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Biogeomorphology of Bedrock Fluvial Systems: Example from Shawnee Run, Kentucky, USA

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BIOGEOMORPHOLOGY OF BEDROCK FLUVIAL SYSTEMS: EXAMPLE FROM SHAWNEE RUN, KENTUCKY, USA

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Arts and Sciences at the University of Kentucky

By

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ABSTRACT OF DISSERTATION

BIOGEOMORPHOLOGY OF BEDROCK FLUVIAL SYSTEMS: EXAMPLE FROM SHAWNEE RUN, KENTUCKY, USA

The dynamic interactions between fluvial processes and vegetation vary in different environments and are uncertain in bedrock settings. Bedrock streams are much less studied than alluvial in all aspects, and in many respects act in qualitatively different ways. This research seeks to fill this lacuna by studying bedrock streams from a biogeomorphic perspective. The first part of this research aims to identify the impacts of woody vegetation that may be common to fluvial systems and rocky hillslopes in general, or that may be unique to bedrock channels. A review of the existing literature on biogeomorphology — mostly fluvial and rocky hillslope environments — was carried out, and field examples of biogeomorphic impacts (BGIs) associated with fluvial systems of six various bedrock environments were then examined to complement the review. This research shows that bedrock streams exhibit both shared and highly concentrated BGIs in relation to alluvial streams and bedrock hillslope environments. It shows that while no BGIs associated with bedrock streams are unique to the environment, the bioprotective function related to root-banks (when the root itself creates the stream bank) and the processes related to bioweathering and erosion are rarely addressed in alluvial fluvial literature, despite their importance in bedrock fluvial environments. The second part of the dissertation is largely grounded upon the important BGIs associated with bedrock fluvial environments identified in the first part. Drawing from ecological lexicon, this part introduces some biogeomorphic concepts, most importantly biogeomorphic keystone species and equivalents, with respect to different biotic impacts on surface processes and forms. Later, it explores these concepts by examining the general vs. species-specific BGIs of trees on a limestone bedrock-controlled stream, Shawnee Run, in central Kentucky. Results suggest that *Platanus occidentalis* plays a keystone role by promoting development of biogeomorphic pools in the study area. Further, some species play equivalent roles with respect to surface processes and landforms by promoting development of avulsion-associated islands and can be recognized as biogeomorphic equivalents. Finally, this dissertation also examines the relative importance of systematic up-to downstream vs. local scale variation explaining channel morphology and biogeomorphological phenomena in Shawnee Run. Results show that local scale variation − primarily attributable to the local scale structural controls, incision status and edaphic variation − largely explains channel morphology and vegetation patterns. These patterns may therefore be common in bedrock rivers strongly influenced by geological controls.

KEYWORDS: Biogeomorphology, Bedrock Streams, Biogeomorphic Impacts, Biogeomorphic Keystone Species, Local Scale

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DEDICATION

To my parents, brothers, husband and Professor Phillips

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Biogeomorphology and Fluvial Systems

Biogeomorphology, an emergent subdiscipline at the interface between geomorphology and ecology (Viles 1988; Naylor *et al*. 2002), has developed extensively in recent decades. Geomorphology and ecology developed as distinct disciplines, and different concepts developed independently in each of these fields (Corenblit *et al.* 2007). Over time, the concept of biogeomorphology evolved as an interdisciplinary domain between ecology and geomorphology. Biogeomorphology studies the bi-directional linkage between geomorphic and ecological structures and processes, while considering multiple casualties and scale dependencies (Phillips, 1999) for understanding the complex emergent landscape patterns linked to active or passive bio-processes (e.g., bioerosion, bioprotection, bioconstruction and bioturbation) (Naylor *et.al*. 2002; Phillips 2006; Stallins 2006). The key components of fluvial biogeomorphology – a domain of biogeomorphology − are the riparian zone and the associated flow regime (flow intensity, duration and frequency) that drive hydrogeomorphic processes. Riparian zones are part of bottomland surfaces that are often inundated or saturated at least once a year, while bottomland includes all fluvially generated landforms and vegetation extends from terraces to the channel bed, in descending order, within the valley section (Hupp and Osterkamp, 1996). The term fluvial corridors is used here, consisting of river channels, their margins, and the zone of frequent floods occupied by riparian vegetation (Corenblit et al. 2010).

Fluvial corridors encompass river channels, their margins and the zone of expansion of frequent floods occupied by riparian vegetation (Corenblit *et al*. 2010). They undergo hydrogeomorphological processes that exhibit variation in intensity, frequency and duration, and consequently alter the feedback mechanisms exist between the continuum of flow regimes and riparian plant communities. Extensive empirical research has been conducted on fluvial biogeomorphology to understand the complex nature of the association between riparian vegetation and hydrogeomorphic processes (e.g., Everitt 1968; Hupp and Osterkamp 1985; Harwood and Brown 1993; Marston *et al*. 1995; Hupp and Osterkamp 1996; Bendix and Hupp 2000; Gurnell *et al*. 2001; Hughes *et al*. 2001; Oswalt and King, 2005; Gurnell and Petts 2006; Hupp and Rinaldi 2007; Bertoldi *et al*. 2009; Stotts *et al*. 2015; Wohl and Scott 2017). However, the nature of dynamic interactions between riparian vegetation and hydrogeomorphological processes vary in diverse environmental settings (Gurnell *et al*. 2001; Gurnell 2014) and bedrock streams have rarely been studied from this context. This research presented here seeks to fill this knowledge gap by exploring the relationships between geomorphic processes and associated forms, and riparian vegetation in bedrock-controlled streams from the context of biogeomorphology.

1.2 Effects of Fluvial Process-Forms on Vegetation Pattern and Distribution

Fluvial corridors are typically characterized by intense reciprocal adjustments between hydrogeomorphic processes and landforms and vegetation communities (Tsujimoto 1999; Steiger *et al*. 2005; Tabacchi *et al*. 2005). Thus, fluvial processes and landforms influence vegetation establishment, pattern and distribution along the fluvial corridors. The distribution pattern of woody vegetation within the bottomland forest is a function of channel geometry, streamflow characteristics and sediment size characteristics (Hupp and Osterkamp 1985), and elevation above the stream channel (e.g. Sigafoos 1961; Hosner and Minckler 1963; Everitt 1968; Chambless and Nixon, 1975; Nixon et al. 1977; Hupp 1983). Independent hydrologic factors such as flood frequency, flow duration, and period of inundation exert influence on vegetation patterns (Hack and Goodlett 1960; Sigafoos 1961; Hupp 1983) by affecting most aspects of their life histories within the fluvial corridors (Hupp and Osterkamp 1996). Disturbance by floods can also affect the diversity of plant species (Decamps and Tabacchi 1994) while some studies emphasized on dispersal patterns and history than on disturbance (Nilsson et al. 1991; 1994). Many others summon the intermediate disturbance hypothesis introduced by Connell (1978), which suggests that diversity is higher when disturbances are intermediate on the scales of frequency and intensity. Connell (1978) also demonstrated that plants are also specialized according to differences in habitats (habitat diversity) caused by variations in the frequency and intensity of disturbances. Recognizing these aspects, several authors have suggested that riparian communities should be considered compositionally stable, maintained by periodic flooding, rather than successional, recovering from floods (Sigafoos 1961; Yanosky 1982; Hupp 1983; Bendix 1998). Further, the impact of fluvial geomorphic processes and forms on riparian vegetation also varies in differential environmental settings characterized by two vital, external, independent variables: climate (e,g. Hupp and Osterkamp 1996) and lithology (Bendix 1999).

1.3 Biogeomorphic Effects of Vegetation on Fluvial Process-Landforms

Both living and dead vegetation influence fluvial hydrodynamics (Green 2005), morphogenesis (Hupp and Osterkamp 1996) and landscape dynamics (Ward *et al*. 2002;

Pettit and Naiman 2005). Riparian vegetation influences fluvial processes in several ways. Living vegetation influences flow regime via (i) imposing roughness to hydraulic shear, (ii) increasing both flow and mechanical resistance of beds, banks, and floodplain surfaces (e.g. Thorne 1990; Hupp 1982), (iii) trapping sediment in channels and on floodplains (e.g. Gurnell *et al*. 2001; 2014) and (iv) initiating or stabilizing bars and islands (e.g. Page and Nanson, 1982). Some studies emphasized on the species-specific impacts of vegetation − from the context of ecosystem engineering (e.g. Gurnell and Petts 2006, Corenblit *et al*. 2009b), and on different fluvial environments (Gurnell et al. 2019).

In addition to riparian plants, woody debris intercepts water and sediment during floods, and thus can drive the physical creation, modification or maintenance of habitat (e.g. islands, bars etc.) mainly through biostabilization and bioconstruction (Gurnell *et al*. 2005). Reviews of wood-sediment dynamics along river corridors can be found in Gurnell *et al* (2001), Wohl (2013) and Wohl and Scott (2017). Gurnell *et al*. (2001) developed a conceptual model of island development recognizing the active role of dead wood on the evolution of fluvial features, for instance, the core of scroll bars (Nanson 1981), bar apex jams (Abbe and Montgomery 1996) and lateral jams (Fethetston *et al*. 1995) behind which sediment and organic matter accumulate where riparian trees can further establish.

1.4 Reciprocal Interactions between Vegetation and Geomorphic Processes

The effect of hydrogeomorphic processes and forms on vegetation, and vice versa function together in a feedback loop, which develop fluvial biogeomorphic systems. While riparian vegetation influences flow-sediment dynamics and the hydraulic and mechanical properties of the substrate, the distribution and vigor of many riparian species (and woody debris) are determined by flow dynamics and water availability (Gurnell 2014). Further, biogeomorphic feedbacks between vegetation growth and sedimentation promote island development and self-assembly (Francis *et al*. 2009). Thus, riparian ecology and fluvial geomorphology are causally connected via bidirectional linkages (Bendix and Cowell 2010). A number of biogeomorphic studies demonstrating the reciprocal linkages between fluvial landforms and riparian ecosystems from the context of intertwined biotic-abiotic interactions include e.g. Corenblit *et al*. (2007, 2009a, 2009b, 2015), Gurnell *et al*. (2001, 2005, 2012), Stoffel and Wilford (2012), Bertoldi *et al*. (2009), Jerin and Phillips (2020).

1.5 Importance of Scale in Fluvial Biogeomorphic Systems

Geomorphic patterns and processes are interlinked and typically scale dependent. Thus, selection of appropriate spatial scale has substantial impacts on result interpretation. If patterns vary in a discontinuous manner across scales, this usually indicates that different processes are acting to produce the pattern (Thorp et al. 2008). For example, the hydrogeomorphic process-form determinants influencing vegetation patterns vary at different (spatial) scales. Hughes et al. (2001) suggested that in riparian systems, site scale researches are concentrated on the influence of hydrology and sediments on vegetation regeneration. Tolerance to drought or flooding and to sedimentation are the key factors explaining vegetation regeneration patterns at the site scale. Moreover, at the drainage basin scale, drainage area and valley characteristics regulate vegetation functions (McKenney et al. 1995). Thus, fluvial biogeomorphic systems are characterized by complexity, caused by multi-causality and variable process-form linkages at different scales (e.g. Smiley and Dibble 2005; Parsons and Thoms 2006). This, as a result, limits the practicality of the reductionism approach in such systems (Thorp et al. 2008).

1.6 Bedrock Streams and Biogeomorphology

Bedrock rivers are more common that is generally supposed (Montgomery *et al*. 1996). Knowledge from alluvial and gravel-bed systems cannot be directly translated to bedrock rivers (Tinkler and Wohl, 1998); such attempts have already fallen into difficulties (e.g. Vaughn 1990; Tinkler and Parish 1998). While a comprehensive review of bedrock stream geomorphology is beyond the scope of this research, it will focus on recent reviews, summaries and syntheses that include the salient characteristic of bedrock streams and distinguish them from the alluvial ones. Important differences with respect to alluvial streams are often attributable to slower change (Schumm and Chorley 1983; Whipple 2004), unidirectional change (Tinkler and Wohl 1998), greater role of bed/bank resistance, more direct influence of lithology and structure (Miller 1991; Tinkler and Wohl 1998; Whipple 2004), and the role of processes such as dissolution, abrasion, cavitation and plucking (Miller 1991; Wohl *et al*. 1994; Wohl and Ikeda 1998; Tinkler and Wohl 1998; Whipple *et al*. 2000). Bedrock channels occur mainly, but not solely, in actively incising portions of landscapes where channels are cut into resistant rock units, most often in actively uplifting areas (Whipple 2004). This explains the greater influence of lithology and structure, greater role of bed/bank resistance and therefore, the dominant erosion processes, and slower change of bedrock channels than that of alluvial rivers (Jerin 2019). In contrast to alluvial streams, the morphological change of bedrock rivers is unidirectional — rock removed from the bed of channels lowers the local base level for all upstream points. Similarly, rock removed from the walls is irreplaceable (Tinkler and Wohl 1998). While some geomorphologists do not consider bedrock streams self-formed, Whipple (2004) argued that flow, sediment flux, substrate properties, and base level conditions dictate self-adjusted combinations of channel gradient, width, and bed morphology in bedrock channels (e.g. Wohl and Ikeda 1998; Wohl *et al*. 1999; Wohl and Merritt 2001).

The research presented here is conducted on a limestone bedrock-controlled stream, Shawnee Run, located in the Kentucky River gorge area of the Inner Bluegrass karst region in central Kentucky (Figure1). It is a tributary of the Kentucky River (note: on U.S. Geological Survey maps, Shawnee Run is incorrectly shown as Shaker Creek) draining about 43.5 km2 of surface drainage area with a total length of about 20 km. Shawnee Run is a bedrock-controlled stream dominated by limestone lithology with discontinuous coarse alluvial cover. The study area was selected because it is part of a nature preserve and has been minimally disturbed along the fluvial corridor.

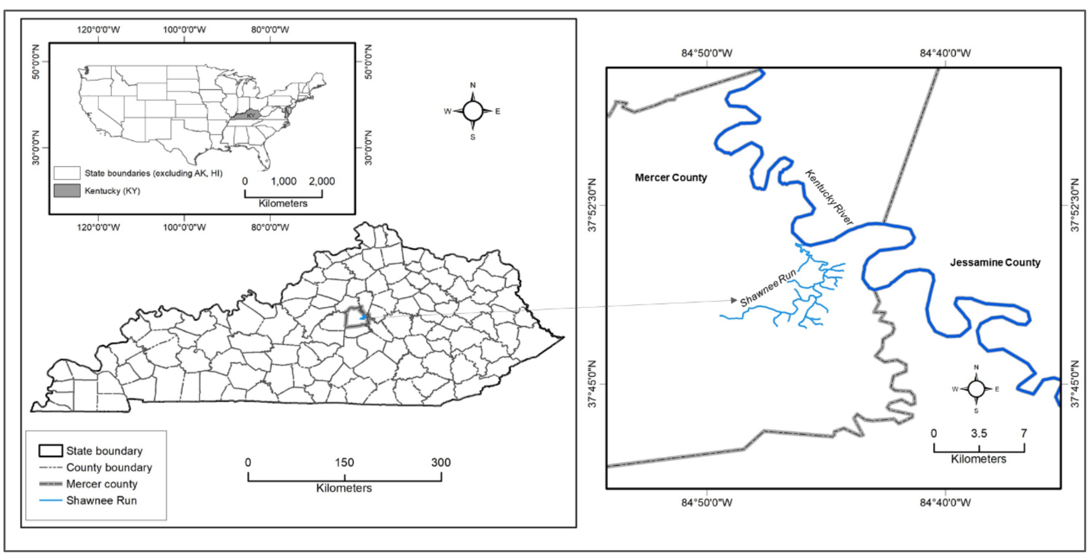

Figure 1.1: Location of the Study Area, Shawnee Run, in central Kentucky.

A number of studies have been conducted on the fluviokarst landscapes of central Kentucky dissected by bedrock streams. Several studies attempt to explain the evolution of fluviokarst landscapes driven by highly localized structural and topographic constraints related to slope changes (e.g. Phillips and Walls 2004; Phillips *et al*. 2004; Phillips 2015; Jerin and Phillips 2017). Further, Phillips and Lutz (2008) examined the longitudinal profiles of bedrock streams in this region, and related profile convexities to environmental controls structure, lithology, and recent geomorphic processes. Andrews (2004), who studied the Plio-Pleistocene history of the Kentucky River, provided a broader understanding of landscape evolution and controls on fluvial system associated with bedrock settings. Parola (2007) provided a quantitative description of the expected values and the variation of the parameters of hydraulic geometries as a function of upstream drainage area within the Bluegrass Region of Kentucky. Nevertheless, none of these studies integrated biotic influences on bedrock streams.

Biotic influences have rarely been integrated in studies dealing with landscape dynamics associated with the nature of bedrock rivers; only a few studies attempted to explore this phenomenon. Rittle (2015) focused on the relationships between flow regime and algae. Furthermore, Russo and Fox (2010) developed a model that examines the fate and transport of the surface fine-grained laminae; here they included biological influences, along with the geomorphic controls, as a model component to depict the processes. Ford and Fox (2017) also quantified carbon sequestration due to algal stabilization in bedrock-controlled stream ecosystems. Some other studies incorporated vegetation impacts on geomorphic processes, but dealt with hillslope hydrology rather than fluvial corridors (e.g. Martin 2006).

The bed and banks of bedrock rivers are not composed of transportable sediments, but are erodible (Whipple 2004). As bedrock streams often do transport appreciable sediment, some biogeomorphic impacts observed in alluvial ones are likely to be important in bedrock rivers too. While the role of vegetation in bed and bank resistance might be minimal, vegetation could still influence flow hydraulics, and work on tree-bedrock interactions in terrestrial settings. This suggests that biogeomorphic impacts on bedrock banks and channels could be significant (Pawlik *et al*. 2016), and needs to be taken into account.

1.7 Dissertation Objectives and Structure

The overarching goal of this research is to understand the biogeomorphic interactions between fluvial processes and forms, and riparian vegetation in a limestone bedrock controlled stream. To accomplish this goal three specific objectives have been developed:

Objective 1: Explore the biogeomorphic impacts of vegetation associated with bedrock streams and contrast these impacts with other geomorphic environments.

Objective 2: Investigate the species-specific vs. the general biogeomorphic impacts of vegetation on fluvial process-forms from the context of biogeomorphic keystone species.

Objective 3: Identify the most important spatial scale of variation of channel morphology and biogeomorphological phenomena.

This dissertation is comprised of three data chapters − Chapter 2 through Chapter 4 − addressing these objectives. Chapter 2 and 3 are published in *Progress in Physical Geography: Earth and Environment,* and *Earth Surface Processes and Landforms* respectively. Chapter 4 is currently under review in the journal *Geomorphology*. A conclusions section (Chapter 5) integrates the findings from earlier chapters, and points out the important aspects of biogeomorphology of bedrock fluvial systems.

CHAPTER 2. BIOGEOMORPHIC EFFECTS OF WOODY VEGETATION ON BEDROCK STREAMS

Abstract

The dynamic interactions between fluvial processes and vegetation vary in different environments and are uncertain in bedrock settings. Bedrock streams are much less studied than alluvial in all aspects, and in many respects act in qualitatively different ways. This research seeks to fill this lacuna by studying bedrock streams from a biogeomorphic perspective. It aims to identify the impacts of woody vegetation that may be common to fluvial systems and rocky hillslopes in general, or that may be unique to bedrock channels. A review of the existing literature on biogeomorphology — mostly fluvial and rocky hillslope environments — was carried out, and field examples of biogeomorphic impacts associated with fluvial systems of various bedrock environments were then examined to complement the review. Results indicate that bedrock streams exhibit both shared and highly concentrated biogeomorphic impacts in relation to alluvial streams, and rocky hillslopes. Bedrock streams display a *bioprotective* geomorphic form — root banks (when the root itself forms the stream bank) —which is distinctive, but not exclusive to this setting. On the other hand, shared biogeomorphic impacts with alluvial streams include sediment and wood trapping, and bar and island development and stabilization (i.e. *bioconstruction/modification and protection*). Shared impacts with rocky hillslopes also include bioprotection, as well as displacement of bedrock due to root and trunk growth, and bedrock mining caused by tree uprooting (i.e. *bioweathering and erosion*). Two biogeomorphic impact (BGI) triangles were developed to graphically display these relationships. Finally, this paper concludes that bedrock streams exhibit some biogeomorphic impacts that also occur either in alluvial channels or on rocky hillslopes. Therefore, no biogeomorphic impacts were identified that are absolutely unique to bedrock fluvial environments.

Keywords: Biogeomorphology, bedrock streams, alluvial streams, biogeomorphic impacts, rocky hillslopes.

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2.1 Introduction

Very little research has been done on biogeomorphic effects of woody vegetation in bedrock-controlled streams. The likely reasons for this neglect are threefold. First, influence of plants on bedrock streams may be assumed to be minimal because bioprotection effects are less important in bedrock owing to greater bed/bank resistance (Miller 1991; Tinkler and Wohl 1998; Whipple 2004). Second, effects of sediment trapping are less significant because of bed load or dissolved load domination, and bed and banks composed of material that is not readily transportable (Whipple 2004). Third, some researchers may have assumed insignificant biogeomorphic impacts owing to a lack of vegetation in-channel and less dense vegetation cover on exposed rocks. However, as biogeomorphic impacts are significant in alluvial streams and on exposed bedrock of hillslopes, the possibility of these impacts in bedrock streams is worth investigating. The purpose of this paper is to identify the impacts of woody vegetation that may be common to fluvial systems and rocky hillslopes in general, or that may be unique to bedrock streams (Figure 2.1).

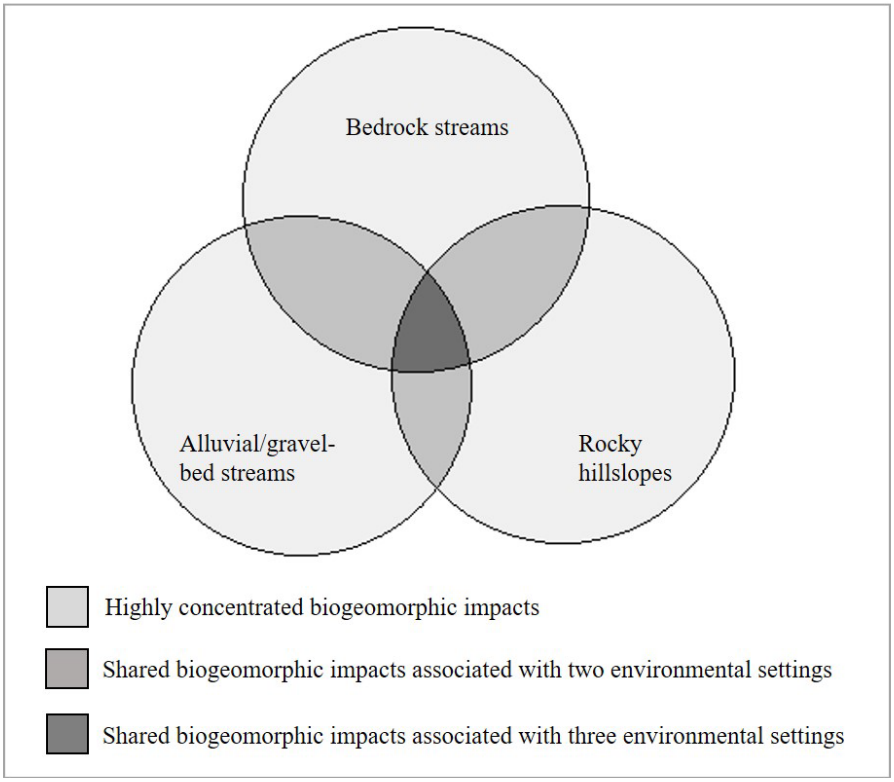

Figure 2.1: Potential overlap of biogeomorphic impacts (BGIs) on alluvial streams, bedrock streams and rocky hillslopes.

Fluvial corridors are comprised of river channels, their margins, and the zone of expansion of frequent floods occupied by riparian vegetation (Corenblit *et al*. 2010; Gurnell *et al*. 2016). They are characterized by intense reciprocal adjustments between hydrogeomorphic processes, landforms, and vegetation (Tsujimoto 1999; Tockner and Stanford 2002; Steiger *et al*. 2005; Tabacchi *et al*. 2005; Gurnell *et al.* 2005; 2012; 2016; Gurnell and Petts 2006). Hydrogeomorphic processes greatly affect habitat diversity, vegetation regeneration and thus, biodiversity (Hughes *et al*. 2001). Furthermore, independent hydrologic factors (e.g. flood frequency, flow duration and period of inundation) exert influence on vegetation patterns (Hack and Goodlett 1960; Sigafoos 1961; Hupp 1983) by affecting most aspects of the life histories of plant species within the fluvial corridors (Hupp and Osterkamp 1996). Conversely, vegetation – both living and dead – influences fluvial hydrodynamics (Green 2005), morphogenesis (Hupp and Osterkamp 1996) and landscape dynamics (Ward *et al*. 2002; Pettit and Naiman 2005). Riparian species also play vital roles in ecosystem engineering, i.e. modifying the physical characteristics of riparian zones (Gurnell and Petts 2006). Absence of these species referred to as biogeomorphic ecosystem engineers may limit the diversity of riparian corridors (e.g. Francis *et al*. 2009). However, while hydrogeomorphic processes and fluvial landforms are important for vegetation establishment, pattern and diversity, this paper primarily concentrates on the biogeomorphic impacts of vegetation on bedrock streams and how such impacts can initiate and grow into reciprocal effects.

The interactions between fluvial landforms and riparian vegetation respond differently in distinct environmental settings (Gurnell *et al*. 2001; Gurnell 2014), and the relationships are uncertain in bedrock settings. Polvi *et al*. (2014) show that significant differences exist between woody and non-woody vegetation with respect to reinforcing root-associated cohesion and stream bank stability, and indicate a need for future investigation considering different streambank types at the reach and watershed scales. Furthermore, a recent study by Gurnell *et al*. (2018) on the differences in root strength between and within species associated with different European river environments indicates that biogeomorphic impacts associated with specific species are variable within and between rivers of different geographical regions, and suggests a need for future research on species in different fluvial environments. By identifying distinctive and shared biogeomorphic impacts associated with bedrock and alluvial fluvial settings this research contributes to these future research concerns.

Bedrock streams are much less studied than alluvial in all aspects and in many respects act in qualitatively different ways. This research aims to identify how bedrock river systems are different or similar to alluvial ones and rocky hillslopes from a biogeomorphic perspective. To fulfill the goal of this research, a review of the existing literature on biogeomorphology — mostly fluvial and rocky hillslope environments — was carried out. Field examples of biogeomorphic impacts associated with fluvial systems of six various bedrock environments were then examined to complement the review. Thus, this research identifies influences of woody vegetation that may be common to fluvial systems in general, or that may be distinctive to bedrock streams.

2.2 Fluvial biogeomorphology and biogeomorphic impacts

Fluvial biogeomorphology studies the bi-directional linkage between hydrogeomorphic and ecological structures and processes. This includes multiple causalities and scale dependencies of the complex emergent patterns along the fluvial corridor linked to active or passive bio-processes (e.g., bioerosion, bioprotection, bioconstruction and bioturbation) (for example, Butler 1995; Naylor *et al*. 2002;Corenblit *et al*. 2007; Viles *et al*. 2008; Wilkinson *et al*. 2009). The vital components of fluvial biogeomorphology are interactions between the flow regime (flow intensity, duration and frequency), sediment and vegetation, particularly those within the riparian zone that can greatly influence the form and dynamics of the river margin. In this context, riparian zones are part of the valley floor that are often inundated by the river whereas the term valley bottomland has been used to refer to a larger area enclosing all fluvially generated landforms and vegetation, potentially extending from terraces to the channel bed (Hupp and Osterkamp, 1996). Thus, valley bottomlands encompass an enormous diversity of physical configurations and species life-forms and assemblages reflecting the regional and local geological, geomorphic and bioclimatic settings (Corenblit *et al*. 2015). Riparian and in-channel vegetation responds to and influences fluvial processes. The outcomes of these plant-physical process interactions vary widely across different bioclimatic, biogeographical and hydrogeomorphological settings. These interactions drive shifting mosaics of landforms and their associated aquatic and terrestrial ecological communities along longitudinal and transverse gradients within fluvial corridors (Poff *et al*. 1997; Thorp *et al*. 2010; Gurnell *et al*. 2016). The interactions between vegetation (both in-stream and riparian) and fluvial geomorphic processes and forms can be expressed with three types of biogeomorphic functions/roles summarized in Table 2.1.

Table 2.1: Biogeomorphic functions/roles terms and definitions

Biogeomorphic function/role	**Definition**	**Examples of Biogeomorphic impact**
Bioconstruction/modification	Construction of landforms, or net accretion or accumulation associated with direct or indirect biotic effects	Sediment trapping by wood accumulations or plants; dam formation by wood accumulations
Bioprotection	Biotic effects that increase resistance to erosion (and weathering or mass movement)	Vegetation anchoring of bars and islands; root buttressing of banks
Bioweathering & erosion	Biotic effects that result in or facilitate entrainment and removal of rock, soil, and sediment. Biotic effects on weathering and mass wasting are typically included in this category.	Soil displacement by tree uprooting; scour induced by wood accumulation; bedrock weathering effects of tree roots

2.2.1 Biogeomorphic impacts of vegetation on alluvial rivers

Vegetation influences fluvial processes in several ways. These include increasing roughness, flow and mechanical resistance of beds, banks and floodplain surfaces (e.g. Thorne 1990; Hupp 1992), trapping sediment in channels and on floodplains (e.g. Gurnell *et al*. 2001; 2014), and initiating or stabilizing bars and islands (e.g. Page and Nanson, 1982). In addition to riparian plants, large wood that has been retained in the river channel also intercepts water and sediment, and thus can influence fluvial landforms (e.g. islands, bars etc.) mainly through the process of biostabilization and bioconstruction (Gurnell *et al*. 2005).

Living vegetation provides resistance to the forces of fluvial processes, and this role of vegetation as a vital mediating agent of hydrogeomorphic processes within the fluvial corridor has been acknowledged in several studies (Gurnell and Petts 2006, 2014; Gurnell *et al*. 2001, 2012) (Table 2.2). Furthermore, living vegetation increases cohesion via root mass, and therefore increases resistance of vegetated landforms (Gran *et al*. 2015). McKenney *et al.* (1995) quantified the Manning's roughness coefficient incorporating vegetation, and showed how vegetation roughness and resistance affect fluvial hydrodynamics and morphogenesis in gravel-bed streams. Vegetation also has substantial influence in trapping and stabilizing fluvially transported sediment. These impacts can foster construction of distinct landforms and accelerate the development of larger landforms such as river banks, vegetated islands and floodplains (e.g. Gurnell *et al*. 2016).

Many studies have focused on deposited wood and its influence on process-form dynamics along the fluvial corridor (Table 2.2). Gurnell *et al*. (2005) discussed the role of wood, particularly when the deposited trees are able to sprout and anchor themselves to bar surfaces, in relation to the formation and dynamics of island-braided rivers. Reviews of wood-sediment dynamics along river corridors include Gurnell *et al* (2001), Wohl (2013) and Wohl and Scott (2017). Gurnell *et al*. (2001) incorporated both the impact of wood and living vegetation in their conceptual model of island development within fluvial systems. Studies have also identified the association of dead wood with the initiation of specific types of fluvial landform such as reinforcing the core of scroll bars (Nanson 1981), or building bar apex jams (Abbe and Montgomery 1996) and lateral jams (Fetherston *et al*. 1995) behind which sediment and organic matter accumulate to provide a substrate on which riparian trees may establish. Kramer and Wohl (2015) describe an extreme example of this phenomenon, driftcretion, where large concentrations of driftwood contribute to sedimentation influencing shoreline morphology and evolution by interacting with vegetation. Furthermore, Fetherston *et al*. (1995) suggested that dead wood plays a vital role in reducing mean boundary shear stress, and thus protects the surfaces and margins of islands and bars. However, while large wood plays a key role in promoting landform protection and stability, they can also destabilize fluvial landforms by promoting erosion. For example, a study of forested and grassed stream banks by Trimble (1997) suggested that forested stream banks, relative to grassed ones, can destabilize stream channels by promoting erosion. Mature forests produce large wood, which may destabilize streams locally by affecting the distribution of stream power via diverting flow against banks (Gregory and Davis, 1992; Gurnell and Gregory 1995).

Table 2.2: Example studies demonstrating biogeomorphic feedbacks associated with alluvial streams.

Type of study or evidence	**Example References**
Bar and island formation and evolution	Nanson 1981; Page and Nanson 1982; Fetheston *et al*. 1995; Hardwood and brown 1993; Abbe and Montgomery 1996; Gurnell *et al*. 2001; Gurnell *et al*. 2005; Gurnell and Petts 2006; Francis *et al*. 2006; Francis *et al*. 2008; Francis *et al*. 2009; Corenblit *et al*. 2011; Gurnell *et al*. 2012; Gurnell 2014.
Floodplain-wood dynamics	Gurnell *et al.* 2001; Gurnell *et al.* 2002; Collins *et al.* 2012; Wohl 2013; Wohl and Scott 2017.
Hotspot zones of species modifying landforms — ecosystem engineering	Collins *et al.* 2012; Gurnell 2014.
Fluvial biogeomorphic succession	Corenblit *et al*. 2007; Corenblit *et al*. 2009a; Corenblit *et al*. 2010.

Finally, there are studies on the effects of fluvial hydrodynamics and forms on vegetation germination and their successful establishment, growth, survival and distribution. These are based on the details of how boundary conditions for vegetation – including flow regime, substrate and channel geometry – are likely to govern vegetation distribution and their influences within fluvial corridors (e.g., Hupp and Osterkamp 1985, 1996; McBride and Strahan 1984; Shafroth *et al.* 1998; Bendix 1998,1999; Corenblit *et al.* 2007; 2009b; Hupp and Rinaldi 2007). However, no comparable studies of these dynamics have been conducted on fluvial systems that are characterized by bedrock controlled channels.

