesia	4	0 3	6	0 9
# Organisms	**1510**		**622**	
# of Taxa	34		31	

Table 6. Total abundance and relative abundance of macroinvertebrate taxa in Barton Creek during post-drought and post-flood periods.

Barton Creek Taxa	**Post-drought Abundance**	**percent**	**Post-flood Abundance**	**percent**
Hirudinea	5	0 7	1	0 1
Oligochaeta	21	2 7	20	2 3
Chironomidae	372	48 6	219	25 9
Argia	39	5 0	25	3 0
Stenelmis	56	7 4	9	1.0
Macrelmis	5	0 7	0	0 0
Heterelmis	1	0 1	0	0 0
Lutrochus	12	1 6	0	0 0
Baetis	55	7 2	255	30 1
Camelobaetidius	1	0 1	12	1 4
Isonychia	0	0 0	2	0 2
Ceratopogonidae	12	1 6	9	1 1
Berosus	56	7 4	3	0 4
Simulium	20	2 6	82	9 7
Chimarra	5	0 7	69	8 1
Stenonema	18	2 4	43	5 1
Thraulodes	4	0 5	0	0 0
Farrodes	5	0 6	1	0 1
Helicopsyche	9	1 2	1	0 1
Caenis	53	6 9	29	3 4
Tricorythodes	4	0 5	0	0 0
Psphenus	11	1 4	3	0.3
Arctopsyche	46	6 0	24	2 8
Claassenia	0	0 0	13	1 5
Perlomyia	0	0 0	20	2 3
Hydroperla	0	0 0	2	0 2
Perlodidae	0	0 0	6	0 7
Odontomyia	7	0 8	12	1 4
Caloparyphus	0	0 0	2	0 2
Tabanus	0	0 0	0	0 0
Petrophila	3	0 4	0	0 0
Sphaeriidae	21	2 7	7	0 9
Hydropsyche	0	0 0	0	0 0
Hyallela	12	1 6	12	1 4
Hydracarina	6	0.7	5	0 6
Ostracoda	12	1 6	0	0 0
Copepoda	3	0 4	0	0 0
Cladocera	1	0 1	0	0 0
Cambaridae	3	0 4	1	0 1
Brechmorhoga	0	0 0	0	0.0
Promogomphus	5	0 7	2	0 2
Oecetis	4	0 5	2	0 2
Glossosomatidae	2	0 3	0	0 0
Corydalus	0	0 0	0	0 0
Rheumatobates	2	0 3	0	0 0
Isopoda	1	0 1	2	0 2
Scirtes	0	0 0	0	0 0
Ephydridae	0	0 0	0	0 0
Peltodytes	0	0 0	0	0 0
Heterosternuta	0	0 0	0	0 0
Macromia	2	0 3	14	1 6
Curculionidae	0	0 0	0	0.0
Ambrysus	3	0 4	1	0 1
Polycentropodidae	4	0 5	1	0.1
Physa	18	2.3	8	0.9
Planorbidae	0	0 0	6	0 7
Planospiral	3	0 4	0	0 0
Dugesia	16	2 1	13	1 5
# Organisms	**765**		**847**	
# of Taxa	42		38	

Table 7. Total abundance and relative abundance of macroinvertebrate taxa in Onion Creek during post-drought and post-flood periods.

Onion Creek	**Post-drought**		**Post-flood**	
Taxa	**Abundance**	**percent**	**Abundance**	**percent**
Hirudinea	0	0 0	0	0 0
Oligochaeta	57	4 7	11	3 4
Chironomidae	247	20 7	89	28 1
Argia	83	7 0	9	2 8
Stenelmis	32	2 6	7	2 1
Macrelmis	2	0 1	0	0 0
Heterelmis	2	0 2	0	0 0
Lutrochus	0	0 0	0	0 0
Baetis	279	23 4	70	21 9
Camelobaetidius	8	0 7	3	0 9
Isonychia	14	1 2	1	0 3
Ceratopogonidae	47	3 9	15	4 8
Berosus	21	1 7	0	0 0
Simulium	23	1 9	37	11 6
Chimarra	191	16 0	28	8 9
Stenonema	19	1 6	13	4 1
Thraulodes	12	1 0	0	0 0
Farrodes	18	1 5	0	0 0
Helicopsyche	1	0 1	0	0 0
Caenis	14	1 1	2	0 6
Tricorythodes	14	1 2	0	0 0
Psphenus	15	1 3	4	1 3
Arctopsyche	172	14 4	27	8 4
Claassenia	0	0 0	9	2 9
Perlomyia	0	0 0	38	11 8
Hydroperla	0	0 0	0	0 0
Perlodidae	0	0 0	2	0 6
Odontomyia	11	0 9	0	0 0
Caloparyphus	1	0 1	0	0 0
Tabanus	2	0 2	0	0 0
Petrophila	21	1 8	2	0 6
Sphaeriidae	0	0 0	1	0 3
Hydropsyche	8	0 6	3	0 9
Hyallela	5	0 4	3	0 8
Hydracarina	2	0 2	1	0 3
Ostracoda	5	0 4	0	0 0
Copepoda	1	0 1	0	0 0
Cladocera	0	0 0	0	0 0
Cambaridae	0	0 0	0	0 0
Brechmorhoga	6	0 5	0	0 0
Promogomphus	10	0 8	0	0 0
Oecetis	0	0 0	0	0 0
Glossosomatidae	0	0 0	2	0 6
Corydalus	1	0 1	0	0 0
Rheumatobates	0	0 0	0	0 0
Isopoda	0	0 0	1	0 3
Scirtes	1	0 1	0	0 0
Ephydridae	1	0 1	0	0 0
Peltodytes	0	0 0	0	0 0
Heterosternuta	2	0 2	0	0 0
Macromia	13	1 0	8	2 5
Curculionidae	1	0 1	0	0 0
Ambrysus	1	0 1	0	0 0
Polycentropodidae	100	8 3	2	0 6
Physa	2	0 2	6	1 7
Planorbidae	0	0 0	7	2 1
Planospiral	3	0 3	1	0 3
Dugesia	30	2 5	2	0 6
# Organisms	**1192**		**317**	
# of Taxa	44		30	

