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Ecohydraulic Investigation of Diatoms in a Bedrock-Controlled Stream

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ECOHYDRAULIC INVESTIGATIONS OF DIATOMS IN A BEDROCK-CONTROLLED STREAM

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Arts in the
College of Arts and Sciences
at the University of Kentucky

By
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Lexington, Kentucky
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2015

ABSTRACT OF THESIS

ECOHYDRAULIC INVESTIGATIONS OF DIATOMS IN A BEDROCK-CONTROLLED STREAM

Recent studies within the past decade or so have shown the importance of algae in geomorphic and hydrologic processes of lotic systems. However, the ecohydraulic role of algae in bedrock systems has largely been ignored. In addition, the utility of algae as indicators of channel dynamics have often been assumed by geomorphologists, but relatively few studies have examined this relationship. The purpose of this study was to determine whether algae, specifically diatoms, are useful indicators of channel geomorphological dynamics, and to examine if distinct habitats or biotopes typical in fluviokarst and bedrock systems provide unique habitat space for diatoms, and to address the potential ecohydraulic implications. The investigation was performed in a 100 m reach of Shawnee Run, a limestone, fluviokarst tributary to the Kentucky River in Mercer County, KY. The results of the study showed that periphyton are not useful indicators of channel dynamics, and that biotopes and other distinct habitats, including riffles, bedforms, and fine sediment, do not provide unique habitat in terms of diatom community composition.

KEYWORDS: Ecohydraulics, biogeomorphology, Diatoms, Periphyton, Bedrock streams

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7 May 2015

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Introduction

Algae are ubiquitous organisms, which has led to many ecosystem-based studies on their ecology. Because of their abundance in a variety of aquatic and marine ecosystems, algae are often considered to an important primary producer (Biggs, 1996). In running waters, algae may account for up to twenty-five percent of oxygen production, and proper functioning of freshwater ecosystems relies on primary producers to anchor the cascade of nutrients flowing within an aquatic system (Stevenson, 1996). In addition, primary producers, such as most algae, are necessary for carbon fixation and generation of biomass (Bellinger and Sigee, 2010).

In lotic ecosystems, algae can be either benthic or planktonic, and may reside in a number of habitats such as on the channel bottom, substrate of various sizes (from fine sediment to large boulders), on submerged organic and plant matter such as macrophytes and moss, or within the water column. The important role of algae in freshwater (as well as marine) systems, along with their intricate and various habitat assemblages and morphology, make them a critical component of investigation and analyses (Stevenson, 1996).

The role of algae in lotic systems may not necessarily be limited to ecosystem contexts. Investigations of the geomorphic functions of algae are also needed. Many studies emphasize the impact of flow regimes on algal distribution within streams (e.g. Horner et al., 1990, Murdock et al., 2004, Ghosh and Gaur, 1998). These studies are important because they establish thresholds for algal immigration and dislodgment, and also provide a framework for the identification of assemblages at various hydraulic and associated sediment transport regimes. However, the discipline of phycology, (sometimes referred to, but less frequently, as algology[1]) lacks a firm understanding of the feedbacks between geomorphic processes and algal ecology. For example, while there are a number of analyses on the relationship between shear stress and algae dislodgement and associated migration (e.g. Power and Stewart, 1987), there are limited

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[1] Algology is also the study of the medical treatment of pain, thus the sparse use in ecology.

investigations researching the role that algae and diatoms play in influencing sediment transport, flow regimes, and bedform formation.

Furthermore, the relationship between algae and stream processes in bedrock-streams has largely been ignored. Therefore, the objective of this study was to investigate whether algal coatings on bedrock channels are indicative of low flow energy or lack of abrasion, and to determine if characteristic bedrock features within such a stream provide unique habitat space. The hypothesis that algae and periphyton can be used as indicators of shear stress was tested in Shawnee Run, a limestone stream in central Kentucky. Periphyton coverage in the stream channel was compared before and after a significant flood event. Algal community assemblages were analyzed in distinct habitat assemblages characteristic of bedrock-controlled fluvial systems. In addition, potential biogeomorphic and ecohydraulic feedbacks within bedrock systems were assessed in regards to both diatom composition and structure, and flow and geomorphic processes within the stream.

Biology and Ecology of Algae and Diatoms

The term algae is often used loosely, and does not necessarily correspond to a formal taxonomic unit. Rather, algae are a hodgepodge of different phyla that broadly include both eukaryotes and prokaryotes: those that contain a cell nucleus and those that lack a cell nucleus, respectively. Members of this paraphyletic group can be single-celled and microscopic such as the diatoms, or large and multicellular such as the charales, which are sometimes mistaken for plants. The algae encompass a wide variety of morphologies and forms, from filamentous to globular, colonial to singular, adnate to motile, symmetric to amorphous, benthic to planktonic, and colors ranging from brown to green to blue (Bellinger and Sigee 2010).

The diatoms are important members within the algae groupings. Located in the taxonomic class *Bacillariophyceae*, diatoms are distinguished by a siliceous cell wall, which not only aids in identification, but also allows for preservation within the rock record. Diatoms have been identified in as early as the Cretaceous (Round et al., 1990*)* and are important in stratigraphy as index fossils. Rocks containing fossil diatoms are known as diatomaceous earth, or diatomite, and are useful not only in paleontological investigations, but also in industry as various filters and abrasives. Diatoms are often major components of study not only because of high rates of preservation, but also because of the beautiful exoskeletons, a silica capsule known as a frustule. Frustules are the main way of identifying diatoms since each species has a distinct morphology.

The frustule is divided into two halves, or valves, analogous to a petri dish, with the top and bottom denoted as the epivalve and hypotheca, respectively. The valves generally exhibit one of two types of symmetry: bilateral or radial. Those diatoms with bilateral symmetry are known as pennate, and those that are radial are called centric. Pennate diatoms are further classified by the presence of a raphe, a slit that bisects the cell. Those with a raphe are referred to as raphid, those without araphid. A series of ribs may radiate or extend from the raphe. In all diatoms, each valve is wrapped by a series of bands referred to as the girdle (Round et al., 1990). When viewing under a microscope, if the valves are perpendicular to the field of view it is termed valve-view, and if the girdle is perpendicular to the field of view it is termed girdle-view (Vinyard, 1979). Recognizing the difference between the two views is essential because a species under girdle view can look significantly different under valve-view. In addition, diatoms contain chloroplasts which are generally brownish-yellow, and as such live specimen may often appear that color (Bellinger and Sigee, 2010).

Diatoms and algae, excluding those that are planktonic, can also be classified based on methods of attachment to a substrate. Diatoms can be epilithic, epipelic, or epipsammic meaning they inhabit rocks/gravel, mud, or sand, respectively. Epilithic and epipelic diatoms can attach to the substrate in two forms- adnate or pedunculate. Those that are closely attached are adnate, and those that attach via a stalk are pedunculate. Pedunculate species tend to be colonial, while adnate are often solitary (Round et al., 1990). Epiphytic diatoms, often the most diverse array within a benthic community, attach themselves to plants and other algae. Diatoms can also be epizoic, which are species that are attached to animals, such as snails and mollusks.

There are three passive mechanisms for dispersal of algae: water, other organisms, and air (Kristiansen, 1996). Water is the major medium for dispersal, including channelized flow such as streams and rills, unchannelized runoff, and moist surfaces such as soil. Algae and diatoms are occasionally consumed by fish, birds, and other organisms, and a few species are known to remain intact following digestion (Velasques 1940). Humans play a major role in dispersal of algae through their alterations of ecosystem, and algae can easily attach to boots or various parts of a person's body. Various aquatic organisms such as macroinvertebrates and fish can carry algae as well. Epizoic algae, such as those attached to snails and mollusks, migrate by movement of the host. In some instances air can be a means of dispersal as some dried diatoms are found in aeolian dust. In addition, algae can be carried through wind as dried individuals come in contact with air (Kristiansen 1996). Wind dispersal is important for those species of algae and diatoms that can survive long periods of desiccation, such as subaerial and aerophytic diatoms (Round et. al.,1990).

Active mobility is dependent on autoecology and morphology, but is considered to be of little importance since such mechanisms cover very small distances within the lifetime of an individual (Kristiansen, 1996). Mobile organisms, such as species of most Navicula, are free-flowing forms that generally move by gliding or body undulations aided by the raphe. However, although some diatoms may be able to move over rock surfaces of notable distance, such movement is typically minor compared to passive dispersal. Stalked algae forms, such as diatoms of the species Melosira, are essentially immobile, and thus sloughing, entrainment, and fluid shear of water will control dispersal. Consumption by predators can also be a means of dispersal, particularly those that avoid complete digestion (Kristiansen, 1996).

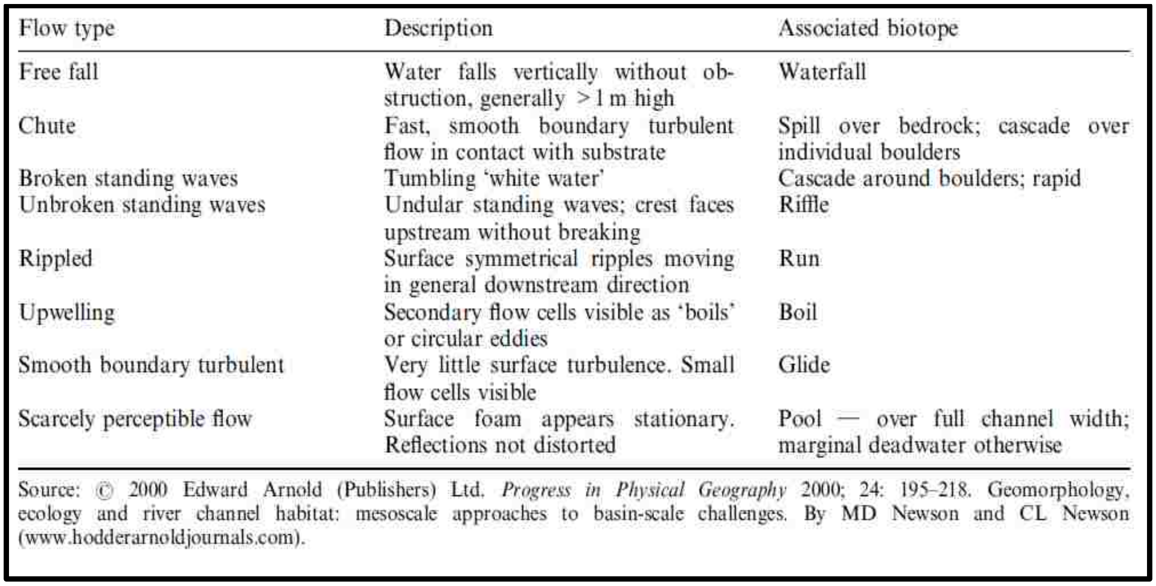
Regardless of mechanism of mobility, all diatoms are subject to passive dispersal due to water flow. However, increased water velocity, due to flooding for example, will increase the amount of dispersal (Biggs in Stevenson, 1996). Such processes are explained in further detail later on.

Algae inhabit a range of habitats, from ephemeral ponds or puddles, to fast flowing streams, brackish waters, marine ecosystems, and even terrestrial systems that can accumulate sufficient moisture. Algae are photosynthetic, meaning that they produce energy from the sun, thus making them important primary producers. The degree of their trophic importance varies based on habitat, but the large number of algae present in unshaded streams, shallow lakes, and continental marine systems is a surrogate for their significance. Areas with limited light availability, such as dense forests and riparian zones, deep portions of lakes and oceans, as well as caves, limit the abundance of most algae, although it rarely excludes them (Stevenson, 1996*)*.

Within streams algal composition varies based on different habitats and biotopes (see Table 1.1). In alluvial streams, habitats may consist of riffle zones that consist of gravel and cobbles, slow moving pools with fine to coarse sediment, runs and glides carrying varying sediment sizes, and large boulders. In bedrock-controlled streams, where the amount of alluvium is often limited, habitat morphology is based on heterogeneity along the bed, which may consist of fractures and bedding planes, abrasive potholes and solutional grooves, step features, and various other discontinuities along the rock interface. In relatively flat streams (slope < 0.002) a layer of fine sediment may accumulate along bedrock patches, which provides an additional habitat constraint for algae (Fox et al., 2014). Fine sediment is sensitive to erosion and transport, thus making it difficult to colonize. In addition, the mixing of fine sediment also increases turbidity, thus attenuating light to the benthos.

A complete, recent compilation of typical algal taxa found in central Kentucky streams is non-existent. However, a study by Neel (1968) found common algae genera in a limestone stream in central Kentucky to include *Cladophora, Spirogyra, Melosira, Fragilaria, Cocconeis, Rhoicosphenia. Achanthes, Gyrosigma, Navicula, Cymbella. Gomphonema, Nitzschia, Surirella, Phormidum, Lyngbya,* and *Calothrix*.