2.2.2 Biogeomorphic impacts of vegetation on hillslopes

Biogeomorphic impacts of vegetation on hillslopes are similar to those of fluvial corridors in a number of cases. Many biogeomorphic and pedologic studies have emphasized the importance of tree root systems in which roots play a primary role in soil development, regolith disturbance, bedrock mining by tree uprooting, and soil displacement by growing roots (Pawlik *et al.* 2016). Pawlik (2013) specified three biogeomorphic impacts of trees on bedrock hillslopes that can be potentially important for bedrock streams as well— (i) *growing root systems:* these disintegrate rock fragments and widen fissures in bedrock; (ii) *growing trunks:* physical displacement of bedrock and (iii) *tree uprooting:* direct bedrock disruption via mining (see Table 2.3 for example studies). Growing root systems can have immense impact on physical and chemical weathering. The radial pressure exerted by tree root systems can reach 0.91 MPa and axial pressures as high as 1.45 MPa (Bennie 1991) which is sufficient to break up bedrock. The roots inevitably increase in length and girth and split the rocks apart slowly (Matthes-Sears and Larson 1995). Phillips (2015) showed that about 90% of the examined trees of his study conducted on limestone bedrock hillslopes exhibited evidence of : i) joint widening both horizontally and vertically by root penetration, ii) mechanical displacement of bedrock along bedding planes and iii) root exposure indicating removal of material at the tree base (Table 2.3). Phillips (2016) further explained how the widening of joints can promote chemical weathering in such karst associated bedrock environments. A combination of root growth in joints, trunk expansion and development of basal flares near the tree-ground interface can displace rock fragments both vertically and horizontally (Phillips 2015). Thus, trees can promote weathering of bedrock and displace mass via root and trunk growth (Lutz and Griswold 1939; Gabet and Mudd 2010) (Table 2.3).

Uprooting of trees usually occurs during storms with strong winds, ice storms or excessive rainfall. Uprooted trees can break down bedrock, transport soil downslope and hinder soil horizonation (Gabet *et al*. 2003). In bedrock settings, uprooting results in bedrock mining as opposed to thicker soils where bioturbation is the key consequence. Uprooting has been characterized as one of the primary mechanisms of downslope mass movement process (Schaetzl *et al.* 1989; Small *et al*. 1990) (Table 2.3), which in turn promotes weathering and erosion of exposed bare soil/rock and slope destabilization(e.g., Phillips *et al*. 2017).

Table 2.3: Example studies demonstrating biogeomorphic impacts associated with rocky or thin-soil hillslopes.

Type of study or evidence	**References**
Displacement and movement of soil and rock fragments by tree uprooting	Lutz 1960; Schaetzl *et al.* 1989; Small *et al*. 1990; Phillips and Marion 2006; Martin 2006; Phillips *et al*. 2008; Pawlik 2013.
Bedrock mining associated with tree uprooting	Pawlik 2013; Phillips 2015; Phillips *et al.* 2016.
Displacement of bedrock by root and trunk growth	Lutz and Griswold 1939; Jackson and Sheldon 1949; Matthes-Sears and Larson 1995; Roering *et al*. 2003; Gabet *et al*. 2003; Birot 1966; Gabet and Mudd 2010; Phillips 2015.
Accelerated weathering along joints and bedding planes	Gabet *et al*. 2003; Bormann *et al*. 1998; Yatsu 1988; Phillips and Marion 2005, 2006; Phillips 2015.

Finally, infilling of stump holes and trapping of sediments from upslope are distinctive biogeomorphic impacts within rocky hillslopes (Pawlik 2013; Phillips 2015; Shouse and Phillips 2016) as bedrock stream environments have limited potential to display such impacts. Additionally, within hillslope environments, tree growth may enclose (or partly enclose) rock fragments and prevent downslope movement of sediments until the death of the tree and wood decomposition (Phillips 2015). However, this may also occur along fluvial environments.

2.2.3 Reciprocal interactions between vegetation and geomorphic processes

Vegetation within fluvial corridors influences the flow hydraulics and landforms by increasing shear strength, retaining sediment and affecting the hydraulic and mechanical properties of the substrate. Similarly, fluvial dynamics, water availability and sediment erosion, transportation and deposition determine the distribution and vigor of many species (Gurnell 2014). Thus, vegetation, and fluvial processes and forms are connected with each other via reciprocal effects that grow or diminish by biogeomorphic feedbacks. For example, Francis *et al*. (2009) explained how biogeomorphic feedbacks between vegetation growth and sedimentation influence island formation and self-assembly. Another example illustrated how feedback relationships between pioneer species and a high magnitude disturbance (i.e. flood) lead to the development of a highly resilient fluvial landscape. Landform accretion, vegetation succession and increasing geomorphic stability governed the development of such resilient landforms (Corenblit *et al*. 2010). In a related context, Gurnell (2014) introduced the idea of hotspots (Table 2.2). Hotspots are environmental envelopes within which 'engineer' plant species interact strongly with fluvial processes. They are enclosed within areas where fluvial processes or interspecies competition dominate. The location of hotspots shifts through time, corresponding to periods of relatively higher or lower fluvial disturbance. Within the hotspots certain 'engineer' species are able to interact with fluvial processes by retaining and reinforcing sediments to build landforms (riverbanks, islands, floodplains) and habitat that are then colonized by other plant species. All these examples indicate that the relationships between riparian vegetation and hydrogeomorphic processes are driven by complex feedback mechanisms, which determine the spatial structure and dynamics of riparian ecosystems

(Hastings *et al*. 1993; Phillips 1999). Moreover, Bendix and Cowell (2010) discussed the effects of wood accumulation on channel hydraulics and morphogenesis where wood accumulation was triggered by post wildfire flooding events. Thus, they showed how riparian ecology and fluvial geomorphology are causally connected with bidirectional influences.

Hillslope environments also exhibit biogeomorphic feedback associated interactions. One example of positive biogeomorphic feedbacks includes development of dissolutional grooves at the root-limestone bedrock interface. Dissolutional activity is enhanced along the roots that penetrate joints and extend across boulder and exposed bedrock surfaces. Thus, root growth promotes further development of solutional grooves in many karst environments (Phillips 2015). Phillips (2015) also showed how root penetration along vertical and horizontal joints can enhance weathering and moisture flux, and increase the susceptibility to bedrock mining. This leads to locally thicker regolith. Literature on root-rock interactions suggests that locally deepened regolith provides favorable sites for future tree establishment, and root-channels and root widened fissures are favored sites for future root penetration (Stone and Kalisz 1991; Martin 2006; Phillips 2008; Estrada-Medina *et al*. 2013; Shouse 2014). Thus, biogeomorphic effects can extend beyond the lifetime of a single tree, and repeated reoccupation can lead to continued localized modification. Crowther (1987), in karst systems in peninsular Malaysia, also found that most chemical activity is associated with bedrock in contact with roots, which indicates the presence of the positive feedback relationships discussed above. Further, in a similar bedrock environment, Phillips (2016) showed how Chinquapin oak roots exert direct impacts on the surrounding trees by creating dissolutional grooves and channels, and lifting and displacing rock plates. Thus he illustrated the reciprocal interactions between vegetation and hillslope processes from an ecosystem engineering perspective.

Biogeomorphic feedbacks influence two aspects of fluvial and hillslope ecosystems: i) state transitions and ii) diversity of landforms and plant species.

2.2.3.1 Ecosystem state transitions

Biogeomorphic interactions may result in ecosystem state transitions (Dent *et al*. 2002 and Francis 2009). In the case of natural fluvial ecosystems state transitions are influenced not only by the disruption of key hydrogeomorphological drivers, but also feedbacks between flow regimes and sediments, and vegetation dynamics (Francis 2009). These feedbacks result in characteristic biogeomorphic patterns and strongly affect ecosystem functioning and biodiversity. The fluvial biogeomorphic succession model suggested by Corenblit *et al*. (2007) is one example. This model illustrates how riparian plant communities and landforms co-evolve via bi-directional linkages associated with feedback mechanisms. It is comprised of four phases: geomorphic, pioneer, biogeomorphic, and ecologic phase, characterized by progressive changes in the relative dominance of hydrogeomorphic and ecological processes. The first stage is characterized by geomorphic systems that are exclusively driven by interactions between flow and sediment or substrate, with a successive amplification of vegetation influence in the next three phases. Gurnell *et al.* (2016)'s model is another example in this context, which conceptualized the nature of vegetation-hydrogeomorphology interactions in the absence of human influences for different European biogeographical settings. This model is founded upon some hydrogeomorphologically centered prior models, most importantly the island development model (Gurnell *et al.* 2001), the large-wood cycle concept (Collins *et* *al.* 2012) and the fluvial biogeomorphic succession model (Corenblit *et al.* 2007). Gurnell *et al.* (2016)'s model explains how hydrogeomorphological constraints vary spatially and temporally within fluvial corridors giving rise to five distinct lateral zones where particular subsets of plant-physical processes prevail. However, because this model considers the distribution of these zones according to valley confinement (i.e. longitudinal variability from confined headwaters to unconfined floodplain reaches) and river types therefore, it is potentially relevant to bedrock streams. In addition to these models, Van Dyke (2016) explicitly discussed biogeomorphic feedback associated channel adjustment and consequent evolution under the framework of a state-and-transition model. His study established that the complex evolutionary pattern of a fluvial corridor is a function of the interactions between bio-hydro-geomorphic fluxes and landscape that vary across space and time. Other biogeomorphic studies demonstrating reciprocal linkages include Bertoldi *et al*. (2009), Corenblit *et al*. (2009a, 2009b, 2015), Gurnell *et al*. (2001, 2005, 2012), and Stoffel and Wilford (2012). In the context of forested hillslopes, Phillips *et al*. (2017) suggested that biogeomorphic succession may be more varied than the linear sequential fluvial biogeomorphic succession model, and may include pathways where biogeomorphic feedbacks are more persistent.

2.2.3.2 Diversity of landforms and species

Biogeomorphic feedbacks may also influence ecosystem diversity within fluvial and hillslope environments. For example, in case of fluvial systems, the engineering activity of some riparian species rooted into the bank toe can develop 'hotspot' zones (see above), which may promote the future colonization of other plant species (Gurnell 2014). Gurnell *et al.* (2005) discussed how water and sediment interception by wood during floods can foster landform diversity by initiating the physical creation, modification or maintenance of habitats (e.g. islands, bars etc.), which in turn can increase biodiversity. Hupp and Rinaldi (2007) denoted riparian zones as the potentially most diverse ecosystems worldwide where species richness substantially increases along the transverse gradient from channel bed to terraces. Other studies relating the idea of biogeomorphic feedbacks and biodiversity includes Gurnell and Petts (2006), Gurnell *et al*. (2007), Bertoldi *et al.* (2009), Francis *et al.* (2009) etc. Moreover, Shouse and Phillips (2016) showed an instance of increasing diversity of geomorphic forms for a non-fluvial hillslope environment. Here, they discussed how vegetation induced regolith thickening driven by mechanisms associated with root penetration in bedrock can promote landform diversity.

Biogeomorphic feedbacks and associated ecosystem engineering by plants do not always increase diversity in geomorphic forms or in the plant species that are present (e.g. Tickner *et al*. 2001; An *et al*. 2007; Fei *et al*. 2014). For example, *Tamarix* – a riparian invasive species, can negatively affect two aspects of fluvial systems – i) channel geometry (e.g. Graf 1978) and ii) diversity of in-stream landforms (e.g. Busby and Schuster 1973). First, Tamarix species foster aggradation and build stable floodplains and riverbanks by increasing roughness to hydraulic shear, trapping and stabilizing transported sediment and debris (Birkeland 1996). Aggradation in turn leads to a narrowing of the river channel (Tickner *et al.* 2001). A similar study on the Green River, Utah, showed that invasion of the same species promoted an average reduction in channel width of 27% (Graf 1978). Second, Busby and Schuster (1973) identified a negative relationship between Tamarix invasion and the extent of sandbar and gravel cover within streams in Texas. Thus, in addition to channel geometry, Tamarix can adversely influence the diversity of landforms within channel. Moreover, Tamarix can also affect species diversity by deteriorating the habitat characteristics for other species. The phreatophytic nature of Tamarix species and their rapid establishment along river margins can significantly depress riparian water-table levels in arid regions. Depletion of watertables is caused by the ability of Tamarix to root directly into the groundwater (Loope *et al.* 1988; Vitousek 1990). Thus, Tamarix can decrease species diversity by reducing the available water for other species.

2.3. Biogeomorphology of bedrock streams

2.3.1 Bedrock vs. alluvial streams

Whipple (2004) defined bedrock streams as channels that lack continuous cover of alluvial sediments, even at low flow, and exist only where transport capacity exceeds bedload sediment flux over a long period of time. Tinkler and Wohl (1998) characterized a bedrock channel as one with 50% bedrock exposed in the bed and banks, or covered by an alluvial veneer which is largely mobilized during high flow events such that the underlying bedrock geometry strongly influences patterns of flow hydraulics and sediment movement. Channels that are not confined by bedrock or terraces, but are flanked by floodplains are called alluvial channels (Schumm 2005). Alluvial channels are those that have formed their channel in bed and bank sediment that the stream can readily entrain and transport for a wide range of flows (Leopold and Maddock 1953; Schumm 1977; Schumm and Winkley 1994).

Knowledge from alluvial and gravel-bed systems cannot be directly transferred to bedrock rivers (Tinkler and Wohl, 1998) as such attempts have already fallen into difficulties (e.g. Vaughn 1990; Tinkler and Parish 1998). Key differences with respect to alluvial streams are often attributable to slower change (Schumm and Chorley 1983; Whipple 2004), unidirectional change (Tinkler and Wohl 1998), greater role of bed/bank resistance, more direct influence of lithology and structure (Miller 1991; Tinkler and Wohl 1998; Whipple 2004), and an enhanced role of processes such as dissolution, abrasion and plucking (Wohl and Ikeda 1998; Tinkler and Wohl 1998; Whipple *et al*. 2000). Bedrock channels occur mainly, but not exclusively, in actively incising portions of landscapes where channels are cut into resistant rock units (Whipple 2004). This explains greater influence of lithology and structure, greater role of bed/bank resistance and therefore, the dominant erosion processes and slower change of bedrock channels than that of alluvial rivers. The bed and banks of bedrock rivers are not composed of transportable sediments, but are erodible (Whipple 2004). As bedrock streams often do transport appreciable sediment, some biogeomorphic impacts observed in alluvial streams are likely important in bedrock systems too, such as sediment trapping and initiating or anchoring bars and islands. While the role of vegetation in enhancing bed and bank resistance might be minimal, vegetation could still influence flow hydraulics and work on tree-bedrock interactions in terrestrial settings indicates vegetation could be important in weathering and the reduction of resistance of bedrock (Pawlik *et al*. 2016). This suggests that biogeomorphic impacts on bedrock banks and channels could be significant and need to be recognized.

In this section, I will discuss the biogeomorphic impacts of woody vegetation on bedrock streams from the context of different biogeomorphic roles (i.e. bioconstruction & modification, bioprotection, and bioweathering & erosion) (see Table 2.1) played by vegetation. In addition, I will address which impacts are common to fluvial systems and rocky hillslopes in general, and which are unique to bedrock channels.

2.3.1.1. Bioconstruction/modification

Effects of vegetation related to the role of bioconstruction and habitat modification are widely documented in the fluvial biogeomorphic literature, but from the alluvial stream perspective (see Table 2.2). However, examples of these biogeomorphic impacts can also be found in bedrock streams (Figure 2.2 & 2.3).

Figure 2.2: Tree growing in limestone bedrock channel, trapping sediment and wood , Shawnee Run, KY (Left); Tree growing in sandstone bedrock stream, trapping sediment and wood, Ouachita Mountains, AR (Right).

Figure 2.3: Island formation, anchoring and modification in Shawnee Run, KY

Sediment can be transported in bedrock channels and subsequently trapped by vegetation. Again, an alteration of flow hydraulics can facilitate riparian vegetation establishment and survival, which in turn can reinforce sediment trapping in bedrock streams (for example Auble *et al.* 1994). Many bedrock streams, such as Shawnee Run (Figure 2.2 left, Figure 2.3 and Figure 2.4), are mixed bedrock and alluvial (cobble, gravel, boulders). Riparian and in-channel plants and large wood associated with bedrock streams have the potential to trap these sediments and thus can create local alluvial reaches. However, these bioconstructive roles played by vegetation and wood are also common in alluvial reaches exemplified in several studies referred in Table 2.2 (floodplain-wood dynamics, hotspot zone studies etc.) Furthermore, in-channel sediment trapping can lead to the development of bars and islands (Figure 2.2 and 2.3) both in bedrock and alluvial streams. The process of bar and island formation, stabilization and modification in bedrock streams can be hypothesized in two ways:

- Initiation, stabilization and development of bars (Figure 2.2) and islands via deposition caused by in-channel live vegetation or log jams (Page and Nanson 1982; Fetherston *et al*. 1995, Gurnell and Petts 2006).
- High flow or secondary channels parallel to the main channel can develop during floods and sometimes expand. More resistant patches with larger trees between the secondary and main channel are not eroded and may remain as islands if the secondary channel persists and grows.

In addition to landform construction, sediment and wood trapping by riparian vegetation has the potential to modify the characteristics of the stream bed, riparian zones and floodplains. Examples of vegetation induced landform modification in alluvial streams can be found in many biogeomorphic literature including Gurnell *et al.* (2002, 2005), Wohl and Scott (2013), and Gurnell (2014). However, sediment and wood trapping by vegetation in bedrock streams also exhibits comparable biogeomorphic outcomes, for example, substrate modification by vegetation induced sediment trapping and subsequent deposition (Figure 2.4, right).

Figure 2.4: Tree growing in-channel (right) and at bank edge (left) in a limestone bedrock channel, trapping sediment and wood, Shawnee Run, KY.

Large wood (LW) in the channel and on the floodplain also contributes to bioconstruction and modification (Table 2.4). Evidence of these biogeomorphic impacts is also found in bedrock rivers (Figure 2.5 & 2.6) – many of which have reaches with small floodplains. LW contributes to flow dynamics via flow diversion, backwater effects, and substrate modification and construction via sediment and wood trapping. For example, large wood pieces or log jams have the potential to alter bedrock reaches into alluvial ones. They can reduce the differences in elevation (thus decreasing slope), which as a result can reinforce deposition and modify substrate characteristics (Massong and Montgomery 2000). Thus, bedrock reaches can be forced into alluvial ones by large wood (Figure 2.5, left).

Figure 2.5: LW in-channel (left) associated with an alluvial reach; LW on floodplain (middle); LW at bank edge (right) in a limestone bedrock channel, Shawnee Run, KY.

2.3.1.2. Bioprotection

The bioprotective role of vegetation is well documented in the biogeomorphic literature. However, bedrock streams intrinsically have greater bed/bank resistance than alluvial channels (Miller 1991; Tinkler and Wohl 1998; Whipple 2004). Therefore, the role of bioprotection is ambiguous for bedrock streams to some extent as they are inherently resistant.

Bioprotective functions in bedrock streams were detected in the form of root banks – when the root itself creates the stream bank (Figure 2.6 and Table 2.4). Hydraulic shear seems to be not capable of eroding root banks just as it cannot erode intact bedrock. Thus, where root banks occur directly overlying bedrock, as has been observed in the field, there may be little or no increase in resistance. Nevertheless, root banks can entrap fine sediment and lead to the formation of extensive fine sediment benches. In such cases, root banks will protect an extended area surrounding them from fluvial erosion, and thus can considerably contribute to bioprotection. On the other hand, root banks along alluvial banks in a bedrock-controlled or alluvial stream considerably increase bank resistance.

While the root bank may be physically bioprotective, in bedrock controlled streams they may enhance chemical and biomechanical weathering of the underlying rock. Therefore, the roots undoubtedly affect the resistance of the banks in the form of protection while the tree is alive, but exposing more weathered and less resistant rock when the root bank is gone. This suggests that the relative importance of bioprotection along bedrock vs. alluvial streams and the protective vs. erosive effects of root banks needs further investigation.

Figure 2.6: Root bank in limestone bedrock channels: Left-Raven Run, KY; Right-San Marcos River, TX.

2.3.1.3 Bioweathering and erosion

Bioweathering and erosion, to some extent, have received less attention in the fluvial biogeomorphic literature. However, widespread evidence of this biogeomorphic role can be seen in bedrock streams (Figure 2.7, 2.8 & 2.9). Even though effects of bioweathering and erosion are widely overlooked in fluvial (more specifically alluvial) biogeomorphic studies, they are frequently addressed in studies associated with hillslopes of rocky environments (see section 2.2.2). Examples of bioweathering and erosion associated with bedrock streams are discussed in section 2.3.2.

Table 2.4: Evidence of biogeomorphic impacts and roles of vegetation on fluvial geomorphic processes and forms in bedrock environments.

Forms of biogeomorphic impacts	**Processes**	**Biogeomorphic roles**
Wood accumulation in channel	Flow diversion, backwater effects, sediment and wood trapping, potential for channel narrowing, habitat creation, island and bar formation	Bioconstruction Bioerosion
Wood accumulation - sediment trapping- on floodplain	Habitat creation and modification, and potential for channel narrowing	Bioconstruction
Live vegetation - wood and sediment trapping – on floodplain	Habitat creation and modification, and potential for channel narrowing	Bioconstruction
Live vegetation - wood and sediment trapping—at bank edge	Development of bars, potential for channel narrowing	Bioconstruction
Live vegetation in-channel	Flow diversion, backwater effects, sediment and wood trapping, potential for habitat creation in the form of bars or islands	Bioconstruction Bioprotection Bioerosion
Live vegetation - bar/island anchoring	Reinforced deposition, habitat creation and modification, and increasing resistance to erosion	Bioprotection Bioconstruction
Root banks/buttresses	Increasing roughness to hydraulic shear and mechanical resistance, wood and sediment trapping, and potential for accelerated biochemical weathering	Bioprotection Bioprotection Bioweathering
Live vegetation–in channel and on floodplain	Displacement of bedrock by root and trunk growth Accelerated weathering along joints and bedding planes	Bioweathering and erosion
Uprooting of vegetation – bank edge, in-channel, and on floodplain	Bedrock mining	Bioweathering

2.3.2 Bedrock streams vs. rocky hillslopes

Biogeomorphic impacts of vegetation on rocky hillslope are similar to those of bedrock dominated fluvial corridors in a number of cases (section 2.2.2. and Table 2.3). All these impacts eventually contribute to the role of bioweathering and erosion.

Root and trunk growth causes weathering and subsequent erosion in bedrock river systems, and the identified examples are analogous to those of rocky hillslopes. Displacement and disintegration of bedrock via root and trunk growth, accelerated weathering along joints and bedding plains are common biogeomorphic impacts of vegetation on bedrock streams (Figure 2.7 and 2.8). These processes can promote supply of sediment in bedrock streams, which in turn can affect channel morphogenesis.

Figure 2.7: Bedrock weathering due to trunk growth along the bank of limestone bedrock rivers: Left- Raven Run, KY; Right- Dix River, KY.

Figure 2.8: Bedrock weathering due to root growth along the bank of bedrock rivers: Left-Granite bedrock, Union County, SC; Right and middle- limestone bedrock, Shawnee Run, KY.

Impacts of tree uprooting on bedrock rivers are similar to those of rocky hillslopes. Biogeomorphic and pedologic studies have emphasized the importance of tree uprooting in which roots play a significant role in soil development, regolith disturbance and bedrock mining (Pawlik *et al.* 2016). Tree uprooting in bedrock controlled streams primarily causes disintegration and mining of bedrock (Figure 2.9). In addition, tree uprooting can potentially weaken the contiguous joints and bedding planes along stream banks, and thus can promote further bank erosion. I observed one case of uprooting and bedrock mining within a channel bed, but it is unknown whether this is common in bedrock fluvial environments.

Figure 2.9: Bedrock mining due to tree uprooting along the bank of a limestone bedrock river, Shawnee Run, KY.

2.4 Fluvial biogeomorphic impacts

2.4.1 Distinct vs. shared biogeomorphic impacts: The BGI triangles

Biogeomorphic impacts (BGIs) associated with bedrock streams can be highly concentrated or common in other environmental settings (e.g. alluvial and hillslope settings). Here, *highly concentrated* refers to those BGIs that are not unique to alluvial streams, bedrock streams or rocky hillslope environments, but are uncommon in the other settings. Figure 2.10 illustrates BGIs that are strongly associated with a specific environmental setting and thus highly concentrated in either alluvial streams, bedrock streams, or rocky hillslopes. In contrast, Figure 2.11 illustrates *shared BGIs* i.e., impacts that are not restricted to a specific environmental setting and are likely to occur in all three environments of bedrock streams, alluvial streams and rocky hillslopes.

The top corner of the BGI triangle in Figure 2.10 illustrates the biogeomorphic impact that is highly concentrated in bedrock streams — development of root banks along fluvial corridors. Evidence of root banks in bedrock streams was identified during field reconnaissance surveys. Root banks are more common in bedrock streams than alluvial ones, and the likely reason for this is primarily attributable to the geological contrasts between bedrock and alluvial streams. The bed and banks of bedrock rivers are more resistant than alluvial ones (Tinkler and Wohl 1998; Whipple 2004) and are not composed of transportable sediments (Whipple 2004). Thus, bank roots are less likely to be either exposed by erosion or covered by deposition in bedrock streams. Again, owing to the greater resistance of bedrock stream banks, the bank line probably largely controls the trees and the root growth in contrast to alluvial streams where roots gradually evolve with tree growth and stabilize the bank. Thus, in the bedrock case, roots become exposed on the river bank partly to stabilize the tree and partly to spread the root system so that side roots can penetrate gaps in the rock to find water and nutrients. All these indicate that root banks are likely to be more concentrated in bedrock streams than alluvial ones. Field reconnaissance work on bedrock streams in Kentucky shows that root banks commonly occur where bedrock is exposed, whereas alluvial banks of the same streams rarely offer any evidence of this feature. However, though root banks may be highly concentrated in bedrock streams, they also occur along alluvial stream banks.

The left corner of the triangle (Figure 2.10) shows the BGIs concentrated in alluvial streams. The impacts include initiation and development of bars and islands (bioconstruction), and root-reinforced deposition of sediment and wood within channels and on floodplains (bioconstruction and protection). Although evidence of these biogeomorphic impacts can be found in bedrock streams as well, mid-channel island and bar creation owing to the presence of live vegetation or wood-reinforced deposition are more concentrated in alluvial streams (e.g. Gurnell 2014; Gurnell *et al.* 2012; Gurnell and Petts 2002, 2006; Gurnell *et al.* 2001). The right corner of the triangle indicates biogeomorphic impacts that are highly concentrated in bedrock hillslopes. Infilling of stump holes and trapping of sediments from upslope (bioconstruction & modification) (Pawlik 2013, Shouse and Phillips 2016) are distinctive biogeomorphic impacts within rocky hillslopes while fluvial environments have limited potential to display such impacts.

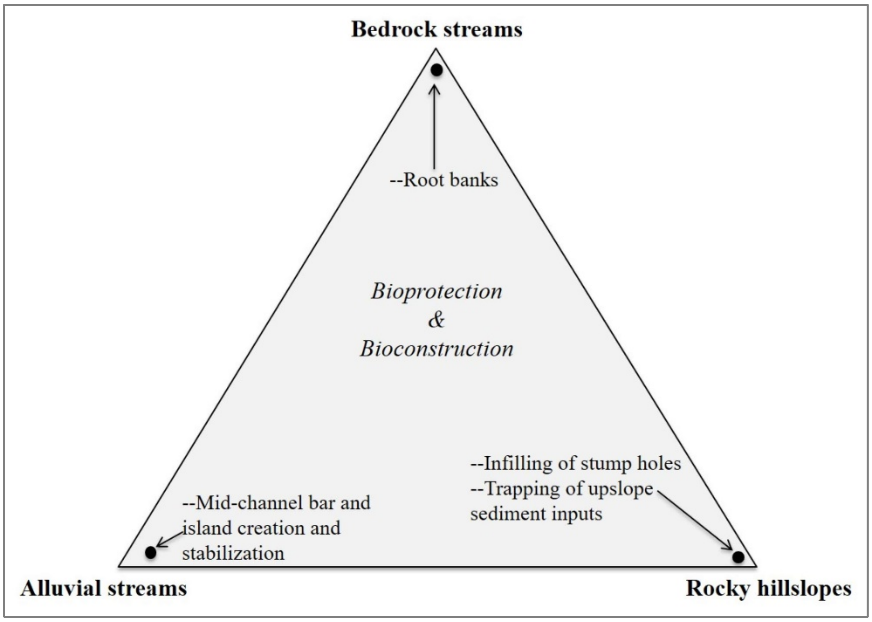

Figure 2.10: Examples of BGIs concentrated in bedrock or alluvial stream or rocky hillslope settings.

Conversely, trapping of sediments and rock fragments on floodplain and in-channel by vegetation (i.e. bioconstruction/modification) is common in all fluvial systems. Therefore, these impacts can be placed in both the top (i.e. bedrock streams) and the left (i.e. alluvial streams) corners of the BGI triangle in Figure 2.11. Again, while evidence of bedrock displacement owing to tree root and trunk growth, and bedrock mining caused by tree uprooting (examples of bio-weathering and erosion) were identified within bedrock fluvial environments, they are also common in bedrock hillslopes (see Table 2.3). As a result, such impacts fit at both the top (bedrock streams) and the right (rocky slopes) corners of the BGI triangle. It is noteworthy that the most common biogeomorphic role played by vegetation is bioprotective in nature (referred as inherent bioprotection in Figure 2.11). In fluvial systems and hillslope environments, vegetation stabilizes and protects landforms from erosion via root cohesion and sediment trapping and deposition. Thus, these biogeomorphic impacts are common in all three geomorphic settings i.e. bedrock streams, alluvial streams and rocky hillslopes.

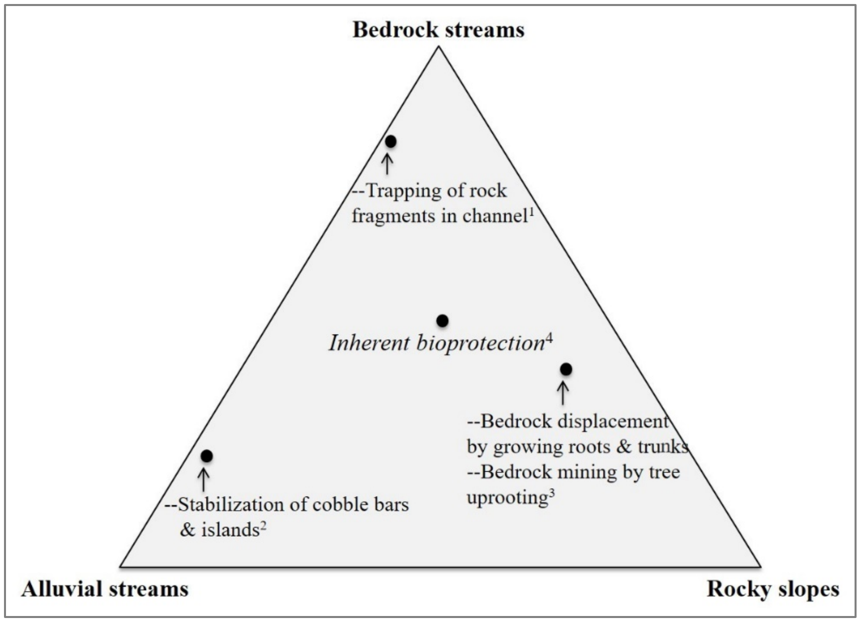

Figure 2.11: Examples of BGIs common in multiple environmental settings where [1]could also occur in cobble and boulder bed alluvial streams but more common in bedrock streams; [2,3]important in bedrock streams as well; [4]resisting erosion via increasing cohesion and imposing roughness.

Bedrock streams share biogeomorphic impacts both with alluvial streams and rocky hillslopes. Shared BGIs of bedrock and alluvial streams (that do not occur in bedrock hillslopes) are caused by the nature of geomorphic work done by fluvial systems and biota regardless of the environmental settings. On the other hand, bedrock streams and rocky hillslopes exhibit common BGIs (that do not occur in alluvial streams) owing to the comparable geological controls maintained in these settings. It is noteworthy that no such BGIs have been identified so far that are common in alluvial streams and rocky hillslope environments, but not present (at least potentially) in bedrock fluvial systems. Further, shared BGIs associated with all three environmental settings (see Table 2.5 and Figure

2.11) indicate entangled relationships among vegetation, geomorphic process-form linkages and environmental settings. While the BGIs of vegetation associated with these three different settings are not similar in all cases, the biogeomorphic roles (i.e. bioconstruction, bioprotection, bioerosion) played by them are analogous.

Table 2.5: Shared and highly concentrated biogeomorphic impacts

Environmental settings	**Biogeomorphic impacts (BGIs)**
Bedrock	Root banks
Alluvial Rivers	Island and bar creation by reinforcing deposition
Hillslopes	Infilling of stump holes; triggering and reinforcing mass movement caused by bioweathering
Alluvial and bedrock rivers	Sediment and wood trapping at bank edge, in-channel and floodplain; island and bar stabilization by reinforced deposition; island and bar creation and stabilization causing channel avulsion
Bedrock hillslopes and bedrock Rivers	Displacement of bedrock due to root and trunk growth; Bedrock mining caused by tree uprooting
Alluvial rivers and bedrock hillslopes	No common impacts that do not also occur on bedrock rivers
Bedrock rivers, alluvial rivers and hillslopes	Trapping upslope sediments and wood; resisting erosion via increasing cohesion

2.4.2 Fluvial biogeomorphic impacts and channel forms and processes

While very few studies specifically address biogeomorphic impacts of vegetation in bedrock streams, some reasonable speculations can be made about the channel form and process dynamics facilitated by them. The possible scenarios for bedrock streams are summarized in Table 2.6 with explanations discussed below.

Table 2.6: Potential biogeomorphic impacts of woody vegetation on bedrock streams; Here, W: channel widening, N: channel narrowing, I: channel incision, A: channel bed aggradation; D: flow divergence (channel splitting) and +, -, 0 = positive, negative, and no direct impacts respectively.

Biogeomorphic impacts of woody vegetation	W	N	I	A	D
Root bioweathering of bedrock banks	+	0	0	0	0
Root bioweathering of bedrock bed	0	0	+	0	0
Uprooting	+	+	+	+	+
Sediment trapping--bank	-	+	0	0	0
Sediment trapping--channel	0	+	-	+	+
Sediment trapping--floodplain surface	0	0	+	-	0
Bar stabilization	+, -	+, -	0	0	+, 0
Bioprotection (increased bank resistance)	-	0, -	0	0	0
Bioprotection (energy dissipation via roughness effects)	-	0, -	0	0	0
Hydraulic effects (flow diversion, turbulence)	+,0,-	+,0,-	+,0,-	+,0,-	0
Island formation	+	-	0	0	+
Large wood dams/jams	+	-	0	+	+

- Root associated bioweathering of bedrock channel bed and banks can potentially influence channel incision and widening, whereas such effects are may be insignificant in alluvial streams.
- Bedrock mining caused by tree uprooting can locally influence channel widening and deepening in bedrock streams, however effects will largely depend on whether the trees are located on bank or in-channel. Other impacts, i.e. channel narrowing, aggradation and flow divergence, will vary not only by the location of the uprooted tree/s but also by their extent to which rootwad and wood impede flow and block channels. However, these impacts occur in all fluvial systems.
- Vegetation induced sediment trapping on banks and in-channel can potentially contribute to channel narrowing for all fluvial systems. Further, in-channel sediment trapping can promote aggradation and subsequent development of islands or mid-channel bars. Thus, these impacts and processes can change single thread

channels to multiple-thread ones. Furthermore, sediment trapping on floodplain surfaces can increase the bank height, which can alter the channel geometry by lowering the width/depth ratio.