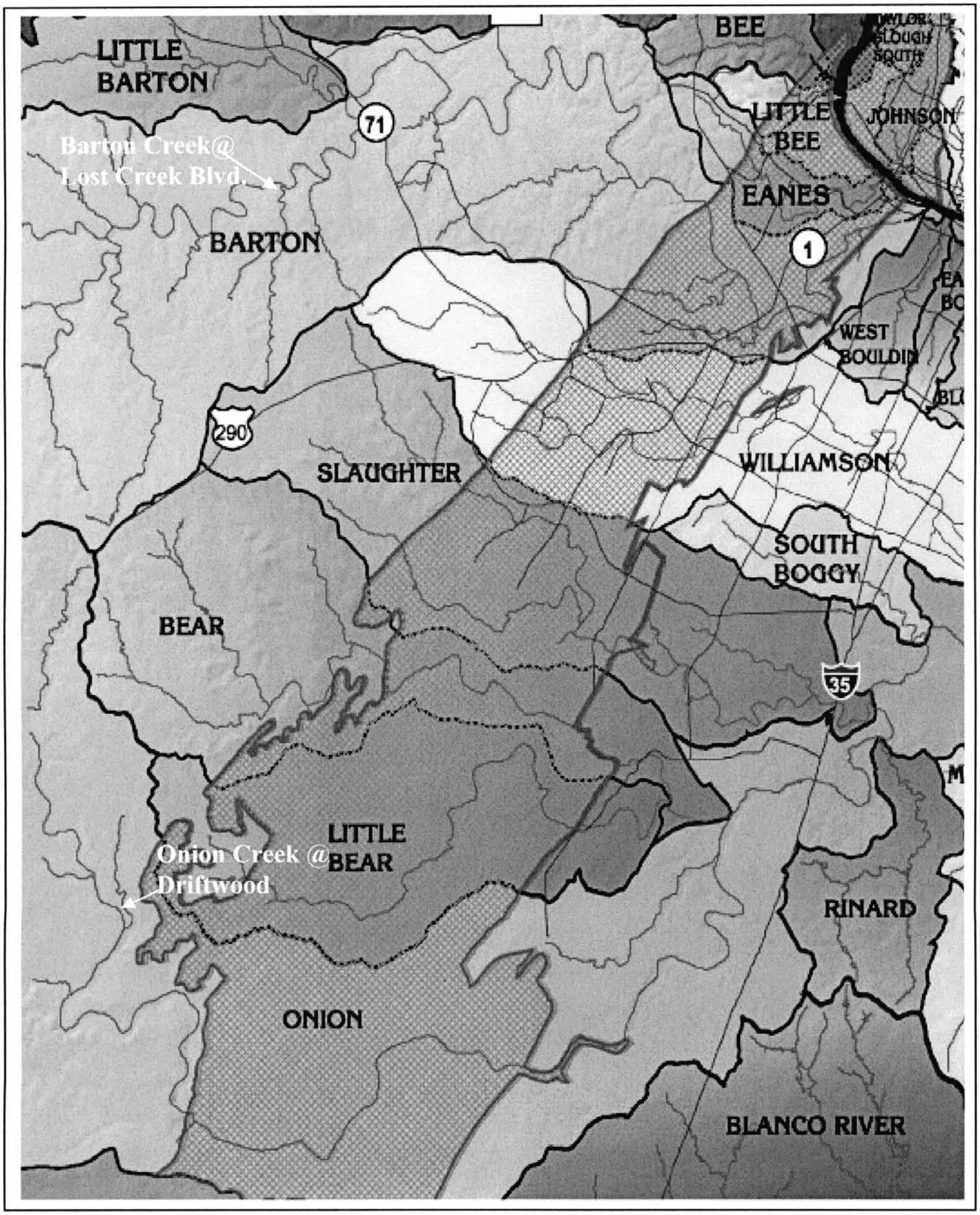

Figure 1. Barton Creek and Onion Creek watersheds and sampling locations.

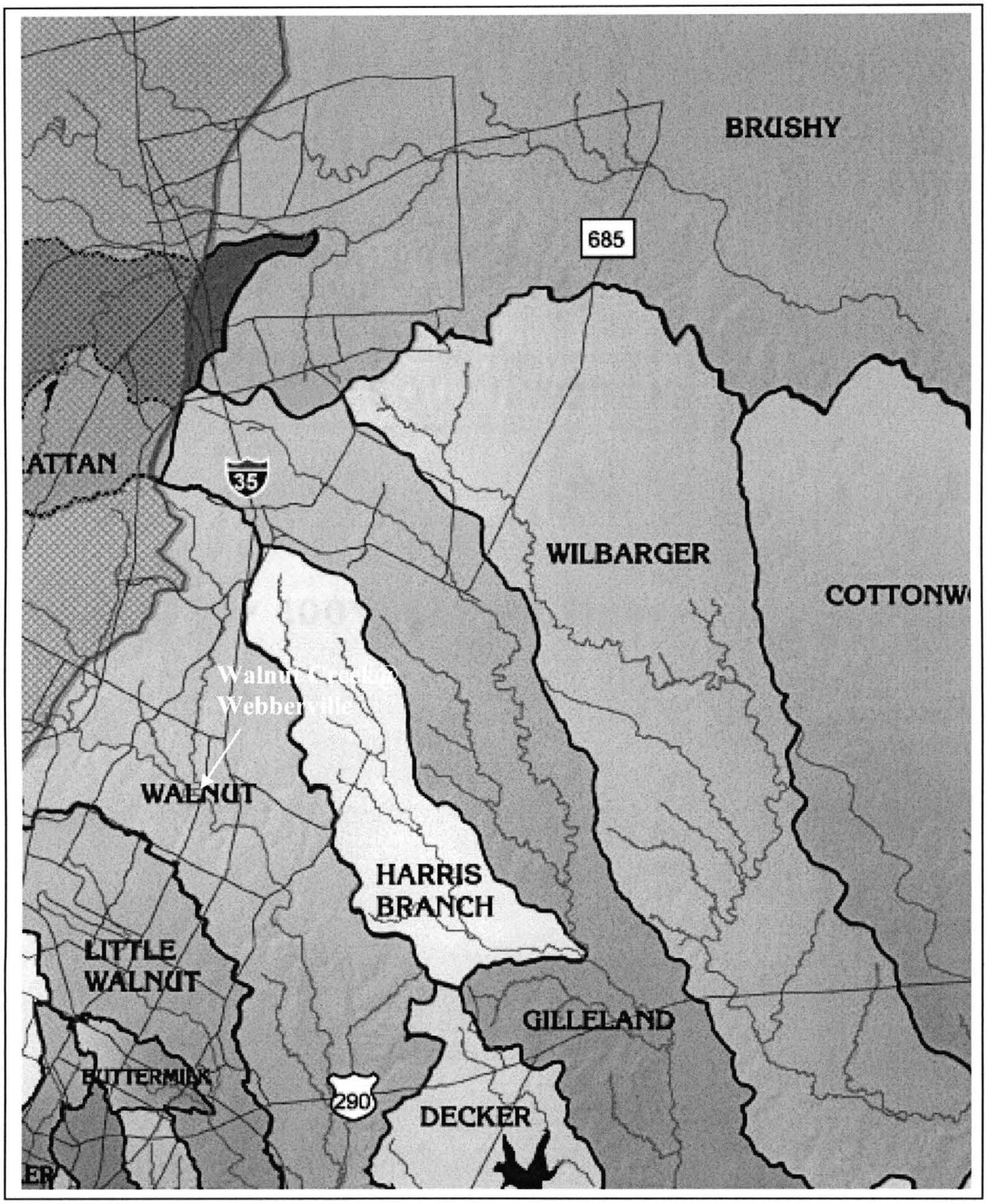

Figure 2.Walnut Creek watershed and sampling location.