Table 1.1. Biotopes associated with fluvial systems



Flow type	Description	Associated biotope
Free fall	Water falls vertically without obstruction, generally >1 m high	Waterfall
Chute	Fast, smooth boundary turbulent flow in contact with substrate	Spill over bedrock; cascade over individual boulders
Broken standing waves	Tumbling 'white water'	Cascade around boulders; rapid
Unbroken standing waves	Undular standing waves; crest faces upstream without breaking	Riffle
Rippled	Surface symmetrical ripples moving in general downstream direction	Run
Upwelling	Secondary flow cells visible as 'boils' or circular eddies	Boil
Smooth boundary turbulent	Very little surface turbulence. Small flow cells visible	Glide
Scarcely perceptible flow	Surface foam appears stationary. Reflections not distorted	Pool — over full channel width; marginal deadwater otherwise

Source: © 2000 Edward Arnold (Publishers) Ltd. *Progress in Physical Geography* 2000; 24: 195–218. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. By MD Newson and CL Newson (www.hodderarnoldjournals.com).

Geomorphology of Bedrock Streams

Bedrock-controlled streams may be defined as those in which the majority of the channel is actively eroding into underlying bedrock, (Tinkler and Wohl, 1998) and have considerably different processes controlling morphology as compared to alluvial rivers. Bedrock streams are generally limited in sediment availability because, unlike alluvial streams, banks are not easily eroded (Fryirs and Brierley, 2013). Bedrock streams may have a veneer of fine sediment that becomes mobilized in flow events, however it is the bedrock itself that controls channel morphology and channel dynamics (Tinkler and Wohl, 1998; Wohl, 1998). In addition, bedrock streams are often eroded vertically rather than laterally, resulting in various bedforms within the channel. Such heterogeneity within the channel bed is controlled by a number of factors, including rock type and structure, climate, historical contingencies, flow characteristics, and other geologic/landscape attributes, as well as many others (Tinkler and Wohl, 1998; Wohl and Merritt 2001).

Common bedforms in bedrock-controlled streams include potholes, grinders, solutional grooves, scallops, flutes, fractures, steps, and joints to name just a few. Processes acting on such forms may be on many scales from mm (microscale) to several km (macroscale) (Wohl, 1998). An exhaustive discussion on the terminology and associated processes of bedrock bedforms are beyond the scope of this study, and is explained in greater detail in Richardson and Carling (2005). However, because bedrock-controlled forms are an important component of this investigation, a brief analysis of some of the more common bedrock forms encountered is necessary. Particularly because bedforms may provide habitat space for a number of organisms, including algae, it is important to understand some defining characteristics, as well as the mechanisms in which they form. This discussion will be limited to potholes, solutional grooves, fractures/joints, steps, and furrows because they have direct applicability to this study.

Potholes are concave, rounded depressions formed by vertical, corkscrew-shaped vortices associated with turbulent flow (Richardson and Carling, 2005) and the subsequent transport of sediment. They are generally fairly deep in relation to flow depth, and may be formed primarily by suspended load where it is dominant (Richardson and Carling, 2005) or by corrosion when bedload is dominant (Fryirs and Brierley, 2013). Corrosion is chemical weathering that weakens rock, common in limestone systems (Wohl, 1998). As such, corrosion can act as a precursor to potholes, which require some form of bed irregularity or weakness for initiation. In contrast, a *furrow* is a curvilinear depression that is at least twice as long as it is wide, and overall much smaller than a pothole, and small in comparison to the width of the channel. The sides are generally smooth, and typically occupy the lowest part of the channel. They are formed by bed irregularities which alter flow, or near large boulders that deflect flow and alter the pressure gradient (Richardson and Carling, 2005).

Solutional grooves form chiefly in limestone by the process of dissolution (a specific form of corrosion). These forms are small, but contain a variety of morphologies from spherical to elongate. Morphologies are controlled by flow characteristics such that elongate forms are created by a dominant, constant flow direction while circular forms are caused by slower, slackwater flow (Richardson and Carling, 2005). Solutional grooves may act as predecessors for potholes and furrows, providing zones of weakness and irregularity for initiation of such features. Processes such as corrasion, the abrasive weathering of bedrock by clasts, (Wohl, 1998) may also help initiate solutional groove, as well as pothole and furrow, formation.

Joints and fractures are distinct from the previously mentioned features in that they do not necessarily form from fluvial processes. Nevertheless, they are still important features within a fluvial bedrock system. Patterns of joints and fractures are generally controlled at the macroscale, and may be influenced by geological controls such as tectonic regime, structural folding and faulting, and longitudinal patterns (Wohl, 1998). Joints and fractures are a type of brittle deformation which occurs in lithological features as a function of stress. Joints differ from fractures in that joints tend to occur in systematic sets, while fractures generally are much more random in distribution. In fluvial systems, weathering and dislocation of fractures and joints can be exacerbated by the fluid force and turbulence of the water, sediment particles tumbling along the bed, as well as biological organisms, both flora and fauna (Wohl, 1998).

The various bedforms and channel irregularities, such as those previously mentioned, have implications for algae distribution. Features such as potholes and furrows are important because they reflect the most actively abraiding portion of the channel (Hancock et al, 1998) and therefore could impact algal colonization. In addition, bedrock features can provide distinct habitat assemblages, as indicated in Figure 1.2. While these features impact algal colonization, there are potential implications for algae to reciprocally control formation of some of these features, which is discussed further in Chapter II.

Geomorphology of Central Kentucky

The Bluegrass Region of central Kentucky consists of four sub-regions: Inner Bluegrass, Outer Bluegrass, the Knobs, and the Eden Shale Belt (see Figure 1.1). The Inner Bluegrass consists of limestone of Ordovician age, with a topography characterized by low relief and gentle ridges. The Outer Bluegrass consists of limestone, shale, and dolomite of Late Ordovician and Silurian age, with a topography characterized by rolling hills with moderate relief. The Knobs consist of thick shale of Devonian and Mississippian age, with a topography characterized by a series of hills and cliffs with surrounding plains. The Eden Shale Belt consists of limestone and shales of Ordovician age, characterized by steep hillsides and rounded ridge tops (McFarlan, 1943).

Figure 1.1. Physiographic regions of Kentucky (from Kentucky Geological Survey, 1980).

Central Kentucky consists of many fluviokarst features. Karst systems are defined as landforms developed by the dissolution of carbonate rocks, such as limestone. Fluviokarst features are described as a combination of a fluvial- and a karst-derived landscape, which may be dominated by either of those processes, i.e. karst-dominated or fluvially-dominated (Phillips et. al. 2004). It is possible for karst-dominated landscapes to be converted to fluvially-dominated landscapes, and vice versa. For example karst-dominated landscapes may become fluvially dominated by the clogging of underground conduits; and fluvially-dominated may become karst-dominated by stream capture through sinkholes and dolines. (Phillips et al., 2004). Geology, topography, and historical contingency all may play a role in the development of fluviokarst systems.

The Kentucky River, which is a tributary to the Ohio River, contains incised meanders as it flows through the Bluegrass, which is related to downcutting occurring over the past 1.5 Ma (Andrews, 2004). The history and evolution of the Kentucky and Ohio River systems provide important clues to the understanding of current fluvial geomorphic processes. Historical analysis shows that the Kentucky River during the Plio-Pleistocene flowed northward from its origin in southeastern Kentucky into the Teays River situated in present-day northeastern Ohio (Teller and Goldthwait, 1991). The Teays was a large drainage system that occupied present day Ohio, Indiana, and Illinois. Interpretation of the Kentucky River's geologic and geomorphic history suggest that glacial advance altered the flow of the Old Kentucky River toward the Teays River, which led to overflow, new channel formations, as well as channel piracy of the Ohio River (Teller and Goldthwait, 1991). Truncation of the Kentucky River's distance to the mainstem led to immediate incision (Andrews, 2004). Subsequent incision during the Pleistocene and throughout the Quaternary has led to channel adjustment of those tributaries that currently flow into the Kentucky River, including Shawnee Run. For Shawnee Run, several major knickpoints shown on the longitudinal profile (Figure 1.3) can likely be attributed to channel adjustment to Kentucky River incision.

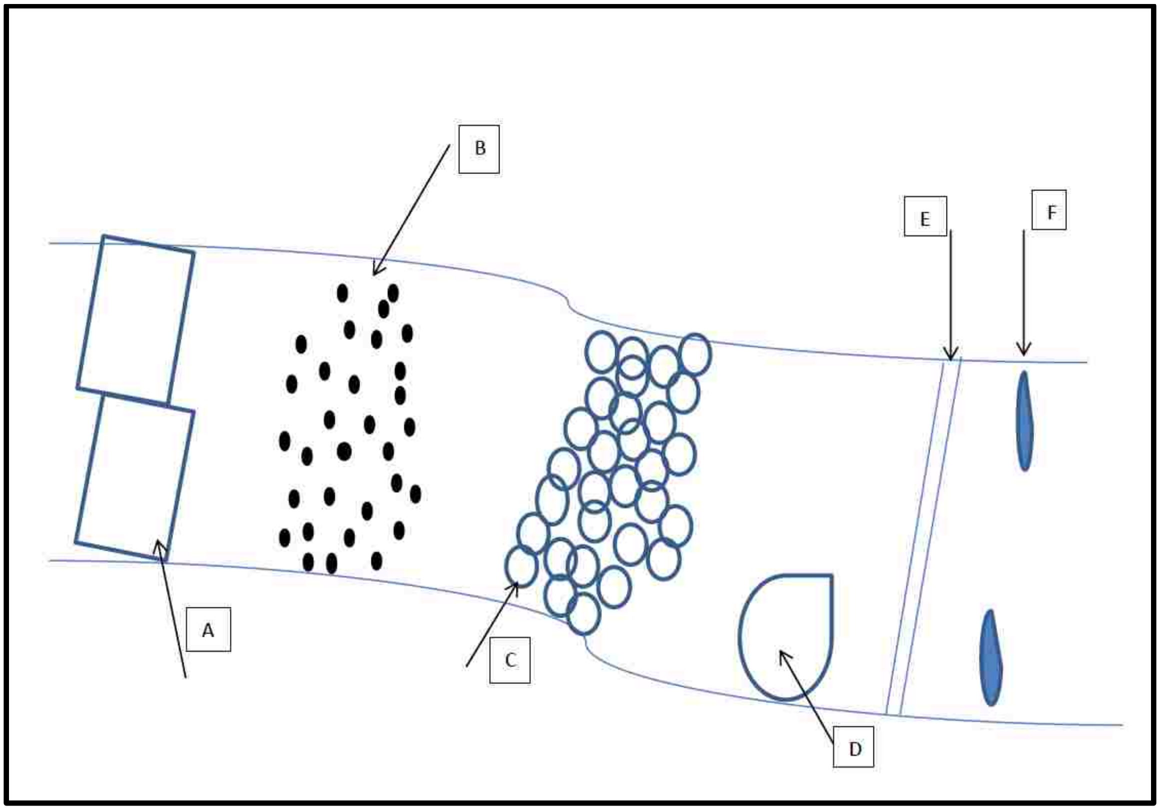


Figure 1.2. Potential habitat assemblages in a bedrock stream. A.) Bedrock slabs and step features. B.) Fine sediment accumulations. C.) Riffle features including cobbles and pebbles. D.) Large boulders, either partially or completely submerged. E.) Joints/Fractures F.) Solutional grooves and potholes.

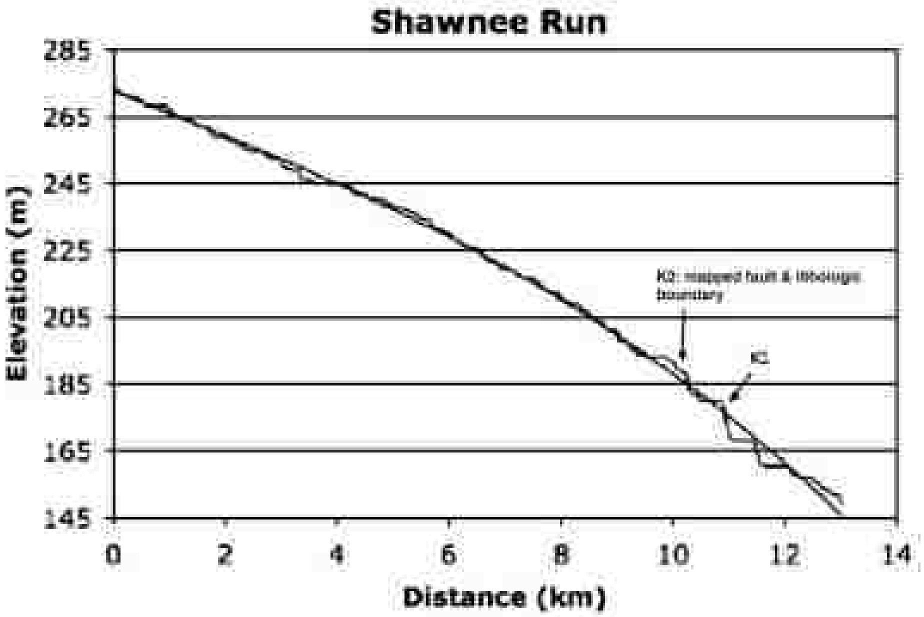


Figure 1.3. Longitudinal profile for Shawnee Run. The smooth line represents the best-fit trend line in each plot. K1, K2 are the two largest knickpoints (from Phillips and Lutz, 2008).