- Bar stabilization by woody vegetation in all fluvial systems can influence channel widening and narrowing both positively and negatively. These impacts will largely depend on two factors: i) the relative magnitudes of bar width vs. erosion of adjacent banks triggered by the bars and ii) location of the bars, i.e. whether a bar is attached to the bank or in mid-channel.
- Bioprotection plays a negative role on channel widening and narrowing in all river systems. It amplifies bank resistance via root cohesion, and aids energy dissipation via roughness effects. Thus, bioprotective impacts of vegetation offset hydraulic stresses.
- Vegetation induced hydraulic effects, most importantly flow diversion and turbulence, can result in heterogeneous impacts on channel forms and processes – for example, island stabilization and/or expansion by inducing deposition, or channel incision by triggering local scour of the channel bed. These impacts will largely depend on the environmental settings and the boundary conditions of the fluvial systems.
- Vegetation can stimulate island formation by promoting in-channel sediment trapping and aggradation. Island formation accompanied by channel splitting further has the potential to foster bank erosion caused by island associated flow deflection. Thus, vegetation can passively promote channel widening.

- Large wood accumulations or wood dams/jams have a positive influence on channel widening, aggradation and divergence. For example, a partial blockage of the channel can lead to flow divergence and subsequent channel widening. Such blockages can also induce turbulence associated local scour (Thomson 2006), which can lead to pool formation i.e. channel deepening. A complete blockage of the channel by wood dam can reduce the local slope, and thus can reinforce channel aggradation (Massong and Montgomery 2000).

The discussion noted above suggest that while bedrock and alluvial fluvial systems exhibit comparable biogeomorphic influences in most cases, they are dissimilar in terms of processes related to bioweathering and erosion. However, as the scenarios discussed above are largely inferential, future field based research should explore bedrock fluvial systems from biogeomorphic perspectives.

2.5. Summary and future research

Bedrock streams are understudied compared to alluvial ones in many aspects. This research seeks to fill this lacuna by studying bedrock streams from a biogeomorphic context. It shows that bedrock streams exhibit both *shared* and *highly concentrated biogeomorphic impacts* (defined in section 2.4) in relation to alluvial streams and bedrock hillslope environments (Table 2.5). The relations are graphically illustrated via two biogeomorphic triangles (Figure 2.10 & 2.11). Analysis reveals that bedrock streams display a bioprotective geomorphic form — root banks (when the root itself forms the stream bank), which is distinctive, but not exclusive, to this setting. On the contrary, shared biogeomorphic impacts include: i) sediment and wood trapping, and bar and island development and stabilization i.e. *bioconstruction/ modification* with alluvial streams; ii) displacement of bedrock due to root and trunk growth, and bedrock mining caused by tree uprooting i.e. *bioweathering and erosion* with bedrock hillslopes. This study concludes that bedrock streams exhibit some biogeomorphic impacts that also occur either in alluvial channels or on rocky hillslope environments. Therefore, no biogeomorphic impacts were identified that are absolutely unique to bedrock fluvial environments. Further, this research brings forth some important research queries related to bioprotection and bioweathering/erosion. Field evidence shows that where bedrock is exposed within the channel or along the bank, the bioprotective roles are minimal at best while bioweathering and erosion related impacts are probably more prominent (e.g. bedrock displacement by root and trunk growth). On the other hand, where bedrock is not exposed, the role of bioprotection associated with bedrock streams appears to be analogous to that of alluvial streams (except for the root bank case). However, further field based investigations are required to understand these relationships by answering the following research questions:

i. what is the relative importance of bioprotection along alluvial and bedrock streams, as bedrock ones are quite resistant anyway?

ii. what is the role of bioweathering and erosion along stream banks in bedrock channel evolution?

Finally, future research needs to look at larger samples of bedrock rivers, including the alluvial-bedrock transitional streams, that are influenced by different types of geology. The following aspects of bedrock streams are worthy of further investigation:

- The ideas presented in this research are relevant to reinforced (human-controlled) river channels where woody vegetation may colonize hard reinforcement such as concrete, laid brick and stone rip-rap. Therefore, future work related to stream restoration and river bank protection should address these ideas, most importantly bioprotection and bioweathering/erosion.

- Biogeomorphic impacts and related processes associated with bedrock streams almost certainly vary spatially and temporally. Future studies should attempt to quantify these variations for different types of bedrock streams.
- This research will allow some assessment of the contrasting biogeomorphic impacts across soil covered vs. bedrock/thin soil hillslopes, and bedrock – transitional – alluvial channels in different biogeographical and energy environments.
- Finally, bedrock channels are present from deserts to wet tropics with a broad range of tree species that exhibit different growth rates, resilience to mechanical disturbance and tolerances for inundation. Therefore, future research should explore the following questions:

i. are there some biomes or hydroclimatic regions where woody vegetation is more likely to influence bedrock channel processes or forms?

ii. does the influence of vegetation depend on factors associated with boundary conditions such as lithology, joint geometry, flow regime and channel geometry that limit the ability of trees to germinate and survive?

CHAPTER 3. BIOGEOMORPHIC KEYSTONES AND EQUIVALENTS: EXAMPLES FROM A BEDROCK STREAM

Abstract

Biogeomorphic keystone species profoundly impact landscapes, such that their introduction or removal would cause fundamental changes in geomorphic systems. This paper explores the concept of biogeomorphic keystone species by examining the general vs. species-specific biogeomorphic impacts (BGIs) of trees on a limestone bedrock-controlled stream, Shawnee Run, in central Kentucky. Field investigation identified three strong BGIs: i) *biogeomorphic pool* formation via bioweathering; ii) root-bank associated bioprotection; and iii) avulsion-originated island development linked to bioprotection. This research evaluates these impacts in the context of keystone or other biogeomorphic roles. Field survey was conducted on nine stream reaches, each consisting of 10-12 hydraulic units of riffle, pool and run. Results suggest that American sycamore (*Platanus occidentalis*) plays a keystone role by promoting development of ~42% of pools of the study area. While geomorphic pools are formed by fluvial process-form linkages, these biogeomorphic pools are developed by sycamore root induced channel bed bioweathering. Only American sycamore and chinquapin oak (*Quercus muehlenbergii*) exhibited *root-bank* development amongst 15 different species identified – and thus play a vital role in bank bioprotection. Lastly, trees can promote avulsion-originated island formation by creating erosion-resistant bioprotective patches. Mature trees (in terms of size), particularly large American sycamore and chinquapin oak, dominate Shawnee Run islands with a mean diameter at breast height (DBH) > 40 cm. However, other trees can provide comparable bioprotection, particularly at mature stages. Because its absence would result in fundamentally different stream morphology, sycamore can be considered a biogeomorphic keystone species in Shawnee Run.

Keywords: Biogeomorphic keystone species, biogeomorphic impacts, species-specific, biogeomorphic pool, bedrock streams.

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3.1 Introduction

Increasing recognition of the importance of biogeomorphic ecosystem engineering from geomorphological and ecological perspectives has raised questions about the relative importance of specific species or higher taxa. For example, dams and ponds created by the North American beaver (*Castor canadensis*) result in local landscape metamorphosis and have profound hydrogeomorphological and ecological impacts. Further, those particular impacts are specific to beaver. A counter-example is the role of woody vegetation in channel planform change – from braided to single-thread or meandering rivers (Thorne, 1990; Gran & Paola, 2001; Gurnell *et al.*2001; Murray & Paola, 2003; Tal *et al.*, 2004; Tal & Paola, 2007, 2010; Braudrick *et al.*, 2009; Bertoldi *et al.*, 2011; Gurnell *et al.*, 2012; Gran *et al.* 2015). The biogeomorphic effects are certainly extensive, but are not species specific. Here we explore the concept of *biogeomorphic keystone species* by examining the general vs. species-specific biogeomorphic effects of trees on a limestone bedrock-controlled stream in central Kentucky.

This paper consists of two key parts. First, we describe the potential biogeomorphic roles of vegetation in bedrock fluvial systems, which are understudied. Drawing from ecological lexicon, we introduce some biogeomorphic concepts with respect to different biotic impacts on surface processes and forms. The second part of this paper explores different biogeomorphic roles of vegetation from the empirical evidence obtained from a bedrock fluvial system in central Kentucky.

The keystone species concept in ecology has been around since 1969 (Paine, 1969). Power *et al.* (1996) defined a keystone species as one whose impact on its community or ecosystem is extensive, and disproportionately large relative to its abundance. Keystone species are often understood to be organisms whose removal from (or addition to) a community would result in wholesale changes. Ecologists have critiqued the concept because it has been variously and vaguely defined over the years (Mills *et al.*, 1993; Paine, 1995; Power *et al.*, 1996), but it remains a key idea in ecology. Drawing from this tradition, we consider that biogeomorphic keystone species have major and disproportionately large impacts relative to their abundance on geomorphic processes, landforms, or material properties, such that addition or removal of the species would result in fundamental changes. Further, the impacts should be species-specific.

The term biogeomorphic equivalent is also drawn from the ecological lexicon—‘ecological equivalents’. Ecologically equivalent species play similar functions in different communities (Lincoln et al. 1998), especially ecologically similar communities that are widely separated (Biggins et al. 2011). Similarly, *biogeomorphic equivalents* are species that have similar biogeomorphic impacts (major or minor) with respect to surface processes and landforms. In both cases, they are essentially interchangeable with each other owing to their similar functionality (after Lincoln et al. 1998). Two other ecological concepts similar to ecological equivalents are ‘functional equivalents’ and ‘functional redundancy’. While functional equivalency stands for equivalency in terms of per capita impact, functional redundancy means equivalent impacts at the population-level i.e. within a community or ecosystem (Resenfeld 2002). We use the term ‘biogeomorphic equivalents’ after the more general term ‘ecological equivalent’.

3.1.1 Biogeomorphic Roles

Based on the literature, we can identify several potential biogeomorphic roles—categories of influence—for a given species in a given environment. Biogeomorphic ecosystem engineering is sometimes contingent on specific environmental conditions (Phillips, 2016) and may be self-limiting (Phillips, 2018). Further, species roles as ecosystem engineers and as keystone or non-keystone species are also often context-dependent (Mills *et al.*, 1993; Power *et al.*, 1996; Matthews *et al.*, 2014). Thus, one cannot designate a particular role for a species independently of a specific environment. Even the archetype biogeomorphic ecosystem engineer, the beaver, does not always build dams and block streams—in settings with existing deep pools or runs they do not construct dams (e.g., Meentemeyer *et al.,*1998). The roles are summarized in Table 2.1. They range from *neutral* species with no direct geomorphic impacts to *bioconstructor* organisms that actively construct landforms, or from which landforms are constructed.

Influencer organisms have direct biogeomorphic impacts, but these are not sufficient to qualify as keystone or separator species. For example, most living vegetation augments river bank strength and thus, inhibits erosion by their root systems (e.g. Millar & Quick, 1993; Millar, 2000, 2005; Pollen-Bankhead & Simon, 2010; Gurnell *et al.,* 2012). Another instance includes riparian and aquatic plants, which in general can alter the landform dynamics by trapping and stabilizing sediments, organic matter and the propagules of other plant species (Gurnell *et al.,* 2012). *Biogeomorphic equivalents* – a particular form of *influencers* – are taxa that have highly similar impacts, such that they are interchangeable with each other, from a geomorphic perspective. For example, the bioprotective roles of root systems of any live vegetation can significantly reduce bank failure and erosion susceptibility by increasing substrate cohesion (Abernethy & Rutherfurd, 2001; Corenblit *et al.,* 2007). Therefore, many species of vegetation are biogeomorphic equivalents from this perspective. Another example is tree uprooting that can lead to bioweathering caused by bedrock mining (Gabet *et al.,* 2003; Gabet & Mudd, 2010) and thus can promote erosion. Species that can cause bedrock mining by their uprooting can be designated as *biogeomorphic equivalents*. Impacts of *keystone species* are specific to certain taxa. Their influence determines or profoundly impacts landscapes such that their introduction or removal would result in fundamental changes in surface processes, morphology, or material properties. A different set of process-form relationships will be established owing to these changes. For example, introduction of invasive salt marsh cordgrass (*Spartina alterniflora* and *Spartina anglica*) in China converted tidal flats to salt marshes (An *et al.,* 2007, Liao *et al.,* 2007), including changes in elevation, topography, substrate, mass flux regimes, hydrology, and both geomorphic and ecological functioning (Wang *et al.,* 2006). In fluvial systems, the reach-scale configuration of geomorphic attributes will be transformed in response to the changes caused by keystone species. Biogeomorphic *foundation species* are those that are locally abundant and regionally common, and help the formation of locally stable landforms that may be required by many other species (after Ellison et al., 2005). A foundation species can either be an influencer or a keystone species determined by their 'disproportionate impacts' relative to their abundance. Because we are interested in the specific biogeomorphic roles of species in this paper, we deal with biogeomorphic keystones and influencer organisms separately, and do not treat foundation species as a separate biogeomorphic category. Biogeomorphic *separators* are organisms that can potentially occupy the same original habitat, whose biogeomorphic effects result in different landform or landscape evolution trends or trajectories. For example, the topographic configuration and development pattern of Atlantic coast barrier dunes depends on the types of plant species established on them (Stallins, 2005). Three dune plant types can be identified based on their function (Hosier, 1973; Woodhouse, 1982; Ehrenfeld, 1990), which include i) dune builders, ii) burial-tolerant stabilizers, and iii) burial-intolerant stabilizers. Dune builders are burial tolerant, and promote vertical dune development. Further, while burial tolerant stabilizers can survive burial, their decumbent growth does not boost vertical dune development. Finally, the burial intolerant stabilizers do not support vertical dune development, but do facilitate effective binding of substrates (Harper, 1977; Fahrig *et al.,* 1994). Thus, for a given habitat type, there may be different biogeomorphic trajectories depending on which types of dune plant establishes. Biogeomorphic *separators* may also be influencer or keystone species. *Bioconstructors* are organisms that construct the landform, or from which the landform is constructed – they can be either active or passive constructors (Naylor et al., 2002). While active constructors create landforms for their own benefit and in many cases purposefully, the passive ones create landforms without deliberate intent. Coral reef formation and ant mounding are examples of active bioconstruction. As coral reefs are constructed by their own hard skeletons (i.e. by calcium carbonate secretion) of corals – primarily by the scleractinian corals (Daly, 1915; Stoddart, 1969) such as *Diploria labyrinthiformis, they* can be termed as autogenic bioconstructors. On the other hand, while ant mounds are created purposefully for the benefit of the ants, they primarily consist of soil particles, and ants are thus allogenic bioconstructors. Formation of landforms via sediment and wood trapping by tree roots is an example of passive, allogenic bioconstruction. Note that we do not seek to be able to classify all species/environment situations definitively in one category or other, but simply to identify a range of possible roles. With respect to trees in fluvial corridors, we are particularly interested in potential keystone species that fundamentally shape fluvial landforms and landscapes via species-specific impacts, vs. equivalents, in which multiple trees may perform the same biogeomorphic function.

Table 3.1: Biogeomorphic Roles

Term	**Definition**	**Examples**
Biogeomorphically neutral species	No detectable direct impacts on surface processes and landforms.	Most birds.
Biogeomorphic influencers	Significant direct impacts, but not sufficient to qualify as keystone or separator species.	All living vegetation that protects landforms from erosion (e.g., Millar, 2000, 2005; Gurnell *et al.,* 2012).
Biogeomorphic keystone species	Impacts of these species determine or profoundly impact landscapes, such that their introduction or removal would result in fundamental changes in surface processes, morphology, or material properties.	Salt marsh cordgrass converting mudflats to salt marsh (e.g. An *et al.,* 2007); dams constructed by beavers (*Castor canadensis* and *Castor fiber*) (e.g. Gurnell, 1998; Butler & Malanson, 2005).
Biogeomorphic separators	Species (potentially) occupying the same habitat whose biogeomorphic effects result in different landscape evolution pathways.	Differential topographic pattern of the Atlantic barrier island dunes caused by establishment of various types of plants (Stallins, 2005).
Biogeomorphic equivalents	Species that have similar biogeomorphic impacts (major or minor), such that they are essentially interchangeable with each other with respect to surface processes and landforms	Bioweathering by tree uprooting (Gabet & Mudd, 2010; Gabet *et al.,* 2003).
Bioconstructors	Organisms that construct the landform, or from which the landform is constructed.	*Sphagnum spp. and* peat bogs (e.g., van Breemen 1995); corals and reefs (Wicander and Wood, 1981); mussels and shell bars (e.g. Crooks & Khim, 1999; Ruesink *et al.,* 2005; Vander Zanden *et al.,* 1999).

Many concepts in this paper are linked to studies that concentrate on wider biogeomorphic concepts and theories (e.g. Naylor et al. 2002; Ellison et al. 2005; Naylor 2005; Viles et al. 2005; Wright & Jones 2006; Jones 2012; Naylor et al. 2012; Coombes et al. 2013; Coombes 2016). The ecological literature on keystone species has focused on their effects on trophic webs and biodiversity, though ecosystem engineering is sometimes considered (Jones et al. 1994; Lawton 1994; Lawton & Jones 1995). However, geomorphic processes and landforms are often recognized as important context factors—that is, factors such as wave forces, turbulent flows, and substrate characteristics may determine whether a species is a keystone or not (Power *et al.*, 1996: Table 3.2). As far as we know this is the first study to explicitly consider potential keystone roles from a geomorphic perspective, though some previous studies (e.g. Fei *et al.,* 2014, Allen 1998) could be interpreted in this context.

3.1.2 Potential biogeomorphic keystones

Although a plethora of research considered the biogeomorphic effects of vegetation on landform dynamics and evolution (e.g. Page & Nanson 1982; Thorne 1990; Hupp & Rinaldi 2007; Gurnell et al. 2001; 2012), very few discussed the species specific biogeomorphic impacts that may provide insight about biogeomorphic keystones (e.g. Corenblit 2018; Hortobágyi et al., 2018; Schwarz et al., 2018). The literature on the biogeomorphic impacts of invasive species shows that introduction of some taxa can result in major geomorphic transformations (landscape metamorphosis; Fei *et al.,* 2014). For example, *Tamarix* – in the southwest United States – has extensive root systems that resists bank erosion and increases sedimentation in fluvial systems, which in turn changes channel dimensions, width/depth ratios (decreases channel width), and flow regimes (Graf 1978; Di Tomaso 1998). Allen (1998) documented another example of landform metamorphosis, which showed instances of reduced erosion and thereby mudflat conversion to monocultural mangrove forests in Hawaii by the invasion of mangroves, *Rhizophora mangle*. Other examples of invasive species causing geomorphic transformation of landforms can be found in Fei *et al.* (2014)'s review.

The field component of this study was designed to link the notion of biogeomorphic keystone species and related concepts to a specific biogeomorphic setting. Reconnaissance survey based field observation identified three important biogeomorphic impacts:

i. Biogeomorphic pool formation linked to bioweathering.

ii. Development of avulsion associated islands related to bioprotection.

iii. Root banks associated with bioprotection.

The goal of this research is to evaluate these biogeomorphic impacts with respect to biogeomorphic keystone species or other biogeomorphic roles (summarized in table 3.1).

3.2 Biogeomorphic effects of trees in bedrock streams

Tinkler and Wohl (1998) characterized a bedrock channel as one with 50% bedrock exposed in the bed and banks, or covered by an alluvial veneer which is largely mobilized during high flow events such that the underlying bedrock geometry strongly influences patterns of flow hydraulics and sediment movement. Knowledge from alluvial systems cannot be directly transferred to bedrock rivers (Tinkler & Wohl, 1998), as they are fundamentally different in many aspects (e.g. Vaughn 1990; Tinkler & Parish 1998). The distinguishing attributes of bedrock vs. alluvial streams include:

- Bedrock streams undergo slower change (Schumm & Chorley 1983; Whipple 2004).
- The bed/bank of bedrock streams are more resistant (Tinkler & Wohl 1998).
- Bedrock streams have more direct influence of lithology and structure (Miller 1991; Tinkler & Wohl 1998; Whipple 2004).
- Bedrock streams experience an enhanced role of processes such as dissolution, abrasion, and plucking (Wohl & Ikeda 1998; Tinkler & Wohl 1998; Whipple *et al.* 2000).

Bedrock channels occur mainly, but not exclusively, in actively incising portions of landscapes where channels are cut into resistant rock units (Whipple 2004). This explains greater influence of lithology and structure, greater role of bed/bank resistance and therefore, the dominant erosion processes, and slower change of bedrock channels compared to alluvial rivers. As the bed and banks of bedrock rivers are not composed of transportable sediment (Whipple 2004) and are more resistant than alluvial ones (Tinkler & Wohl 1998), they are less erodible than alluvial rivers. However, as bedrock streams often do transport appreciable sediment, some biogeomorphic impacts observed in alluvial streams are likely important in bedrock systems, too, such as sediment trapping and initiating or anchoring bars and islands.

While many studies have recognized the importance of biogeomorphic impacts (BGIs) in alluvial systems, bedrock river systems remain less understood. Due to lack of literature specifically addressing the effects of vegetation on bedrock streams, field reconnaissance surveys were carried out for collecting real world instances of BGIs associated with bedrock streams. An inventory of the evidence of BGIs identified in bedrock streams is summarized in Table 3.2 (see also Jerin, 2019), and discussed in detail later in this section.

Table 3.2: Biogeomorphic impacts, the corresponding biogeomorphic functions and the associated field criteria identified in bedrock streams.

Identified BGIs associated with bedrock streams	Biogeomorphic function	Observed field criteria
1. Sediment trapping	Bioconstruction	1. Observed sediment accumulation upstream of trunk and/or roots
2. Trapping woody debris and large woody debris (LWD)		2. Observed wood accumulation upstream of trunk and/or roots
3. Root bank	Bioprotection	3. Identified when ~100% of the bank surface consists of tree root.
4. Vegetation anchoring bars and islands		4. When >50% living vegetation cover is identified with limited evidence of erosion or sediment mobility.
5. Bedrock weathering	Bioweathering	5. Bedrock displacement (and disintegration in cases) by root penetration along joints, fractures, and bedding; observed bedrock displacement by trunk and root growth.
6. Bedrock mining		6. Excavation of bedrock by tree uprooting (i.e., bedrock fragments within root wads)

3.2.1 Bioconstruction/modification

Examples of vegetation-induced bioconstruction identified in fluvial biogeomorphic literature are predominantly passive, allogenic. Passive, allogenic bioconstruction in bedrock streams can occur in several ways. Sediment can be transported in bedrock channels and subsequently trapped by vegetation. Alteration of flow hydraulics can facilitate riparian vegetation establishment and survival, which in turn can reinforce sediment trapping in bedrock streams (e.g. Auble *et al.* 1994). Furthermore, in-channel sediment trapping can lead to the development of bars and islands both in bedrock and alluvial streams (e.g. Gurnell *et al.* 2001; Gurnell & Petts 2002, 2006).

Live vegetation in-channel and on floodplains can lead to substrate modification and construction in alluvial streams (Wohl & Scott 2017, Gurnell 2014). Riparian vegetation and wood intercept water and sediment during high flow events, and thus drive the physical creation, modification or maintenance of habitat such as islands and bars through biostabilization and construction (Gurnell *et al.* 2005). Bedrock streams also exhibit these biogeomorphic impacts, which can eventually convert a bedrock reach into an alluvial segment, modify habitat characteristics promoting further growth of vegetation, and facilitate the development of bars and islands. Large wood in channels and on floodplains also contributes to bioconstruction and modification in bedrock rivers.

3.2.2 Bioprotection

The bioprotective roles of vegetation are well documented in the literature. Frequently referenced forms of bioprotection in rivers include the role of vegetation in i) imposing roughness to hydraulic shear and ii) mechanical resistance of beds, banks and floodplain surface (e.g. Gurnell *et al.* 2001, 2014; McKenney *et al.* 1995). Bioprotective function of vegetation in bedrock streams was also detected in the form of root banks – when the root itself creates the stream bank (Jerin, 2019). Root banks directly impact flow dynamics via increasing roughness, can entrap wood and sediment, and probably can accelerate biochemical weathering. The biophysical form of root banks plays a bioprotective role along the fluvial corridors, as hydraulic shear seems to be not capable of eroding root banks, just as it cannot erode intact bedrock. Thus, where root banks occur directly overlying bedrock, as has been observed in the field, there may be little or no increase in resistance, as bedrock streams are intrinsically more resistant than alluvial ones. (Miller 1991; Tinkler and Wohl 1998; Whipple 2004). However, by entrapping sediment root banks can lead to the formation of extensive fine sediment benches. In such cases, root banks will protect an extended area surrounding them from fluvial erosion, and thus can considerably contribute to bioprotection.

3.2.3 Bioweathering and erosion

Bioweathering and erosion have received less attention than other biogeomorphic effects on streams in the geomorphic literature. However, numerous examples of bioweathering and erosion were identified in the study area and are likely present in other bedrock streams (Jerin, 2019). Biogeomorphic impacts of vegetation identified in bedrock dominated fluvial corridors are similar to those of rocky hillslope settings in a number of cases — (i) *impact of growing root systems:* disintegrate rock fragments and widen fissures in bedrock (ii) *impact of growing trunk:* physical displacement of bedrock (iii) *impact of* *tree uprooting:* direct bedrock disruption via mining (e.g. Gabet & Mudd, 2010; Pawlik 2013; Pawlik *et al.* 2016).

3.3 Study area

The study area, Shawnee Run, is located in the Kentucky River gorge area of the Inner Bluegrass karst region within Mercer County in central Kentucky, USA (Figure 3.1). It is a bedrock-controlled stream dominated by limestone lithology with discontinuous coarse alluvial cover. Shawnee Run is within a nature preserve, and has been minimally disturbed along the fluvial corridor. It is a tributary of the Kentucky River (note: on U.S. Geological Survey maps, Shawnee Run is incorrectly shown as Shaker Creek) draining about 43.5 km^2 of surface drainage area with a total length of 19.84 km.

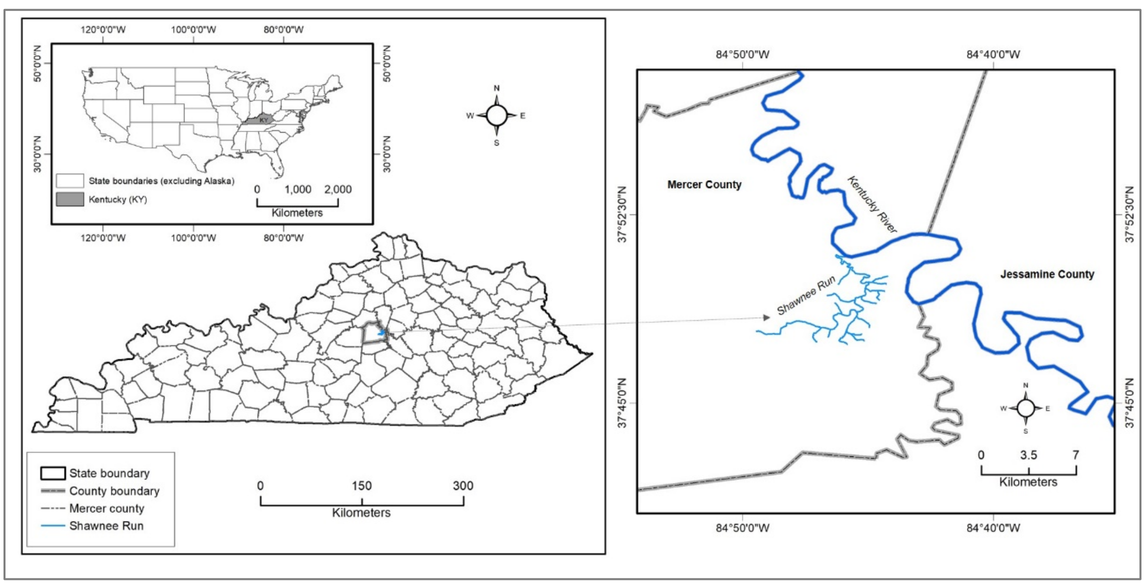

Figure 3.1: Location of the study area in Mercer County, Kentucky. (base map: Kentucky Geologic Map Information Service).

The Inner Bluegrass region has a topography characterized by low relief and gentle ridges, except in the Kentucky River gorge area. Local relief of 100 m is common there, and river-to-cliff or bluff top relief ranges from 61 to 131 m. The bedrock in the area is comprised of the High Bridge Group and the Lexington Limestone (Sparks *et al.*, 2001). The High Bridge Group further consists of three formations: in ascending order, the Camp Nelson Limestone, the Oregon Formation (dolomite interbedded with limestone), and the Tyrone Limestone.

The Kentucky River and its tributaries are strongly incised. Incision from the former course to the modern channel apparently was triggered by base-level changes, a result of glacial modification of the Ohio River drainage system ca. 1.3 to 1.8 Ma (Teller & Goldthwait, 1991; Andrews, 2004). The evidence of headward incision via slope is reflected in three distinct incision zones (see figure 3.2):

i) Strongly incised: The downstream reaches where incision has reached the Kentucky River base level; Camp Nelson Limestone is exposed.

ii) Incising: Middle reaches that are still incising, and have yet to reach the Camp Nelson formation; younger Tyrone Limestone and Oregon Formation are exposed.

iii) Unincised: The upstream portion is not noticeably incised; youngest Lexington Limestone is dominantly exposed.

The climate is humid subtropical, and mean annual precipitation is about 1200 mm. The dominant land use in the the study area is pasture (cattle and horse grazing) and forest. Potential natural vegetation is dominantly forest, though savanna and grassland ecosystems existed (and some still persist) in the Bluegrass Region (Campbell, 1989).

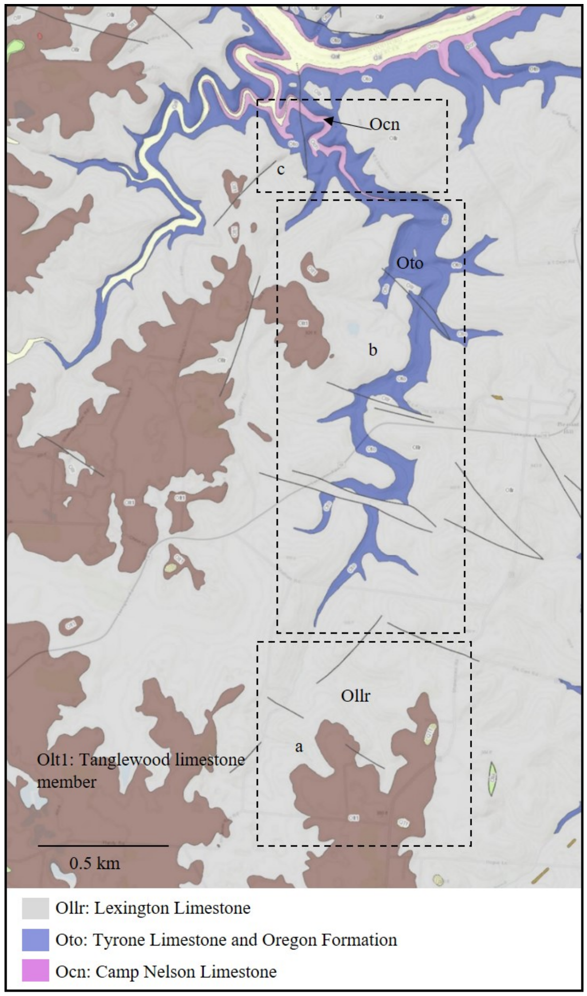

Figure 3.2: The geologic map of Shawnee Run where (a) displays unincised portion, (b) displays moderately incised portion and (c) displays strongly incised portion (base map: Kentucky Geologic Map Information Service).

3.4 Methods

3.4.1 Sampling Scheme

The field survey is based on a hierarchical scheme, with smaller spatial scales nested within higher-level scales. It was conducted between April and July 2018. The study area was divided into three hierarchical scales: domains, reaches and hydraulic units, where hydraulic units were nested within reaches, and reaches were within domains. Domains were designated based on a morphological distinction between unincised, incising and strongly incised channels. The distinctions were based on the valley side relief of approximately 5-15 m in unincised (or mildly incised) portion vs. ~ 25-35 m in incising portion vs. ~50-70 m in strongly incised section. These also correspond with the exposure of the deeper strata as reflected in the geologic map (Figure 3.2). These three domains were termed unincised, moderately incised or incising, and strongly incised regime (see section 3.3 and figure 3.2) with lengths of 461 m, 472 m and 410 m respectively. Further, three reaches were selected from each of the three defined domains and each reach consisted of ten to twelve hydraulic units (HUs). The cumulative length of the HUs of a reach defined the length of each reach, which ranged from 117 to 177 m (see table 3.3). The starting point of each reach was selected randomly from each domain. Therefore, a stratified random sampling method was undertaken for this field survey (Rice 2010) in which each domain was equivalent to a stratum from where the reaches were selected randomly.

Hydraulic units (HUs) are the smallest spatial units of this research and are spatially distinct patches of relatively homogenous surface flow and substrate character (Fryirs & Brierley, 2012). The average length of hydraulic units measured in the unincised, incising, and strongly incised domains are 13.6, 15.2 and 13.7 m, respectively. Four distinct categories of hydraulic units were identified during the field reconnaissance survey: high gradient riffle (HGR), low gradient riffle (LGR), pool and run (Figure 3.3).

Table 3.3: Morphological characteristics of Shawnee Run (based on field measurements).