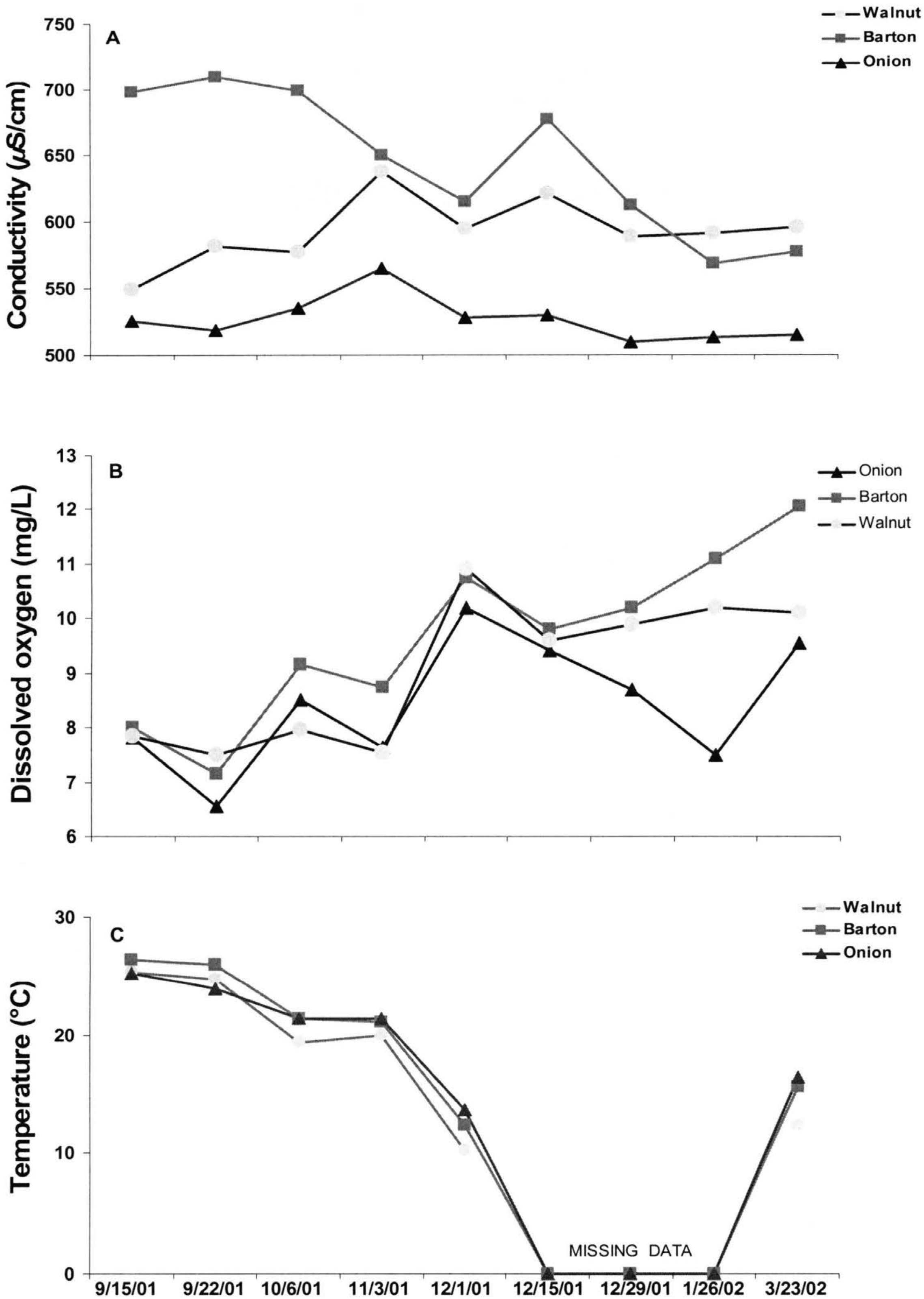

Figure 3. Temporal variation in A- Conductance, B-Dissolved Oxygen and C-Temperature of Walnut, Barton and Onion creeks in Austin, Texas.

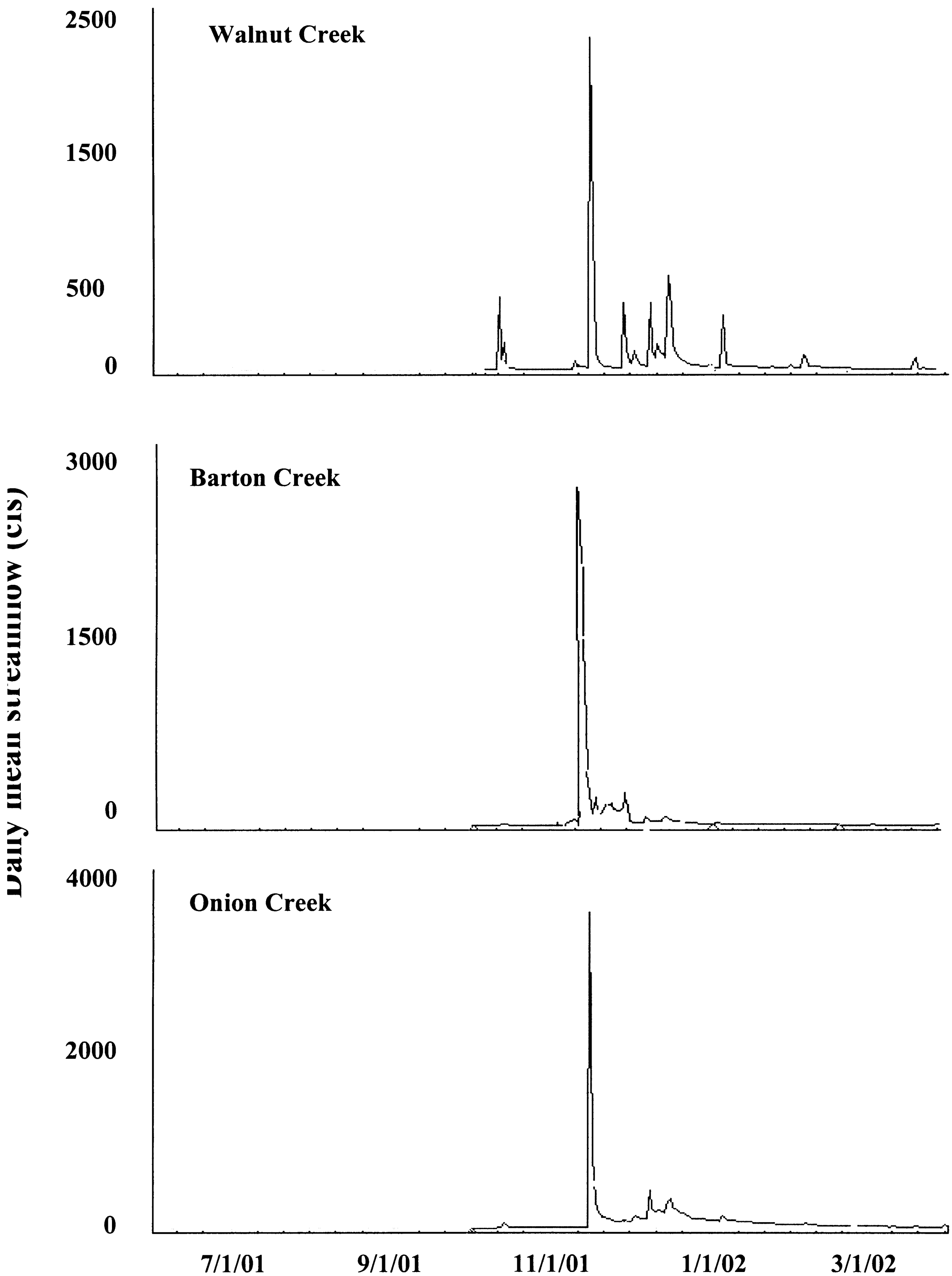

Figure 4. Hydrographs showing the daily mean stream flow at Walnut, Barton and Onion creeks.