Chapter II: Theories in Ecohydraulics

Basic Concepts

Ecohydraulics is often considered a subcategory of both ecology and hydrology, although it can also be a subcategory of geomorphology, where it is part of the subdiscipline of biogeomorphology (Wheaton et al., 2014). The term ‘ecohydraulics’ can be slightly reworded when incorporated into specific investigations; for example, it is referred to as ecohydrology when investigating the role of organisms on flow, and hydroecology when investigating the role of water processes on organisms (Hannah et. al. 2004). Such investigations have received heightened attention over the last couple decades or so, and ‘the hydroecology revolution’ (Hannah et. al 2004) has been considered a new paradigm by some (Zalewski et al., 1997) as well as an important emerging discipline (Bond 2003) for watershed science.

It may be argued that the first major work regarding hydroecology/ecohydrology was the River Continuum Concept (Vannote et. al. 1980). Since then, research coupling ecological dynamics with hydrological processes has garnered much attention. Examples of such work include the flood-pulse concept (Junk et. al., 1989), the riverine productivity model (Thorpe and Delong, 1994), the connectivity concept (Ward and Stanford, 1995; Petts and Amoros, 1996; Bornette et. al. 1998)), as well as many others (see Janauer, 2000 for a more comprehensive discussion). Such work is important for further analysis and comprehension of ecologic-geomorphic interactions in stream processes.

The ecohydrology of algae is fairly well studied, but mainly limited to alluvial streams. In addition, most of these studies examine geomorphological influences on ecological makeup, but not the other way around. For example, many investigations have focused on flow regimes and the subsequent periphyton dislodgment and detachment from the substratum at particular flow thresholds (e.g. Horner et. al. 1990, Murdock et. al. 2004, Ghosh and Gaur 1998). Others have focused on physiochemical factors influencing algal growth and distribution, including pH (Schneider et. al., 2013), temperature (DeNicola, 1996), dissolved nutrient loads (Borchardt, 1996), and light availability (Hill, 1996). However, there is a dearth of information not only on the impact of benthic ecology on geomorphic processes, but even less so in bedrock streams.

The exception to the above is on fine sediment, where there are a handful of experiments that address such questions, mainly in laboratory settings. In particular, studies by Battin et al. (2003), Fox et al., (2014), Salant (2010), Nikora et al., (2002) and Jones et al., (2012) have examined the impact of biofilms and diatoms on fine sediment in flowing water. For example, Battin et. al., (2003) showed the hydrodynamic impact of biofilms on transient storage of fine sediment. The study also found that biofilms increased the deposition velocity of suspended organic particles, which indicates the influence of the cohesiveness caused by biofilm secretions. Nikora et. al. (2002) focused on the role of periphyton in fluid mechanics, including vertical velocity profiles and bed roughness. In this experiment, studies using flumes showed that periphyton reduced mean velocities and turbulent intensities, and that the presence of periphyton on a rough bed adjusts the velocity profile by shifting the origin of the bed upwards. Salant (2010) investigated the role of algae and diatoms in altering infiltration and dispersal of sediments. Her study showed that filamentous algal assemblages increase Reynolds shear stresses more significantly than diatom and bacterial biofilms; that diatoms can decrease suspended sediment particles; that surface deposition was greater in diatoms than filamentous algae; and that as diatom biomass increases, particle infiltration to the subsurface layer decreases due to blockage of pore spaces. Fox et al. (2014) examined surface fine grain lamina (SFGL) in low gradient bedrock streams and its impact on sphericity and consequent transport within a seasonal context. This research, expounding on earlier efforts by Russo and Fox (2010; 2012) found that biological activity, including the role of algae, can decrease the rate of sediment transport in lowland, unforested streams during summer periods when biological density and activity are high. Jones et al. (2012) analyzed the reciprocity between diatoms and fine sediment to a range of freshwater systems. The analysis showed that diatoms influence fine sediments by contributing to the bedload as particles, increasing sediment settlement by cohesion, and reducing particle infiltration by clogging pore spaces. Conversely, fine sediment impacts diatoms through shading effects, burial and erosion, scouring of the bed and the benthos, and by either increasing or decreasing nutrient availability.

However, a lack of understanding of geomorphic feedbacks beyond the realm of fine sediment is apparent. Feedbacks linking the role of bedform formation to ecological processes, and the subsequent bi-directional relationship, should be considered and addressed. Furthermore, a clear biogeomorphic framing of the range of feedbacks between microorganisms and hydraulic/geomorphic processes has yet to be produced.

Geomorphological Influences on Algal Ecology

Studies examining the impact of geomorphic and hydraulic controls on algal assemblages have identified geomorphic and hydraulic factors that influence algae, summarized as follows:

1) Flow dynamics (velocity, Froude number, etc.)
2) Sediment Entrainment
3) Sediment Deposition
4) Bed Roughness
5) Scour and Abrasion
6) Turbidity

There are many studies that highlight the flow thresholds by which algal colonization and distribution are governed (Francoeur and Biggs 2006; Labiod et. al. 2007; Saraviea et. al. 1998). Flow has a number of implications; for example, Labiod et a. (2007) showed that velocity controls algal colonization and detachment at a relatively constant threshold, in which the specific value depended on site parameters, such as channel dimensions. High velocities can also prevent new algal patches from attaching. Saravia et. al. (1998) specifically address the relationship between current velocity and algal settlement, which was found to have a negative correlation. In addition, their model showed that velocity was the most important parameter controlling biomass dynamics. However, as Francouer and Biggs (2006) express, velocity alone does not account for the removal of algae during disturbance events. Therefore, scour and abrasion by saltating particles must also be considered.

Sediment scour and abrasion play a major role in algal dislodgment and re-colonization. Francouer and Biggs (2006) found that sediment scour increased algal removal by up to forty percent more than water alone. Luce et. al. (2010) found that the abrasive impacts of sand strongly influence algal detachment. In addition, the tool and cover effect may be a critical component on the proportion or rate of abrasion occurring along the bed. Individual sediment grains can act as tools that pluck away at the bed, thus impacting habitat for benthic organisms present within the bed. However, if the bed is littered with grains of varying sizes, these can armor, or cover, the bed from the abrasion of sand and other particles.

The impact of both sediment deposition and entrainment is important. The deposition of sediment can drape existing algal colonies, thus depriving them of sunlight. Sediment deposition also encourages the attachment of new forms, thus creating competition for both light and resources. Sediment entrainment is a function of fluid shear along the bed, which directly impacts those organisms along the bed. Sediment entrainment leads to abrasion and scour.

Bed roughness is essentially a characterization of the particle heterogeneity and form variability of the streambed. Bed roughness is an important parameter when calculating such variables as the velocity distribution, particularly using the law of the wall, and for accounting for Reynolds stress distribution. Bed roughness is correlated with Reynolds stress distribution, so the greater the roughness, the greater the stress distribution (Nezu and Nakagawa 1993). Therefore, roughness can impact algal colonization due to the high probability of sediment entrainment and fluid shear (Labiod et. al. 2007).

Lastly, turbidity is important due to its effects on light attenuation and phytoplankton. Turbidity relates to the clarity of water, and is often influenced by sediment concentration and by phytoplankton. Turbidity typically increases following a flood disturbance event (high flow) which mobilizes sediment. A highly turbid stream limits the amount of sunlight emitted through the water column. Because algae are photosynthetic, sunlight availability is crucial. Therefore, a highly turbid stream will likely impact a large portion of the algal community.

Influence of Algae on Hydraulic and Geomorphological Dynamics

While geomorphology and hydraulics may appear to be independent of biological systems, many studies have supported the opposite. Algae can be significant drivers in ecohydraulic processes. The following is a list of some of the ways in which algae impact hydraulic and geomorphic regimes:

1) Sediment entrainment alteration
2) Alteration of bed roughness
3) Increase/decrease in sediment deposition
4) Reduction of flow
5) Reduce/Increase turbidity

Salant (2012) emphasized the ‘sticky business’ of periphyton, essentially showing that certain species of algae and biofilms produce extrapolymerase secretions (EPS), a polysaccharide matrix that increases the cohesiveness of sediments. As outlined by Jones (2014), such cohesiveness can either increase or decrease deposition. It can decrease deposition by means of planktonic algae suspending sediments through EPS secretions, or it can increase deposition by the weight of benthic algae increasing the drag force, thus encouraging particle settlement. This has implications for turbidity as well, but would likely depend on the ratio of planktonic to benthic organisms in terms of sedimentation. A high amount of planktonic algae can suspend the particles for a greater period, while a greater proportion of benthic algae would support particle deposition, and consequently lower turbidity.

Nikora et al. (2002) and Laboid et al. (2007) have shown that benthic algae, once developed into a mature periphyton system, can significantly increase the roughness height of the bed. Velocity profiles within a stream typically are considered to follow the law of the wall, which in its most basic form is (adapted from Chang, 1988):

$$u/U_* = 1/k \ln(z/z_0) + C$$

where C is a constant based on boundary conditions, z is the total flow depth, z_0 is the height of the bed, k is the von Karmen constant, U_* is the shear velocity, and u is the mean flow velocity in the streamwise direction. It is important to note that there are many variations to this equation, most of which are site specific, but the one used here is very general for the purpose of this discussion. In addition, this equation assumes a planar bed, and thus does not account for bedforms. Studies (i.e. Nikora et al. 2002) have shown that the addition of algae, however, can impact the roughness height (z_0), which then alters the parameter for a site-specific log-law velocity distribution.

A dense periphyton mat can also reduce the flow to a laminar level. A laminar flow has various implications on several different parameters, including Reynolds distribution, flow variability, Froude number, and hydraulic roughness. The key characteristic for algae to make flow laminar is the density, because if it is not dense enough it may actually increase the turbulence of flow (Nikora et. al. 2002).

Chapter III: Methods and Study Site

Study Site

The location of field work is Shawnee Run, a tributary to the Kentucky River, in the Shaker Village trail complex, near Harrodsburg, KY (Figures 3.1, 3.2). Shawnee Run is a forested, bedrock-controlled, limestone stream with occasional coarse alluvial cover. Shawnee Run has a drainage area of 43.50 km^2 , a total length of 19.84 km, an average slope of 0.006, a sinuosity of 2.21 and local elevation of 231 m (760 ft. above sea level). Flow is variable and may be discontinuous over extended dry periods. The climate of the region is humid subtropical with an average precipitation of 43 inches (1110 mm). The area of interest is an approximately 100 m reach, with a local drainage area of 40.82 km^2, and is crossed by the Shawnee Run foot and horse trail; therefore the stream does experience occasional foot trampling by both humans and horses. The sampling reach consists of portions dominated by coarse sediment, particularly cobbles, and associated riffles, as well as bedrock zones dominated by fine sediment (sand and silt) approximately 0.5 to 1 cm in thickness. Exposed bedrock dominated portions of the reach consist of bedding planes, joints, and abrasive grooves and potholes with smoothed surfaces.

Shawnee Run has a number of bedrock features, but the prominent ones of interest to this study, are: dissolution features (Figures 3.3a and 3.3.b); step features resulting from the plucking of joints (Figures 3.3c and 3.3d); large boulders/cobbles that are partially (Figure 3.3e) and completely (Figure 3.3f) submerged, likely derived from weathering and plucking upstream; fractures (Figure 3.3g) and potholes/grinders (Figure 3.3h). These will be discussed in both a geomorphic context, as well as implications for algal assemblages.

The dissolution features, as shown in Figures 3.3a and 3.3b, appear to be formed by a combination of dissolution processes and abrasion. Because the origin of these features appears to be controlled primarily from water dripping from outside the bed, they will be simply labeled as dissolution features, rather than potholes or solution grooves. The dissolution features are significant because of potential impacts on flow, particularly by the ability to significantly modify turbulence. However, these forms also could provide significant habitat patches for algae, as the leeward side of the grooves may provide hiding space from flow shearing. The potential as a significant habitat space for algae is indicated by the small collection of fine sediment accumulated within them.

Steps and joints are quite prevalent within the Shawnee Run study reach. The steps are assumed to primarily be formed by plucking of the streambed, meaning that saltating clasts remove, or “pluck,” the streambed, especially along discontinuities such as joints and bedding planes, leading to dislodgement of blocks of bedrock. Steps and joints are significant for several reasons: 1) steps may lead to hydraulic jumps which could alter the flow regime (i.e. Froude number, turbulence); 2) they may provide habitat space, and 3) they provide clues to some of the geomorphic processes occurring within the stream. These features are shown in figures 3c and 3d, with the step features very prominent in figure 3c. Transitions into step features can lead to hydraulic jumps, in which the Froude number bounces from supercritical to subcritical. Those regions with low Froude numbers may provide significant patches for various algal taxa to thrive. Algal colonization could also be prevalent between joint sets, as well as towards the downstream side of the steps flow variation is minimal or protected.

Large boulders and rocks are scattered throughout Shawnee Run, with various sizes that include both completely submerged, and those that are above the water surface (figures 3.3e and 3.3f). On top of exposed boulders there is often a coating of moss, which can provide an important habitat for algae, particularly those that can adapt to the occasional drying periods. On the downstream side of boulders and rocks, both exposed and submerged, there could be a significantly different community than the stoss region (Peterson, 1996).

Fractures can serve a similar function to that of joints. The fracture depicted in figure 3g runs along the width of the channel. Abrasive potholes and grooves (or furrows) are also quite common in Shawnee Run. These can potentially serve as significant habitat spaces, depending on the dimensions of the feature, particularly its length and depth.