	Domains	Reaches	Total length (m)	Average bankfull width (m)
Up-stream	Unincised (Upstream)	Reach 1	176.9	6.5
		Reach 2	116.8	6.5
Longitudinal continuum of the stream		Reach 3	167.4	8.8
	Moderately Incising (Midstream)	Reach 1	153.3	10.5
		Reach 2	174.1	12.7
		Reach 3	144.61	13.74
	Strongly Incised (Downstream)	Reach 1	136.3	10.7
Down-stream		Reach 2	124.4	13.7
		Reach 3	149.6	10.5

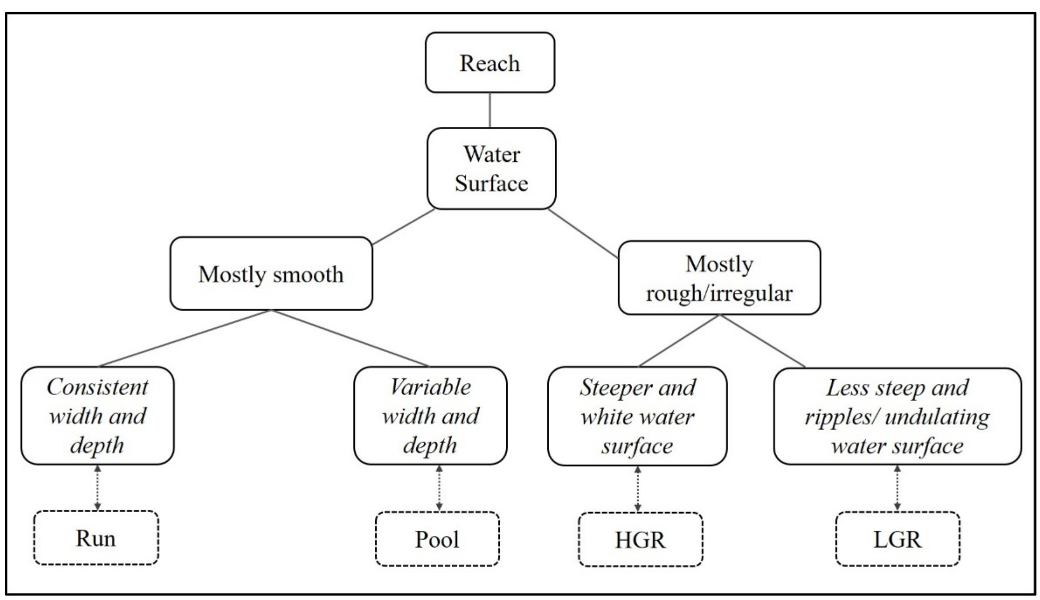

Figure 3.3: The classification scheme of hydraulic units (HUs) at each reach.

The irregularity of the water surface within a reach, which separates the runs and pools from riffles, is caused by slope and roughness variations. Furthermore, the classification scheme (Figure 3.3) reflects that while the pools and the runs are distinguishable based on width and depth variability, the HGR and LGR are differentiated based on variability in slope. Based on reconnaissance survey results, the threshold value of slope steepness to distinguish HGR and LGR in the study area is 0.02 m/m.

3.4.2 Geomorphic survey

Cross section data were acquired with a measuring tape and a rod at the mid-point of each HU, totaling 95 cross-sections. Bankfull channel width and depth were measured at the approximate mid-point of each hydraulic unit. Bankfull channel depth was measured at 0.5 m intervals or less. These measurements were used to calculate bankfull average depth, maximum and minimum depth, and width/depth ratio. Bankfull flow elevations were identified based on the floodplain surface following methods described by Stream Systems Technology Center (2002). The key to identify the bankfull elevation is to locate the relatively flat depositional surface of the floodplain as bankfull stage occurs when water just begins to overtop the floodplain. Best locations for demarcating bankfull elevations are along the inside of meander bends (the level top of a point bar is a reliable indicator of bankfull elevation), and along both sides of straight reaches where the floodplain is easily detectable. The longitudinal profile was measured using a laser level and prism along the thalweg, which was used to determine the HU and reach scale slopes. The HU scale slope values were further used for discerning HGR and LGR.

3.4.3 Vegetation survey

The vegetation survey was conducted within the riparian zone of each HU. Any tree with a portion of trunk within 2 m of the banktop, on the bank, or within the channel was included. All woody plants with a diameter at breast height (1.37 m above ground level) ≥ 5 cm were identified. Circumference at breast was measured using a measuring tape to derive diameter at breast height (DBH) and basal area (BA).

3.4.4 Biogeomorphic survey

A biogeomorphic survey was conducted based on identification of impacts associated with vegetation measured during the vegetation survey. An inventory of potential BGIs associated with bedrock streams was developed (see table 3.2). BGIs observed and recorded during the field survey include sediment trapping by live vegetation, wood accumulation, bar and island anchoring, root banks, weathering of bedrock by root penetration and trunk growth, and bedrock mining caused by tree uprooting.

3.4.5 Statistical analysis

Chi-square analysis was used to identify the statistical significance of the relationship between tree species and types of hydraulic units. ANOVA was conducted to compare the age of island vegetation to the adjacent floodplain vegetation linked to avulsion-originated island formation. Linear regression was carried out to explore the relationship between species richness and stem density.

3.5 Results

3.5.1 Riparian vegetation and spatial distribution

Field data were collected from 95 hydraulic units (HUs) -- 29 HGRs, 19 LGRs, 26 Pools and 21 Runs. The vegetation survey provided data about the riparian species composition, richness, basal area, and stem density (Table 3.4, figure 3.4).

Table 3.4: Species composition, and their basic characteristics.

Species	**Scientific name**	**# of individuals**	**Total basal area (m^2)**	**Mean DBH (cm)**	**Min DBH (cm)**	**Max DBH (cm)**
Chinquapin oak	*Quercus muehlenbergii*	209	8.05	19.0	5	66
American sycamore	*Platanus occidentalis*	109	35.18	55.2	4	140
Red maple	*Acer rubrum*	67	3.51	22.5	5	71
Osage orange	*Maclura pomifera*	39	3.38	27.7	6	73
Green ash	*Fraxinus pennsylvanica*	24	0.38	12.8	2	25
Ohio buckeye	*Aesculuc glabra*	16	0.11	9.1	4	18
Japanese honey suckle	*Lonicera japonica*	15	0.10	8.8	5	14
Elm	*Ulmus americana*	13	0.55	21.8	7	37
Hickory	*Carya ovata*	11	0.87	27.8	11	70
Red cedar	*Juniperus virginiana*	6	0.30	22.9	6	35
Others (5 species)		13	1.00	29.9	8	60

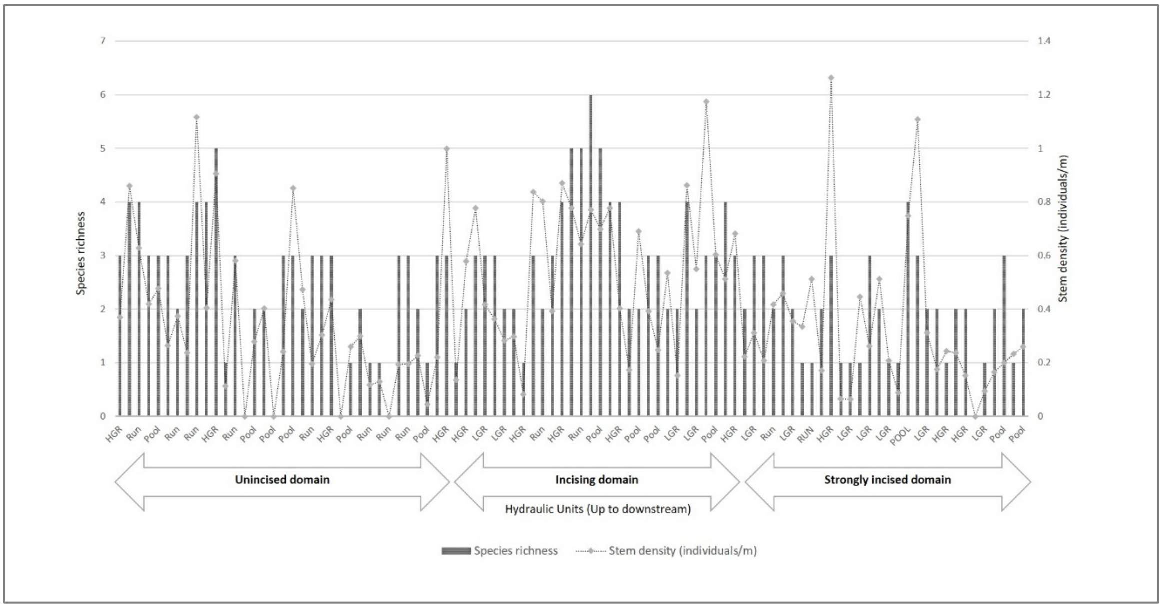

Figure 3.4: Species richness and stem density (number of individuals/length of HU) per hydraulic unit from up to downstream.

15 different tree species occur along the riparian corridor of Shawnee Run, and all species are common in central KY forests. Chinquapin oak (*Quercus muehlenbergii*) is the most common, representing more than 40% of all trees. American sycamore (*Platanus occidentalis)* is dominant with respect to basal area, accounting for ~21% of the total. Red maple (*Acer rubrum)*, osage orange (*Maclura pomifera)* and green ash (*Fraxinus pennsylvanica)* are less common than sycamore and chinquapin oak, but are more abundant than the remainder. Therefore, the remainder of the species are grouped together and labelled as 'others'. The invasive Japanese honeysuckle (*Lonicera japonica*), included in the 'others' group, was common at some sites, but generally below 5 cm threshold DBH. During fieldwork, BGIs of all 15 species were noted separately. While chinquapin oak is the most abundant species, its total basal area, and mean and maximum DBH is substantially lower than American sycamore. Furthermore, although red maple and osage orange have smaller total basal area compared to chinquapin oak, attributable to their

smaller numbers in total, their mean and maximum DBH is larger. While there were no apparent trends relating the vegetation variables to hydraulic units, simple linear regression indicates linkage between stem density and species richness ($R^2 = 0.44$, $p < 0.000$, $N = 95$). The spatial distribution of species (Figure 3.5a) shows no definite pattern in species-distribution across different types of hydraulic units, with chinquapin oak and American sycamore the dominant ones in most cases. On the contrary, at the regime scale, reflecting upstream to downstream patterns, (Figure 3.5b) a pattern in species distribution is evident. Chinquapin oak and American sycamore are substantially more common at the midstream reaches. By contrast, red maple exhibits an increasing, and osage orange and green ash show a decreasing, up to downstream trend in Shawnee Run.

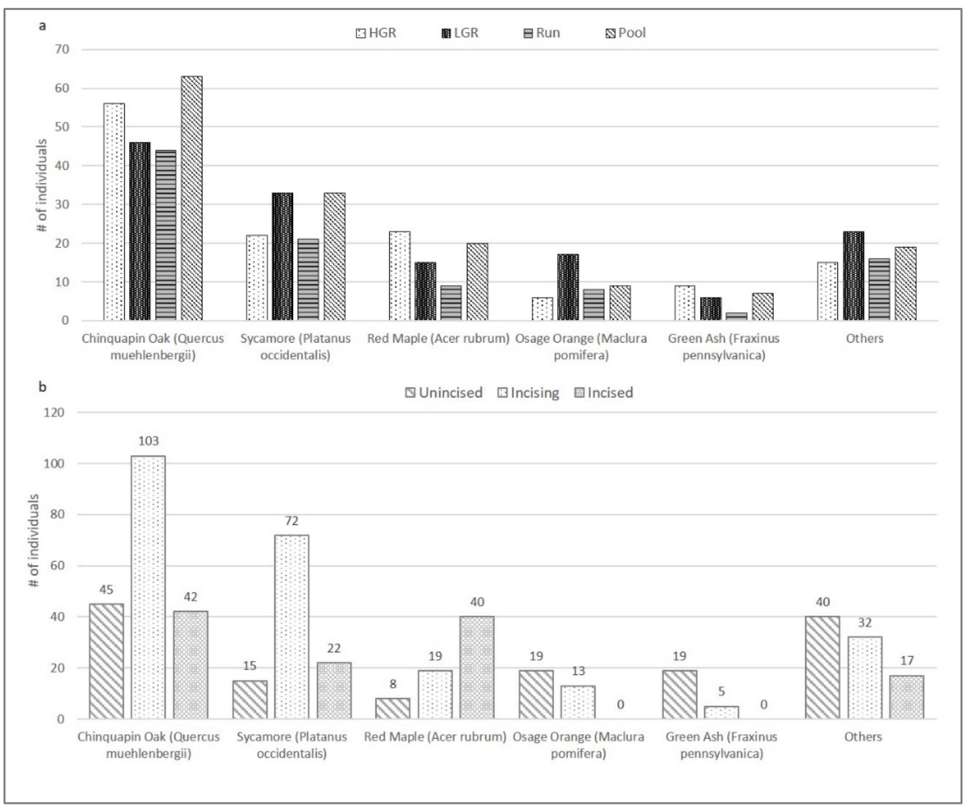

Figure 3.5: Spatial distribution of riparian species in Shawnee Run where a) shows hydraulic unit scale spatial distribution; b) shows regime scale distribution up- to downstream.

3.5.2 Biogeomorphic impacts

Biogeomorphic impacts (BGIs) associated with riparian vegetation recorded during the field survey includes evidence of trapping sediment, trapping woody debris (small branches, twigs etc.), trapping large woody debris (part of trunk of a large tree), displacement of bedrock due to root penetration and trunk growth, and root banks. While bedrock mining associated with tree uprooting was observed in the vicinity, no cases were recorded at our field sites.

Figure 3.6 (a) shows proportion of individuals contributing to different BGIs across Shawnee Run. Among the listed impacts, any live vegetation of a fluvial system could trap sediment and woody debris (small and large). Therefore, these impacts can be considered as generalized BGIs for all fluvial systems. Our results show that all the identified trees of our study area contribute in proportion to their numbers to these generalized BGIs (Figure 3.6). On the other hand, vegetation that can grow and develop on bedrock contributes to root and trunk bedrock weathering. About 44% of American sycamore contributed to bedrock weathering caused by root penetration and trunk growth – the highest among all species. However, only 22% of chinquapin oak took part in bedrock weathering in spite of their highest abundance amongst all species (Figure 3.6a). Further, figure 3.6(b) shows that the percent contribution of each species to total BGIs approximately coincides with the proportion of individual species out of total individuals. For example, chinquapin oak comprises ~40% of total individuals and its contribution to total BGIs is 38%. Thus, this figure clearly indicates that the contribution to total BGIs is related to species abundance.

However, the largest anomaly is American sycamore – while they represent ~21% of total individuals their contribution to total BGIs is around 30%.

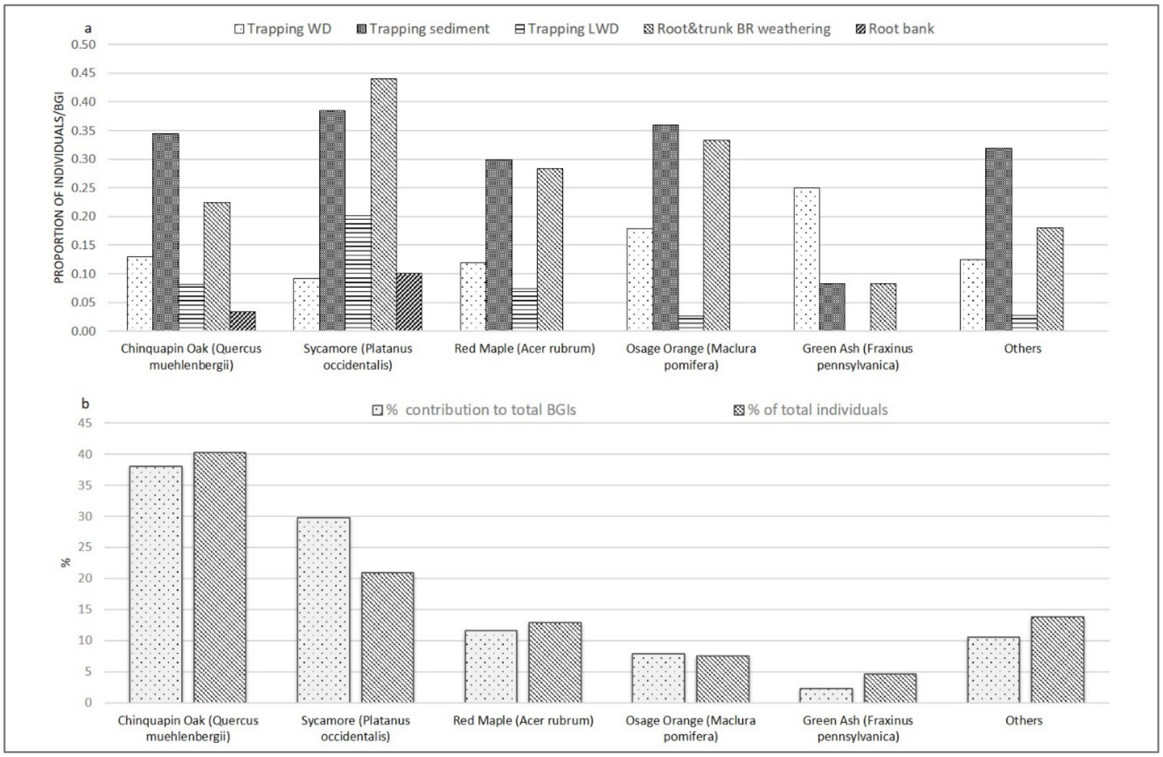

Figure 3.6: a) Proportion of individuals contributing to different biogeomorphic impacts ; for example, the first column indicates that 13% of chinquapin oak (*Q. muehlenbergii* were observed trapping woody debris, and b) percent contribution of each species to total biogeomorphic impacts and percent of individual species out of total individuals.
Note: One individual may have contributed to multiple biogeomorphic impacts, whereas some individuals may not contribute at all. Therefore, the sum of the proportion for each species may not yield a result of 1.

3.5.3 Species specific and general biogeomorphic impacts

Field observations suggest that trapping sediment and wood, and bedrock weathering are general biogeomorphic impacts, not closely linked to specific trees. Any species that can trigger bedrock weathering along the channel bed may play a distinct biogeomorphic role along bedrock fluvial corridors. Sediment trapping may occur in any vegetated stream. Field evidence identified three biogeomorphic outcomes that represent strong biogeomorphic influences not necessarily common in fluvial systems in general:

1. Biogeomorphic pool formation associated with bioweathering.
2. Development of avulsion associated islands related to bioprotection
3. Root banks

In addition, trees can also facilitate supply of sediment along the fluvial corridor via bioweathering.

3.5.4 Biogeomorphic pool formation

Pools can be formed by a diversity of mechanisms. Three distinct types of pools were identified in our study area, summarized in table 3.5, formed by variable process-form linkages.

Table 3.5: Types of pools in the study area, and their process of development

Pool Types	Process of development	# of pools identified
Log-dam pools	Blockage of flow by log jams or dams (e.g. Andrus et al. 1988; Figure 3.7)	2
Geomorphic Pools[*]	Formed by fluvial process-form linkage; for example helical hydraulics driven lateral migration (Thomson 1986); differential scour due to differences in sediment size distributions along a channel (De Almeida & Rodriguez, 2012; figure 3.8).	13 (2 with no vegetation)
Biogeomorphic pools	Vegetation induced bioweathering of channel beds (*P. occidentalis* for our study area) can initiate local depth variation. Subsequent flow-convergence routing driven by locally varying cross-sectional areas (MacWilliams *et al.* 2006) thus can lead to the development of pools (Figure 3.9, 3.10).	11

[*]Pools without any evident impact of vegetation on their formation are considered as geomorphic.

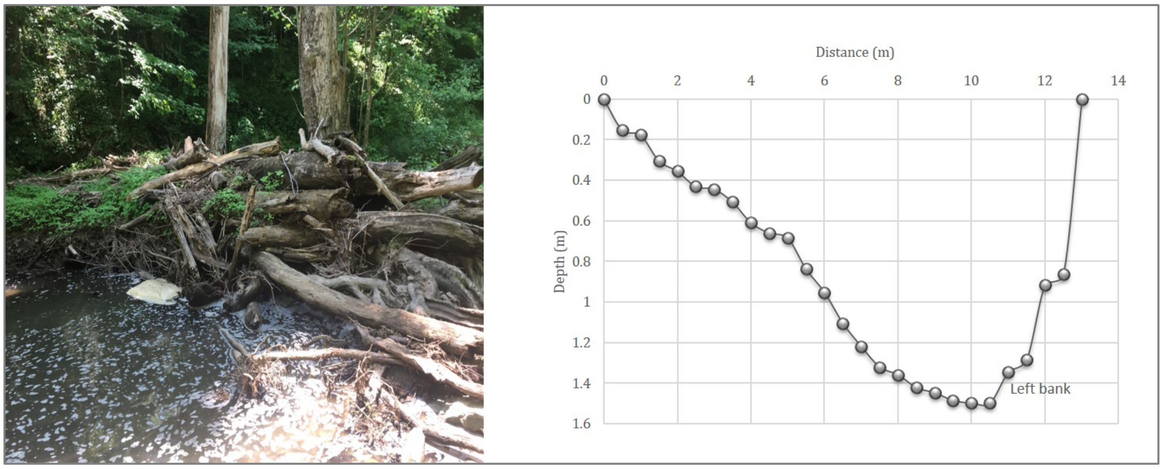

Figure 3.7: Example of a log-dam pool and the corresponding cross-section.

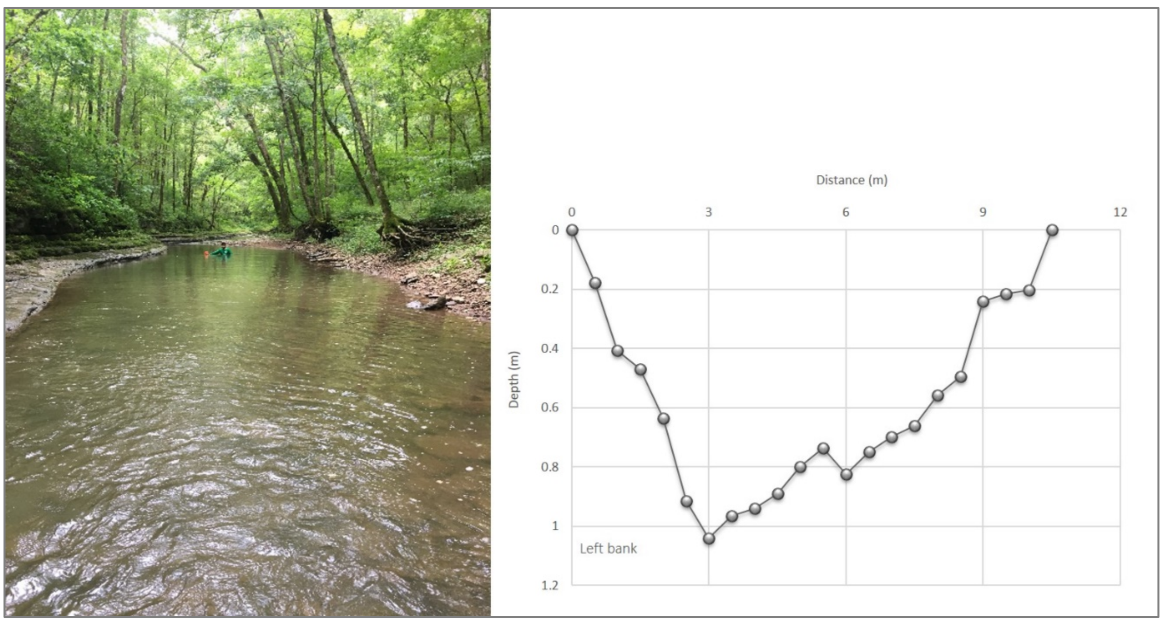

Figure 3.8: Example of a geomorphic pool and the corresponding cross-section, where the thalweg is on the left side of the bank. Despite presence of vegetation near bank, there is no evident impact of vegetation on pool formation.

Biogeomorphic pools can be defined as pools formed by direct impacts of biota induced channel bed weathering, which may subsequently evolve by fluvial erosion. In our study area biogeomorphic pools were only associated with American sycamore located on the bank top near the channel margin or within the channel. We set out two criteria for designating a pool as biogeomorphic:

1. A portion of the tree root impact should be within the bankfull channel, and roots must extend to the channel bed (Figure 3.9).
2. Thalweg should be close to the tree side of the channel (Figure 3.10).

Tsukahara and Kozlowski (1985) found that flooding of soil with standing water for 50 or 110 days drastically reduced growth of American sycamore seedlings, with longer flooding duration resulting in more growth inhibition. Sycamores typically responded to inundation by production of adventitious roots and hypertrophied lenticels (raised pores assisting in gas exchange) on saturated or submerged roots. Bonner (1966) also found that prolonged saturation caused severe growth reductions in sycamore. Tang and Kozlowski (1982) showed that flooding of American sycamore inhibited root elongation and led to root death. Conversely, American sycamore is more productive on well-drained sites and tolerates, but does not thrive, in hypoxic conditions (Bryan *et al.*, 2010). Field observation also supports this statement, as in several cases dead roots were identified within the hollows created by the sycamore roots. Additionally, in two instances, two dead sycamores were found in association with biogeomorphic pools (Figure 3.9).

This evidence suggests that American sycamore is extremely unlikely to extend roots into bedrock joints that are perpetually saturated, as is the case of pools of all types in Shawnee Run. This supports the suggestion that root extension into the channel bed occurred *before* pool formation. In many reaches, particularly riffles, channels are partially or fully dry (or flow is confined to the thalweg) during low flow periods all year long, and often for extensive periods during summer and early fall— this can potentially allow root penetration. After root-induced weathering initiates pool formation, adaptations such as adventitious roots and hypertrophied lenticels would allow roots to persist in the saturated rock.

However, none of the other tree species found in the study area exhibit these particular adaptations to saturated conditions (Tiner, 2016: ch. 6). Thus, even though chinquapin oak often penetrates bedrock and red maple is adapted to saturated soils, no other tree in the study area has the particular traits that would allow significant weathering of bedrock on the channel bed that could create or expand pools.

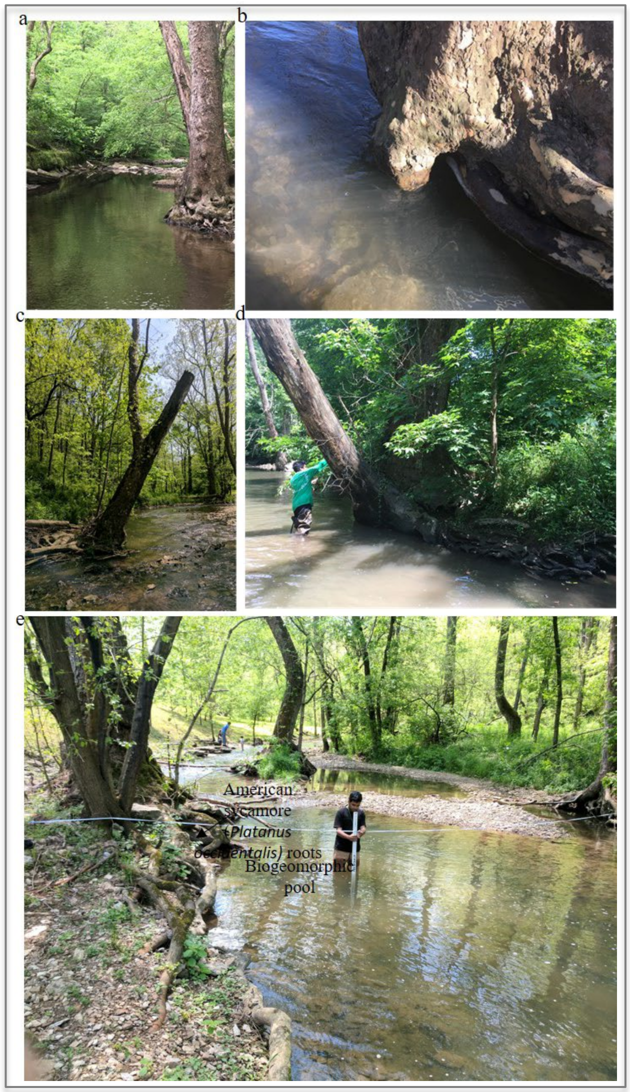

Figure 3.9: Examples of a biogeomorphic pool where (a,b) the American sycamore (*P. occidentalis)* tree root impact is within the bankfull channel and root extending to the channel bed; (c,d) two dead *P. occidentalis* associated with their pools; (e) a *P. occidentalis* root induced biogeomorphic pool— looking upstream (the corresponding cross section of this pool is displayed in figure 3.10a).

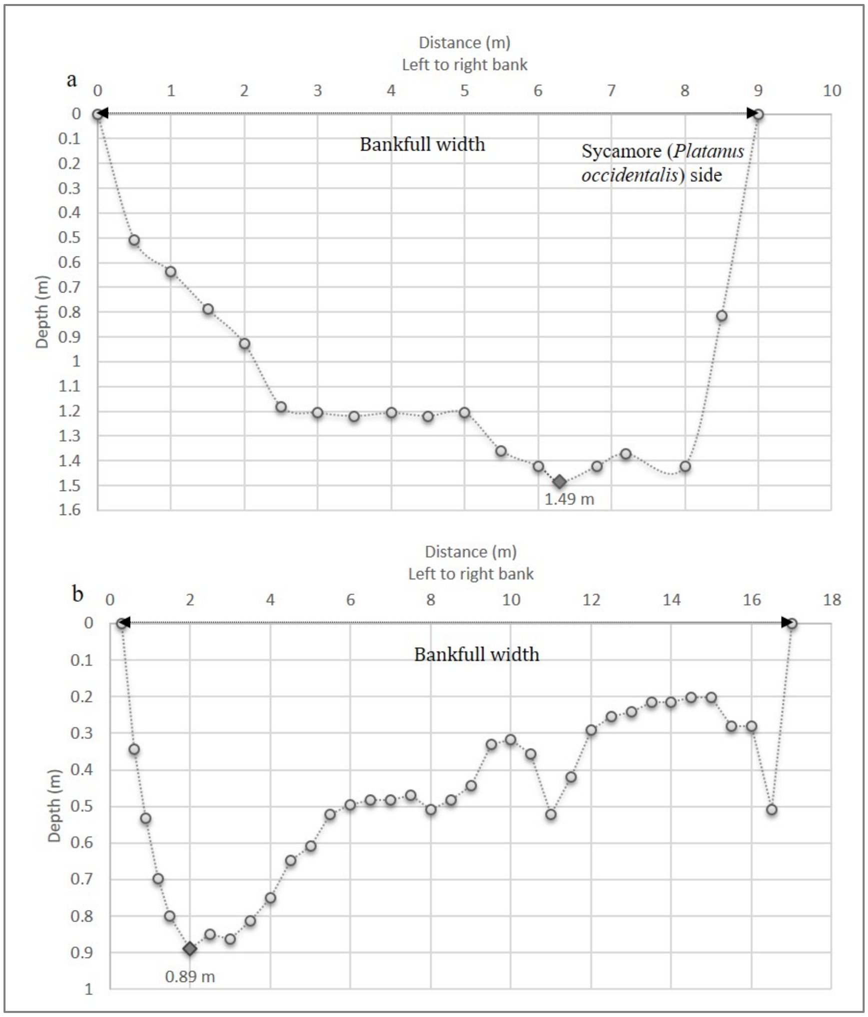

Figure 3.10: Two example cross-sections of biogeomorphic pools (with depth of the thalwegs demarcated) where (a) corresponds with the image displayed in figure 3.9e.

Identification of biogeomorphic pools was based on specific field observations – the criteria described above, plus visible evidence of sycamore root penetration of channel bed limestone and of displaced blocks in mid-channel (Figure 3.11 shows block displacement mechanism by sycamore root penetration comparable to areas where biogeomorphic pools were formed). For a more general test, a Chi-square analysis was performed to test relationships between dominant tree species and hydraulic units. The contingency table entries consisted of the number of sites of each HU (with riffles combined) with either American sycamore only, chinquapin oak only, both species, or neither (see table 3.6). The Chi-square test (Chi-square = 18.692, p-value <0.05, N = 95) indicates that there is a statistically significant relationship between the presence of sycamore and chinquapin oak, and the occurrence of pools, riffles and runs in the study area.

Figure 3.11: Block displacement mechanism by American sycamore (*P. occidentalis)* root penetration.

Table 3.6: Number of different hydraulic units associated with *P. occidentalis* (American sycamore) and *Q. muehlenbergii* (chinquapin oak).

Presence of species	*# of pools (%)*	*# of riffles (%)*	*# of runs (%)*
P. occidentalis only	9 (35%)	5 (10%)	2 (10%)
Q. muehlenbergii only	1 (4%)	18 (38%)	11 (52%)
Both	13 (50%)	18 (38%)	5 (24%)
None	3 (12%)	7 (15%)	3 (14%)

3.5.5 Avulsion associated island formation

The bioprotective role of vegetation may lead to the development of islands. Four such islands (three in the incising domain and one in the incised domain) were identified during the field survey. Field evidence indicates that these identified islands are of avulsion origin rather than that of newly accreted bar origin. Figure 3.12 shows an example of an avulsion-originated island recorded in our study area.

Figure 3.12: Example of an avulsion originated island located at the midstream section of Shawnee Run (looking upstream).

The proposed scenario is that a high-flow channel across the floodplain or valley bottom becomes incised and persists, and rejoins the main channel downstream. High resistance attributable to trees prevents erosion of the island area (McKenney et al. 1995). If this is the case, then there should be a total widening of the channel (width of the two channels minus island width) relative to upstream and downstream reaches. The substrate and vegetation characteristics should also be similar between the island and the adjacent riparian area. Thus the idea of avulsion-originated islands was grounded upon the following field evidence:

- *Distinct outer-bank-to-outer bank widening relative to upstream and downstream sections*: Field data show that the bankfull channel width increases noticeably at the island section compared to the channel width measured just upstream and/or downstream section without island (Figure 3.13). The data are presented in table 3.7.
- *Substrate characteristics:* Field observation indicates similar substrate characteristics between island surface and the adjacent floodplain surface.
- *Vegetation composition:* Vegetation composition between island and adjacent floodplain surface were similar – common species include American sycamore, chinquapin oak, red maple and honeysuckle.

Table 3.7: Channel width comparison between island reaches, and reaches just up and downstream of them.

Location of the island	Channel width (m) at the island section[1]	Channel width (m) just upstream of the island section	Channel width (m) just downstream of the island section
Midstream section-LGR	16.5	10-12[2]	14.2
Midstream section-LGR	16.5	9.5	11.5
Midstream-section-LGR & HGR	21.0	13.5	8-10.5[2]
Downstream-section-HGR	18.0	14.2	10-12[2]

[1]Not including island width.
[2]Indicates estimated value based on field photographs and Google Earth™ images.