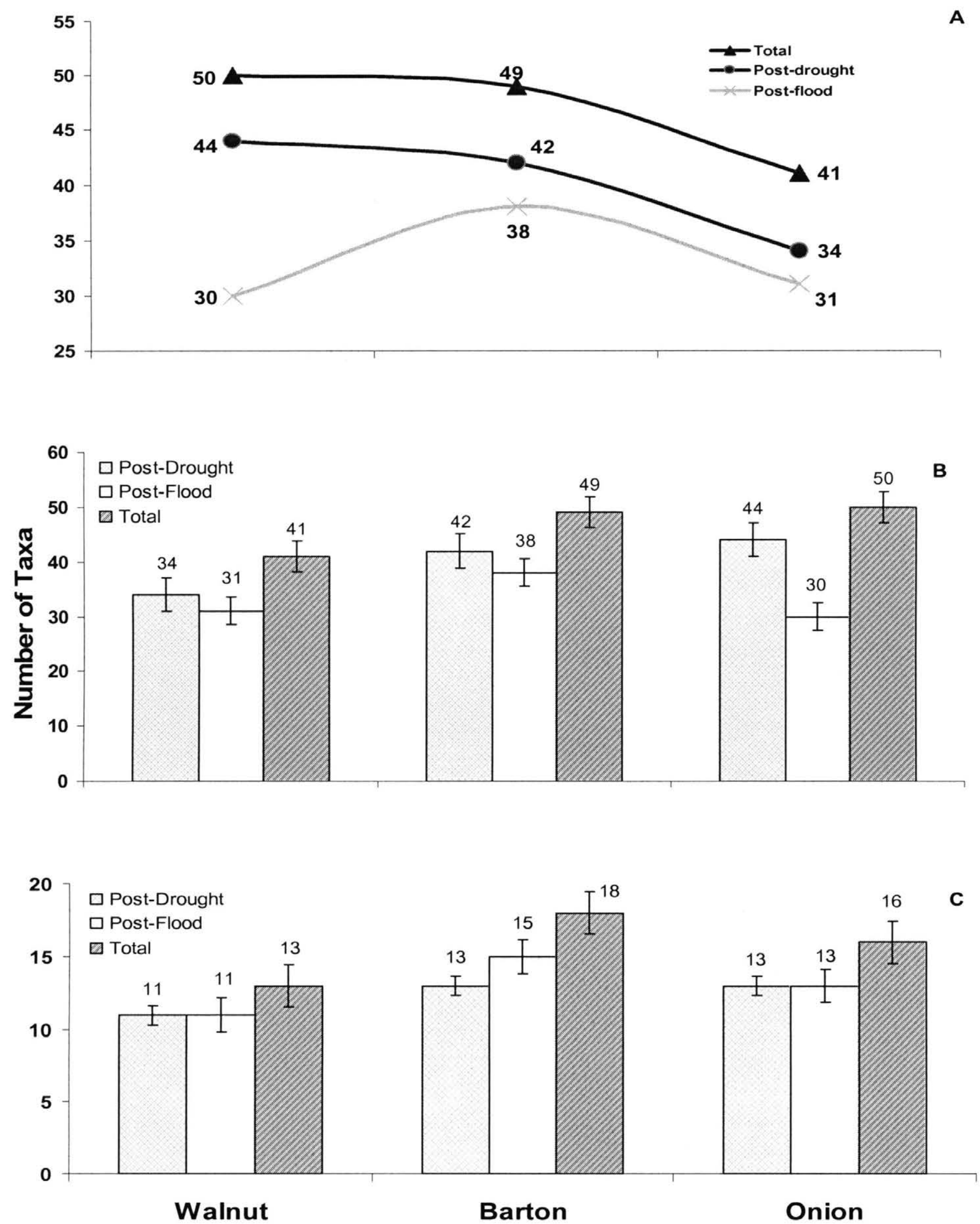

Figure 5. A- Variation in macroinvertebrate taxonomic richness following post-drought and post-flood periods in three Austin Texas streams; B-Number of taxa and C-EPT taxa following drought and flood in three Austin, Texas streams. The error bars on the graph represent 1 standard error.

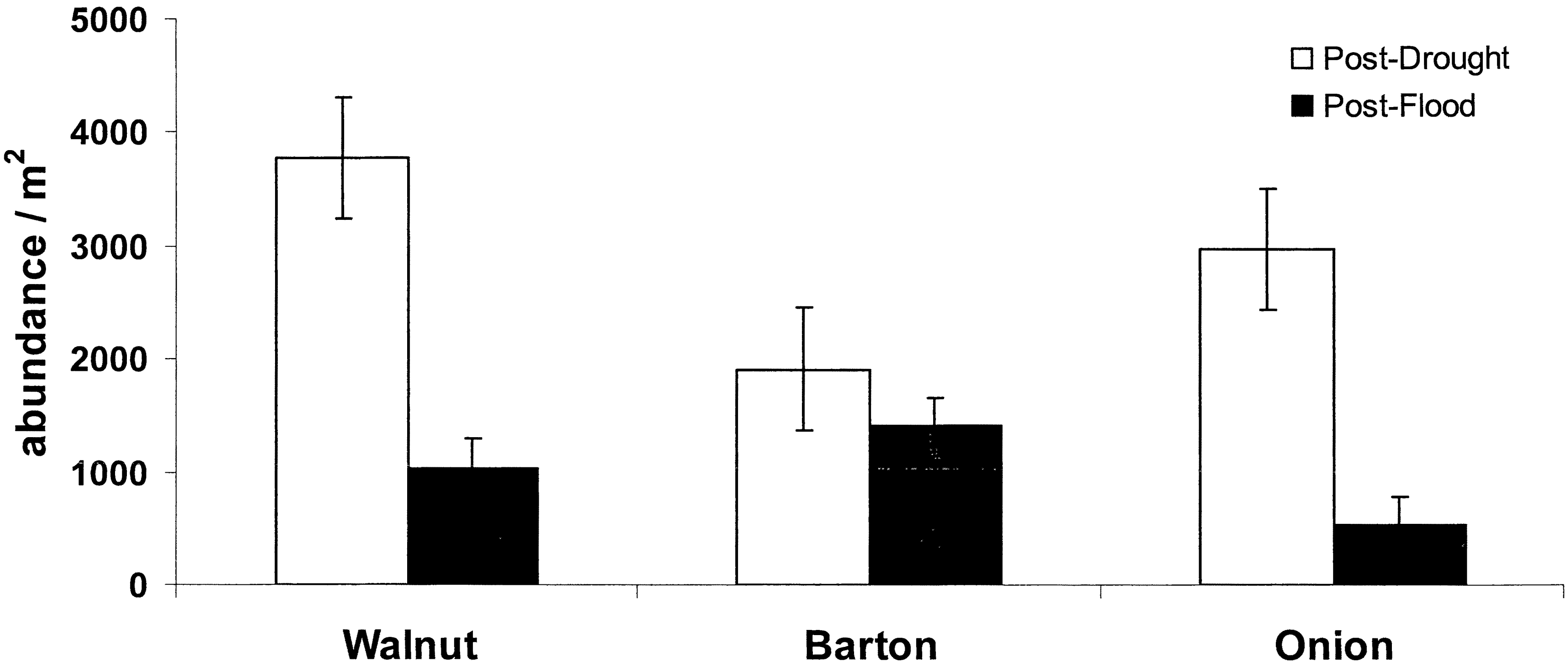

Figure 6. Mean macroinvertebrate abundance at Walnut, Barton and Onion creeks averaged over all sample dates after flows resumed after drought and receded after flood. The error bars on the graphs represent 1 standard error.