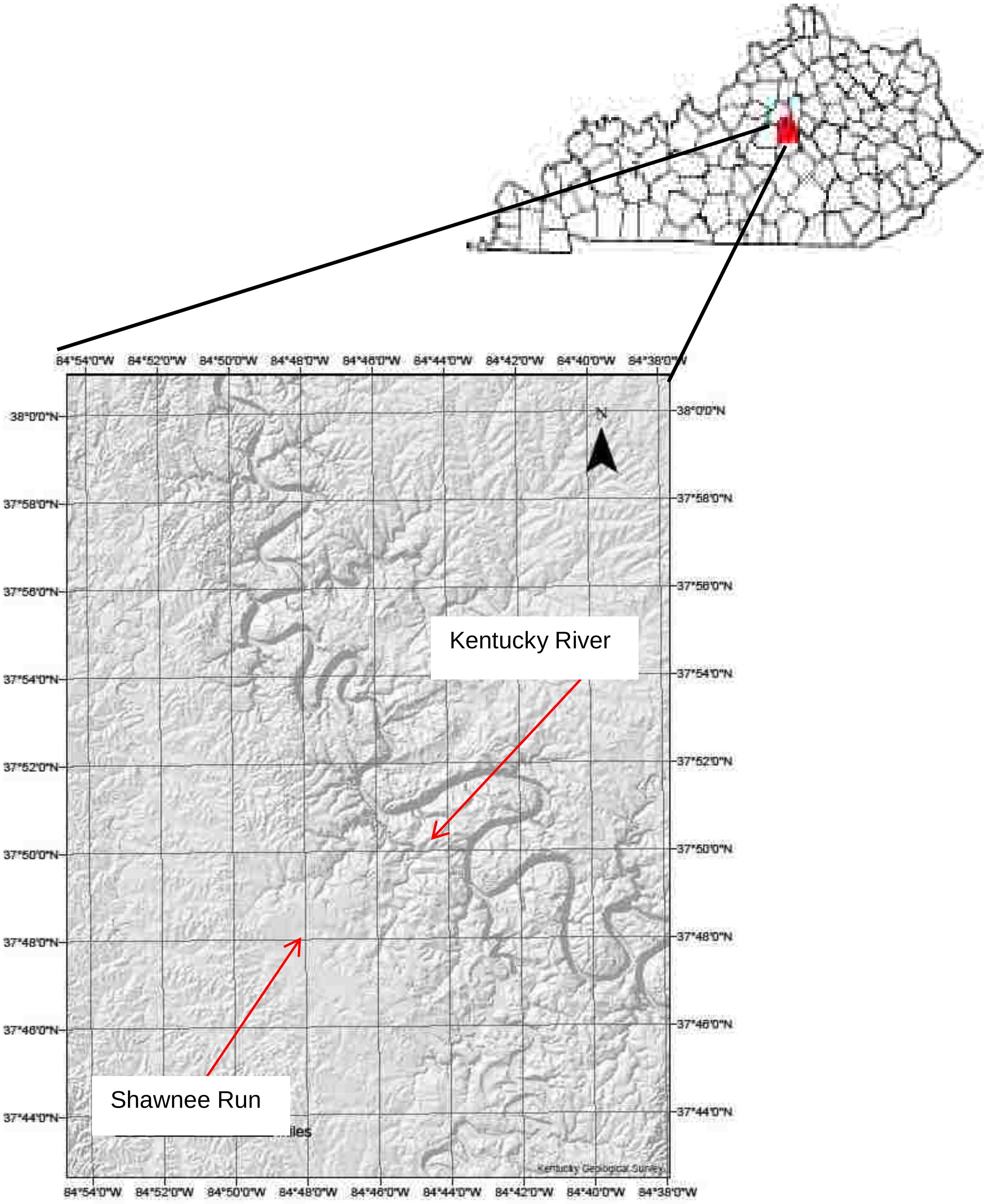


Figure 3.1. Map of study site

Figure 3.2. Sampling site at Shawnee Run. Left: downstream view. Right: upstream view.

Figure 3.3. Bedrock features at Shawnee Run from top left to bottom right:. a) dissolution features; b) exposed roughness elements. C) jointing; d) steps; e) exposed boulders; f) submerged rocks; g) fractures; h) potholes

Diatom Sampling

Samples were collected at four distinct habitats along the sample reach: riffle sections characterized by pebbles and cobbles, fine sediment accumulated above relatively flat-lying bedrock within the channel, along grooves/potholes/fractures and other bedrock discontinuities, and on the leeward side of boulders either submerged or partially exposed. Diatoms were the dominant algal taxa present. Because other algae taxa were practically non-existent except for the infrequent patch of filamentous algae, only diatoms were sampled. Samples were collected either by hand-grabbing and suction by a large pipette (in the case of fine sediment) or by scrubbing substrate with a stiff brush. To collect diatoms from immovable submerged substrate, a modified scrubber was utilized as developed by Davies and Gee (1993). Samples were stored in separate 25 mL sampling jars for each habitat, and preserved with 1 mL of Lugol's solution, and stored in a dark refrigerator. Subsamples were then cleaned in the lab by acid digest to remove excess organic matter and sediment, which was achieved by adding sulfuric acid and potassium dichromate to create an exothermic reaction. Samples were diluted with distilled water until the mixture became clear, and several drops were added to a microscope slide for analysis.

Samples from each site were mounted on two slides for a total of 8 replicates. Samples were mounted by pipette onto a coverslip then heated until dried. The coverslip was inverted onto a slide, and then analyzed using a light microscope (*AmScope B100 Series)*. Up to 100 individuals were examined per slide and distinct genera were noted, using keys described in Round (et al, 1990), Bellinger and Sigee (2010) and Vinyard (1979). Taxa were identified to genus scale because accurate identification to species level requires equipment unavailable to this project. In some instances there were not 100 individuals present within a sample, so the totality of the organisms on the slide were analyzed rather than a subsample.

Samples were collected at three different periods: October 2014, as a control for seasonal variations; late February 2015, directly following a major flow event, and mid-March 2015, two weeks post-flood event. Because there is no USGS gaging station at the Shawnee Run field site in which to gather discharge and gage height values, Hickman Creek, located near Camp Nelson, KY, was used as a proxy, because it is also a fluviokarst tributary to the Kentucky River (see Figures 3.4 and 3.5). Hickman Creek, at the USGS gage datum, has a drainage area of 100 m^2, an elevation of 235 m (770 ft.) above sea level, and is located approximately 20 km from Shawnee Run. Reconstruction of the March flooding event was performed from channel surveys to estimate discharge and water depth, which is described in more detail in the next two sections.

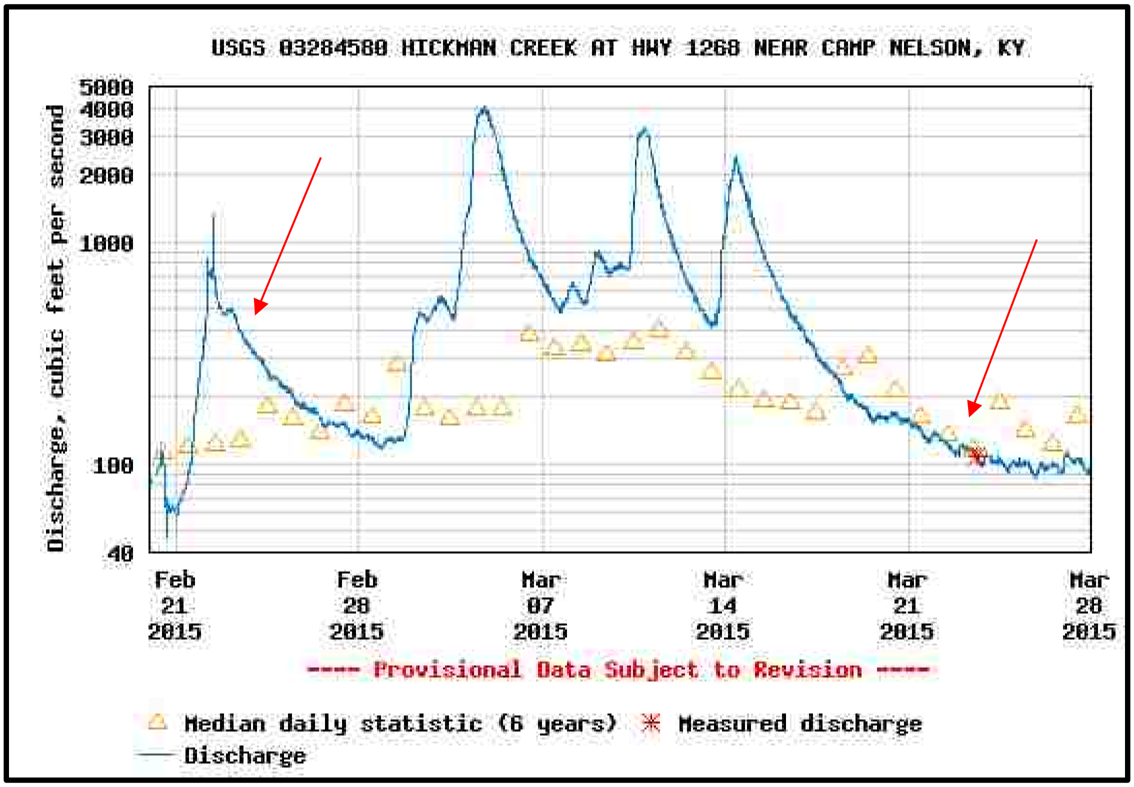


Figure 3.4. Discharge data during the range of dates inclusive of the sampling periods (acquired from waterdata.usgs.gov) for the proxy system used for this study, Hickman Creek, located near Camp Nelson, KY. The arrow on the left designates the February sampling period, and the arrow on the right designates the March sampling period.

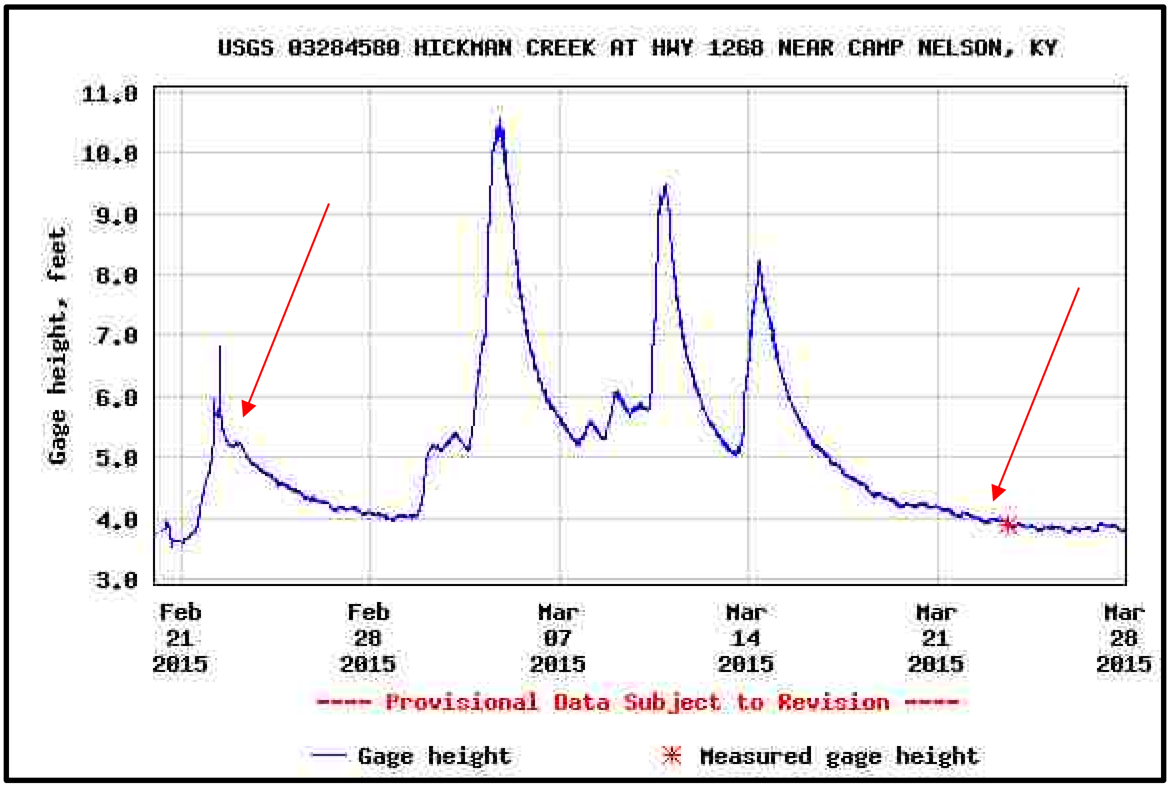


Figure 3.5. Gage height (stage) data during the range of dates inclusive of the sampling periods (acquired from waterdata.usgs.gov) for the proxy system used for this study, Hickman Creek, located near Camp Nelson, KY. The arrow on the left designates the February sampling period, and the arrow on the right designates the March sampling period