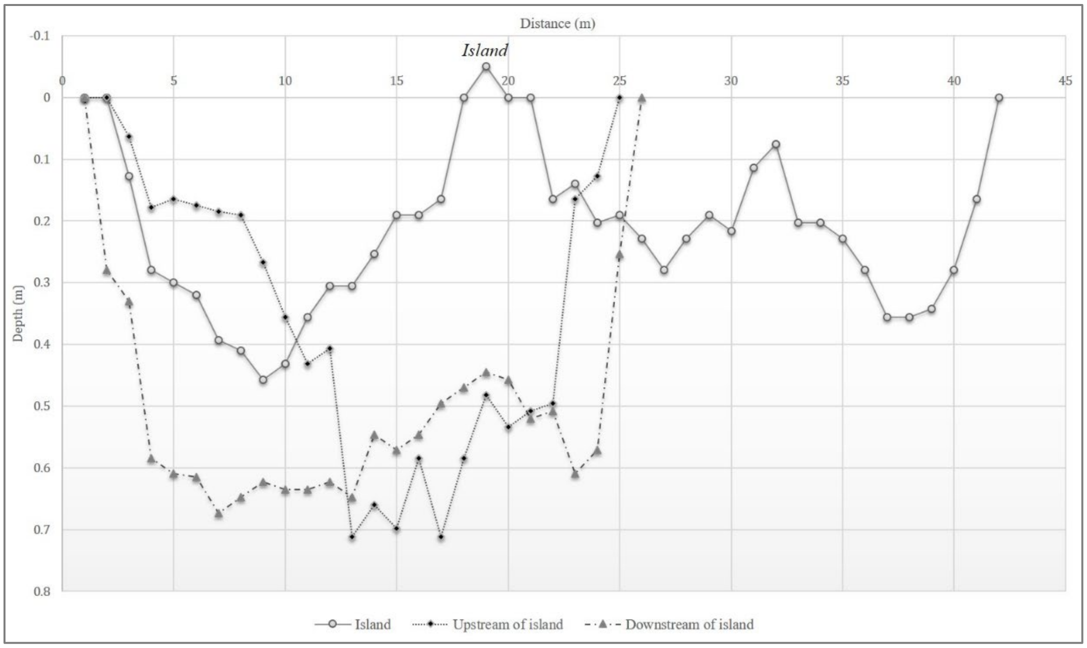

Figure 3.13: Example of channel cross-sections located at an island section, and just upstream and downstream of the island section.

Based on the field evidence, supporting our premise of the recorded islands having an avulsion origin, we hypothesized that the DBH of the dominant trees – a surrogate for the age (Gibbs 1963; Leak 1985) – located on the islands and the adjacent floodplains are equivalent. It is important to note that, the size (i.e., DBH) of a tree does not necessarily reflect its age because of site variation and history (Gibbs 1963; Leak 1985). However, in our case we choose to retain DBH as the surrogate of age because the site variation was insignificant. In addition, we were interested in the relative age difference rather than the true age variability.

The two most dominant species identified in the islands and the adjacent floodplains are American sycamore and chinquapin oak, making up ~81% and ~68% of the island and floodplain species respectively. Therefore, we carried out one-way ANOVA analysis, one for American sycamore and another for chinquapin oak, to test whether the mean DBH of the island and adjacent floodplain trees are significantly different. One-way ANOVA shows that there is no significant difference in DBH between island and adjacent floodplain trees (for sycamore $F(1, 10) = 0.181$, $P = 0.679$, $N = 12$; for chinquapin oak ($F(1, 9) = 0.457$, $P = 0.516$, $N = 11$). This confirms that the age of the island trees is comparable to that of floodplain trees, consistent with the islands being of avulsion rather than bar origin.

The species composition of the islands shows that about 48.5% of the island species are American sycamore, and about 33.3% is chinquapin oak. While these two species together make up about 81% of the island species, they constitute 61% (chinquapin oak ~ 40.2% and sycamore 21%) of the total species. Red maple, honeysuckle, and black walnut comprise the rest of the 18% of the island species. Results also show that mature trees, in terms of DBH, particularly large sycamore and chinquapin oak, dominate our study area islands with a mean and maximum DBH of ~43.40 and ~100 cm respectively. Grounded upon the above discussion of islands being of avulsion origin and species composition primarily dominated by mature American sycamore and chinquapin oak, we suggest that the bioprotective role of trees can lead to the development of avulsion-associated islands. While any woody vegetation might provide comparable bioprotection, large trees may play this role better.

3.5.6 Root banks

In our study area, root banks (Figure 3.14) commonly occur where bedrock is exposed, whereas alluvial banks rarely show evidence of this feature. The few examples of root banks in alluvial banks were associated with shallow soil covering the bedrock. Only chinquapin oak and American sycamore formed root banks (Figure 3.6), and only 14 individuals had this form out of 520 recorded

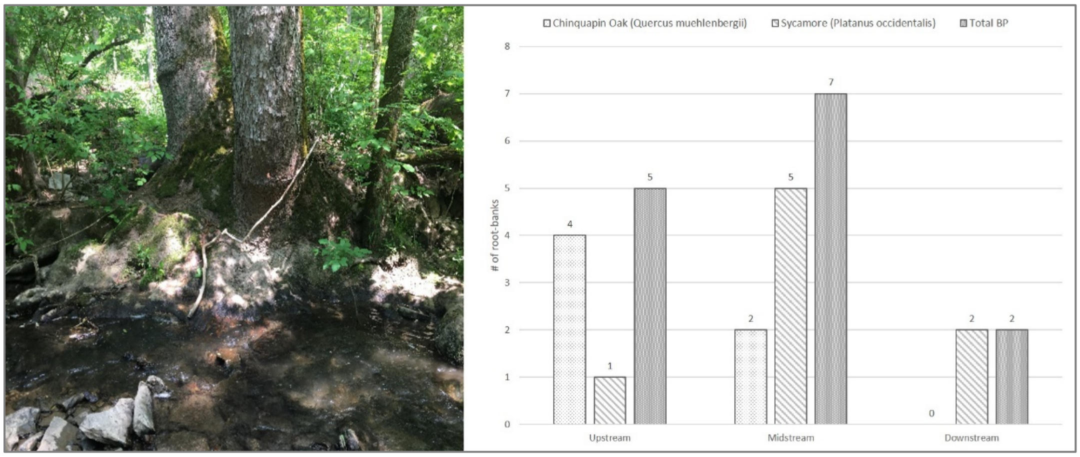

Figure 3.14: Root banks forming the bank of the channel and their distribution. Here, BP indicates bioprotection

3.5.7 Biogeomorphic sediment source

While bedrock weathering of channel beds caused by American sycamore can lead to the development of biogeomorphic pools, bedrock weathering across the riparian corridor can be a significant source of sediment in bedrock streams. Ample evidence of bedrock weathering triggered by root penetration (and also trunk growth) was identified during the field survey (Figure 3.15; also see figure 3.11).

Figure 3.15: Evidence of bedrock weathering caused by root penetration across Shawnee Run.

Results show that except for green ash, all other species significantly contributed to bedrock weathering associated with root penetration (see section 3.5.2 and figure 3.6). About 32% of the total BGIs recorded were associated with root-induced bedrock weathering. This BGI can potentially supply an extensive amount of sediment to a bedrock fluvial system, and thus can affect fluvial process-form dynamics.

3.6 Discussion

We conceptualized different biogeomorphic roles of live vegetation in table 3.1. In this section, we provide examples of these roles played by vegetation in our study area.

3.6.1 Biogeomorphic keystone species

Certain species can lead to biogeomorphic pool development by channel bed weathering along bedrock fluvial corridors (see section 3.5.4). Based on field evidence, this is a species-specific biogeomorphic impact, as it was exclusively associated with American sycamore in our study area. We developed a conceptual model consisting of three stages (Figure 3.16).

Stage 1 — Sycamore establishment and root penetration during dry/low flow period:

During the dry periods many riffles/runs dried out with minimal or no flow occurrence. During these periods, the sycamore (esp. those located near the channel margin) root can penetrate along the joints/bedding planes of the channel bed and bank.

Stage 2 — Local channel deepening due to root effects:

Penetration of sycamore roots and their subsequent growth along the channel bank margin and bed can promote bedrock displacement, detachment and/or disintegration, and weakening of resisting force of bedrock (e.g. Naylor et al. 2012). Thus, root penetration initiates the process of pool formation.

Stage 3 — Erosion and root persistence during high flows:

Greater shear stresses allowed weakened, detached, disintegrated bedrock from stage 2 to be removed by fluvial erosion. This can promote further root penetration and development during the later dry periods, and therefore pool growth and expansion. Meanwhile, existing roots persist. Though sycamore root growth is inhibited during wet conditions, adaptations such as adventitious roots and hypertrophied lenticels would allow roots to persist in the saturated rock during high flow conditions (Tsukahara & Kozlowski 1985).

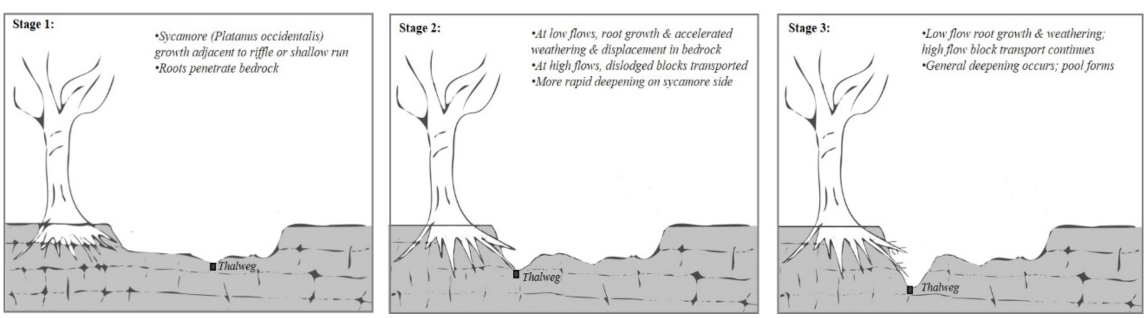

Figure 3.16: Conceptual model of biogeomorphic pool formation.

This model of biogeomorphic pool development shows how biotic influences can have a destabilizing effect on by promoting fluvial erosion. Such destabilization via root growth produces positive feedbacks fostering the development of biogeomorphic pools. Thus, this model indicates that feedback relationships between biotic and landform processes are needed to operate before a species becomes a biogeomorphic keystone. These feedbacks on biogeomorphic pool development occur in a specific envelope of conditions, which depend on the fluvial process magnitude and plant species traits that determine species response to wet and dry conditions (c.f. Eichel et al. 2015).

Biogeomorphic pool development brings about a local scale transformation of the stream channel caused by hydraulic unit modification. Thus, removal of American sycamore would result in fundamental changes in surface processes and morphology of the fluvial corridor. Therefore, we propose that American sycamore is a biogeomorphic keystone species in Shawnee Run, and perhaps more broadly in bedrock-controlled streams that are associated with well-defined bedding planes, joints and fractures – for example, limestone. Our field evidence, in the context of Power *et al.*'s (1996) concepts of ecological keystone species, suggests the following:

- Biogeomorphic pool development has considerable impact in the evolution of fluvial systems, and its development is linked to American sycamore in our study area. Further, American sycamore is not the most abundant species in our riparian system. A keystone species is one whose impact on its community or ecosystem (in our case on its fluvial system) is disproportionately large relative to its abundance (Power *et al.* 1996), and in our case American sycamore meets this criterion.
- According to Power *et al.* (1996), keystone species are context dependent, and not dominant in all parts of their range or at all times, but only play keystone roles under certain conditions. Further, Mills *et al.* (1993) indicated that the idea of

keystone species is often misleading as it may indicate the existence of a species-specific property of an organism; in reality the keystone role depends on many other factors, of which a particular environmental setting is crucial (Gautier-Hion & Michaloud 1989, Jackson & Kaufmann 1987, Levey 1988, Palumbi & Freed 1988). Similarly, American sycamore plays its keystone role when they are:

i) established on exposed bedrock or shallow soil/sediment along a fluvial corridor; otherwise root penetrating biophysical weathering would not be possible.

ii) located along stream banks (near channel margin), or in-channel, so that root-induced weathering directly affects the channel.

iii) larger with higher basal areas (threshold DBH > 60 cm based on field data), i.e. they are at the mature stage of their life.

iv) given enough time of dry periods (i.e. the windows of opportunity, after Balke 2014), for the root penetration and growth along the joints, fractures and bedding planes of channel bed.

The conversion of a riffle/run to a pool by American sycamore signposts that removal of this species would fundamentally change fluvial processes and morphology. Biogeomorphic pool formation by American sycamore thus demonstrates a new process of bed degradation. Therefore, it can be considered as a biogeomorphic keystone species.

3.6.2 Bioconstructors

Bioconstructors are organisms that construct the landform, or from which the landform is constructed. Root banks are developed when the root system of a living vegetation itself form the bank of the channel – a biophysically originated geomorphic form. They function as a bioprotective form that are resistant to fluvial erosion and thus equivalent to intact bedrock (Figure 3.13). As American sycamore, and chinquapin oak exhibit the form of root banks in our study area, therefore they can be designated as bioconstructors. Furthermore, they are autogenic bioconstructors as the root banks are comprised of the root system of these species. However, while this autogenic bioconstruction also appears to be passive bioconstruction i.e. the root banks are not formed for the benefit of that vegetation, it is unclear that in which situation these trees tend to form root banks.

3.6.3 Biogeomorphic equivalents

Biogeomorphic equivalents are species that have similar BGIs, such that they are essentially interchangeable with respect to surface processes and landforms. The proposed idea of *avulsion originated island formation* is an example of biogeomorphic roles caused by biogeomorphic equivalents. The development of resistant patches of landforms, caused by bioprotective function of vegetation, promotes island growth – a process equivalent to geomorphic processes and forms. As American sycamore and chinquapin oak dominated the avulsion originated islands, therefore they can be designated as biogeomorphic equivalents for our study area. However, any live vegetation, particularly larger mature trees, are likely to be able to play this bioprotective role. Thus, the role of biogeomorphic equivalents are linked to the generalized BGIs of vegetation rather than that of species-specific.

3.6.4 Other biogeomorphic roles

Live vegetation can play role as biogeomorphic influencers and/or separators. Separators may also be influencer or keystone species based on the effectiveness of their role on geomorphic forms. Biogeomorphic influencers, although exhibit significant direct impacts on surface processes and landforms, but not sufficient to bring fundamental changes. For example, we identified osage orange and red maple in our study area that have substantial impact on bioweathering caused by root penetration along the joints and fractures of bedrock. However, we could not designate them as 'keystone separator species' since the root system of osage orange and red maple do not cause weathering of channel bed such that it would bring any significant alteration of the fluvial system. Hence, other than chinquapin oak and American sycamore, the rest of the thirteen species of our study area (table 3.4) can be classified as biogeomorphic influencers. Moreover, osage range and red maple, are also *biogeomorphic equivalents* (a particular form of *influencer*) as they play interchangeable biogeomorphic role by promoting bedrock bioweathering.

3.7 Conclusions

This research deals with species-specific and general BGIs from the context of keystone and other biogeomorphic roles. Our empirical study on a bedrock controlled stream in Kentucky identified that American sycamore is exclusively associated with *biogeomorphic pool* development via bioweathering. . These pools can substantially alter the fluvial-process-form dynamics, and the absence of American sycamore would result in fundamentally different channel morphology. Further, we found that certain species, American sycamore and chinquapin oak, can play the role of autogenic bioconstructors by developing a distinct bioprotective forms, root banks – a biophysically originated geomorphic form. We also identified that trees can promote avulsion-originated island formation by creating erosion-resistant bioprotective patches. While any live vegetation can play comparable bioprotective roles (i.e. a generalized BGI), certain species may play this role better than others, particularly at the mature stage. We found that large (in terms of DBH) American sycamore and chinquapin oak dominated the islands of our study area and play comparable roles with respect to avulsion-originated island development via bioprotection. Thus they are designated as biogeomorphic equivalents. Lastly, we discovered that vegetation-induced bedrock weathering functions as an important source of sediment in bedrock streams. However, just about all species identified in our study area can play this biogeomorphic role, and thus can be recognized as biogeomorphic influencers that are also equivalents.

Our research brings forth some important future research concerns. The biogeomorphic pool formation analysis needs further investigation in other bedrock fluvial environments. Future research should examine whether biogeomorphic pools are exclusively associated with American sycamore in other fluvial systems. Further, while root-banks are characterized as important bioprotective form in our study area, a key question is whether root banks, in the long term, actually facilitate bank erosion over protection. While living roots are highly resistant and shield bedrock from hydraulic forces, the roots probably facilitate dissolution, rock slab displacement, and other forms of weathering. When the tree dies, the exposed bank may be more weathered and erodible than bedrock banks that have not had root banks. This deserves further research (Jerin 2019).

Finally, while we did not find any examples of biogeomorphic separators in our study area, the existence of keystone species at least suggests that possibility. Thus, the identification of biogeomorphic separators and keystone species can potentially facilitate the recognition of critical points in the coevolution of geomorphological and ecological systems.

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CHAPTER 4. SCALE ASSOCIATED COUPLING BETWEEN CHANNEL MORPHOLOGY AND RIPARIAN VEGETATION IN A BEDROCK-CONTROLLED STREAM

Abstract

Most fluvial systems exhibit systematic, continuous upstream-to-downstream variations in channel morphology and related ecological and hydrological parameters (emphasized by conceptual frameworks such as downstream hydraulic geometry and the river continuum concept), and discontinuous, shorter range variations (emphasized by hierarchical patch dynamics). This study investigates the relative importance of broader-scale up-to-downstream variation and local variation at the hydraulic unit scale in a bedrock-controlled stream in central Kentucky. A nested ANOVA analytical approach was used to determine the relative importance of three nested spatial scales in explaining variations in channel morphology and riparian trees. Results show that channel morphology is largely controlled by local-scale variation explaining about 92% of slope, 46% of bankfull width, 99% of average depth, 54% of width-depth ratio, 86% of channel cross-section area, and 100% of the hydraulic radius of the channel. Different categories of substrate characteristics, however, represent anomaly with respect to variance explained at different levels. Furthermore, local-scale controls explain 60% variations in species richness, 59% variations in the total number of individual trees, 68% variation in the proportion of Platanus occidentalis basal area and 43% of variation in the total number of biogeomorphic impacts. These results are consistent with the idea of tight coupling between channel morphology and riparian vegetation, although they do not, by themselves, prove such interactions. The morphological variation of the channel at the local scale is primarily attributable to the geological controls (e.g. faults, bedding planes, joints and fractures) and incision status associated with the study area. The local scale variation in vegetation pattern can be explained by the highly local edaphic differences along the riparian corridor which is likely to be related to the local scale fluvial process-form variations, and biogeomorphic impacts and feedbacks. These patterns may therefore be common in bedrock rivers strongly influenced by geological controls.

Keywords: Bedrock rivers; channel morphology; riparian vegetation; local scale.

Chapter under review as:

Jerin, T., 2020. Scale associated coupling between channel morphology and riparian vegetation in a bedrock-controlled stream. *Geomorphology* (under review).

4.1 Introduction

The interplay of physical forms and processes and biota in a fluvial system generates a complex network of interactions. These interactions have traditionally been construed under the framework of the River Continuum Concept (RCC). RCC considers a river system as a continuous gradient of physical conditions from up- to downstream resulting in a continuum of biotic adjustments and consistent patterns of loading, transport, utilization, and storage of organic matter along its length (Vannote *et al.* 1980). While RCC remained a dominant idea in stream ecology through the twentieth century (Thorp et al. 2008), divergence from this continuum assumption is reflected in many biogeomorphic and ecological studies (e.g. Statzner and Higler 1985, 1986; Townsend 1996; Montgomery 1999; Rice et al. 2001; Benda et al. 2004; Parsons and Thoms 2007). New perspectives on riverine environments emphasize discontinuity and patchiness (Thorp et al. 2008) and focus on the importance of fine-scale functional units – hydrogeomorphic patches. Local controls can lead to the development of spatially distinct patches of relatively homogenous surface flow and substrate characteristics (defined as hydraulic units; see Kemp et al., 2000; Newson and Newson, 2000; Thomson et al., 2001). Studies on the spatial arrangement of river systems have shown that rivers exhibit abrupt changes in hydraulic character, morphology, and biology, rather than displaying a gradient of change reinforced by the notion of continuum (Townsend 1989; Montgomery 1999; Poole 2002). According to Weins (2002) rivers have an internal structure of their own, and the spatial pattern of this heterogeneity within rivers comprises a landscape that is quite dynamic, varying in patch composition and configuration in response to changes in hydrologic flow regimes (Marald et al. 2002). Belletti et al. (2017) pointed out the importance of patch scale for linking the physical and biological conditions in a river system. According to them hydrogeomorphic patches, for instance riffles, pools, bars, islands etc. create distinct habitats for aquatic and riparian biota. Thus, they provide physical template that supports the delivery of the key environmental conditions required to support life in rivers (Belletti et al. 2017). However, most (if not all) fluvial systems display both systematic up- vs. downstream differences and hydrogeomorphic patches. What is the relative importance of these in explaining spatial variation of channel morphology and biogeomorphological phenomena? In this paper, I explore a limestone bedrock-controlled stream, Shawnee Run — located in central Kentucky, USA. The aim is to identify the most important scale of variation controlling geomorphic, vegetation and biogeomorphic components.

The river continuum concept depicts riverine systems, together with their biotic elements, as intergrading, linear networks from headwaters to the mouth (Vannote et al. 1980). It is related to the classical downstream hydraulic geometry (DHG) theory. DHG was first described qualitatively by Leonardo da Vinci (Shepherd and Ellis, 1997) and later analyzed quantitatively by Leopold and Maddock (1953). DHG states that as discharge increases in the downstream direction, channel morphology increases consistently to accommodate the discharge. However, the river continuum concept is founded on the premise that physical river environment provides energy, organic matter, and habitat to organisms such that ecological patterns in the downstream direction are established by the DHG. Thus, distributions of biotic communities in the downstream direction parallel the physical changes in the fluvial geomorphology (Rosenfeld et al. 2007; Fonstad and Marcus 2010). The key question is then the extent to which the latter vary continuously upstream-to-downstream, versus a more complex, patchy spatial pattern.

The river continuum concept is currently the dominant theory used deliberately or *de facto* by riverine ecologists or environmental scientists/managers (Thorp et al. 2008). However, several researchers have argued that while predictable downstream patterns may exist from a large spatial-scale context, fluvial systems are not characterized by gradual physical and biotic adjustments. For example, Statzner and Higler (1985, 1986) contended that hydraulics were the most important factors controlling stream benthonic zonation on a worldwide scale. They argued that rather than a steady gradient of stream hydraulics (i.e. river as a continuum), discontinuities associated with transition zones in flow and resulting substrate size were the critical determinants of changes in species assemblages. A study carried out on the network scale has shown that while relationships between width, depth, velocity, slope and other variables often show general trends with increasing discharge area in a fluvial system, they are overlaid by massive variability that is not at all consistent with DHG (Fonstad and Marcus 2010) — and therefore RCC. Other studies that depict rivers as a compounding system of broad scale trends in energy, matter, and habitat structure, in addition to local discontinuous zones and patches, include Fausch et al. (2002), Poole (2002), Ward et al. (2002), Wiens (2002), and Carbonneau et al. (2012).

Several studies promoted the use of the framework of hydrogeomorphic patches for studying the spatial arrangement of river systems (Belletti et al. 2017; Phillips 2017; Eros and Grant 2015; Milan et al. 2010; Shoffner and Royall 2008; Wiens 2002; Newson and Newson 2000). According to Belletti et al. (2017), the analysis of relationships between patch scale geomorphic units i.e., physical habitats and biota, can provide a physical basis for biological surveys with respect to habitat heterogeneity, composition, and attributes at a scale that is geomorphologically meaningful. Phillips (2017) points out the importance of patch scale over the repeated sequence of patches (e.g. riffles, pools and runs) by examining richness and diversity of hydraulic units along a river corridor.

Further, some researchers have pointed out potential circumstances fostering deviations from the RCC predictions. For example, Minshall et al. (1983) noted that divergence from the RCC predictions occur owing to the disparate influence of watershed climate and geology, riparian conditions, tributaries, and location-specific lithology and geomorphology. While some researchers consider any divergence from RCC as *exceptions*, some others (e.g. Poole 2002, Thorp et al. 2006), contend that these exceptions are in fact the rule (after Thorp et al. 2008).

River systems often display abrupt changes in hydraulic character, morphology, and biology, and thus can contradict with the idea of exhibiting gradual changes purported by DHG and RCC. For example, in large floodplain settings, river systems are largely influenced by the lateral exchanges of water, sediment, and nutrients in addition to upstream processes (Junk et al. 1989). Further, Ward and Stanford (1983) point out how dams can reset the longitudinal continuum of a river via abrupt transition. Carbonneau et al. (2012) indicate that discrete hydraulic barriers such as waterfall and hydraulic jumps can hinder the upstream-downstream connectivity, and consequently organisms' mobility. As a result, alternative perspectives were developed emphasizing discontinuity and patchiness of the spatial organization (Thorp et al. 2008). Discontinuities are often linked to regional and local variations in climate, geology, riparian conditions, tributaries, lithology, and/or geomorphology, or with human interruptions disrupting the flow, sediment, and/or disturbance regimes. Thus, discontinuities and deviations indicate a break in the contiguous up- to downstream network, whereas RCC is primarily dependent on the idea of all components being strongly connected with each other (Callum et al. 2009).

Fluvial biogeomorphic systems are characterized by complexity, caused by multi-causality and variable process-form linkages at different scales (e.g. Smiley and Dibble 2005; Parsons and Thoms 2006), which limits the practicality of the reductionism approach in such systems (Thorp et al. 2008). However, studying the spatial arrangements of river systems under the framework of *hydrogeomorphic patches* can be a useful approach for interpreting system complexity. Many studies in ecology and Earth sciences have adopted this approach for understanding complexity in their system (e.g. Clifford et al. 2006; Milan et al. 2010; Eros and Grant 2015, Belletti et al. 2017).

4.2 Study area

The study area, Shawnee Run, is located in the Kentucky River gorge area of the Inner Bluegrass karst region in central Kentucky (figure 4.1). It is a tributary of the Kentucky River (note: on U.S. Geological Survey maps, Shawnee Run is incorrectly shown as Shaker Creek) draining about 43.5 km^2 of surface drainage area with a total length of about 20 km. Shawnee Run is a bedrock-controlled stream dominated by limestone lithology with discontinuous coarse alluvial cover. The study area was selected because it is part of a nature preserve and has been minimally disturbed along the fluvial corridor.

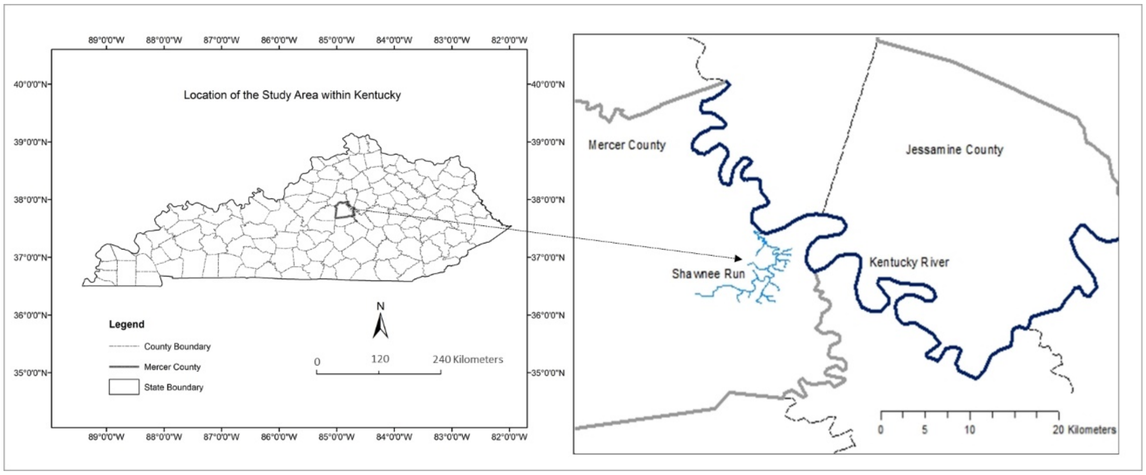

Figure 4.1: Location of the study area in Mercer County, Kentucky.

The Inner Bluegrass region has a topography characterized by low relief and gentle ridges, except in the Kentucky River gorge area. Local relief of 100 m is common there, and river-to-cliff or bluff top relief ranges from 61 to 131 m. The bedrock in the area is comprised of the High Bridge Group and the Lexington Limestone, both Middle Ordovician (Sparks *et al.*, 2001). The High Bridge Group further consists of three formations: in ascending order, the Camp Nelson Limestone, the Oregon Formation, and the Tyrone Limestone.

The Kentucky River and its tributaries are strongly incised. Incision from the former course to the modern channel apparently was triggered by base-level changes, a result of glacial modification of the Ohio River drainage system ca. 1.3 to 1.8 Ma (Teller and Goldthwait, 1991; Andrews, 2004). The evidence of headward incision via slope adjustment is conspicuously detectable in Shawnee Run. The downstream, strongly incised section has reached the base level of the Kentucky River and exposed the relatively older Camp Nelson Limestone formation. The mid-stream) section is still incising, and has yet to reach the Camp Nelson formation; this part has uncovered the younger Tyrone

Limestone and Oregon Formation. The upstream part displays little or no prominent incision; the youngest Lexington Limestone is predominantly exposed, with partial exposure of Tyrone Limestone and Oregon formation near the end of this section.

The climate is humid subtropical, and mean annual precipitation is about 1200 mm. The dominant land use in the vicinity of the study area is pasture (cattle and horse grazing) and forest. Potential natural vegetation is dominantly forest, though savanna and grassland ecosystems existed (and some still persist) in the Bluegrass Region (Campbell, 1989).

4.3 Methods

4.3.1 Sampling method

This research is based on a hierarchical sampling method where smaller spatial scales are nested within larger scales. Field data was collected between April and July 2018.

The study areawas divided into three hierarchical scales: domains, reaches and hydraulic units. Domains were the broadest spatial scale, and classified as unincised, incising and incised based on the morphological contrasts related to the incision status and valley side relief of the channel. The unincised domain located at the upstream portion exhibited ~ 5-15 m of valley side relief while valley side relief of the incised domain displayed was ~ 50-70 m at the downstream section of Shawnee Run. In between, the incising domain ranges has ~ 25-35 m of valley side relief. From each domain, three reaches were surveyed where the starting point of each reach was selected randomly. Thus, a stratified random sampling method was used. Each reach consisted of ten hydraulic units, the smallest spatial scale of this study, and the total length of the HUs of a reach determined the reach length, which ranged from 117 to 177 m. The locations of the domains, reaches and hydraulic units are shown in Figure 4.2.

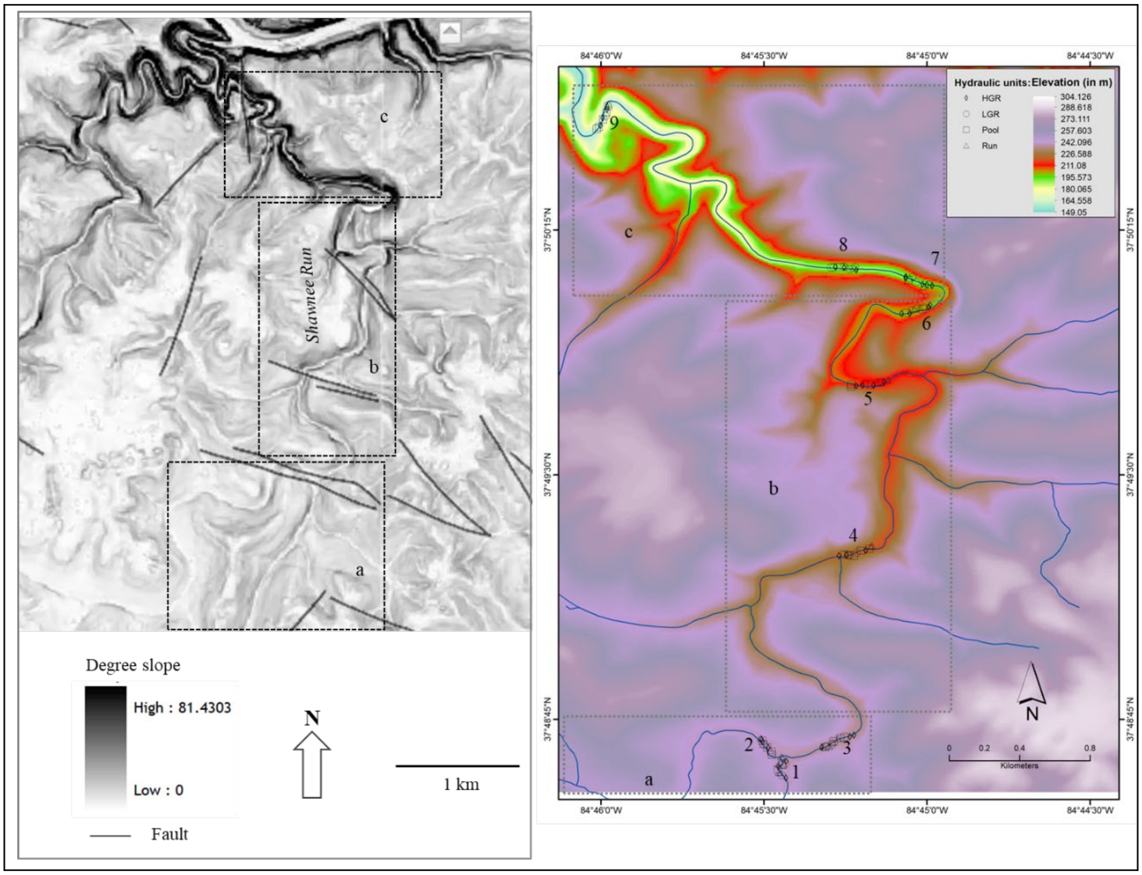

Figure 4.2: The slope map (left) and elevation map of Shawnee Run with sampling sites demarcated in the elevation map. The dotted boxes display (a) unincised portion and reaches 1-3; (b) moderately incised portion and reaches 4-6; (c) strongly incised portion and reaches 7-9 (base map: Kentucky Geologic Map Information Service).