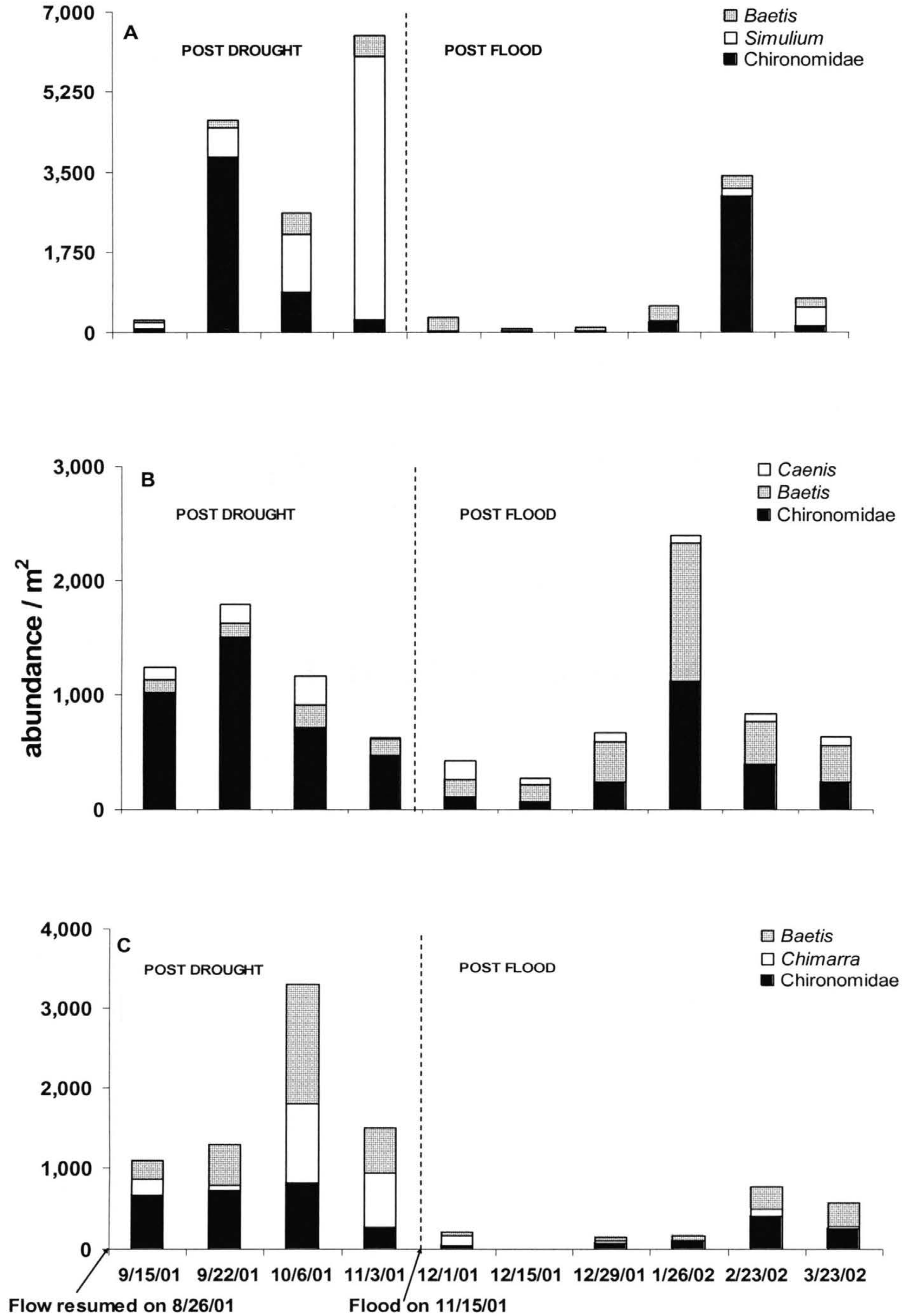

Figure 7. Temporal dynamics in abundance of dominant taxa at A- Walnut Creek, B-Barton Creek and C-Onion Creek after the post-drought and post-flood disturbances.

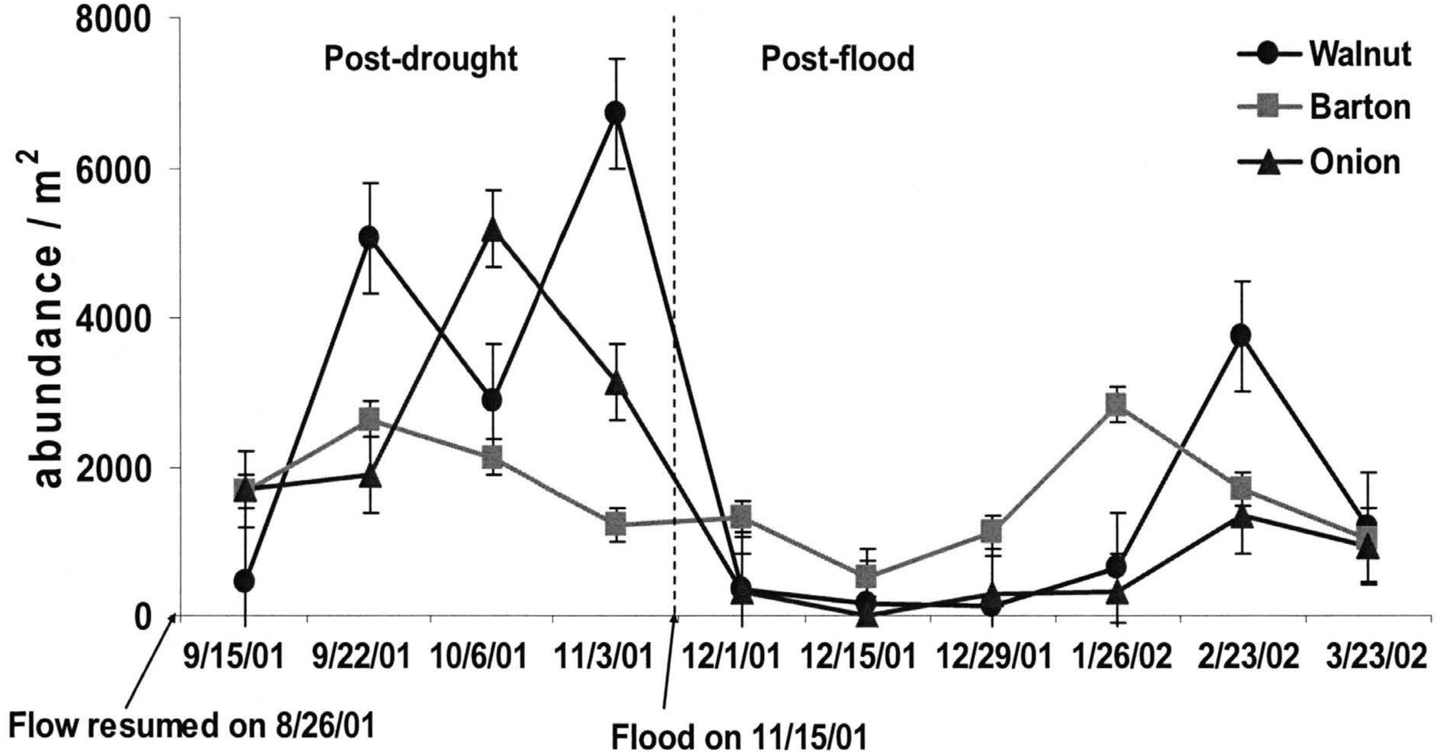

Figure 8. Temporal variation in macroinvertebrate abundance at Walnut, Barton and Onion creeks following drought and flood. The error bars on the graph represent 1 standard error.