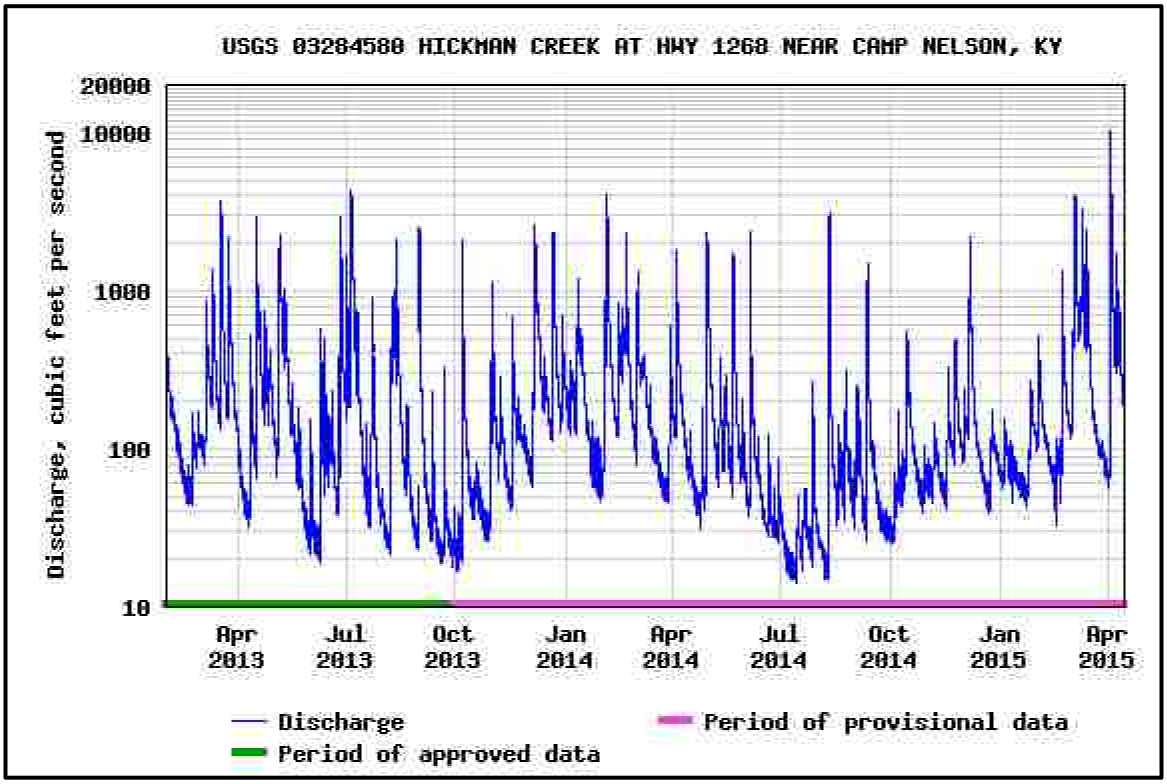


Figure 3.6. Discharge measurements for Hickman Creek from April 2013 to April 2015, acquired from waterdata.usgs.gov.

Channel Measurements

Channel cross-sections were measured at 10 m intervals for a total of 100 m. At each cross-section bankfull width was measured using a standard measuring tape. Bankfull width was determined by visual inspection of morphological bank tops. Channel bed slope was also measured using a laser level and prism. Water depth was measured at each cross-section in the thalweg, in addition to measurements made in the left and right side of the channel. Average water velocity was measured using a flow meter at the same location of the water depth measurements at each cross-section. Velocity and depth measurements were also made behind submerged cobbles/boulders where samples were collected.

Percent algae coverage was determined visually at each cross-section by choosing 10 equal-interval points along a transect running the width of the channel. At each point the presence of algae was noted by a simple binary of yes/no, and the percent coverage of that particular transect was the ratio of ‘yes’ to total points surveyed at the cross-section. For example, if there were six points where algae were present along a single transect, the percent coverage was recorded as 60%. Percent algal coverage was also determined on 10 random cobbles within riffle sections, as well as behind boulders. For these instances, percent coverage was determined by overlaying a 10 x 10 transparent grid, in which each square was 2.10 cm^2 for a total area of 21 cm^2 and 100 squares total. For each square, algae coverage was rounded to the nearest 25 percent (i.e. 25, 50, 75, 100%) and the sum of all squares was used to determine the total coverage.

Post-Flood Measurements

Channel measurements were conducted on 30 March 2015 to estimate flow for the flood events occurring in mid-March. Maximum flow stage was determined by the presence of wrack and other debris deposited by the recent flood event. Five transects measuring maximum width and mean depth were then measured using a measuring tape to develop a channel cross-section. Using the measured widths and depths, channel area and wetted perimeter were calculated (see Appendix A). Channel depth was substituted for hydraulic radius in Manning’s equation, using the modified Manning’s n developed by Jarrett (1984) (See Appendix A). Modified Manning’s n (Jarrett 1984) was used because it is recommended for steeper gradient streams. From this, velocity and discharge were estimated, as well as shear stress. The recurrence interval (RI) for the flood occurring at

Shawnee Run was estimated using data produced by Hodgins and Martin (2003), and compared to Hickman Creek data, which showed that the recurrence for the March flood was approximately 2 years for Hickman, but approximately 200 for Shawnee. The likely reason for the large difference in RI can be attributed to the nature of fluviokarst systems, in which a significant amount of flow can be subsurface, and thus drainage area is vastly underestimated.

Using the data collected from both the channel measurements and the flood reconstruction, the following variables were determined: Froude number, shear stress, shear velocity, average velocity, discharge, and average depth. Appendix A describes the equations used for each variable, and Appendix B lists the recorded and calculated data.

Periphyton coverage at the ten cross sections for the February and March sampling periods were plotted against several of the hydraulic parameters calculated, including velocity, shear stress, shear velocity, Froude number, and depth. Relative and absolute abundances of all organisms sampled were also calculated and recorded.

Chapter IV: Results

Hydraulic and Geomorphic Results

Hydraulic and geomorphic variables (Table 4.1 and Figure 4.1) including Froude number, average velocity, shear velocity, and shear stress were highest in the riffle sections for both sampling periods. Froude number, average velocity, shear velocity, average depth, and shear stress were lowest in the bedforms for both sampling periods. Average depth was highest in the fine sediment for both sampling periods.

The average Froude number for the ten transects was 0.23 for February, immediately following the flood event, and 0.25 for March, two weeks following the flood event. The average shear velocity was 0.25 m/s for February and 0.24 m/s in March. Shear stress was calculated at 7.02 Pa for February and 6.33 Pa for March. Average velocity for the ten transects was recorded as 0.29 m/s for February, and 0.30 m/s in March. Average depth was 18.67 cm in February and 11.33 cm in March.

Table 4.1 shows that the values of shear stress were higher at all 4 sampling sites in February. The same pattern is also true for shear velocity and average depth. Average velocity remained the same in the riffle and boulder habitats for both sampling periods. Average velocity was higher in the March sampling period for the fine sediment habitat, but lower for the bedform habitat. Froude number was higher in the March sampling period for fine sediment, boulders, and riffle habitats. Froude number was lower in bedforms for the March sampling period.

Figure 4.1 shows the reconstructed cross-sections from the flood event. A description of the calculated measurements for the cross section, including cross-sectional area, wetted perimeter, and discharge can be found in Appendix B. The reconstructed shear stresses for the flood are shown in Appendix B. The average shear stress calculated for the five cross-sections was approximately 116 Pa. Using Shield’s parameter (Appendix A) The largest boulder size present in the sample site (and adjacent areas) was less than 2 m in diameter, which suggests that the shear stress of the reconstructed flood is likely to remove benthic diatoms.

Periphyton Coverage

Tables 4.2 and 4.3 show the percent periphyton coverage for the ten transects for the February and March sampling periods. Figure 4.2 is a bar graph comparing the percent periphyton coverage for the ten measured transects, as well as on cobbles in the riffle section, and the leeward side of boulders for the two sampling periods. The average periphyton coverage for the ten transects was 64% for February and 55% for March. The average periphyton coverage for the cobbles in the riffle section was 79.5% for February and 43.3% for March. The average periphyton coverage for the downstream side of boulders was 20% for February and 33.3% in March. Sample pictures of some periphyton coverage on rocks and along the bed are found in Figure 4.3.

A simple regression analysis plotting periphyton coverage at the ten transects for each sampling period versus individual hydraulic/geomorphic parameters, showed no statistical relationship for shear velocity and shear stress for either sampling period, as well as average depth, velocity, and Froude number for the March sampling period. However, there was a negative correlation to Froude number for the February sampling period ($r^2 = 0.66$) and average velocity for February ($r^2 = 0.59$). There was also a positive correlation to average depth for the February sampling period ($r^2 = 0.52$).

Diatom Results

Tables 4.4-4.6 and Figures 4.4-4.6 show the relative abundance of diatoms sampled for the three sampling periods. In all three sampling periods (October, March, February) *Diatoma* was consistently one of the top three dominant taxa, with the exception of boulders in October in which *Diatoma* was not present. Similarly, *Synedra* was also dominant in all three sample periods, with the exception of riffles in March. *Navicula* was one of the top three dominant taxa in all but three instances. Therefore, *Diatoma, Synedra*, and *Navicula* were the three most dominant taxa sampled overall. *Fragillaria* was the least dominant taxa, occurring in only one sample- fine sediment in October.

Twelve different genera were identified for the three diatom sampling periods of October, February and March. Tables 4.7-4.9 show the genera identified at the four habitat locations for each of the three sampling periods. Although there were no genera present at all four locations for all three sampling periods, *Navicula* and *Synedra* were present at all but one site: *Navicula* was not present in fine sediment in March, and *Synedra* was not present in riffles in March. In general, *Navicula* and *Synedra* were the most common genera identified. *Diatoma* was the third most common genera, and was present in 10 of the 12 possible sites. *Fragilaria* was the least common organism, appearing at only one site- fine sediment in October.

Fragilaria is an araphid diatom, commonly occurring in fine sediments (Round et al., 1990). Other araphid taxa found in this study were *Synedra* and *Diatoma*, Centric diatoms sampled were *Melosira* and *Cocconeis*. The rest of the diatoms were raphid (*Stauroneis, Navicula, Rhoicosphenia, Stauroneis, Gyrosigma, Meridion,* and *Nitzschia*). Therefore, raphid taxa were the most abundant taxa type sampled. However, no clear pattern appears to have emerged based on morphology type.

Table 4.10 shows the diatoms present at the four habitat types for the three sampling periods. The species composition in fine sediment showed a dramatic change from the October sampling period to the February/March sampling period. *Nitzschia, Cymbella, Rhoicosphenia*, *and Stauroneis* were present during February/March, but not in October. In general, *Rhoicosphenia* was present in most habitats during the February/March sampling periods, but not present at all during the October sampling period. Diatom taxa within the bedform habitats varied between the three sampling periods. 7 taxa were present in October, while there were only 4 in February, and 6 in March. However, in all three sampling periods *Diatoma, Synedra*, and *Navicula* were present. The community composition behind boulders changed relatively little between the three sampling periods.

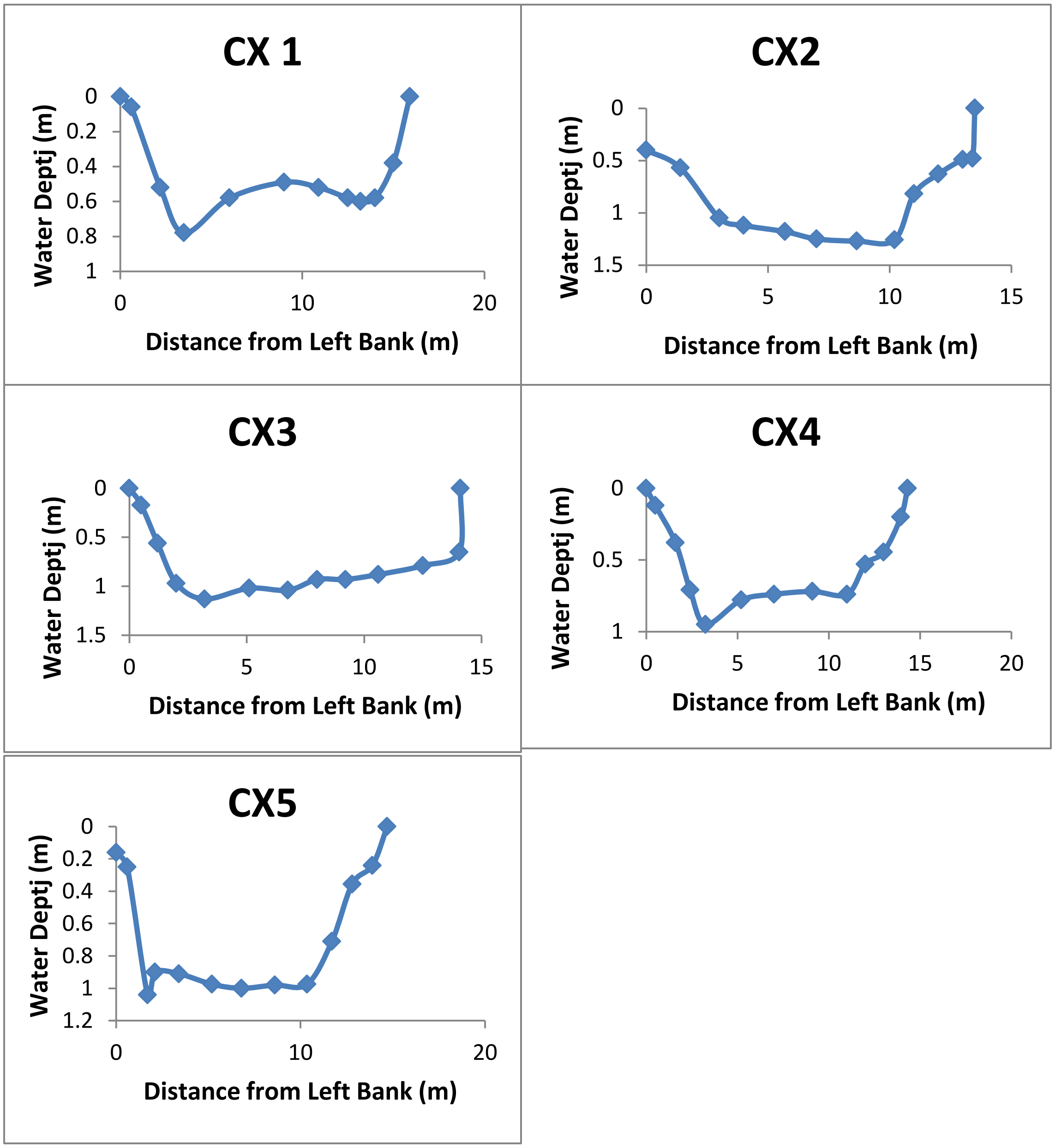


Figure 4.1 Channel Cross-Sections of flood event. CX 1 corresponds to farthest downstream reach, CX5 corresponds to farthest upstream reach.