Hydraulic units are spatially distinct patches of relatively homogenous surface flow and substrate character (Fryirs & Brierley, 2012). Four distinct categories of hydraulic units were identified: high gradient riffle (HGR), low gradient riffle (LGR), pool and run (Figure 4.3). The average lengths of hydraulic units are 13.6, 15.2 and 13.7 m surveyed in the unincised, incising, and strongly incised domains, respectively.

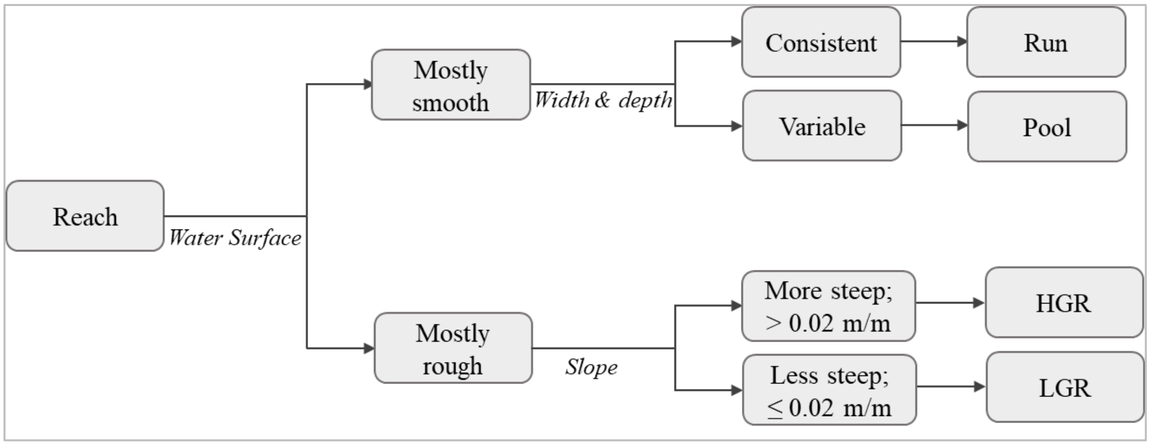

Figure 4.3: The classification scheme of hydraulic units (HUs) at each reach. (redrawn after Jerin and Phillips 2020).

The classification scheme of HUs (Figure 4.3) is primarily based on the channel morphological variation associated with channel bed slope, and width and depth. The irregularity of the water surface within a reach, caused by channel slope and roughness variations, distinguishes the runs and pools from the riffles. Further, pools and runs were separated based on the width and depth variability within a reach. The distinction between low and high gradient riffles were based on the variation in steepness of the slope. The threshold value of slope steepness separating HGR and LGR in the study area is 0.02 m/m, determined based on the field reconnaissance results. As the determination of HUs is unavoidably influenced by streamflow and stage, they were demarcated at flows below bankfull, but well above summer low-flow levels.

4.3.2 Geomorphic survey

The geomorphic field data obtained via field survey includes channel bed elevation and cross-section data. The longitudinal profile of each reach was developed using the bed elevation values measured using a laser level and prism along the thalweg of the channel.

The longitudinal profiles were used to determine the HU and reach scale slopes. The HU values were further used for discerning HGR and LGR.

A total of 90 channel cross sections were measured. Bankfull channel width and depth were measured at the approximate mid-point of each HU using a measuring tape and a rod. Bankfull channel depth was measured at 0.5 m intervals or less. These measurements were used to calculate bankfull average depth, maximum and minimum depth, and width/depth ratio. Bankfull flow elevations were identified based on the floodplain surface following methods described by Stream Systems Technology Center (2002). The key to designate the bankfull elevation is to identify the relatively flat depositional surface of the floodplain, as bankfull stage occurs when water just begins to overtop the floodplain. Along the inside of meander bends (the level top of a point bar is a reliable indicator of bankfull elevation), and along both sides of straight reaches where the floodplain is easily detectable are optimal locations for delineating bankfull elevations.

For each hydraulic unit, dominant substrate characteristics was determined. While channel width and depth data were collected for each hydraulic unit, substrate characteristics per interval (≤0.5 m) of the channel width was recorded. The substrates were categorized as intact bedrock; fine grained alluvium (FGA); cobbles; boulders; gravels; mixture of gravel, cobbles, boulders and FGA; mixture of bedrock, fine grained alluvium and others; tree roots.

4.3.3 Vegetation survey

The vegetation survey was conducted within the riparian zone of each HU. Any tree with a portion of trunk within 2 m of the banktop, on the bank, or within the channel was included. All woody plants with a diameter at breast height (1.37 m above ground level) ≥ 5 cm were identified. Circumference at breast was measured using a measuring tape to derive diameter at breast height (DBH) and basal area (BA). Also determined from the vegetation survey were species richness, total number of individuals, and proportion of American sycamore (*Platanus occidentalis)* basal area. American sycamore, in comparison to other identified species, exhibits larger contribution to biogeomorphic impacts relative to their proportion (Jerin and Phillips 2020). Further, their total basal area is larger than that of any other species identified in the study area.

4.3.4 Biogeomorphic survey

The biogeomorphic survey scheme is based on the designation of impacts of vegetation on channel forms and processes measured during the vegetation survey. An inventory of important biogeomorphic impacts associated with bedrock streams was developed based on the field reconnaissance survey and after Jerin (2019). The biogeomorphic impacts observed include live vegetation associated sediment and wood trapping, anchoring of bars and islands, root banks promoting bioprotection, root and trunk growth fostering bioweathering, and bedrock mining caused by tree uprooting. Individual trees may be associated with multiple biogeomorphic impacts. Therefore, the number of biogeomorphic impacts associated with each riparian tree was recorded too.

4.3.5 Statistical analysis

The spatial variability of geomorphic, vegetation and biogeomorphic variables was investigated using nested or hierachical ANOVA, which allows evaluation of the contributions of multiple spatial scales to overall variance. While ANOVA is a common statistical method used to analyze differences between group means, nested ANOVA is a special case of ANOVA that allows for the variance of the lowest level of a hierarchy to be used to estimate the variance of all other levels. Nested ANOVA procedures have been an accepted statistical analysis method in geography dating back at least to 1965 (Haggett et al. 1965; Phillips 1986). While this method lacks the resolution of geostatistics and autocorrelation (Campbell 1978), it provides information about key scales of variation and has been successfully implemented in several geographic applications (e.g. Jamieson et al. 1983; Nortcliff 1978; Shouse 2014). The nested ANOVA procedure provides important clues about the key scale of variation via variance partitioning; i.e. it allows determination of the percent of variance attributable to each hierarchical level. For this research, a nested analysis of variance is performed at three levels: i) among domain locations based on valley side relief and incision status, ii) among reaches nested within each domain, and iii) among hydraulic units nested in each reach. For each level, two sets of hypotheses were formulated; one for the channel morphology data block (set A), and another for vegetation and biogeomorphology (set B).

Classical notions of downstream hydraulic geometry (Leopold and Maddock 1953) as well as the RCC produce a hypothesis (H1A) that variation of channel morphology is controlled and explained mainly by systematic upstream to downstream variation. Two alternatives linked to more spatially complex hierarchical patterns of variability are: H2A--variation of channel morphology is controlled and explained mainly by reach-scale variations related to local variations in geomorphic controls superimposed on general upstream to downstream trends; and H3A--channel morphology variability is linked mainly to highly local variations related to local lithological and structural controls.

These are associated with analogous hypotheses regarding riparian trees. These are that variation of riparian trees is controlled and explained mainly by: systematic upstream to downstream variation (H1B); reach-scale variations related to local variations in habitat superimposed on general upstream to downstream trends (H2B); or highly local edaphic variations related to the hydraulic unit scale (H3B). Variation in riparian trees refers to variation in species richness, total number of individuals, proportion of American sycamore basal area, and total number of biogeomorphic impacts associated with vegetation. Further, this study aimed to identify at which scale the spatial patterns and distribution of channel morphology and riparian trees are most tightly coupled. The hypotheses are:

H_o: Spatial patterns and distributions of channel morphology and riparian trees are only loosely coupled, such that their variation occurs at different scale levels.

H_A: Spatial patterns and distributions of channel morphology and riparian trees are tightly coupled, such that their variation occurs at the same scale level.

Results of the hierarchical ANOVA are also directly comparable to semivariance analysis (Miesch 1975). Data transformation was conducted for maintaining the normality assumption required for ANOVA analysis.

4.4 Results

4.4.1 Channel morphology

The geomorphic data block, representing channel morphology, includes eight variables: channel slope, bankfull width, bankfull average and maximum depth, width-depth ratio, channel cross-section area, wetted perimeter and hydraulic radius. Nested ANOVA was carried out on six of these variables excluding maximum depth and wetted perimeter, as maximum and mean depth, and wetted perimeter and channel width are closely related.

Results show that slope values vary considerably at local hydraulic unit scale while the reach-scale slope values are similar at each domain. The mean slope value of the unincised reaches is 0.01, and of incising and incised reaches is 0.02. For all reaches, the minimum slope is zero and the maximum slope values can be found in midstream reaches. Bankfull channel width increases from up- to midstream. However, from mid- to downstream a decreasing pattern is observed. A similar trend can be observed for the channel cross-section area and the width-depth ratio variables. Width-depth ratio also shows the largest standard deviation in all nine reaches (table 1) and all three domains (table 2) among all variables. While the bankfull average depth and hydraulic radius variables locally vary considerably, the mean values of these two variables at reach and domain scale remain more or less consistent. However, the maximum values of the bankfull average depth and hydraulic radius can be found at the midstream-incising reaches, while the lowest values are in upstream unincised reaches. A summary of the data is presented in tables 4.1 and 4.2, and results are discussed in more detail below.

Table 4.1: Descriptive statistics of geomorphic data block by reaches.

Reach ID	Descriptive Statistics	Slope (m/m)	Bank-full Width (m)	Bankfull Ave Depth (m)	Width-depth ratio	Cross-section area (sq. m)	Hydr-aulic radius (m)
1	*Mean*	0.01	6.54	0.55	13.23	3.49	0.50
	Max	0.03	8.90	0.76	23.62	4.17	0.64
	Min	0.00	4.60	0.30	6.68	2.19	0.30
	Standard deviation	0.01	1.39	0.15	6.13	0.69	0.10
2	*Mean*	0.01	6.55	0.44	15.99	2.95	0.44
	Max	0.05	8.00	0.66	30.60	5.25	0.66
	Min	0.00	5.60	0.19	11.97	1.10	0.19
	Standard deviation	0.02	0.71	0.12	5.73	1.04	0.12
3	*Mean*	0.01	8.53	0.50	17.35	4.31	0.50
	Max	0.04	10.50	0.60	24.15	5.92	0.60
	Min	0.00	6.00	0.37	13.40	2.41	0.37
	Standard deviation	0.02	2.81	0.24	9.61	3.06	0.22
4	*Mean*	0.02	10.76	0.52	23.80	5.74	0.51
	Max	0.06	14.60	1.02	44.48	11.58	0.91
	Min	0.00	6.55	0.23	8.82	1.49	0.23
	Standard deviation	0.02	2.81	0.24	9.61	3.06	0.22
5	*Mean*	0.02	12.72	0.47	31.61	6.04	0.47
	Max	0.04	16.50	0.85	73.53	11.02	0.85
	Min	0.00	8.15	0.22	15.34	2.93	0.22
	Standard deviation	0.01	2.71	0.19	17.61	2.87	0.19
6	*Mean*	0.02	13.74	0.39	40.44	5.24	0.38
	Max	0.06	21.70	0.82	80.77	9.22	0.73
	Min	0.00	7.00	0.18	8.51	1.84	0.18
	Standard deviation	0.02	5.28	0.18	19.17	2.53	0.15
7	*Mean*	0.02	10.67	0.47	24.18	5.17	0.47
	Max	0.04	20.00	0.68	48.24	10.32	0.68
	Min	0.00	5.80	0.23	12.55	2.51	0.23
	Standard deviation	0.01	3.89	0.13	11.15	2.69	0.13
8	*Mean*	0.01	13.66	0.44	33.60	6.16	0.44
	Max	0.02	16.00	0.67	52.84	9.78	0.67
	Min	0.00	12.00	0.24	21.50	3.00	0.24
	Standard deviation	0.01	1.48	0.15	9.53	2.49	0.15
9	*Mean*	0.02	10.65	0.46	25.92	4.88	0.46
	Max	0.05	12.20	0.67	38.86	7.25	0.67
	Min	0.00	8.30	0.27	13.67	2.30	0.27
	Standard deviation	0.02	1.31	0.15	8.49	1.74	0.15

Table 4.2: Descriptive statistics of geomorphic data block by domains.

Domain	Descriptive Statistics	Slope (m/m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Width-depth ratio	Cross-section area (sq. m)	Hydraulic radius (m)
Unincised	*Mean*	0.01	7.21	0.50	15.52	3.58	0.48
	Max	0.05	10.50	0.76	30.60	5.92	0.66
	Min	0.00	4.60	0.19	6.68	1.10	0.19
	Standard deviation	0.01	1.54	0.13	5.27	1.16	0.10
Incising	*Mean*	0.02	12.41	0.46	31.95	5.67	0.45
	Max	0.06	21.70	1.02	80.77	11.58	0.91
	Min	0.00	6.55	0.18	8.51	1.49	0.18
	Standard deviation	0.02	3.87	0.20	16.93	2.75	0.19
Strongly Incised	*Mean*	0.02	11.60	0.46	27.40	5.44	0.46
	Max	0.05	20.00	0.68	52.84	10.32	0.68
	Min	0.00	5.80	0.23	12.55	2.30	0.23
	Standard deviation	0.01	2.85	0.14	10.44	2.32	0.14

4.4.1.1 Slope

Slope is represented via the channel longitudinal profile of the nine reaches (Figure 4.4). The longitudinal profile shows that the local scale slope can substantially. Even elevation values in several cases increase downstream; these locations primarily indicate the presence of pools. Large drop in elevation downstream at local scale largely manifests riffles (high or low gradient) while minor or zero slope exhibits runs. Drop in elevation at the reach scale is larger in the midstream and downstream reaches than the upstream reaches.

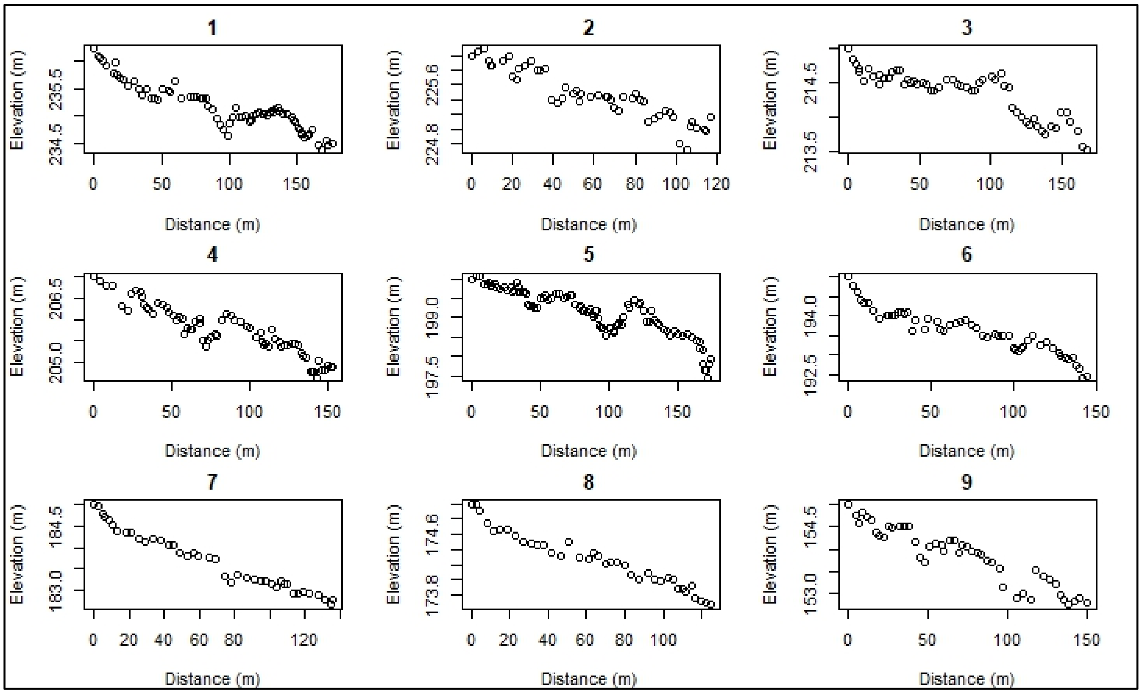

Figure 4.4: Longitudinal profile of nine reaches where 1-3 represents upstream reaches, 4-6 represents midstream reaches and 7-9 represents downstream reaches. (Note: initial elevation data for each longitudinal profile was approximated from the elevation map in figure 4.2)

Channel slope value of each hydraulic unit was used for conducting nested ANOVA. Results (Table 4.3) indicate that slope variation is predominantly explained at the local hydraulic unit (HU) scale. The between HU and within HU slope variations accounts for ~93% of total variance of the dataset. Further, while the domain scale slope variation explains ~7% of the total variance, reach scale slope explains no variance at all. While this is partially expected, given that HUs are defined, indirectly at least, on the basis of slope, the minimal influence of upstream-downstream trends is contrary to expectations.

Table 4.3: Results from three factor nested ANOVA for slope variation.

Variance source	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Total	89			0.0039	100.00
Domains	2	10.43	0.011	0.0003	7.30
Reaches	6	0.25	0.958	-0.0003	0.00
HUs	81			0.0036	92.70

4.4.1.2 Bankfull width, depth and width-depth ratio

Bankfull channel width, depth and width-depth ratio display an overall increasing trend from upstream to midstream, and then a decreasing trend from midstream to downstream (Figure 4.5). Channel width ranges from ~5 m – 10.5 m in upstream reaches (Fig. 6:1-30), ~6 m – 24.5 m in midstream reaches (Figure 4.5: 31-60) and ~6 m -16 m in downstream reaches (Figure 4.5: 61-90).

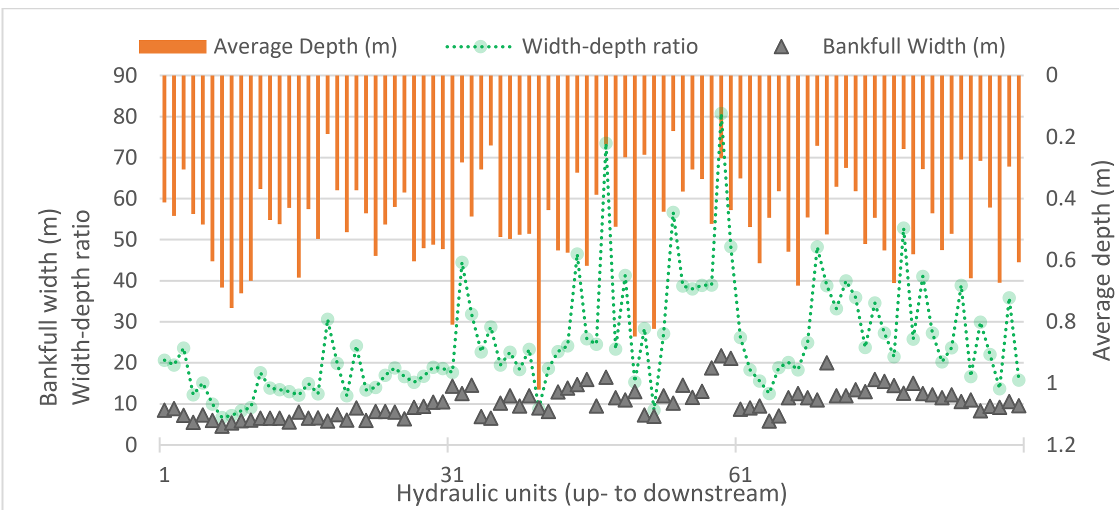

Figure 4.5: Bankfull width, maximum depth and width-depth ratio at hydraulic unit scale where 1, 31 and 61 mark the beginning of unincised, incising and strongly incised domain respectively.

Nested ANOVA on channel width shows that about 46% of width variation is explained at the HU scale, while the domain scale accounts for ~44% (Table 4.4).

Because bankfull average depth and maximum depth are closely related, nested ANOVA was conducted only for average depth. More than 99% of average depth variation is explained at the HU scale. Nested ANOVA on channel width-depth ratios show that ~54% of variance is explained at local HU scale, while ~36.5% and 9.5% is explained at domain and reach scale respectively (Table 4.4).

Table 4.4: Results from three factor nested ANOVA for bankfull channel width and width-depth ratio.

Variable	*Variance source*	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Channel width	Total	89			16.0368	100.00
	Domains	2	10.36	0.011	7.0742	44.11
	Reaches	6	3.05	0.010	1.5234	9.50
	HUs	81			7.4391	46.39
Average depth	Total	89			0.0239	100.00
	Domains	2	1.19	0.366	0.0001	0.59
	Reaches	6	0.91	0.493	-0.0002	0.00
	HUs	81			0.0237	99.41
Width-depth ratio	Total	89			0.0562	100.00
	Domains	2	8.39	0.018	0.0205	36.50
	Reaches	6	2.74	0.018	0.0053	9.41
	HUs	81			0.0304	54.09

4.4.1.3 Cross section area and hydraulic radius

Channel cross-section area for each hydraulic unit was determined from bankfull channel width and average depth measured during field survey. Further, hydraulic radius for each hydraulic unit was determined using the cross-sections. While channel width, and bankfull average and maximum depth depict an increasing trend from upstream to downstream (Figure 4.5 & Figure 4.6), local scale variations of these variables are important in influencing the cross-section area (Figure 4.6).

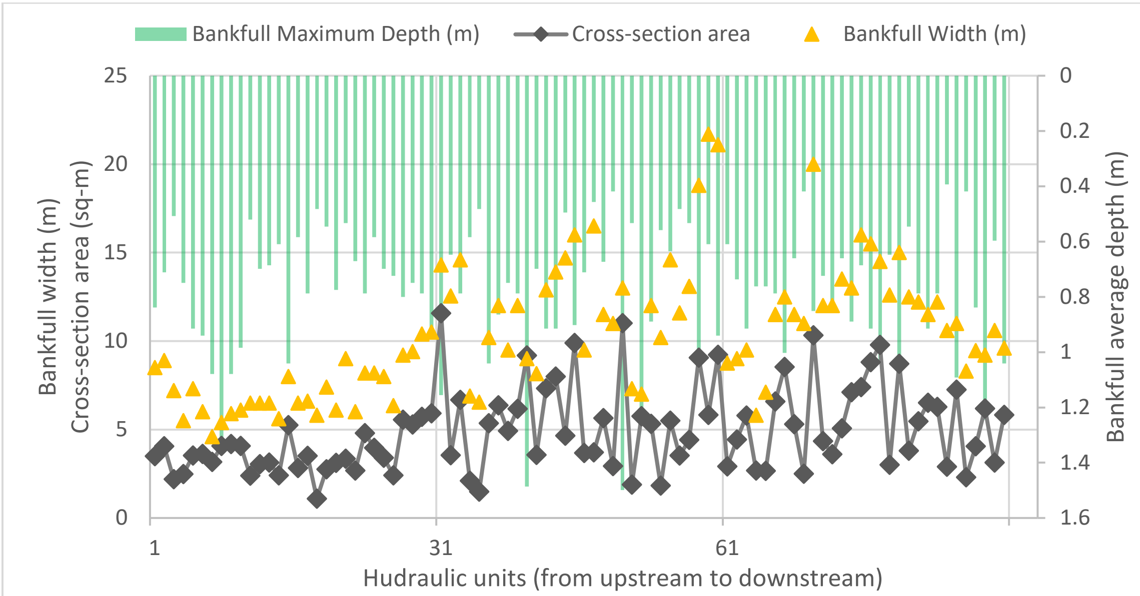

Figure 4.6: Bankfull width, maximum depth and cross-section area per HU scale where 1, 31 and 61 mark the beginning of unincised, incising and strongly incised domain respectively.

Again, while the hydraulic radius values display no discernable distribution pattern at HU scale, it is noticeable that incising domain shows greater values compared to the unincised and strongly incised domain (Figure 4.7).

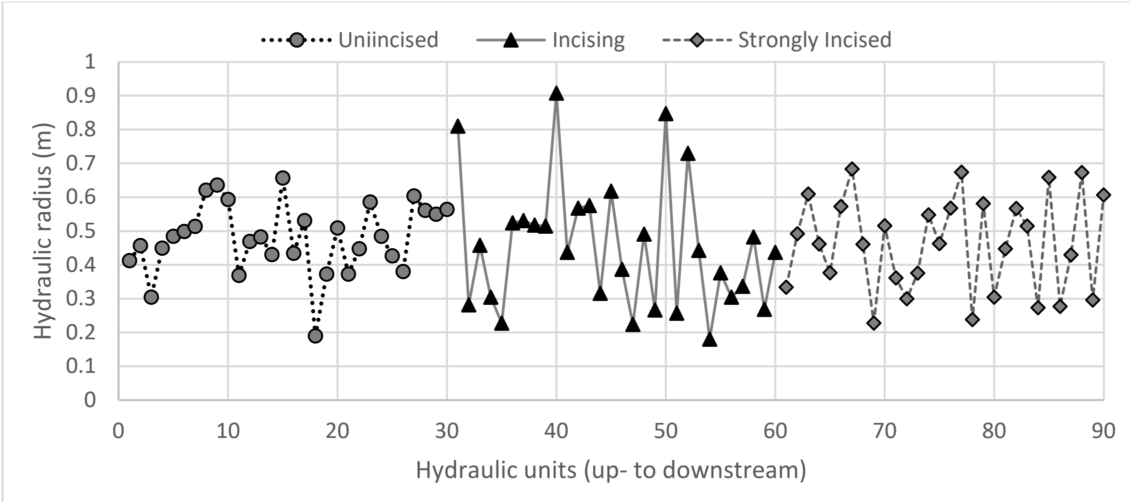

Figure 4.7: Hydraulic radius per HU along the longitudinal profile of Shawnee Run

Nested ANOVA results of channel cross-section area (Table 5) show that ~86% of the cross-section variation is explained at local hydraulic unit scale. The remaining 14% is explained at the domain scale. However, for the hydraulic radius 100% of its variation is explained at local hydraulic unit scale (Table 4.5).

Table 4.5: Results from three factor nested ANOVA for channel cross-section area.

Variable	*Variance source*	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Cross-section area	Total	89			6.1444	100.00
	Domains	2	5.27	0.048	0.8206	13.35
	Reaches	6	1.09	0.374	0.0491	0.80
	HUs	81			5.2747	85.85
Hydraulic radius	Total	89			0.0225	100.00
	Domains	2	0.27	0.770	000.00	000.00
	Reaches	6	0.82	0.559	000.00	000.00
	HUs	81			0.0225	100.00

4.4.2 Substrate characteristics

The geomorphic data block, representing substrate characteristics, includes variation in intact bedrock, fine grained alluvium and mixed substrates of gravels, cobbles, boulders, fine grained alluvium, bedrock and others. While Shawnee Run is a bedrock-controlled stream, local scale variations in substrate characteristics were evident. Field data shows variability in substrate characteristics at hydraulic unit scale (Figure 4.8a). By up-scaling substrate characteristics from the local HU to domain scale, dominant substrates for each incision domain were determined (Figure 4.8b). Figure 4.8b shows that upstream (unincised) reaches were predominantly FGA, and a mixture of FGA, gravels, cobbles and boulders. On the other hand, incising reaches were dominated by mixture of FGA, gravels, cobbles and boulders with secondary dominance of bedrock, particularly near the end of the incising domain. The substrate of the strongly incised reaches is largely comprised of intact bedrock (Figure 4.8).

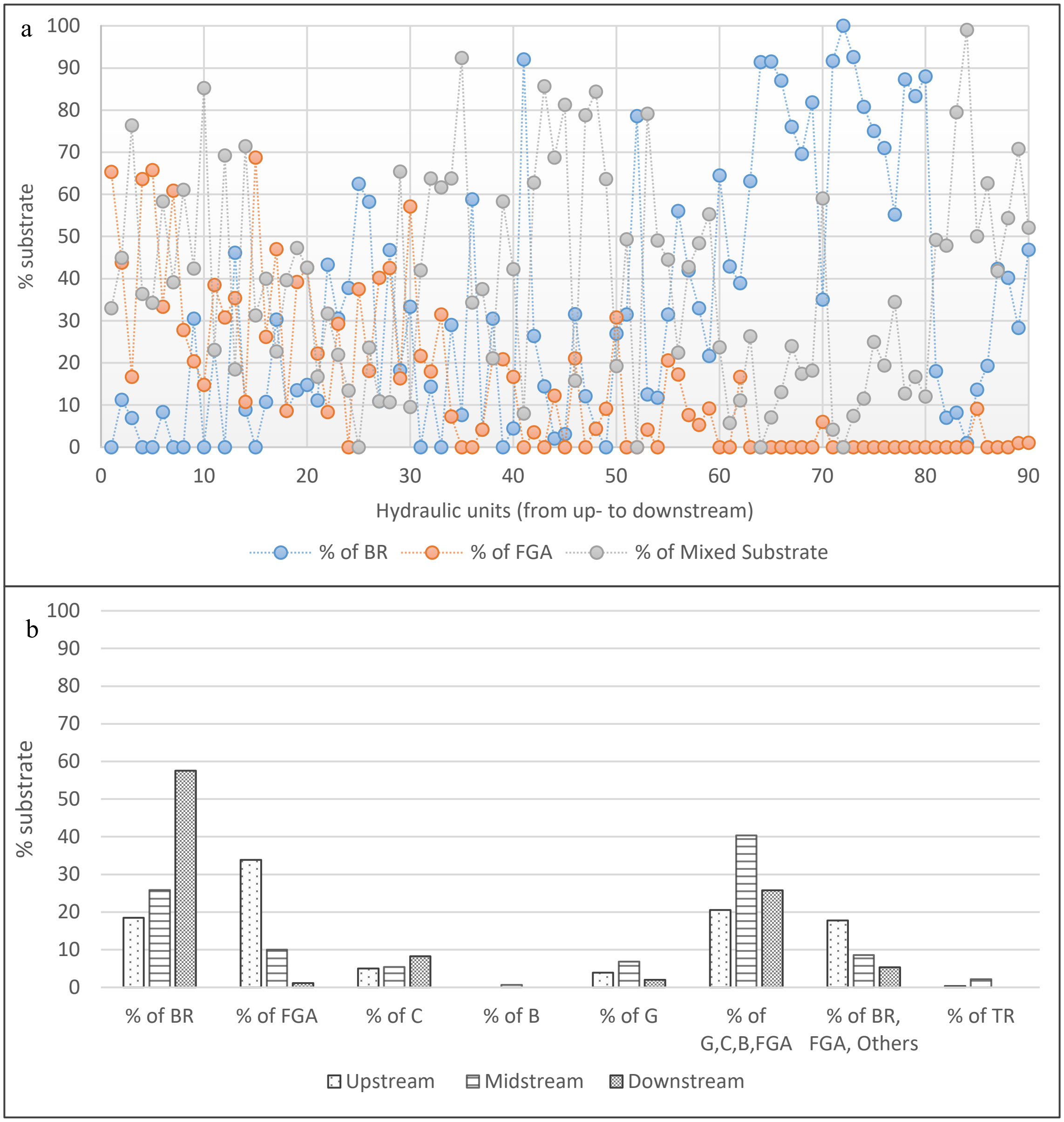

Figure 4.8: Variation of substrate characteristics at HU scale (a) and domain scale (b) where BR = bedrock, FGA = fine grained alluvium, C = cobble, B = boulder, G = gravel, TR = tree root, Mixed Substrate = G,C,B,FGA,BR and others. (Note: Fig. 8a only contains the three main categories of substrates; thus total substrate per HU may not yield a result of 100)

Nested ANOVA results shows that variation of proportion of intact bedrock variable is largely explained at reach scale (~40% variance explained) and hydraulic unit scale (~33%). Domain scale also explains ~27% of variation of proportion of intact bedrock (BR) variable. In contrast, variation of proportion fine grained alluvium (FGA) variable is dominantly explained at domain scale, while reach scale is the least important, accounting for only ~2% of variance of this variable. Proportion of mixed substrate variable is primarily explained at HU scale (~58% variance explained) and reach scale (~42% variance explained); domain scale explains no variance (Table 4.6).

Table 4.6: Results from three factor nested ANOVA for proportion of three different substrates including intact bedrock, fine-grained alluvium and mixed substrate.

Variable	*Variance source*	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Intact Bedrock (BR)	Total	89			0.1048	100.00
	Domains	2	2.89	0.132	0.0283	27.10
	Reaches	6	12.91	0.000	0.0415	39.63
	HUs	81			0.0349	33.27
Fine grained alluvium (FGA)	Total	89			0.0452	100.00
	Domains	2	40.09	0.000	0.0291	64.56
	Reaches	6	1.46	0.201	0.0007	1.57
	HUs	81			0.0153	33.87
Mixed substrate (G,C,B,FGA,BR and others)	Total	89			0.0672	100.00
	Domains	2	0.86	0.469	-0.0014	00.00
	Reaches	6	8.30	0.000	0.0283	42.20
	HUs	81			0.0389	57.80

Results shows some anomaly with respect to variance explained at three different levels for the proportion of three different categories of substrates (Table 7). While variation in proportion of FGA is dominantly explained at domain scale, variation in proportion of intact BR and mixed substrate is dominantly explained at reach and hydraulic unit scale respectively.

4.4.3 Vegetation pattern and distribution

The vegetation and biogeomorphic data block consists of four variables: species richness, total number of individuals, total number of biogeomorphic impacts, and proportion of total basal area accounted for by American sycamore (*Platanus occidentalis)*. Field investigation identified 15 different species, of which *Quercus muehlenbergii* and *P. occidentalis* are the two most dominant. However, the total basal area of *P. occidentalis* sampled is 35.18 m^2, while the second highest total basal area is 8.05 m^2 (*Q. muehlenbergii*). As a result, I wanted to specifically investigate *P. occidentalis*. For details of the impacts of *P. occidentalis,* a biogeomorphic keystone species in Shawnee Run, see Jerin and Phillips (2020).