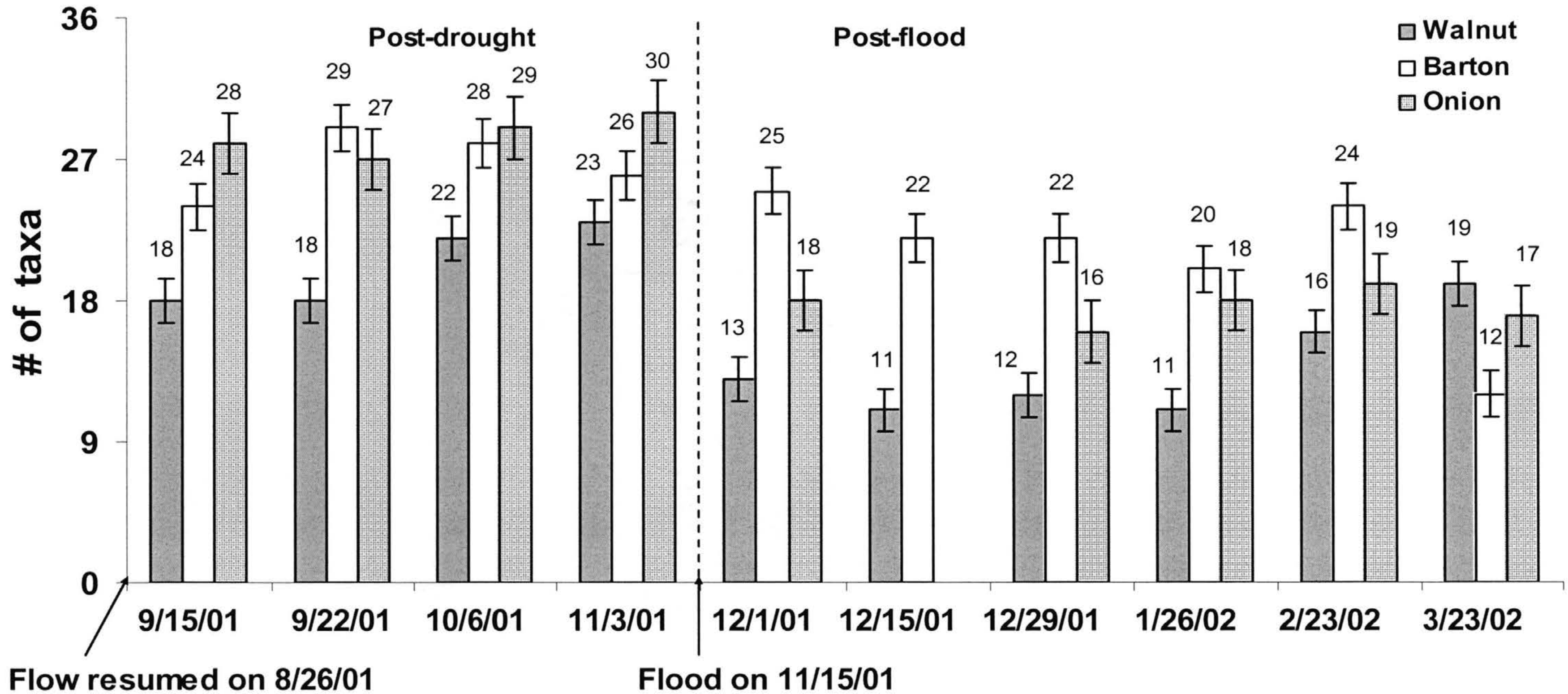

Figure 9. Temporal variation in macroinvertebrate taxonomic richness in Walnut, Barton and Onion creeks following drought and flood. The error bars on the graph represent 1 standard error.

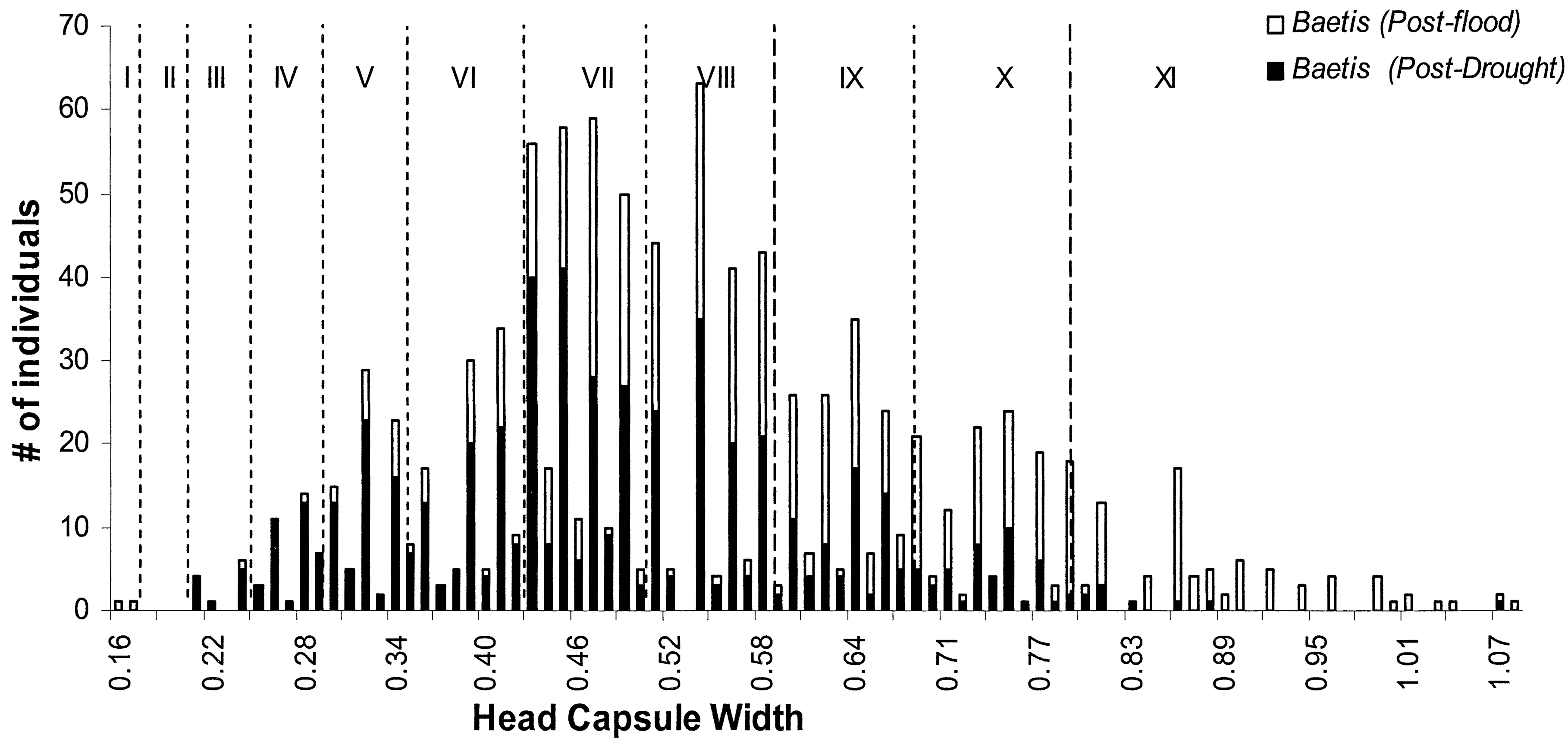

Figure 10. Distribution of larval head capsule widths of *Baetis* spp. from September 2001 to March 2002. Roman numerals and dashed lines indicate the approximate instar size ranges.