Table 4.1. Hydraulic variables calculated for the reconstructed flow event

	V(m/s)	**Q (cms)**	**Shear Stress (Pa)**	**U* (m/s)**	**Froude**	**Hydraulic Radius (m)**	**Greatest particle size moved* (m)**
CX1	0.93	67.65	82.18	0.29	0.25	0.42	1.69
CX2	1.55	182.02	151.83	0.39	0.31	0.77	3.13
CX3	1.35	143.28	129.03	0.57	0.29	0.66	2.66
CX4	1.04	77.71	93.62	0.48	0.27	0.48	1.93
CX5	1.32	136.05	124.74	0.56	0.29	0.64	2.57
Avg	1.24	121.34	116.28	0.46	0.28	0.59	2.39

* based on Shields formula*, Appendix A*

Table 4.2. Hydraulic variables for the four habitat sampling locations for March and February.

		Fine sed.	**Boulders**	**Bedforms**	**Cobbles**
March	**Avg. slope (m/m)**	0.02	0.03	0.02	0.06
	Avg. velocity (m/s)	0.24	0.02	0.19	0.36
	Avg. depth (cm)	15.73	12.5	12.67	14.67
	Shear stress (Pa)	3.08	3.675	2.48	8.63
	Shear velocity (m/s)	0.18	0.19	0.16	0.29
	Froude #	0.19	0.02	0.17	0.30
February	**Avg. slope (m/m)**	0.02	0.03	0.02	0.06
	Avg. velocity (m/s)	0.21	0.02	0.231	0.36
	Avg. depth (cm)	19.13	16	17.78	16.33
	Shear stress (Pa)	3.75	4.704	3.48	9.60
	Shear velocity (m/s)	0.19	0.22	0.19	0.31
	Froude #	0.16	0.02	0.17	0.28

Table 4.3. Average periphyton coverage along each transect, and associated hydraulic variables for February sampling period. CX-10 –CX6 correspond to riffle zones, and CX 1-5 correspond to fine sediment zones. Boulder habitats are found in CX 1-CX3, and bedforms correspond to CX2-CX4.

Location	**% Periphyton Coverage**	**Channel Slope**	**Average Water Depth (cm)**	**Average Water Velocity (m/s)**	**Channel Width (m)**
CX-10	70	0.05	30	0.56	9.91
CX-9	70	0.05	34	0.45	8.76
CX-8	60	0.05	20	0.37	6.50
CX-7	50	0.08	24	0.65	9.09
CX-6	40	0.08	17	0.70	6.92
CX-5	70	0.02	17	0.35	6.17
CX-4	80	0.04	24	0.15	7.94
CX-3	70	0.01	20	0.55	6.96
CX-2	60	0.02	34	0.46	10.25
CX-1	60	0.02	30	0.45	11.84

Table 4.4. Average periphyton coverage along each transect, and associated hydraulic variables for February sampling period. CX-10 –CX6 correspond to riffle zones, and CX 1-5 correspond to fine sediment zones. Boulder habitats are found in CX 1-CX3, and bedforms correspond to CX2-CX4.

Location	**% Periphyton Coverage**	**Channel Slope**	**Average Water Depth (cm)**	**Average Water Velocity (m/s)**	**Channel Width (m)**
CX-10	50	0.05	11.33	0.20	9.91
CX-9	50	0.05	7.33	0.19	8.76
CX-8	70	0.05	19.33	0.17	6.50
CX-7	50	0.08	20.00	0.21	9.09
CX-6	80	0.08	20.67	0.41	6.92
CX-5	30	0.02	18.00	0.39	6.17
CX-4	70	0.04	15.67	0.26	7.94
CX-3	50	0.01	16.00	0.41	6.96
CX-2	50	0.02	12.33	0.47	10.25
CX-1	50	0.02	11.33	0.26	11.84

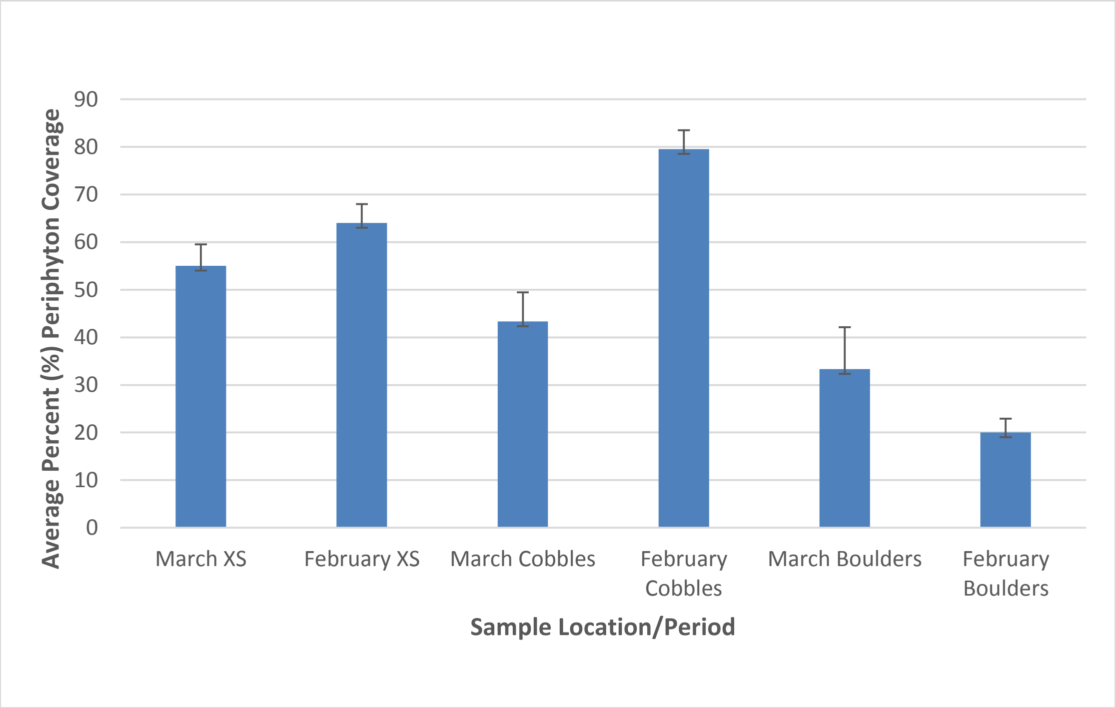


Figure 4.2. Average percent periphyton coverage with standard error bars during the two sample periods, February and March, for the 10 transects (denoted "XS"), cobbles in the riffle section (denoted "cobbles") and behind boulders (denoted "boulders").

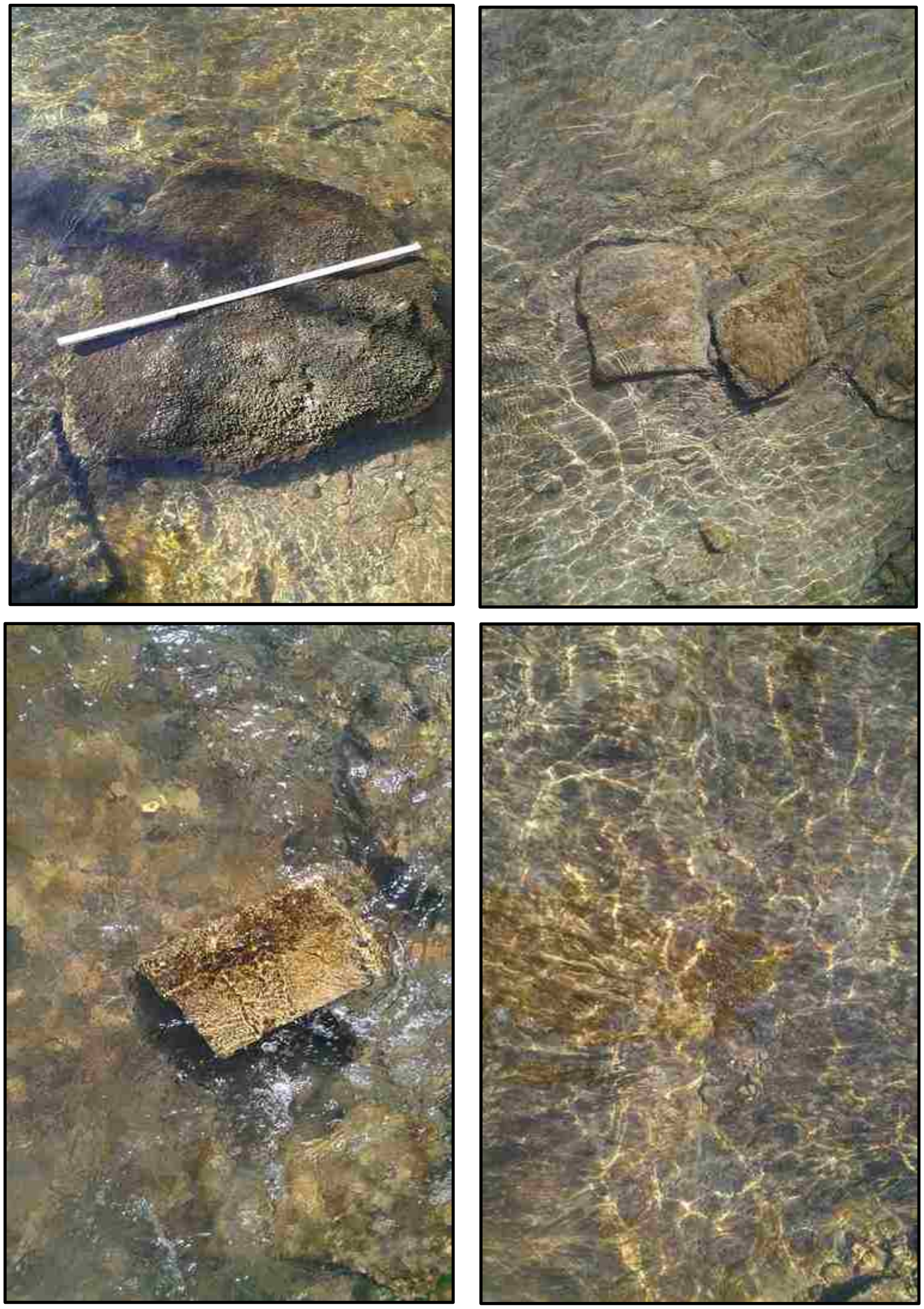


Figure 4.3. Photographs of periphyton coverage at Shawnee Run. Photo on the top left is partially submerged with some moss; photos on top right and bottom left are cobbles with moderate periphyton coverage. Photo on bottom right is a periphyton patch within a veneer of fine sediment.