Results show that the largest species richness values can be identified in midstream reaches. About 13% of HUs in the upstream reaches and 3% of HUs in the downstream reaches exhibit absence of any riparian tree, while all HUs in the midstream reaches include at least one riparian tree. The mean species richness, however, shows no definite pattern from up-to-downstream reaches. In contrast, the mean total number of individuals show an increasing pattern from up- to midstream, and then a declining pattern from mid- to downstream. This trend closely parallels to the mean total number of biogeomorphic impacts indicating that if the number of trees increases, more biogeomorphic impacts are likely. However, species-specific impacts are important too, particularly biogeomorphic impacts associated with American sycamore in bedrock-controlled streams (see Jerin and Phillips 2020). In our study, while American sycamore was not present in every reach, it accounted for all tree basal area in one HU. Mean proportion of basal area occupied by sycamore was about 20 percent in upstream, unincised reaches, 63 percent in the middle reaches, and 32 percent in the downstream, incised reaches. Further, biogeomorphic impacts per tree − derived from total BGIs and total number of individuals – increases from up to midstream and declines from mid to downstream at reach scale. However, the lowest mean occurs in an unincised reach. A similar pattern is observed at the domain scale. The descriptive statistics are reported in Table 4.7 and 4.8.

Table 4.7: Descriptive statistics of vegetation and biogeomorphic data block by reach.

Reach ID	Descriptive Statistics	Species richness	Total # of individuals	Proportion of *Platanus occidentalis* basal area	Total BGIs	BGIs per tree
1	*Mean*	3.30	6.90	0.122	5.80	0.841
	Max	4.00	10.00	0.780	10.00	1.000
	Min	2.00	3.00	0.000	2.00	0.667
	Standard deviation	0.67	2.56	0.269	3.68	1.438
2	*Mean*	2.10	4.10	0.234	1.00	0.244
	Max	3.00	6.00	0.989	5.00	0.833
	Min	0.00	0.00	0.000	0.00	0.000
	Standard deviation	1.20	2.51	0.336	1.63	0.649
3	*Mean*	1.60	2.40	0.229	0.80	0.333
	Max	3.00	5.00	0.976	3.00	0.600
	Min	0.00	0.00	0.000	0.00	0.000
	Standard deviation	0.82	3.63	0.413	3.28	0.904
4	*Mean*	2.30	6.40	0.555	5.90	0.922
	Max	3.00	12.00	1.000	10.00	0.833
	Min	1.00	1.00	0.000	1.00	1.000
	Standard deviation	0.82	3.63	0.413	3.28	0.904
5	*Mean*	4.00	10.20	0.577	10.80	1.059
	Max	6.00	15.00	0.896	21.00	1.400
	Min	2.00	3.00	0.000	1.00	0.333
	Standard deviation	1.33	4.08	0.360	5.94	1.456
6	*Mean*	2.90	7.30	0.752	8.20	1.123
	Max	4.00	14.00	0.947	19.00	1.357
	Min	2.00	2.00	0.126	3.00	1.500
	Standard deviation	0.74	3.23	0.273	4.98	1.542
7	*Mean*	2.20	5.00	0.548	4.20	0.840
	Max	3.00	11.00	0.960	7.00	0.636
	Min	1.00	3.00	0.000	1.00	0.333
	Standard deviation	0.79	2.40	0.473	2.53	1.054

Table 4.7 (continued)

Reach ID	Descriptive Statistics	Species richness	Total # of individuals	Proportion of *Platanus occidentalis* basal area	Total BGIs	BGIs per tree
8	*Mean*	1.90	4.50	0.000	2.90	0.644
	Max	4.00	13.00	0.000	7.00	0.538
	Min	1.00	1.00	0.000	1.00	1.000
	Standard deviation	1.10	4.25	0.000	1.97	0.464
9	*Mean*	1.64	2.73	0.368	2.36	0.864
	Max	3.00	6.00	0.981	5.00	0.833
	Min	0.00	0.00	0.000	0.00	0.000
	Standard deviation	0.84	1.77	0.443	1.84	1.040

Table 4.8: Descriptive statistics of vegetation and biogeomorphic data block by domain.

Domain	Descriptive Statistics	Species richness	Total # of individuals	Proportion of *Platanus occidentalis* basal area	Total BGIs	BGIs per tree
Unincised	*Mean*	2.33	4.47	0.195	2.53	0.566
	Max	4.00	10.00	0.989	10.00	1.000
	Min	0.00	0.00	0.000	0.00	0.000
	Standard deviation	1.24	2.92	0.326	3.31	1.134
Incising	*Mean*	3.07	7.97	0.628	8.30	1.041
	Max	6.00	15.00	1.000	21.00	1.400
	Min	1.00	1.00	0.000	1.00	1.000
	Standard deviation	1.20	3.90	0.352	5.11	1.310
Strongly Incised	*Mean*	1.90	4.07	0.318	3.17	0.779
	Max	4.00	13.00	0.981	7.00	0.538
	Min	0.00	0.00	0.000	0.00	0.000
	Standard deviation	0.92	3.06	0.431	2.20	0.719

Species richness and total number of individuals show no evident trends by HUs (Figure 4.9). Nested ANOVA on species richness and total number of individuals show that about 59% of variance is explained at HU scale for both of these variables. Domain scale accounts for~10% and ~22% variance of species richness and total number of individuals respectively. Further, proportion of *P. occidentalis* basal area and total biogeomorphic impacts (BGIs) are dominantly explained at local HU scale (Table 4.9).

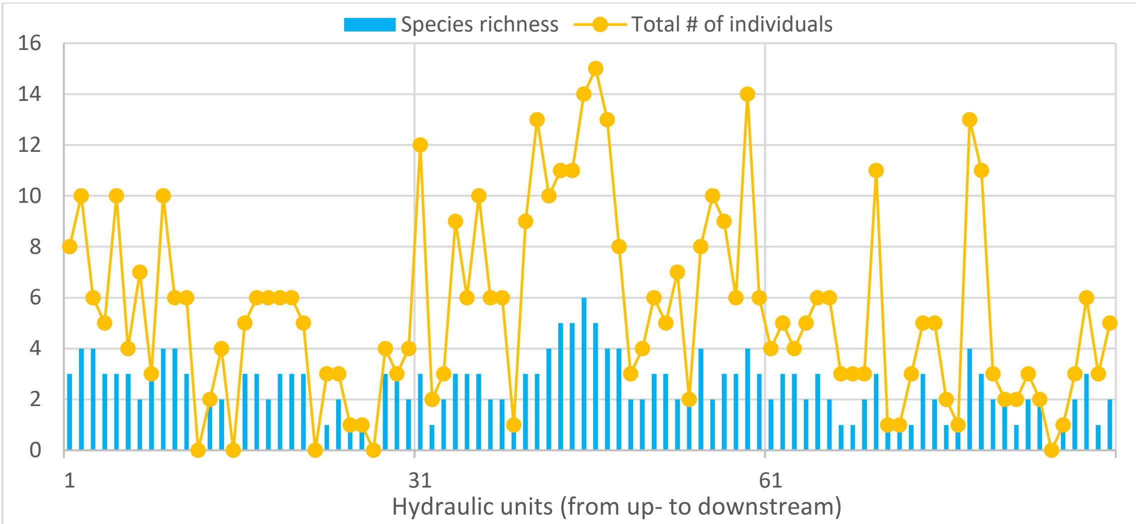

Figure 4.9: Species richness and total number individuals at hydraulic unit scale where 1, 31 and 61 mark the beginning of unincised, incising and strongly incised domain respectively.

Table 4.9: Results from three factor nested ANOVA for species richness, total number of individuals, proportion of *Platanus occidentalis* and total number of BGIs.

Variable	*Variance source*	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Species richness	Total	89			1.6052	100.00
	Domains	2	1.82	0.241	0.1607	10.01
	Reaches	6	6.14	0.000	0.4901	30.53
	HUs	81			0.9543	59.45
Total number of individuals	Total	89			15.5415	100.00
	Domains	2	3.73	0.089	3.4748	22.36
	Reaches	6	4.16	0.001	2.9000	18.66
	HUs	81			9.1667	58.98

Table 4.9 (continued)

Variable	*Variance source*	*DF*	*F value*	*P value*	*Variance component*	*Percent of Total*
Proportion of Platanus occidentalis	Total	89			0.1841	100.00
	Domains	2	4.64	0.061	0.0391	21.22
	Reaches	6	2.57	0.025	0.0196	10.67
	HUs	81			0.1254	68.11
Total number of BGIs	Total	89			0.1581	100.00
	Domains	2	4.63	0.061	0.0532	33.67
	Reaches	6	6.51	0.000	0.0372	23.56
	HUs	81			0.0676	42.77

4.5 Discussion

4.5.1 Local scale controls of hydraulic geometry on fluvial systems

Patterns and process are interlinked and almost always scale-dependent (Thorp et al. 2008). Despite the importance of the domain scale, the local hydraulic unit scale predominantly explains the variation of geomorphic variables controlling the channel morphology of the study area (Figure 4.10). This indicates that the fundamental processes creating the pattern can be understood best at the local scale. Because channel morphology variability is linked primarily to local hydraulic unit scale variations, hypothesis H3A (see section 4.3.5) was accepted and hypotheses H1A and H2B rejected. This indicates a deviation from the river continuum concept and downstream hydraulic geometry framework widely used in fluvial studies.

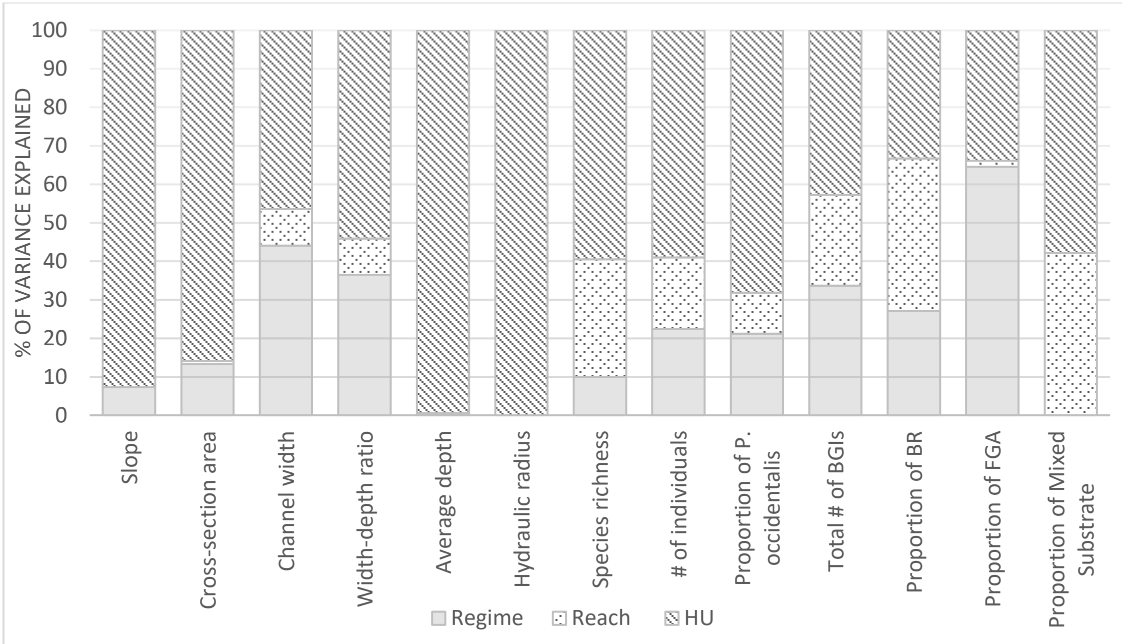

Figure 4.10: Comparison of variance components explained at three hierarchical levels for geomorphic, vegetation and biogeomorphic variables.

The local scale variation of channel morphology is largely attributable to the local geological controls, along with the inherent differences among pools, runs, and high- and low-gradient riffles. Bedrock channels occur mainly, but not exclusively, in actively incising portions of landscapes where channels are cut into resistant rock units (Whipple 2004). As a result, they undergo greater influence of lithology and structure compared to alluvial rivers. Similarly, Shawnee Run is evolving via incision. As the dominant lithology is limestone (see section 4.2), lithological control is likely to be less important influencing the local scale geomorphic variations of Shawnee Run. However, local structural controls (see Figures 4.2 and 4.11) can play vital roles prompting the local scale hydraulic geometry variations. While Figure 4.2 confirms presence of fault lines dissecting Shawnee Run, Figure 4.11 shows structural controls of bedding planes and joints controlling the hydraulic geometry of the river.

Figure 4.11: Local structural controls of bedding planes and joints on Shawnee Run; looking upstream (images obtained at incising and strongly incised domains)

Further, results show differences with respect to variance explained at three different levels for the proportion of three different categories of substrates (Table 4.6, Figure 4.10). Distribution of FGA is largely controlled at the domain scale, which aligns with the field observation indicating a gradient of lesser FGA domination downstream. This is largely attributable to the incision status defining the domains of this research, which in turn is likely related to the frequency of overbank flow and thus alluvial deposition. Further, as the dominant substrate characteristics largely varies at different domains (Figures 4.8 and 4.10) therefore, incision status is an important control on substrate variation.

While variation in the proportion of intact BR is dominantly explained at the reach scale, the other two scales are important too. Structural controls e.g. bedding planes, joints, faults (Figure 4.11) create discontinuities, which may control the distribution of bedrock along the longitudinal gradient of the stream. However, this deserves future research.

Variation in the proportion of mixed substrates (gravels, cobbles, boulders, FGA, BR and other) is largely controlled at the hydraulic unit scale, paralleling results associated with all channel morphology variables. At the same time, nested ANOVA results show that local scale variation is important for the proportion of all three substrate categories. This is because local scale dissimilarities in substrate characteristics (Figure 4.8a) are largely controlled by local scale hydraulic geometry and channel morphological variations, which in turn are closely linked to structural controls and incision status. Nevertheless, localized incision itself functions as a crucial factor controlling channel morphology and its association with riparian trees. This idea aligns with Shoffner and Royall (2008) who showed localized incision as an important control on the variability of hydraulic unit scale biotope (hydraulically homogenous abiotic environments of communities) composition. Substrate disparity influences hydraulic roughness − important for variation in flow velocity along a stream. Therefore, local scale geomorphic processes creating the pattern is reflected via feedback relationships whereby local structural controls and incision influence channel morphology, which again influence substrate characteristics. Substrate characteristics further impacts flow velocities and thus channel morphology.

Local scale variation in structural controls and substrate characteristics can create discontinuity and patchiness in fluvial systems. According to Thorp et al. (2008), discontinuities are often related to regional and local variations in climate, geology, riparian conditions, tributaries, lithology, and/or geomorphology, or with human interruptions disrupting the flow, sediment, and/or disturbance regimes. Local variations in structural controls (Figure 4.11), substrate characteristics (Figure 4.8), riparian vegetation, and presence of karst springs (Figure 4.12) and tributaries are evident controls influencing discontinuities and patchiness in Shawnee Run. As a result, the geomorphic and biotic components determined in the Shawnee Run system are primarily explained at hydraulic unit scale (or patch scale). Thus, the study stream does not conform to the RCC or DHG expectations, and more closely corresponds to discontinuity-based frameworks.

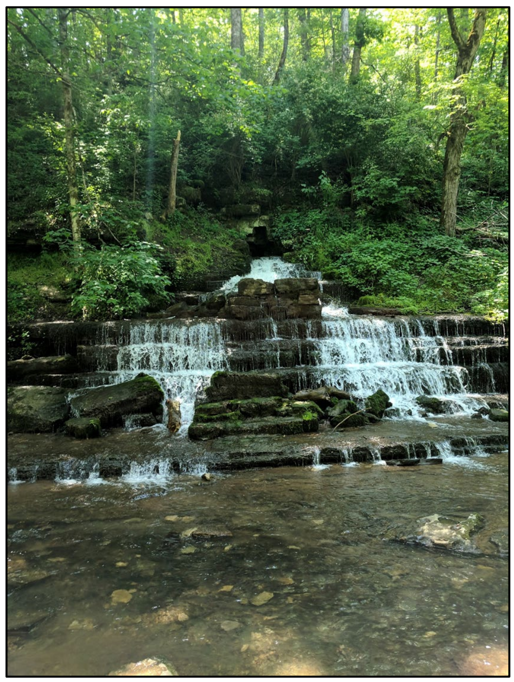

Figure 4.12: Karst spring influencing patchiness and discontinuities in Shawnee Run

4.5.2 Local scale controls of riparian vegetation on fluvial systems

Variation of riparian tree numbers and richness is largely controlled and explained at the local hydraulic unit scale (Figure 4.9) — results equivalent to that of hydraulic geometry variation (see section 4.5.1). This local scale variation can be explained by the highly local edaphic differences along the riparian corridor. Local edaphic variation is likely to be related to the local scale fluvial process-form variations, and biogeomorphic impacts and feedbacks. For instance, Jerin and Phillips (2020) show that pools can be formed via species-specific biogeomorphic impacts and feedbacks along a fluvial corridor, and thus can develop edaphic heterogeneity in bedrock-controlled flowing channels. Further, riparian vegetation controls sediment transport and cohesiveness, and thus influences the size, shape and stability of resulting landforms. These landforms, further, determine habitat conditions mediating micro-scale plant species interactions and vegetation dynamics (e.g. Bendix and Hupp 2000; Stallins 2006; Corenblit et al. 2007; Kim 2012). Additionally, some trees (particularly *Q. muehlenbergii* and *P. occidentalis*) more readily adapt to exposed rock and thin-soil sites by exploiting rock joints with their roots; while FGA sites may support these and other species. Because variation of riparian trees is dominantly explained at local HU scale, hypothesis H3A was accepted (see section 4.3.5). This further signposts a divergence from the river continuum concept and affinity to discontinuity-based frameworks.

4.5.3 Local scale interactions in fluvial biogeomorphology

If an Earth surface system is hierarchically structured, system components can be disparately explained at different levels—that is, the dominant controls of process-response relationships vary with spatial scale (e.g. Sherman 1995; Bergkamp 1998; Parsons and Thoms 2007; Phillips 2008; Reuter et al. 2010). This is also reflected in the results obtained from nested ANOVA analysis for the geomorphic, vegetation and biogeomorphic data blocks (Figure 4.9). Channel morphology and vegetation patterns are primarily controlled and explained by local scale variations rather than systematic upstream to downstream variation or reach scale variation in Shawnee Run. These results are consistent with the idea of tight coupling between channel morphology and riparian vegetation, although they do not, by themselves, prove such interactions. This suggests that Shawnee Run is potentially a strongly coupled fluvial biogeomorphic system evolving via local scale interactions between fluvial process-form and biogeomorphic impacts and feedbacks. However, this deserves future research.

Hydraulic units and domains were selected based on observed morphological differences, while reaches were randomly selected within domains as aggregation of HUs. The majority of the geomorphic, vegetation and biogeomorphic variables associated with this research were primarily explained at HU scale and secondarily the domain scale, and little variation was explained at reach scale (Figure 4.10). If systematic, more-or-less continuous variation were dominant, the domain scale would have accounted for most of the variation. Conversely, if (as turned out to be the case) local patch-scale variation is dominant, most variation would be associated with the HU scale. The inclusion of reaches in this study, and their general unimportance in contributing to variation in channel morphology, tree, and biogeomorphic variables, indicates that, at least in Shawnee Run, the highly localized variations and the broader up-to-downstream context are indeed the critical scales.

4.6 Conclusions

Most fluvial systems depict systematic, continuous upstream-to-downstream variations in channel morphology and linked ecological and hydrological parameters, emphasized by conceptual frameworks including the downstream hydraulic geometry and the river continuum concept. While this conception has been widely used in many geomorphological, hydrological, and ecological studies, this research presents divergence from it by investigating the relative importance of broader-scale up-to-downstream variation vs. local hydraulic unit scale variation in a bedrock-controlled stream.

Channel morphology and vegetation patterns in the study area are primarily controlled and explained by local scale variations rather than systematic upstream to downstream variation or reach scale variation. Local scale variation in channel morphology is primarily attributable to the local scale structural controls and incision status that can potentially develop discontinuity and patchiness in fluvial systems, Furthermore, local scale variation in riparian trees is largely controlled by local edaphic differences linked to fluvial process-forms, and biogeomorphic impacts and feedbacks. While both up-to-downstream and local scale variations are common in all fluvial systems, local scale controls are probably the most important scale for understanding bedrock-controlled fluvial geomorphic systems.

Acknowledgements

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CHAPTER 5. CONCLUSIONS

5.1 Research synthesis

The interactions between fluvial process-forms and riparian vegetation vary in different environments and are uncertain in bedrock settings. Bedrock streams are much less studied than alluvial in all aspects, and in many respects act in qualitatively different ways. This research seeks to fill this lacuna by studying bedrock streams from a biogeomorphic perspective. To facilitate this contribution this research addresses three research objectives (Table 5.1 and Figure 5.1) that help to identify and assess the important biogeomorphic impacts (BGIs) – species-specific vs. generalized – and feedbacks developing a fluvial biogeomorphic system via interactions across scales.

Table 5.1: Relationship between dissertation objectives, research approach and data chapters.

Research objectives	**Research approach**	**Ch.**
1. Explore the BGIs of vegetation associated with bedrock streams.	• Review the fluvial biogeomorphic and rocky hillslope environment literature. • Identify the biogeomorphic impacts of vegetation on bedrock streams from six different bedrock environments • Introduce biogeomorphic impact triangles to represent the common vs. unique biogeomorphic impacts associated with alluvial and bedrock fluvial environments, and rocky hillslopes.	Ch. 2

Table 5.1 (continued)

Research objectives	**Research approach**	**Ch.**
2. Investigate the species-specific vs. the general BGIs of vegetation on fluvial process-forms from the context of biogeo-morphic keystone species.	• Develop the concepts of biogeomorphic keystone species and equivalents under the ecological theoretical framework of keystone species and ecological equivalents. • Relate these concepts with field examples obtained from the study area Shawnee Run. • Introduce a conceptual model of *biogeomorphic pool* development in bedrock streams. • Introduce an avulsion-originated island development framework associated with biogeomorphic equivalents.	Ch. 3
3. Identify the most important spatial scale of variation of channel morphology and biogeomor-phological phenomena.	• Understand the relative importance of broader-scale up-to-downstream variation vs. local scale variation in a bedrock-controlled stream. • Relate these findings with the River Continuum Concept and Downstream Hydraulic Geometry Concept. • Investigate the importance of geological controls on bedrock fluvial systems identifying the important scale of variation of channel morphology and riparian vegetation.	Ch. 4

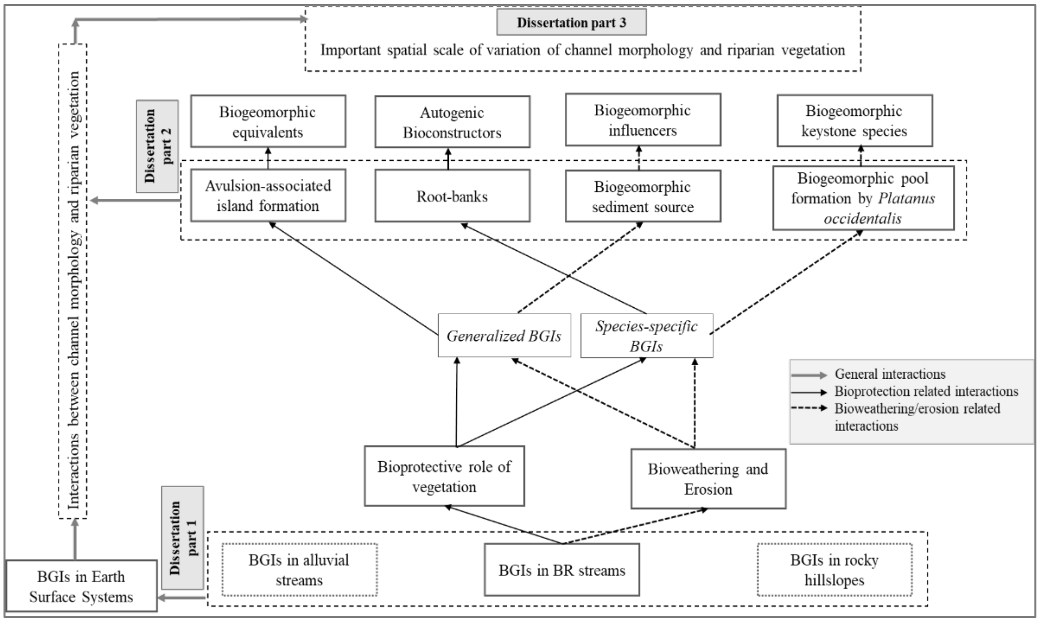

Figure 5.1: Organization of the research and the relationship between dissertation objectives and associated findings.

Biogeomorphic impacts associated with bedrock fluvial systems remain understudied, though alluvial fluvial systems have been extensively studied from this context. The first part of the dissertation aims to fill this gap. This research shows that bedrock streams exhibit both shared and highly concentrated biogeomorphic impacts in relation to alluvial streams and bedrock hillslope environments. It shows that while no biogeomorphic impacts associated with bedrock streams are unique to the environment, the bioprotective function related to root banks and the processes related to bioweathering and erosion are rarely addressed in alluvial fluvial literature − however important in bedrock fluvial environments. Thus, this research not only contributes to the knowledge gap but also points out towards some important research questions which are:

i) What is the relative importance of bioprotection along alluvial and bedrock streams, as bedrock ones are quite resistant anyway?

ii) What is the role of bioweathering and erosion along stream banks in bedrock channel evolution?

The second part of the dissertation is largely founded upon the biogeomorphic impacts identified in the first part. Further, it investigates the importance of bioprotection, bioweathering and erosion in bedrock channel processes and forms from the context of species-specific vs. generalized BGIs. Thus, the second part addresses the research questions raised in the first part of the dissertation.

The second part of the dissertation has two specific goals. First, drawing from ecological lexicon, it introduces some biogeomorphic concepts with respect to different biotic impacts on surface processes and forms largely identified in the first part of the dissertation. Second, it explores different biogeomorphic roles of vegetation from the empirical evidence obtained from a bedrock fluvial system in central Kentucky. Field investigation of the biogeomorphic impacts associated with bedrock streams identified three important biogeomorphic roles of riparian vegetation:

i. Biogeomorphic pool formation linked to bioweathering.

ii. Development of avulsion associated islands related to bioprotection.

iii. Root banks associated with bioprotection.

The second part of the dissertation evaluates these biogeomorphic impacts with respect to biogeomorphic keystone species or other biogeomorphic roles (Figure 1). This study identified that *Platanus occidentalis* is exclusively associated with *biogeomorphic pool* development via bioweathering – a species-specific biogeomorphic impact – and these pools can substantially alter the fluvial-process-form dynamics. Because the absence of *Platanus occidentalis* would result in fundamentally different channel morphology, it is designated as biogeomorphic keystone species in Shawnee Run. This study further identified that certain species can play the role of autogenic bioconstructors by developing a distinct bioprotective forms, root banks – a biophysically originated geomorphic form. Moreover, trees can promote avulsion-originated island formation by creating erosion-resistant bioprotective patches. While any live vegetation can play comparable bioprotective roles (i.e. a generalized BGI), certain species may play this role better than others, particularly at the mature stage. This research found that large (in terms of DBH) *Platanus occidentalis* and *Quercus muehlenbergii* dominated the islands of the study area and play comparable roles with respect to avulsion-originated island development via bioprotection. Thus, they are designated as biogeomorphic equivalents. Lastly, this study discovered that vegetation-induced bedrock weathering functions as an important source of sediment in bedrock streams. However, just about all species identified in the study area can play this biogeomorphic role, and thus can be recognized as biogeomorphic influencers that are also equivalents.

This research brings forth some important future research concerns. The biogeomorphic pool formation analysis needs further investigation in other bedrock fluvial environments. Future research should examine whether biogeomorphic pools are exclusively associated with *Platanus occidentalis* in other fluvial systems. Further, while root-banks are characterized as important bioprotective form in our study area, a key question is whether root banks, in the long term, actually facilitate bank erosion over protection. While living roots are highly resistant and shield bedrock from hydraulic forces, the roots probably facilitate dissolution, rock slab displacement, and other forms of weathering. When the tree dies, the exposed bank may be more weathered and erodible than bedrock banks that have not had root banks. This deserves further research (for details see Chapter 2). Thus, the identification of biogeomorphic keystone species, equivalents and other biogeomorphic roles can potentially facilitate the recognition of critical points in the coevolution of geomorphological and ecological systems.

The first two parts of the dissertation signpost that Shawnee Run is a strongly coupled fluvial biogeomorphic system evolving via interactions between fluvial process-form and biogeomorphic impacts and feedbacks. This also brings forth an important research question − what is the most important spatial scale of variation controlling geomorphic, vegetation and biogeomorphic components of a bedrock-controlled fluvial biogeomorphic system? The third part of the dissertation deals with this research question.

Most fluvial systems depict systematic, continuous upstream-to-downstream variations in channel morphology and linked ecological and hydrological parameters, emphasized by conceptual frameworks including the downstream hydraulic geometry and the river continuum concept. While this conception has been widely used in many geomorphological, hydrological, and ecological studies, this study shows deviation from it by investigating the relative importance of broader-scale up-to-downstream variation vs. local hydraulic unit scale variation in a bedrock-controlled stream.

Channel morphology and vegetation patterns in the study area are primarily controlled and explained by local scale variations rather than systematic upstream to downstream variation or reach scale variation. Local scale variation in channel morphology is primarily attributable to the local scale structural controls and incision status that can potentially develop discontinuity and patchiness in fluvial systems, Furthermore, local scale variation in riparian trees is largely controlled by local edaphic differences linked to fluvial process-forms, and biogeomorphic impacts and feedbacks. The variation of channel morphology and riparian trees being controlled at the same scale level is consistent with these variables being strongly interconnected, suggesting that Shawnee Run is a strongly coupled fluvial biogeomorphic system.

Lastly, while most, if not all, fluvial systems are characterized by systematic up- to downstream variations and local, patchy variability, the relative importance of these almost certainly varies with watershed size, environmental context, and other factors. Analogous studies are called for on other fluvial systems.

5.2 Implications for Management and Future Research

This research points out towards some important aspects that needs to consider and investigate in future. Firstly, future research needs to look at larger samples of bedrock rivers, including the alluvial–bedrock transitional streams, which are influenced by different types of geology. The significance of geological control on fluvial process-form and riparian vegetation interactions has been identified in the second and third part of the dissertation. The following aspects of bedrock streams are worthy of further investigation for river management:

- The ideas presented in Chapter 2 and 3 of this research are relevant to reinforced (human-controlled) river channels where woody vegetation may colonize hard reinforcement such as concrete, laid brick, and stone riprap. Therefore, future work related to stream restoration and river bank protection should address these ideas, most importantly bioprotection and bioweathering/erosion.
- Biogeomorphic impacts and related processes associated with bedrock streams almost certainly vary spatially and temporally. For example, the third part of the dissertation shows that the local hydraulic unit scale is the most important spatial scale of variation of channel morphology and biogeomorphological phenomena. Future studies should attempt to quantify these variations for different types of streams.
- Bedrock channels are present from deserts to wet tropics, with a broad range of tree species that exhibit different growth rates, resilience to mechanical disturbance, and tolerances for inundation. Therefore, future research should explore the following questions:

  i. Are there some biomes or hydroclimatic regions where woody vegetation is more likely to influence bedrock channel processes or forms?

  ii. Does the influence of vegetation depend on factors associated with boundary conditions such as lithology, joint geometry, flow regime, and channel geometry that limit the ability of trees to germinate and survive?

The findings of the research presented in this dissertation can provide the contextual biogeomorphic understanding necessary to conduct future research in fluvial biogeomorphic systems particularly in bedrock-controlled ones. Further, the conceptual framework presented in the second part of the dissertation can be useful for biogeomorphic studies in different Earth surface systems. As our understanding of improves, future research can investigate other bedrock systems under the conceptual framework of biogeomorphic keystone species, equivalents and other biogeomorphic roles. Lastly, future research on bedrock streams should be conducted with an understanding that local scale variations may well be more important than broad scale variation, with data collection and analysis carried out accordingly.

Finally, the key findings of this research point to some future analyses of Shawnee Run, which include:

1. Determining the strength of coupling among channel morphology, vegetation and substrate characteristics using a 3-block partial least square analysis following the method of Bookstein et al. (2003) and Kim et al. (2015).
2. Quantifying the configuration of the fluvial biogeomorphic system of Shawnee Run under the theoretical and mathematical framework of 'graph theory' for understanding the complexity, stability, sensitivity, and synchronization properties of the system (after Heckmann et al. 2015, Phillips 2012, 2016).
3. Investigating the species richness-hydraulic unit area relationship to understand the relative importance of intrinsic factors (reflected by the types of hydraulic units) vs. extrinsic factors (reflected by the size of the riparian corridor) on riparian vegetation diversity.