APPENDIX I

Walnut Creek @ Webberville road

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/15/01	12/29/01	1/26/02	2/23/02	3/23/02
Annelida	Hirudinea	Gnathobdellida					1	2						
Annelida	Oligochaeta					3	2	1			1		1	4
Arthropoda	Insecta	Diptera	Chironomidae		8	382	87	27	3	2	3	22	295	14
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	2	3	8	8	2					
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	5	16	20	7	7	4	1	2	20	7
Arthropoda	Insecta	Coleoptera	Elmidae	*Macrelmis*	2	4	1	2		1			1	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Heterelmis*		1	3			1			2	1
Arthropoda	Insecta	Coleoptera	Lutrochidae	*Lutrochus*	2	6	7							
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Baetis*	6	16	48	48	29	5	7	32	28	22
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Camelobaetidius*	2	2	3	3	4		1	2	1	
Arthropoda	Insecta	Ephemeroptera	Isonychiidae	*Isonychia*				2						2
Arthropoda	Insecta	Diptera	Ceratopogonidae			9	3						2	
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Berosus*	1						1		2	1
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	13	63	126	575	1		1	2	18	39
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*			6	2	4		1			1
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Stenonema*			3	4	1					
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Thraulodes*				4						
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Farrodes*				1				6		
Arthropoda	Insecta	Ephemeroptera	Caenidae	*Caenis*	2	11	8		2				1	
Arthropoda	Insecta	Coleoptera	Psphenidae	*Psphenus*						2				1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Arctopsyche*	1	4	21	5		3		1		13
Arthropoda	Insecta	Plecoptera	Perlidae	*Claassenia*									2	3
Arthropoda	Insecta	Plecoptera	Leuctridae	*Perlomyia*						1		4	7	10
Arthropoda	Insecta	Diptera	Stratiomyidae	*Odontomyia*					1					
Arthropoda	Insecta	Diptera	Stratiomyidae	*Caloparyphus*									1	

Walnut Creek @ Webberville road

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/15/01	12/29/01	1/26/02	2/23/02	3/23/02
Arthropoda	Insecta	Lepidoptera	Pyralidae	*Petrophila*	1			2				2		
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*				11	7		1			3
Arthropoda	Crustacea	Amphipoda	Talitridae	*Hyallela*		4							2	3
Arthropoda	Arachnoidea	Hydracarina				1	1	2						1
Arthropoda	Crustacea	Ostracoda				9								
Arthropoda	Insecta	Odonata	Libellulidae	*Brechmorhoga*		1		2						
Arthropoda	Insecta	Odonata	Gomphidae	*Promogomphus*	1		4	1						1
Arthropoda	Insecta	Trichoptera	Glossosomatidae							1				
Arthropoda	Insecta	Hemiptera	Gerridae	*Rheumatobates*	1									
Arthropoda	Insecta	Isopoda			1	2								
Arthropoda	Insecta	Coleoptera	Haliplidae	*Peltodytes*	3									
Arthropoda	Insecta	Trichoptera	Polycentropodidae		1		12	2						
Mollusca	Gastropoda	Limnophila	Physidae	*Physa*	3		1	2		2	2	1		1
Mollusca	Gastropoda	Limnophila	Planorbidae						3	1	1			
Mollusca	Gastropoda	Lepidoptera	Planospiral				1							
Platyhelminthes	Turbellaria	Tricladida	Planaridae	*Dugesia*			1	3	2		2	1	1	
				# of Taxa	18	18	22	23	13	11	12	11	16	19
				# Organisms	44	505	289	672	36	15	14	64	375	118

Barton Creek @ Lost Creek Boulevard

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/15/01	12/29/01	1/26/02	2/23/02	3/23/02
Annelida	Hirudinea	Gnathobdellida			2		1	2	1					
Annelida	Oligochaeta				4	2	10	6	3	2	3	6	1	6
Arthropoda	Insecta	Diptera	Chironomidae		102	151	71	48	11	7	24	112	40	25
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	11	6	13	10	8	1	6	4	1	5
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	10	20	16	10	2	1	2	1	3	
Arthropoda	Insecta	Coleoptera	Elmidae	*Macrelmis*	4		1							
Arthropoda	Insecta	Coleoptera	Elmidae	*Heterelmis*			1							
Arthropoda	Insecta	Coleoptera	Lutrochidae	*Lutrochus*		3	9							
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Baetis*	9	12	20	14	16	15	35	121	37	31
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Camelobaetidius*				1	2	1	2	4	1	2
Arthropoda	Insecta	Ephemeroptera	Isonychiidae	*Isonychia*					1				1	
Arthropoda	Insecta	Diptera	Ceratopogonidae		4	4	4			4		2	2	2
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Berosus*	17	16	15	8	3					
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	11	2	5	4	12	9	2	3	54	3
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	5				32	5	16	12	5	
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Stenonema*		5	13		14	2	6	6	13	4
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Thraulodes*		2		2						
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Farrodes*		5							1	
Arthropoda	Insecta	Trichoptera	Helicopsychidae	*Helicopsyche*			2	7				1		
Arthropoda	Insecta	Ephemeroptera	Caenidae	*Caenis*	11	16	25	1	17	2	8		3	
Arthropoda	Insecta	Ephemeroptera	Tricorythidae	*Tricorythodes*		4								
Arthropoda	Insecta	Coleoptera	Psphenidae	*Psphenus*	1	3	4	3	1					2
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Arctopsyche*	2	3	28	13	4	3	2	6	5	5
Arthropoda	Insecta	Plecoptera	Perlidae	*Claassenia*							1	3	2	7
Arthropoda	Insecta	Plecoptera	Leuctridae	*Perlomyia*					3	1	3	4	10	
Arthropoda	Insecta	Plecoptera	Perlodidae	*Hydroperla*									2	
Arthropoda	Insecta	Plecoptera	Perlodidae						3		3			
Arthropoda	Insecta	Diptera	Stratiomyidae	*Odontomyia*	6	1			3	3		5	1	
Arthropoda	Insecta	Diptera	Stratiomyidae	*Caloparyphus*							1		1	