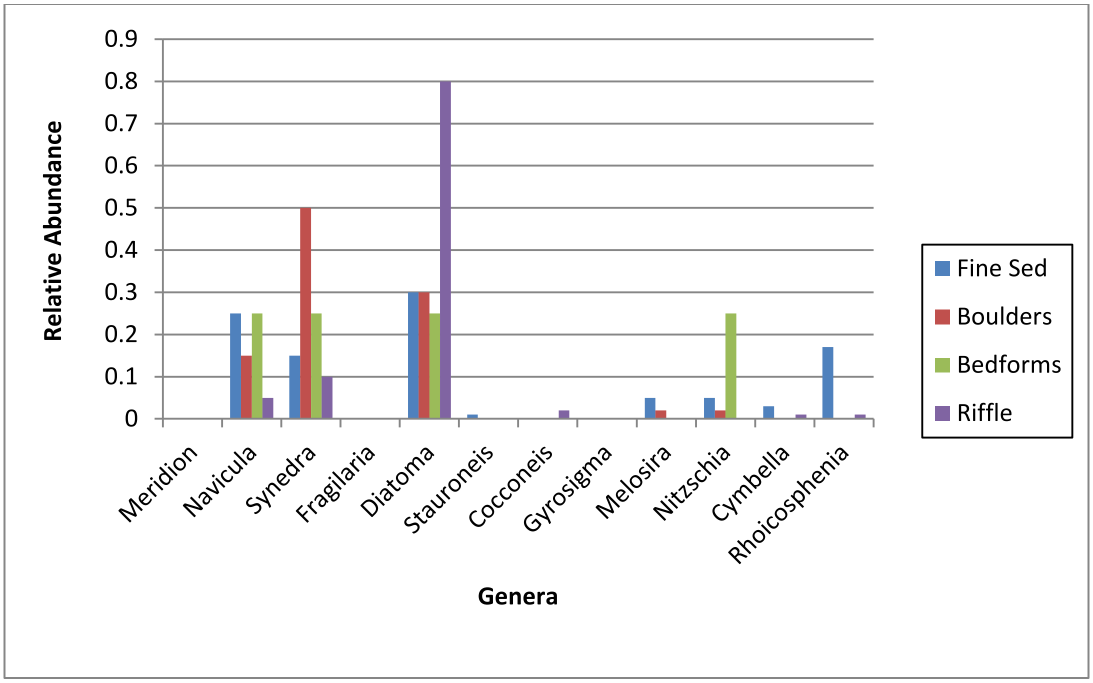


Figure 4.4. Relative abundance of diatoms sampled in October

Table 4.5 Total number of genera sampled for each habitat in October

Habitat	**H1**	**H2**	**H3**	H4
Meridion	30	0	10	30
Navicula	30	40	25	30
Synedra	20	40	20	30
Fragilaria	10	0	0	0
Diatoma	10	0	40	0
Stauroneis	0	2	0	5
Cocconeis	0	0	2	5
Gyrosigma	0	3	2	0
Melosira	0	15	1	0
Nitzschia	0	0	0	0
Cymbella	0	0	0	0
Rhoicosphenia	0	0	0	0

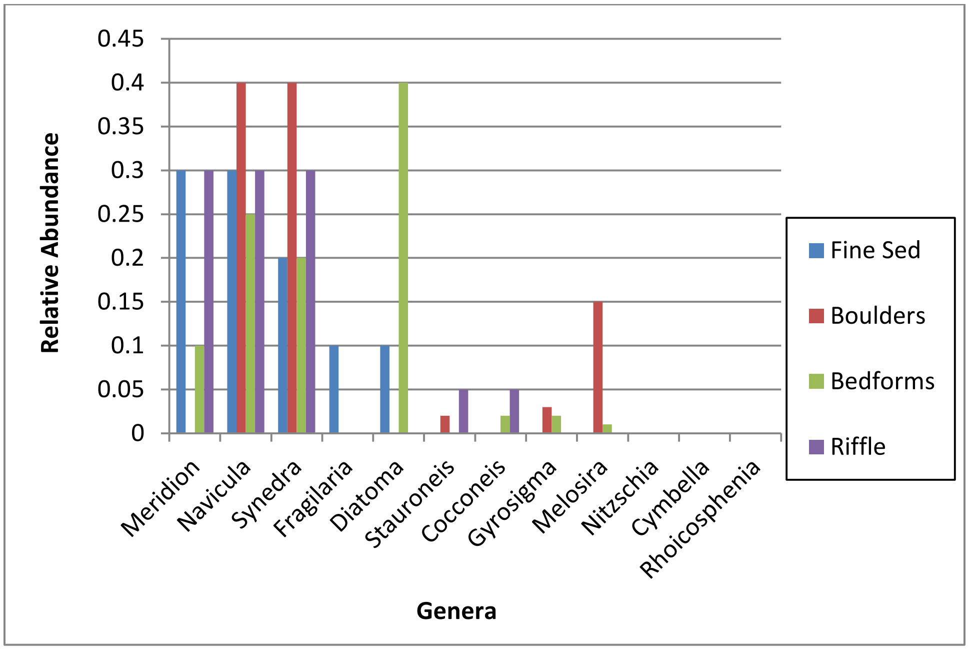


Figure 4.5. Relative abundance of diatoms sampled in February

Table 4.6. Total number of genera sampled for each habitat in Februray

Habitat	**H1**	**H2**	**H3**	**H4**
Meridion	0	0	0	0
Navicula	25	15	10	5
Synedra	15	50	10	10
Fragilaria	0	0	0	0
Diatoma	30	30	10	80
Stauroneis	1	0	0	0
Cocconeis	0	0	0	2
Gyrosigma	0	0	0	0
Melosira	5	2	0	0
Nitzschia	5	2	10	0
Cymbella	3	0	0	1
Rhoicosphenia	17	0	0	1

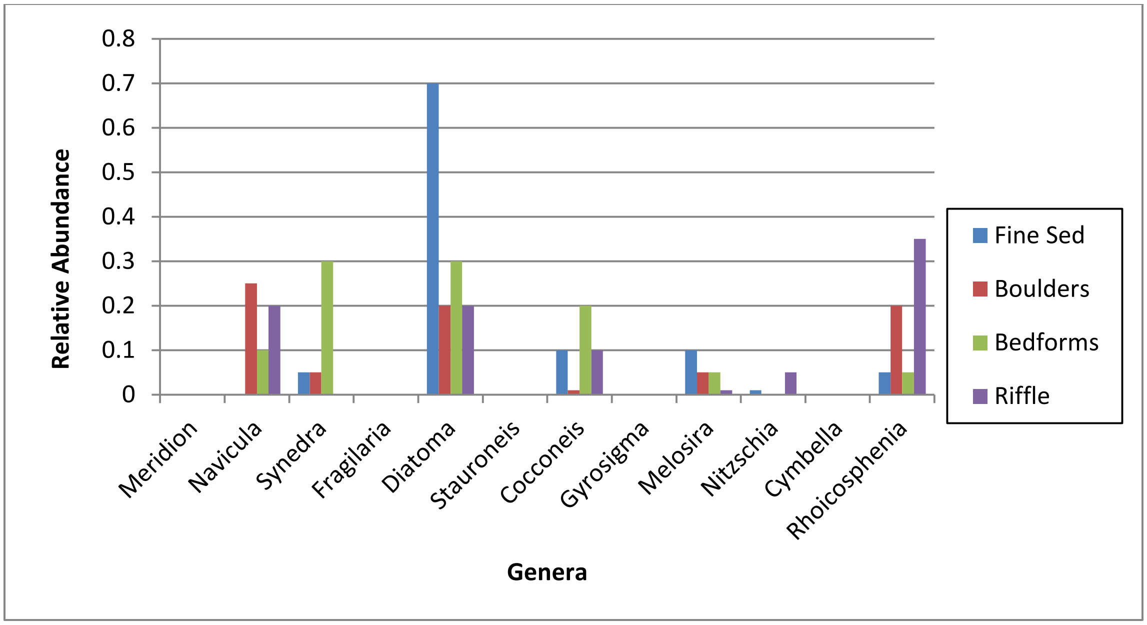


Figure 4.6. Relative abundance of diatoms sampled in March.

Table 4.7. Total number of genera sampled for each habitat in March

Habitat	**H1**	**H2**	**H3**	**H4**
Meridion	0	0	0	0
Navicula	0	25	10	20
Synedra	5	5	30	0
Fragilaria	0	0	0	0
Diatoma	70	20	30	20
Stauroneis	0	0	0	0
Cocconeis	10	1	20	10
Gyrosigma	0	0	0	0
Melosira	1	5	5	1
Nitzschia	1	0	0	5
Cymbella	0	0	0	0
Rhoicosphenia	5	20	5	35

Table 4.8. Genera identified for October sample period. X denotes the presence of genus.

Genera	**Site 1 (Fine Sediment)**	**Site 2 (Boulder)**	**Site 3 (within potholes, joints, other bedforms)**	**Site 4 (Riffle)**
Navicula	X	X	X	X
Nitzschia	X	X		X
Melosira			X	X
Rhoicosphenia	X			
Diatoma	X	X	X	X
Synedra	X	X	X	X
Meridion	X	X	X	
Gyrosigma		X		X

Table 4.9. Genera identified for February sample period. X denotes the presence of genus.

Genera	**Site 1 (Fine Sediment)**	**Site 2 (Boulder)**	**Site 3 (within potholes, joints, other bedforms)**	**Site 4 (Riffle)**
Navicula	X	X	X	X
Nitzschia	X	X		X
Melosira			X	X
Rhoicosphenia	X			
Diatoma	X	X	X	X
Synedra	X	X	X	X
Meridion	X	X	X	
Gyrosigma		X		X

Table 4.10. Genera identified for March sample period. X denotes the presence of genus

Genera	**Site 1 (Fine Sediment)**	**Site 2 (Boulder)**	**Site 3 (within potholes, joints, other bedforms)**	**Site 4 (Riffle)**
Navicula	X	X	X	X
Nitzschia	X	X		X
Melosira			X	X
Rhoicosphenia	X			
Diatoma	X	X	X	X
Synedra	X	X	X	X
Meridion	X	X	X	
Gyrosigma		X		X

Table 4.11. Contingency table of genera identified at the four habitat sites for the three sampling periods

	Fine Sediment	**Behind Boulders**	**Within potholes, joints, other bedforms**	**Cobbles in riffles**
October	Melosira, Navicula, Synedra, Fragilaria, Diatoma	Navicula, Synedra, Stauroneis, Gyrosigma, Melosira	Meridion, Navicula, Synedra, Diatoma, Cocconeis, Gyrosigma, Melosira	Meridion, Navicula, Synedra, Stauroneis, Cocconeis
February	Navicula, Synedra, Diatoma, Stauroneis, Melosira, Nitzschia, Cymbella, Rhoicosphenia	Navicula, Synedra, Diatoma, Melosira, Nitzschia	Navicula, Synedra, Diatoma, Nitzschia	Navicula, Synedra, Diatoma, Cocconeis, Cymbella, Rhoicosphenia
March	Synedra, Diatoma, Cocconeis, Melosira, Nitzschia, Rhoicosphenia	Navicula, Synedra, Diatoma, Cocconeis, Melosira, Rhoicosphenia	Navicula, Synedra, Diatoma, Cocconeis, Melosira, Rhoicosphenia	Navicula, Diatoma, Cocconeis, Gyrosigma, Melosira, Nitzschia, Rhoicospenia

Chapter V: Discussion and Conclusions

Discussion

Based on the results, periphyton, and diatoms in general, do not appear to be useful indicators of hydraulic or geomorphic activity. Periphyton coverage was higher immediately following the flood event, compared to two-weeks post-flood. There was no clear correlation for periphyton coverage against hydraulic variables measured for both flood sampling periods. Also, diatoms did not have distinct assemblages within the four habitats sampled. There are likely several explanations to this, including geomorphic, hydraulic/hydrologic, ecological, and biogeomorphic factors. In addition, experimental design and site location may also be contributing factors to a lack of verifying results.

One potential explanation for the lack of correlation between periphyton coverage and disturbance event is the general ecological nature of diatoms. Diatoms are often reported as one of the first colonizers following a flood (Biggs, 1996), and depending on the amount of time elapsed between a particular flood event and sampling, the diatom composition may not reflect conditions immediately as a result of the event. In addition, as Tornes et al., (2015) point out, the resultant benthic algal configuration following a flood is often a mosaic of patches controlled by both spatial and ecological variability over time (Peterson, 1996). Also, it has been hypothesized that benthic diatoms settle more quickly than planktonic algae because of a greater specific gravity, (Stevenson, 1996) which would confirm that even among algae diatoms are probably the least suitable for diagnosis of a recent scour event.

During the February sampling period, the percentage of periphyton coverage was higher within the cobbles of the riffle section compared to the overall periphyton coverage within the ten transects. This aligns with Biggs (1996) who mentions that immediately following floods algal communities tend to be dominant in larger substrata that resist mobilization. Although the shear stress produced was likely great enough to remove any of the substrate clasts present in the riffle zone, most clasts appeared to have remained immobilized based on visual inspection. Therefore, the riffle zone was the habitat that would have provided the most protection from scouring. However, periphyton coverage was low in areas directly behind boulders for both sampling periods in comparison to overall periphyton coverage of the transects (20% coverage on the leeward side of boulders for February, and 33% coverage on the leeward side of boulders for March). Although regions behind boulders may protect from sedimentation during flood events, rhe low percent coverage may likely be related to shade caused by the boulders, which prevents a significant population from developing, regardless of event.

Resistance versus resilience may also be a key contributing factor. Diatoms can be highly resilient to scour events, meaning they can recolonize quite rapidly (Peterson, 1996). However, some diatoms may be resistant, meaning that they are able to withstand relatively high and/or frequent scouring events, but not necessarily resilient-meaning it takes a while for taxa to recolonize. Diatom genera *Cocconeis, Cymbella*, and *Synedra* are often reported as relatively resistant taxa (Biggs, 1996), which means they are likely to be more abundant following a disturbance event compared to other taxa. However, as noted by Peterson (1996) complete scouring of the benthos following a disturbance event may increase the rate of colonization such that biomass may actually be greater than pre-flood conditions in as little as ten days. Therefore, a likely explanation for the higher periphyton coverage may be due to the rapid recolonization of diatoms following initial removal.

Algal composition can be different between riffle, run, and pool sequences due to differences in shear stress (Biggs, 1996). However, this study did not see a significant difference in diatom community composition between the four habitat types, despite relatively significant differences in shear stress values for the riffle habitat compared to the other three habitat sites. For example, the average shear stress during the March sampling period in the riffle habitat site was 8.62 Pa, but ranged from 2.48 to 3.68 Pa in the other three habitat sites. Similarly, in the February sampling period, the shear stress was computed at 9.60 Pa, compared to 3.48 to 4.70 Pa in the other three habitats. In addition, there were more taxa identified in the riffle habitat (7 genera) compared to the other three habitats, which each had 6 genera identified.

Consideration of other ecological variables may also be necessary as bed scour and particle abrasion may not be major factors in terms of controlling diatom resilience and/or resistance. Water chemistry may play an important role in terms of nutrient availability, and predator-prey relationships should be considered as well. Shawnee Run contains a significant population of snails, *Pleurocera spp*., which are known to be significant grazers of algae and diatoms within central Kentucky limestone streams (Houp, 1970). Taxa that develop a significant over story are more likely to be grazed by snails and other herbivores, compared to more prostrate growth forms (Steinman, 1996). Therefore, fluctuations in diatom density may correlate with population levels of *Pleurocera*, as well as other grazers including fish and various macroinvertebrates.

In terms of morphology, whether a diatom is adnate or pedunculate might dictate its susceptibility to grazing and scour (Peterson, 1996). Adnate species adhere more firmly to the substrate and thus may be more resistant to floods. However, such morphological traits may say little about its resilience. There are particular taxa, such as *Synedra*, which are resistant to grazing. Therefore, the frequency of *Synedra* in the habitats measured for both the February and the March sampling periods may be explained by its morphological features, which allow it to avoid being grazed by *Pleurocera*, as well as remain attached to the substrate following a disturbance event.

In addition, raphid diatom species have a distinct advantage in attaching to the substrate compared to araphid taxa due to the functionality of the raphe in aiding in attachment (Stevenson, 1996). Organisms identified in the samples which are raphid include the genera *Cymbella, Navicula, Rhoicosphenia, Sauroneis, Nitzschia*, and *Gyrosigma*, which account for half of the total genera identified.

However, active movement of diatoms within habitat locations is another factor that might inhibit their utility as indicators of bed processes. For example, taxa such as *Fragillaria spp*., *Synedra spp*., and some members of *Nitzschia* may not be good indicators of hydraulic and channel processes because they are often both benthic and planktonic, and may alternate between site selections within its own life-cycle (Stevenson, 1996).

The heterogeneity within the bed of Shawnee Run may simply not be significant enough to allow for distinct habitat assemblages. Hydraulic variables, in general, did not appear to vary much from habitat to habitat, and conversely, may not have represented significantly different biotopes. The average slope for the habitat types of fine sediment, behind boulders, and within bedforms was similar, which ranged from 0.02 to 0.03 m/m.

Matthaei et al., (2003) suggest that the flood history of a particular system may play a key role in designing and controlling the spatial variability and patchiness of epilithic algae. Their findings suggest that disturbance history is often more important than sediment composition, flow velocity, and water depth. In addition, the severity and intensity of a particular flood event is an important consideration, because most floods do not completely remove all benthic diatoms (Tornes, 2015). The return interval for the Hickman Creek site was determined to be 2, which upon initial observation would probably not suggest a major event. However, the velocity exceeded 1 m/s, which is probably high enough to cause significant scouring.

In addition, Matthaei et al, (2003) found that algal biomass was highest in depositional patches several months following a disturbance event, and that the composition in depositional patches often differed from a scour zone. It is possible that comparison of areas of deposition and areas of scour may show more distinct differences in algal composition and biomass, rather than biotopes or habitat sites such as those analyzed in this study. The habitat types in this study, consisting of fine sediment, behind boulders, and within most bedforms, could probably be considered depositional zones for the time periods analyzed; however, in terms of cobbles within a riffle zone, a deposition or scour designation is somewhat ambiguous due to the combination of deposition and scour which may be co-occurring at any given time.

The role of riparian cover and shading is important as well. Shawnee Run is located within relatively dense forest cover, which restricted the sampling to times when forest cover was not a controlling factor, particularly between late fall and early spring. It may be more useful to consider such systems that are not impacted by cover, so that yearly trends can be considered without bias towards periods when sunlight is more available to benthic algae.

Furthermore, additional spatial data may be needed. The study reach of Shawnee Run represents a small fraction of the limestone streams in central Kentucky, and thus a more comprehensive analysis would require sampling of additional streams. It is also possible that a higher resolution of data may be needed, such as identification to the species level, as well as long term temporal trends, such as data over many seasons or years.

Figure 5.1 represents the potential feedbacks between algae and geomorphic/hydraulic processes. The purpose of this model is to conceptualize the relationship between these two components, and to show the importance of algae, not only from an ecological standpoint, but in a geomorphic framework as well. The direction of the arrow indicates the parameter for which a particular feature influences or controls. If there are arrows trending in both directions between two parameters, then this is considered to be a bi-directional feedback. Of particular interest is the bi-directional feedback of parameters directly related to algae. As shown in the model there are bi-directional feedbacks between algae for parameters including: roughness, flow dynamics, sediment entrainment, and sediment deposition. Scour/abrasion and bedforms lack a known bi-directional feedback.

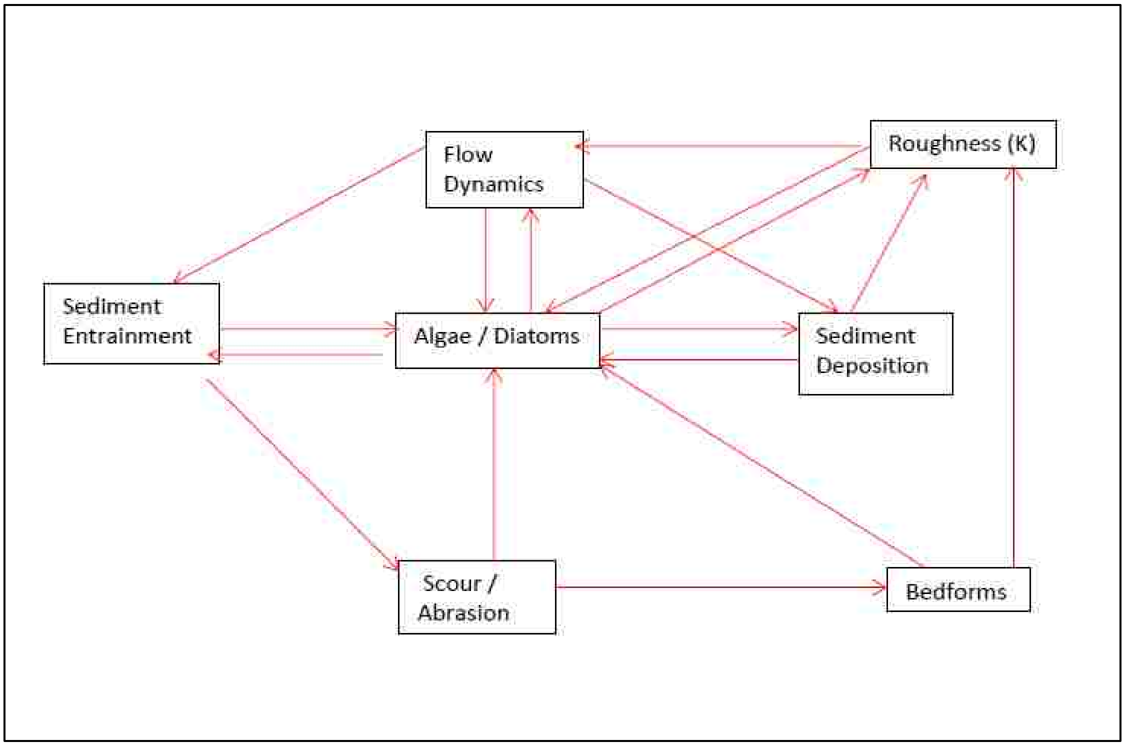


Figure 5.1 Model of potential biogeomorphic interactions among algae/diatoms. One arrow signifies one-way feedback, and two arrows signify bi-directional feedback.

Conclusions

Relationships between algal community dynamics and bedrock-controlled geomorphic processes remain largely unexplored. This study examined the utility of diatoms for correlating geomorphic and hydraulic events in a fluviokarst, limestone stream in central Kentucky. The results of the experiment showed that algae, particularly diatoms, do not appear to be useful indicators of geomorphic or hydraulic activity in bedrock streams. Diatoms are more reflective of ecological regimes and other non-geomorphic processes, such as flood history and frequency, community patchiness within a reach, and the ability to recolonize rapidly. A thorough analysis of the relationship between diatoms and geomorphology and hydraulics likely requires a multi-year study that incorporates ecological variables such as seasonal variation in community composition and density, predator-prey relationships among organisms such as macroinvertebrates and fish, as well as periphyton patchiness; and geomorphic and hydraulic variables such as frequency of floods, the role of deposition versus entrainment in controlling diatom density, as well as examining community composition following many floods and detecting any long-term trends.

The results of this project can be summarized as follows:

- Average periphyton coverage along transects within the stream bed was higher in the February sampling period (64%) than the March sampling period (55%).
- Periphyton coverage on rocks within the riffle zone was higher in February (79.5%) than March (43.3%).
- There was no hydraulic variable that correlated with periphyton coverage for all sampling periods, such as Froude number, velocity, shear stress, or depth.
- Diatom community structure was not significantly affected by the measured flood in terms of the February and March sampling periods.
- Diatom community structure did not appear to vary significantly within the four habitat types for either sampling period.
- *Synedra, Diatoma*, and *Navicula* were the three dominant diatom taxa identified during the study period.

Although the study did not produce results suggesting that diatoms may be useful indications of hydraulic and/or geomorphic processes, understanding the ecohydraulic reciprocity that exists between the physical functions of streams and diatom and algal ecology is important and necessary for the field of fluvial biogeomorphology. Additional experiments and inquiries should be pursued in order to further examine the implications of algae in scour and abrasion, and the subsequent bedforms produced by such processes. However, even with linkages that appear to be more understood, such as the bi-directional feedbacks between algae and sediment entrainment/deposition, additional experimentation needs to be performed in order to better incorporate such processes into management practices, for example. The role of algae and diatoms is potentially a significant component of hydraulic processes and geomorphic functioning in many streams.

Appendix A. *Equations and Symbols*

Parameter	***Equation***
Froude Number	$\frac{V}{\sqrt{g/D}}$
Shear Stress:	$\gamma\mathrm{R}S$
Shield's Parameter	τ_{cr} = kg(ρ_s-ρ)D
Modified Manning's n (Jarrett, 1984):	$0.39*(S^{0.38} * R^{-0.16})$
Shear Velocity:	$\sqrt{gRS}$
Wetted Perimeter:	$\sum\sqrt{\mathrm{D^\wedge 2 + w^\wedge 2}}$
Hydraulic Radius	$\frac{A}{W}$
Manning's Equation:	$U = \frac{1}{n}R^{2/3}S^{1/2}$

Symbol	***Definition***
A	Cross-sectional area
D	Water depth
g	Force of gravity (9.81m/s)
n	Manning's n
Pa	Pascal
Q	Discharge
R	Hydraulic radius
S	Channel slope
U	Q/A
U*	Shear velocity
V	Water velocity
w	channel width
W	Wetted Perimeter
γ	Specific gravity of water
ρ_s	Density of sediment (2.65)
ρ	Density of water (1.00)
k	Constant (0.003)
τ	Mean boundary shear stress
τ_{cr}	Critical shear stress

Appendix B. Cross sectional measurements, reconstructed flood flow.

CX1		***CX2***		***CX3***	
Distance from L Bank (m)	**Channel Depth (m)**	**Distance from L Bank (m)**	**Channel Depth (m)**	**Distance from L Bank (m)**	**Channel Depth (m)**
0	0	0	0.4	0	0
0.6	0.06	1.4	0.57	0.5	0.17
2.2	0.52	3	1.05	1.2	0.56
3.5	0.78	4	1.12	2	0.97
6	0.58	5.7	1.18	3.2	1.13
9	0.49	7	1.25	5.1	1.02
10.9	0.52	8.65	1.27	6.75	1.04
12.5	0.58	10.2	1.26	8	0.93
13.2	0.6	11	0.82	9.2	0.93
14	0.58	12	0.63	10.6	0.88
15	0.38	13	0.49	12.5	0.79
15.9	0	13.4	0.48	14.05	0.65
		13.5	0	14.1	0
Mean Depth (m)	0.42		0.81		0.70
CX Area (m)	6.74		10.92		9.84

Appendix B (cont'd). Cross sectional measurements, reconstructed flood flow.

CX4		***CX5***	
Distance from L Bank (m)	**Channel Depth (m)**	**Distance from L Bank (m)**	**Channel Depth (m)**
0	0	0	0.16
0.5	0.12	0.6	0.25
1.6	0.38	1.7	1.04
2.4	0.71	2.1	0.9
3.25	0.95	3.4	0.91
5.2	0.78	5.2	0.975
7	0.74	6.8	1
9.1	0.72	8.6	0.98
11	0.74	10.35	0.975
12	0.53	11.7	0.71
13	0.445	12.8	0.355
13.95	0.2	13.9	0.24
14.32	0	14.7	0
Mean Depth (m)	0.49		0.65
CX Area (m)	6.96		9.61

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