Barton Creek @ Lost Creek Boulevard

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/15/01	12/29/01	1/26/02	2/23/02	3/23/02
Arthropoda	Insecta	Lepidoptera	Pyralidae	*Petrophila*	1	1		1						
Arthropoda	Gastropoda	Pelecypoda	Sphaeriidae		5	7	5	4	1	1	2		3	
Arthropoda	Crustacea	Amphipoda	Talitridae	*Hyallela*	1	7		4	7	2		3		
Arthropoda	Arachnoidea	Hydracarina			2		3	1		1	1	1	2	
Arthropoda	Crustacea	Ostracoda				4	6	2						
Arthropoda	Insecta	Copepoda			1		2							
Arthropoda	Insecta	Cladocera				1								
Arthropoda	Crustacea	Astacoidea	Cambaridae			2		1		1				
Arthropoda	Insecta	Odonata	Gomphidae	*Promogomphus*			2	3				2		
Arthropoda	Insecta	Trichoptera	Leptoceridae	Oecetis		4					1		1	
Arthropoda	Insecta	Trichoptera	Glossosomatidae			2								
Arthropoda	Insecta	Hemiptera	Gerridae	*Rheumatobates*	1	1								
Arthropoda	Insecta	Isopoda						1			2			
Arthropoda	Insecta	Odonata	Macromiidae	*Macromia*			2		8		6			
Arthropoda	Insecta	Hemiptera	Naucoridae	*Ambrysus*			2	1	1					
Arthropoda	Insecta	Trichoptera	Polycentropodidae		2		2			1				
Mollusca	Gastropoda	Limnophila	Physidae	*Physa*	1	7	6	4	1	2	3	1	1	
Mollusca	Gastropoda	Limnophila	Planorbidae						3	2	1			
Mollusca	Gastropoda	lepidoptera	Planospiral			1	1	1						
Platyhelminthes	Turbellaria	Tricladida	Planariidae	*Dugesia*	1	2	4	9	3	1		2	5	2
				# of Taxa	24	29	28	26	25	22	22	20	24	12
				# Organisms	167	264	213	122	130	50	111	283	170	102

Onion Creek @ Driftwood

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/29/01	1/26/02	2/23/02	3/23/02
Annelida	Oligochaeta				12	4	32	9	1	4		5	1
Arthropoda	Insecta	Diptera	Chironomidae		67	73	81	27	4	8	10	41	26
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	8	13	23	39	5	1	2	2	
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	3	3	9	16	1	2	1	1	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Macrelmis*				2					
Arthropoda	Insecta	Coleoptera	Elmidae	*Heterelmis*			2						
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Baetis*	23	50	151	56	4	4	6	28	28
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Camelobaetidius*		2	6		1			2	
Arthropoda	Insecta	Ephemeroptera	Isonychiidae	*Isonychia*	1	3	2	8				1	
Arthropoda	Insecta	Diptera	Ceratopogonidae		8	9	16	15	2	5	1	2	6
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Berosus*	10	1	7	3					
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	3	2	7	12	7	1	3	25	1
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	19	6	99	67	13	3	1	9	3
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Stenonema*	5	4	11		5	4		1	3
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Thraulodes*	3		6	3					
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Farrodes*	4	4	9	1					
Arthropoda	Insecta	Trichoptera	Helicopsychidae	*Helicopsyche*			1						
Arthropoda	Insecta	Ephemeroptera	Caenidae	*Caenis*	10	4				2			
Arthropoda	Insecta	Ephemeroptera	Tricorythidae	*Tricorythodes*			14						
Arthropoda	Insecta	Coleoptera	Psphenidae	*Psphenus*	3	1	3	9			1	2	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Arctopsyche*	16	13	99	44	5	5	1	5	10
Arthropoda	Insecta	Plecoptera	Perlidae	*Claassenia*							1	5	3
Arthropoda	Insecta	Plecoptera	Leuctridae	*Perlomyia*					4	2	4	15	14
Arthropoda	Insecta	Plecoptera	Perlodidae								2		
Arthropoda	Insecta	Diptera	Stratiomyidae	*Odontomyia*	2	2	7						
Arthropoda	Insecta	Diptera	Stratiomyidae	*Caloparyphus*		1							
Arthropoda	Insecta	Diptera	Tabanidae	*Tabanus*				2					

Onion Creek @ Driftwood

Phylum	Class	Order	Family	Genus	9/15/01	9/22/01	10/6/01	11/3/01	12/1/01	12/29/01	1/26/02	2/23/02	3/23/02
Arthropoda	Insecta	Lepidoptera	Pyralidae	*Petrophila*	4	2	12	4			1	1	
Arthropoda	Gastropoda	Pelecypoda	Sphaeriidae										1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	2		3	3	1			2	
Arthropoda	Crustacea	Amphipoda	Talitridae	*Hyallela*	1	1	1	2	1				2
Arthropoda	Arachnoidea	Hydracarina			2						1		
Arthropoda	Crustacea	Ostracoda				1	2	2					
Arthropoda	Insecta	Copepoda			1								
Arthropoda	Insecta	Odonata	Libellulidae	*Brechmorhoga*		3	3						
Arthropoda	Insecta	Odonata	Gomphidae	*Promogomphus*	2	1		7					
Arthropoda	Insecta	Trichoptera	Glossosomatidae										2
Arthropoda	Insecta	Megaloptera	Corydalidae	*Corydalus*				1					
Arthropoda	Insecta	Isopoda											1
Arthropoda	Insecta	Coleoptera	Scirtidae	*Scirtes*				1					
Arthropoda	Insecta	Diptera	Ephydridae					1					
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Heterosternuta*	2								
Arthropoda	Insecta	Odonata	Macromiidae	*Macromia*	2	2	2	7	2	2	2		2
Arthropoda	Insecta	Coleoptera	Curculionidae					1					
Arthropoda	Insecta	Hemiptera	Naucoridae	*Ambrysus*				1					
Arthropoda	Insecta	Trichoptera	Polycentropodidae		6	5	66	23				2	
Mollusca	Gastropoda	Limnophila	Physidae	*Physa*	1		1		1	3	2		
Mollusca	Gastropoda	Limnophila	Planorbidae						2	3	1	1	
Mollusca	Gastropoda	lepidoptera	Planospiral			1		2			1		
Platyhelminthes	Turbellaria	Tricladida	Planariidae	*Dugesia*	3	8	11	9	1	1			
				# of Taxa	28	27	29	30	18	16	18	19	17
				# Organisms	170	189	520	313	31	29	31	134	91

VITA

G.Karma Chhopel was born in Trashigang in east Bhutan on August 18, 1970, son of Dorji Khandu and Aum Karma. After completing High School at Paro Gaupey, he went to Kanglung Sherubtse College where he completed his Bachelor of Science in General Biology in 1993. Chhopel worked for the meteorological organization in Bhutan and represented the country in meteorological related fields in various South Asian conferences. He was an active member of the country's first GreenhouseGas Inventory Preparation Team for the purpose of reporting to the United Nations Framework Convention on Climate Change on the sources and sinks ın Bhutan. He is currently the Assistant Director of the National Environment Secretariat in Bhutan.

In 2000 he was selected through a nationwide competition to acquire expertise on aquatic biology and be the foremost Aquatic Scientist in the nation. Consequently he attended Texas State University in 2001 where he was awarded a Bachelor of Science degree in Aquatic Biology within a year and went on to enter the Graduate College the following year. He will be completing his Master of Science in Aquatic Biology in December of 2003.

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This thesis was typed by G. Karma Chhopel.