APPENDICES

Appendix 1: Hydraulic units (HUs) sampled from up-to-downstream

Regime ID	**Reach ID**	**HU # from up-to-downstream**	**HU category**
Unincised	Up1	1	HGR
Unincised	Up1	2	LGR
Unincised	Up1	3	Run
Unincised	Up1	4	Run
Unincised	Up1	5	Pool
Unincised	Up1	6	HGR
Unincised	Up1	7	Run
Unincised	Up1	8	Pool
Unincised	Up1	9	Run
Unincised	Up1	10	LGR
Unincised	Up2	11	Run
Unincised	Up2	12	HGR
Unincised	Up2	13	Pool
Unincised	Up2	14	HGR
Unincised	Up2	15	Pool
Unincised	Up2	16	LGR
Unincised	Up2	17	Pool
Unincised	Up2	18	HGR
Unincised	Up2	19	Run
Unincised	Up2	20	Pool

Appendix 1 (table continued)

Regime ID	Reach ID	HU # from up-to-downstream	HU category
Unincised	Up3	21	HGR
Unincised	Up3	22	Run
Unincised	Up3	23	Pool
Unincised	Up3	24	LGR
Unincised	Up3	25	Run
Unincised	Up3	26	LGR
Unincised	Up3	27	Run
Unincised	Up3	28	Pool
Unincised	Up3	29	Run
Unincised	Up3	30	Pool
Incising	Mid1	31	HGR
Incising	Mid1	32	Pool
Incising	Mid1	33	HGR
Incising	Mid1	34	Pool
Incising	Mid1	35	LGR
Incising	Mid1	36	Pool
Incising	Mid1	37	LGR
Incising	Mid1	38	Pool
Incising	Mid1	39	HGR
Incising	Mid1	40	Pool
Incising	Mid2	41	Run

Appendix 1 (table continued)

Regime ID	Reach ID	HU # from up-to-downstream	HU category
Incising	Mid2	42	HGR
Incising	Mid2	43	Pool
Incising	Mid2	44	Run
Incising	Mid2	45	HGR
Incising	Mid2	46	Pool
Incising	Mid2	47	LGR
Incising	Mid2	48	HGR
Incising	Mid2	49	HGR
Incising	Mid2	50	Pool
Incising	Mid3	51	HGR
Incising	Mid3	52	Pool
Incising	Mid3	53	HGR
Incising	Mid3	54	LGR
Incising	Mid3	55	Run
Incising	Mid3	56	LGR
Incising	Mid3	57	Run
Incising	Mid3	58	Pool
Incising	Mid3	59	LGR
Incising	Mid3	60	HGR
Incised	Down1	61	HGR
Incised	Down1	62	LGR

Appendix 1 (table continued)

Regime ID	Reach ID	HU # from up-to-downstream	HU category
Incised	Down1	63	HGR
Incised	Down1	64	Run
Incised	Down1	65	HGR
Incised	Down1	66	LGR
Incised	Down1	67	LGR
Incised	Down1	68	RUN
Incised	Down1	69	POOL
Incised	Down1	70	HGR
Incised	Down2	71	HGR
Incised	Down2	72	LGR
Incised	Down2	73	RUN
Incised	Down2	74	LGR
Incised	Down2	75	RUN
Incised	Down2	76	LGR
Incised	Down2	77	HGR
Incised	Down2	78	Pool
Incised	Down2	79	HGR
Incised	Down2	80	LGR
Incised	Down3	81	Run
Incised	Down3	82	HGR
Incised	Down3	83	Pool

Appendix 1 (table continued)

Regime ID	**Reach ID**	**HU # from up-to-downstream**	**HU category**
Incised	Down3	84	HGR
Incised	Down3	85	Pool
Incised	Down3	86	LGR
Incised	Down3	87	HGR
Incised	Down3	88	Pool
Incised	Down3	89	HGR
Incised	Down3	90	Pool

Appendix 2: Hydraulic unit (HU) based channel morphology dataset

HU*	Slope (m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Cross section area (m sq.)	W/d ration	Hydraulic radius (m)
1	0.026	8.50	0.412	3.502	20.629	0.412
2	0.019	8.90	0.456	4.063	19.496	0.456
3	0.008	7.20	0.305	2.195	23.622	0.305
4	0.004	5.50	0.450	2.474	12.228	0.450
5	0.006	7.30	0.484	3.535	15.077	0.484
6	0.021	6.00	0.604	3.622	9.938	0.498
7	0.000	4.60	0.688	3.167	6.681	0.514
8	0.020	5.40	0.756	4.081	7.146	0.621
9	0.001	5.90	0.707	4.172	8.344	0.636
10	0.007	6.10	0.667	4.069	9.145	0.594
11	0.005	6.50	0.369	2.399	17.608	0.369
12	0.038	6.50	0.469	3.049	13.856	0.469
13	0.004	6.50	0.483	3.137	13.469	0.483
14	0.048	5.60	0.430	2.408	13.024	0.430
15	0.010	8.00	0.657	5.255	12.179	0.657
16	0.006	6.50	0.434	2.823	14.965	0.434
17	0.001	6.60	0.531	3.504	12.433	0.531
18	0.028	5.80	0.190	1.099	30.603	0.190
19	0.003	7.40	0.373	2.761	19.836	0.373
20	0.001	6.10	0.509	3.108	11.973	0.509

Appendix 2 (table continued)

HU*	Slope (m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Cross section area (m sq.)	W/d ration	Hydraulic radius (m)
21	0.042	9.00	0.373	3.355	24.145	0.373
22	0.009	6.00	0.448	2.686	13.405	0.448
23	0.001	8.20	0.586	4.802	14.002	0.586
24	0.013	8.20	0.484	3.969	16.942	0.484
25	0.002	8.00	0.427	3.413	18.754	0.427
26	0.018	6.35	0.380	2.414	16.704	0.380
27	0.002	9.20	0.604	5.555	15.238	0.604
28	0.003	9.40	0.561	5.275	16.749	0.561
29	0.007	10.40	0.549	5.714	18.929	0.549
30	0.003	10.50	0.564	5.922	18.617	0.564
31	0.026	14.30	0.810	11.581	17.658	0.810
32	0.008	12.55	0.282	3.541	44.484	0.282
33	0.062	14.60	0.458	6.681	31.904	0.458
34	0.004	6.90	0.305	2.103	22.638	0.305
35	0.018	6.55	0.228	1.492	28.759	0.228
36	0.002	10.20	0.524	5.348	19.453	0.524
37	0.012	12.00	0.531	6.373	22.597	0.531
38	0.003	9.50	0.518	4.916	18.357	0.518
39	0.034	12.00	0.515	6.175	23.319	0.515
40	0.011	9.00	1.021	9.186	8.818	0.908

Appendix 2 (table continued)

HU*	Slope (m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Cross section area (m sq.)	W/d ration	Hydraulic radius (m)
41	0.010	8.15	0.437	3.563	18.644	0.437
42	0.042	12.90	0.568	7.324	22.722	0.568
43	0.001	13.90	0.576	8.003	24.143	0.576
44	0.008	14.70	0.316	4.645	46.525	0.316
45	0.022	16.00	0.618	9.895	25.871	0.618
46	0.011	9.50	0.387	3.677	24.545	0.387
47	0.011	16.50	0.224	3.703	73.531	0.224
48	0.031	11.50	0.491	5.649	23.410	0.491
49	0.022	11.00	0.266	2.928	41.327	0.266
50	0.040	13.00	0.848	11.019	15.337	0.848
51	0.056	7.30	0.257	1.877	28.385	0.257
52	0.001	7.00	0.823	5.761	8.506	0.730
53	0.043	12.00	0.443	5.316	27.090	0.443
54	0.011	10.20	0.180	1.837	56.632	0.180
55	0.001	14.60	0.377	5.503	38.737	0.377
56	0.017	11.60	0.305	3.536	38.058	0.305
57	0.005	13.10	0.337	4.412	38.897	0.337
58	0.009	18.80	0.482	9.067	38.983	0.482
59	0.016	21.70	0.269	5.830	80.767	0.269
60	0.051	21.10	0.437	9.218	48.297	0.437

Appendix 2 (table continued)

HU*	Slope (m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Cross section area (m sq.)	W/d ration	Hydraulic radius (m)
61	0.036	8.75	0.334	2.924	26.181	0.334
62	0.009	9.00	0.492	4.428	18.294	0.492
63	0.021	9.50	0.610	5.791	15.584	0.610
64	0.003	5.80	0.462	2.680	12.552	0.462
65	0.043	7.10	0.376	2.671	18.871	0.376
66	0.010	11.50	0.573	6.584	20.085	0.573
67	0.014	12.50	0.683	8.536	18.305	0.683
68	0.016	11.50	0.461	5.299	24.959	0.461
69	0.003	11.00	0.228	2.509	48.235	0.228
70	0.032	20.00	0.516	10.317	38.770	0.516
71	0.022	12.00	0.361	4.338	33.199	0.361
72	0.012	12.00	0.300	3.601	39.987	0.300
73	0.003	13.50	0.376	5.073	35.929	0.376
74	0.016	13.00	0.548	7.118	23.744	0.548
75	0.002	16.00	0.462	7.395	34.617	0.462
76	0.011	15.50	0.568	8.803	27.292	0.568
77	0.020	14.50	0.674	9.778	21.503	0.674
78	0.005	12.60	0.238	3.005	52.835	0.238
79	0.022	15.00	0.581	8.714	25.821	0.581
80	0.011	12.50	0.304	3.804	41.074	0.304

Appendix 2 (table continued)

HU*	Slope (m)	Bankfull Width (m)	Bankfull Ave Depth (m)	Cross section area (m sq.)	W/d ration	Hydraulic radius (m)
81	0.001	12.20	0.448	5.465	27.237	0.448
82	0.046	11.50	0.567	6.517	20.292	0.567
83	0.001	12.20	0.515	6.278	23.708	0.515
84	0.054	10.60	0.273	2.891	38.860	0.273
85	0.005	11.00	0.659	7.246	16.698	0.659
86	0.007	8.30	0.277	2.302	29.921	0.277
87	0.041	9.45	0.429	4.057	22.015	0.429
88	0.017	9.20	0.673	6.193	13.668	0.673
89	0.026	10.60	0.296	3.137	35.815	0.296
90	0.020	9.60	0.607	5.823	15.827	0.607

*HUs are numbered along the longitudinal gradient of Shawnee Run

Appendix 3: Riparian vegetation and associated biogeomorphic impact dataset

HU*	Species richness	Species abundance	Total basal area (m sq.)	Number of Biogeomorphic Impacts	A. sycamore Basal Area (m sq.)
1	3	8	7784.65	10	0.00
2	4	10	3574.69	10	0.00
3	4	6	2182.25	3	0.00
4	3	5	2128.69	2	0.00
5	3	10	3710.36	8	0.00
6	3	4	2128.77	3	932.80
7	2	7	2893.19	2	0.00
8	3	3	4455.53	2	3476.02
9	4	10	4365.45	10	0.00
10	4	6	5200.46	8	0.00
11	3	6	961.39	2	420.43
12	0	0	0.00	0	0.00
13	2	2	181.54	0	97.48
14	2	4	778.43	0	38.52
15	0	0	0.00	0	0.00
16	3	5	1810.96	0	0.00
17	3	6	5389.21	2	1747.62
18	2	6	5865.96	5	0.00
19	3	6	2325.57	1	2299.78
20	3	6	3661.91	0	13.45

Appendix 3 (table continued)

HU*	Species richness	Species abundance	Total basal area (m sq.)	Number of Biogeomorphic Impacts	A. sycamore Basal Area (m sq.)
21	3	5	1902.69	0	962.89
22	0	0	0.00	0	0.00
23	1	3	331.20	0	0.00
24	2	3	416.19	0	0.00
25	1	1	688.26	1	0.00
26	1	1	2787.11	2	0.00
27	0	0	0.00	0	0.00
28	3	4	6346.21	2	5128.76
29	3	3	1360.85	0	0.00
30	2	4	17905.21	3	17481.14
31	3	12	4589.60	6	0.00
32	1	2	9938.49	4	9938.49
33	2	3	602.98	1	0.00
34	3	9	11352.28	7	6692.45
35	3	6	7073.96	6	3781.83
36	3	10	25716.99	10	21749.19
37	2	6	10883.71	9	10264.20
38	2	6	11758.98	5	11197.00
39	1	1	4011.01	1	0.00
40	3	9	21795.34	10	14919.87

Appendix 3 (table continued)

HU*	Species richness	Species abundance	Total basal area (m sq.)	Number of Biogeomorphic Impacts	A. sycamore Basal Area (m sq.)
41	3	13	20571.25	21	18431.21
42	4	10	14442.92	16	12041.79
43	5	11	4474.05	11	0.00
44	5	11	4234.90	11	1208.78
45	6	14	6643.13	12	3148.48
46	5	15	21174.64	8	17655.41
47	4	13	12472.41	16	10272.87
48	4	8	9013.98	8	7145.16
49	2	3	4901.88	4	4066.48
50	2	4	1274.51	1	0.00
51	3	6	2204.47	6	277.01
52	3	5	9831.46	5	9307.68
53	2	7	7611.51	7	7111.19
54	2	2	134.01	3	62.39
55	4	8	11007.71	9	9007.35
56	2	10	13604.31	15	8188.28
57	3	9	8050.75	6	7105.54
58	3	6	6955.37	7	6429.05
59	4	14	22079.45	19	19663.65
60	3	6	7349.36	5	6815.48

Appendix 3 (table continued)

HU*	Species richness	Species abundance	Total basal area (m sq.)	Number of Biogeomorphic Impacts	A. sycamore Basal Area (m sq.)
61	2	4	5191.86	1	4545.53
62	3	5	13355.77	7	12821.89
63	3	4	7045.85	4	6699.21
64	2	5	10968.77	2	9970.48
65	3	6	9681.15	7	8236.57
66	2	6	1660.56	7	0.00
67	1	3	542.74	1	0.00
68	1	3	848.15	2	0.00
69	2	3	8146.57	6	7647.38
70	3	11	1173.57	5	0.00
71	1	1	89.31	1	0.00
72	1	1	97.48	1	0.00
73	1	3	727.50	3	0.00
74	3	5	1140.50	3	0.00
75	2	5	1316.29	5	0.00
76	1	2	1206.25	2	0.00
77	1	1	97.48	1	0.00
78	4	13	5432.78	7	0.00
79	3	11	1987.01	4	0.00
80	2	3	1202.87	2	0.00

Appendix 3 (table continued)

HU*	Species richness	Species abundance	Total basal area (m sq.)	Number of Biogeomorphic Impacts	A. sycamore Basal Area (m sq.)
81	2	2	494.75	4	0.00
82	1	2	6029.99	5	5588.31
83	2	3	2671.33	1	2024.76
84	2	2	2565.27	2	0.00
85	0	0	0.00	0	0.00
86	1	1	175.79	2	0.00
87	2	3	3474.74	3	3407.82
88	3	6	5960.12	2	3130.67
89	1	3	1674.15	0	0.00
90	2	5	14251.75	5	12155.91

*HUs are numbered along the longitudinal gradient of Shawnee Run

REFERENCES

Abbe TB and Montgomery DR (1996) Large woody debris jams channel hydraulics and habitat formation in large rivers. *Regulated Rivers Research & Management* 12(23): 201-221.

Abernethy B and Rutherfurd ID (2001) The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes* 15: 63–79.

Allen JA (1998) Mangroves as alien species: the case of Hawaii. *Global Ecology & Biogeography Letters* 7:61–71.

An SQ, Gu BH, Zhou CF, Wang ZS, Deng ZF, Zhi YB, Li HL, Chen L, Yu DH, and Liu YH (2007) Spartina invasion in China: implications for invasive species management and future research. *Weed Research* 47(3):183-191.

Andrews WM Jr. (2004) Geologic controls on Plio-Pleistocene drainage evolution of the Kentucky River in central Kentucky, PhD Dissertation. University of Kentucky, Lexington, KY.

Andrus CW, Long BA and Froehlich HA (1988) Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Canadian Journal of Fisheries and Aquatic Sciences 45*(12): 2080-2086.

Auble GT, Friedman JM and Scott ML (1994) Relating riparian vegetation to present and future streamflows. *Ecological applications 4*(3):544-554.

Balke T, Herman PM and Bouma TJ (2014) Critical transitions in disturbance-driven ecosystems: identifying Windows of Opportunity for recovery. *Journal of Ecology* 102(3):700-8.

Belletti B, Rinaldi M, Bussettini M, Comiti F, Gurnell AM, Mao L, Nardi L and Vezza P (2017) Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology* 283:143-157.

Benda LEE, Poff NL, Miller D, Dunne T, Reeves G, Pess G and Pollock M (2004) The network dynamics hypothesis: how channel networks structure riverine habitats. *BioScience* 54(5):413-427.

Bendix J (1992) Scale-related environmental influences on Southern Californian riparian vegetation. *PhD Dissertation,* University of Georgia.

Bendix J (1998) Impact of a flood on southern California riparian vegetation. *Physical Geography* 19(2): 162-174

Bendix J (1999) Stream power influence on southern Californian riparian vegetation. *Journal of Vegetation Science* 10(2): 243-252

Bendix J and Cowell CM (2010) Fire, floods and woody debris: interactions between biotic and geomorphic processes. *Geomorphology* 116(3): 297-304

Bendix J and Hupp CR (2000) Hydrological and geomorphological impacts on riparian plant communities. *Hydrological processes* 14(16): 2977-2990

Bennie AT (1991) Growth and mechanical impedance In: Waisel Y, Eshel A and Kafkafi (eds) *Plant Roots: The Hidden Half*. New York: Marcek Dekker, 393–414.

Bergkamp G (1998) A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena* 33(3-4): 201-220.

Bertoldi W, Drake N and Gurnell AM (2011) Interactions between river flows and colonising vegetation on a braided river: exploring spatial and temporal dynamics in riparian vegetation cover using satellite data. *Earth Surface Processes and Landforms* 36(11):1474-86.

Bertoldi W, Gurnell A, Surian N, Tockner K, Zanoni L, Ziliani L and Zolezzi G (2009) Understanding reference processes: linkages between river flows sediment dynamics and vegetated landforms along the Tagliamento River Italy. *River Research and Applications* 25(5): 501-516.

Biggins DE, Hanebury LR, Miller BJ and Powell RA (2011) Black-footed ferrets and Siberian polecats as ecological surrogates and ecological equivalents. *Journal of Mammalogy*.16: 92(4):710-20.

Birot P (1966) General physical geography. George G Harrap & Co Ltd, London UK.

Bonner FT (1966) Survival and first-year growth of hardwoods planted in saturated soils. *Research note SO–32. U.S. Forest Service, Southern Forestry Experiment Station*, Asheville, NC.

Bookstein FL, Gunz P, Mitteroecker P, Prossinger H, Schaefer K and Seidler H (2003) Cranial integration in Homo: singular warps analysis of the midsagittal plane in ontogeny and evolution. *Journal of Human Evolution* 44(2): 167-187.

Bormann BT, Wang D, Bormann FH, Benoit G, April R and Snyder MC (1998) Rapid plant-induced weathering in an aggrading experimental ecosystem. *Biogeochemistry* 43: 129–155.

Braudrick CA, Dietrich WE, Leverich GT and Sklar LS (2009) Experimental evidence forthe conditions necessary to sustain meandering in coarse-bedded rivers. *Proceedings of the National Academy of Sciences of the United States of America* 106:16936–16941.

Bryan DL, Arnold MA, Volder A, Todd Watson W, Lombardini L, Sloan JJ, Valdez-Aguilar LA and Cartmill AD (2010). Transplant season, irrigation, and planting depth effects on landscape establishment of baldcypress and sycamore. *Journal of Arboriculture* 36(2):57.

Busby FE and Schuster JL (1973) Woody phreatophytes along the Brazos River and selected tributaries above Possum Kingdom Lake. *Texas Water Development Board Report 168.* Austin, TX: TWDB.

Butcher R W (1933) Studies on the ecology of rivers: I On the distribution of macrophytic vegetation in the rivers of Britain. *The Journal of Ecology* 58-91.

Butler DR (1995) Zoogeomorphology: animals as geomorphic agents. Cambridge University Press, New York.

Butler DR and Malanson GP (2005) The geomorphic influences of beaver dams and failures of beaver dams. *Geomorphology 71*(1-2):48-60.

Campbell JJ (1989) Historical evidence of forest composition in the bluegrass region of central Kentucky. *Proceedings of 7th Central Hardwood Forest Conference*, USDA Forest Service General Technical Report, 231–246.

Campbell, J.B., 1978. Spatial variation of sand content and pH within single contiguous delineations of two soil mapping units. *Soil Science Society of America Journal* 42(3): 460-464.

Carbonneau, P, Fonstad MA, Marcus WA and Dugdale SJ, (2012) Making riverscapes real. *Geomorphology* 137(1): 74-86.

Chambless LF and Nixon ES (1975) Woody vegetation--soil relations in a bottomland forest of east Texas. *Texas Journal of Science* 26: 407-416.

Clifford NJ, Harmar OP, Harvey G and Petts GE (2006) Physical habitat, eco-hydraulics and river design: a review and re-evaluation of some popular concepts and methods. *Aquatic conservation: marine and freshwater ecosystems* 16(4): 389-408.

Collins BD, Montgomery DR, Fetherston KL and Abbe TB (2012) The floodplain large-wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology* 139: 460-470.

Connell JH (1978) Diversity in tropical rain forests and coral reefs. *Science* 199(4335):1302-1310.

Coombes MA (2016) Biogeomorphology: diverse, integrative and useful. *Earth Surface Processes and Landforms 41*(15): 2296-2300.

Coombes MA, Naylor LA, Viles HA and Thompson RC (2013) Bioprotection and disturbance: seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. *Geomorphology 202*: 4-14.

Corenblit D (2018) Species signature in landscapes. *Nature Geoscience* 11: 621-622.

Corenblit D, Baas A, Balke T, Bouma T, Fromard F, Garófano-Gómez V, González E , Gurnell AM, Hortobágyi B, Julien F and Kim D (2015) Engineer pioneer plants respond to and affect geomorphic constraints similarly along water–terrestrial interfaces world-wide. *Global Ecology and Biogeography* 24(12): 1363-1376.

Corenblit D, Baas A, Balke T, Bouma T, Fromard F, Garófano-Gómez V, González E, Gurnell AM, Hortobágyi B, Julien F. and Kim D (2015). Engineer pioneer plants respond to and affect geomorphic constraints similarly along water–terrestrial interfaces world-wide. *Global Ecology and Biogeography* 24(12): 1363-1376.

Corenblit D, Baas AC, Bornette G, Darrozes J, Delmotte S, Francis RA, Gurnell AM, Julien F, Naiman RJ and Steiger J (2011) Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: a review of foundation concepts and current understandings. *Earth-Science Reviews* 106(3): 307-331.

Corenblit D, Gurnell AM, Steiger J and Tabacchi E (2008) Reciprocal adjustments between landforms and living organisms: extended geomorphic evolutionary insights. *Catena* 73(3): 261-273.

Corenblit D, Steiger J Gurnell AM Tabacchi E and Roques L (2009a) Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processes and Landforms* 34(13): 1790-1810.

Corenblit D, Steiger J, Gurnell AM and Naiman RJ (2009b) Plants intertwine fluvial landform dynamics with ecological succession and natural selection: a niche construction perspective for riparian systems. *Global Ecology and Biogeography* 18(4): 507-520.

Corenblit D, Steiger J, Tabacchi E (2010) Biogeomorphologic succession dynamics in a Mediterranean river system. *Ecography* 33(6) 1136-1148.

Corenblit D, Tabacchi E, Steiger J, Gurnell AM (2007) Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. *Earth-Science Reviews* 84(1): 56-86.

Crooks JA and Khim HS (1999). Architectural versus biological effects of a habitat-altering, exotic mussel, Musculista senhousia. *Journal of Experimental Marine. Biology and. Ecology*. 240:53–75.

Cullum C, Brierley GJ and Thoms M (2008). The spatial organization of river systems. In G.J. Brierley and K. A Fryirs (eds.), *River futures: an integrative scientific approach to river repair*, 43. Island Press, Washington DC, USA.

Daly RA (1915). The glacial-control theory of coral reefs. Proceedings of the American Academy of Arts and Sciences. *American Academy of Arts & Sciences* 51(4):157-251.

De Almeida GA and Rodríguez JF (2012). Spontaneous formation and degradation of pool-riffle morphology and sediment sorting using a simple fractional transport model. *Geophysical Research Letters* 39(6). Doi:10.1029/2012GL051059.

Decamps HENRI and Tabacchi ERIC (1994). Species richness in vegetation along river margins. In Giller PS, Hildrew AG, Raffaelli DG (Eds.) *Aquatic Ecology: Scale, Pattern and Process*, 1-20. Blackwell Scientific Publications, Oxford.

Dent CL, Cumming GS and Carpenter SR (2002) Multiple states in river and lake ecosystems. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 357(1421): 635-645.

Di Tomaso JM (1998). Impact, biology, and ecology of saltcedar (Tamarix spp.) in the southwestern United States. *Weed Technology* 12:326–36.

Eaton BC and Giles TR (2009) Assessing the effect of vegetation-related bank strength on channel morphology and stability in gravel-bed streams using numerical models. *Earth Surface Processes and Landforms* 34(5):712-24.

Edwards PJ, Kollmann J, Gurnell AM, Petts GE, Tockner K and Ward J V (1999) A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. *Wetlands Ecology and Management 7*(3):141-153.

Ehrenfeld JG (1990). Dynamics and processes of barrier-island vegetation. *Reviews in Aquatic Sciences*. 2: 437–480.

Eichel J, Corenblit D and Dikau R (2016) Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: a biogeomorphic feedback window. *Earth Surface Processes and Landforms* 41(3):406-19.

Ellison AM, Bank MS, Clinton BD, Colburn EA, Elliott K, Ford CR, Foster DR, Kloeppel BD, Knoepp JD, Lovett GM, Mohan J (2005). Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment 3*(9): 479-486.

Erős, T and Campbell Grant, EH (2015) Unifying research on the fragmentation of terrestrial and aquatic habitats: patches, connectivity and the matrix in riverscapes. *Freshwater Biology* 60(8): 1487-1501.

Everitt BL (1968) Use of the cottonwood in an investigation of the recent history of a flood plain. *American Journal of Science* 266(6):417-439.

Fahrig L, Coffin DP, Lauenroth WK and Shugart HH (1994) The advantage of long distance clonal spreading in highly disturbed habitats *Evolutionary Ecology* 8:172–187.

Fausch KD, Torgersen CE, Baxter CV and Li HW (2002). Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes. *BioScience* 52 (6): 483-498.

Fei S, Phillips JD and Shouse M (2014) Biogeomorphic impacts of invasive species. *Annual review of ecology evolution and systematics* 45: 69-87.

Fetherston KL, Naiman RJ and Bilby RE (1995) Large woody debris physical process and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13(1-4): 133-144.

Fonstad MA and Marcus WA (2010). High resolution, basin extent observations and implications for understanding river form and process. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group* 35(6), pp.680-698.

Ford WI and Fox JF (2017) Stabilization of benthic algal biomass in a temperate stream draining agroecosystems. *Water Research* 108: 32-443.

Francis RA (2009) Ecosystem prediction and management In: Castree N, Demeritt D, Liverman D and Rhoads B (Eds) *A companion to environmental geography*, 421-441. Blackwell, London.

Francis RA, Corenblit D and Edwards PJ (2009) Perspectives on biogeomorphology ecosystem engineering and self-organisation in island-braided fluvial ecosystems. *Aquatic sciences* 71(3): 290-304.

Fryirs KA and Brierley GJ (2012). Geomorphic analysis of river systems: an approach to reading the landscape. John Wiley & Sons, NJ, USA.

Gabet EJ and Mudd SM (2010) Bedrock erosion by root fracture and tree throw: a coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils. *Journal of Geophysical Research* 115 F04005.

Gabet EJ, Reichman OJ and Seabloom EW (2003) The effect of bioturbation on soil processes and sediment transport. *Annual Review of Earth and Planetary Sciences* 3: 249–273.

Gabet EJ, Reichman OJ and Seabloom EW (2003). The effect of bioturbation on soil processes and sediment transport. *Annual Review of Earth and Planetary Sciences* 3: 249–273.

Gautier-Hion A and Michaloud G (1989). Are figs always keystone resources for tropical frugivorous vertebrates? A test in Gabon. *Ecology* 70(6): 1826-1833.

Gibbs CB (1963). Tree diameter a poor indicator of age in West Virginia hardwoods. *Research Note NE-11. Upper Darby, PA: US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 1-4, 11.*

Graf WL (1978) Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geological Society of America Bulletin* 89(10): 1491-1501.

Gran K and Paola C (2001). Riparian vegetation controls on braided stream dynamics. *Water Resources Research*. 37: 3275–3283.

Gran KB, Tal M and Wartman ED (2015) Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system Mount Pinatubo Philippines. *Earth Surface Processes and Landforms* 40(8): 1101-1115.

Green JC (2005) Modelling flow resistance in vegetated streams: review and development of new theory. *Hydrological processes* 19(6): 1245-1259.

Gregory KJ and Davis RJ (1992) Coarse woody debris in stream channels in relation to river channel management in woodland areas. *Regulated Rivers Research & Management* 7(2):117-136.

Gregory SV, Swanson FJ, McKee WA and Cummins KW (1991) An ecosystem perspective of riparian zones. *BioScience* 41(8): 540-551.

Gurnell A (2014) Plants as river system engineers. *Earth Surface Processes and Landforms* 39(1): 4-25.

Gurnell A and Petts G (2006) Trees as riparian engineers: the Tagliamento River Italy. *Earth Surface Processes and Landforms* 31(12):1558-1574.

Gurnell A, Goodson J, Thompson K, Clifford N and Armitage P (2007) The river-bed: a dynamic store for plant propagules? *Earth Surface Processes and Landforms* 32(8): 1257-1272.

Gurnell A, Tockner K, Edwards P and Petts G (2005) Effects of deposited wood on biocomplexity of river corridors. *Frontiers in Ecology and the Environment* 3(7): 377-382.

Gurnell AM (1998). The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography* 22(2):167-189.

Gurnell AM and Gregory KJ (1995) Interactions between semi-natural vegetation and hydrogeomorphological processes. *Geomorphology* 13(1-4): 49-69.

Gurnell AM and Petts GE (2002) Island-dominated landscapes of large floodplain rivers a European perspective. *Freshwater Biology* 47(4): 581-600.

Gurnell AM, Bertoldi W and Corenblit D (2012) Changing river channels: The roles of hydrological processes plants and pioneer fluvial landforms in humid temperate mixed load gravel bed rivers. *Earth-Science Reviews* 111(1): 129-141.

Gurnell AM, Corenblit D, García de Jalón D, González del Tánago M, Grabowski RC, O'Hare, MT and Szewczyk M (2016). A Conceptual Model of Vegetation–hydrogeomorphology Interactions Within River Corridors. *River Research and Applications* 32(2): 142-163.

Gurnell AM, Holloway JV, Liffen T, Serlet AJ, Zolezzi G (2019) Plant root and rhizome strength: Are there differences between and within species and rivers? *Earth Surface Processes and Landforms* 44(1):389-92.

Gurnell AM, Petts GE, Hannah DM, Smith BP, Edwards PJ, Kollmann J, James VW and Tockner K (2001) Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento Italy. *Earth Surface Processes and Landforms* 26(1): 31-62.

Hack JT and Goodlett JC (1960) Geomorphology and forest ecology of a mountain region in the central Appalachians. *United States Geological Survey Professional Paper,* 347.

Haggett P, Chorley RJ and Stoddart DR (1965). Scale standards in geographical research: a new measure of areal magnitude. *Nature* 205: 844-847.

Harper JL (1977). Population Biology of Plants. Academic Press, London.

Hastings A, Hom CL, Ellner S, Turchin P and Godfray HCJ (1993) Chaos in ecology: is mother nature a strange attractor? *Annual review of ecology and systematics* 24(1): 1-33.

Heckmann T, Schwanghart W and Phillips JD (2015). Graph theory—Recent developments of its application in geomorphology. *Geomorphology* 243: 130-146.

Hortobágyi B, Corenblit D, Steiger J and Peiry JL (2018). Niche construction within riparian corridors. Part I: Exploring biogeomorphic feedback windows of three pioneer riparian species, Allier River, France. *Geomorphology* 305: 94-111.

Hosier PJ (1973). The effects of oceanic overwash on the vegetation of Core and Shackleford Banks. North Carolina. Ph.D. dissertation, Duke University, Durham, NC.

Hosner JF and Minckler LS (1963) Bottomland Hardwood Forests of Southern Illinois. *Regeneration and Succession Ecology* 44(1): 29-41.

Hughes FM, Adams WM, Muller E, Nilsson C, Richards KS, Barsoum N, Decamps H, Foussadier R, Girel J, Guilloy H and Hayes A (2001) The importance of different scale processes for the restoration of floodplain woodlands. *River Research and Applications* 17(4-5):325-345.

Hupp CR (1982) Stream-grade variation and riparian-forest ecology along Passage Creek Virginia. *Bulletin of the Torrey Botanical Club* 109: 488-499.

Hupp CR (1983) Vegetation pattern on channel features in the Passage Creek Gorge Virginia. *Castanea* 48: 62-72.

Hupp CR (1986). Upstream variation in bottomland vegetation patterns, northwestern Virginia. Bulletin of the Torrey Botanical Club, 421-430.

Hupp CR (1992) Riparian vegetation recovery patterns following stream channelization: a geomorphic perspective. *Ecology* 73(4): 1209-1226.

Hupp CR and Osterkamp WR (1985) Bottomland vegetation distribution along Passage Creek Virginia in relation to fluvial landforms. *Ecology* 66(3): 670-681.

Hupp CR and Osterkamp WR (1996) Riparian vegetation and fluvial geomorphic processes. *Geomorphology* 14(4): 277-295.

Hupp CR and Rinaldi M (2007) Riparian vegetation patterns in relation to fluvial landforms and channel evolution along selected rivers of Tuscany (Central Italy). *Annals of the Association of American Geographers* 97(1): 12-30.

Jackson G and Sheldon J (1949) The vegetation of magnesian limestone cliffs at Markland Grips Near Sheffield. *Journal of Ecology* 37: 38–50.

Jackson JB and Kaufmann KW (1987). Diadema antillarum was not a keystone predator in cryptic reef environments. *Science* 235(4789): 687-689.

Jamieson E, Jeans DN and Forster JJH (1983). The spatial scale of European colonization and land alienation in Northern New South Wales, 1850–1910. *Australian Geographer* 15(5): 322-325.

Jerin T (2019). Biogeomorphic effects of woody vegetation on bedrock streams. *Progress in Physical Geography: Earth and Environment* 43(6): 777-800.

Jerin T and Phillips J (2017). Local efficiency in fluvial systems: Lessons from Icicle Bend. *Geomorphology* 282: 119-130.

Jerin T and Phillips J (2020). Biogeomorphic Keystones and Equivalents: Examples from a Bedrock Stream. *Earth Surface Processes and Landforms (in press).* DOI: 10.1002/esp.4853.

Jones CG (2012). Ecosystem engineers and geomorphological signatures in 310 landscapes. *Geomorphology* 157–158: 75-87.

Jones CG, Lawton JH and Shachak M (1994). Organisms as ecosystem engineers. In *Ecosystem management* Springer, 130-147. New York, NY.

Kemp JL, Harper DM, and Crosa GA (1999). Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems* 9(1): 159-178.

Kershner B, Tufts C and Nelson G (2008). National Wildlife Federation field guide to trees of North America. Sterling Publishing Company Incorporated.

Kim D, DeWitt TJ, Costa CS, Kupfer JA, McEwan RW and Stallins, JA (2015). Beyond bivariate correlations: three-block partial least squares illustrated with vegetation, soil, and topography. *Ecosphere* 6(8): 1-32.

Kim, D (2012). Biogeomorphic feedbacks drive dynamics of vegetation–landform complex in a coastal riparian system. *Ecosphere* 3(8): 1-16.

Kingsford RT (2000) Ecological impacts of dams water diversions and river management on floodplain wetlands in Australia. *Austral Ecology 25*(2): 109-127.

Kramer N and Wohl E (2015) Driftcretions: The legacy impacts of driftwood on shoreline morphology. *Geophysical Research Letters 42*(14): 5855-5864.

Langendoen EJ, Lowrance RR, Simon A. 2009. Assessing the impact of riparian processes on streambank stability. *Ecohydrology* 2 (3):360–369.

Lawton JH (1994). What do species do in ecosystems? *Oikos*, 367-374.

Lawton JH and Jones CG (1995). Linking species and ecosystems: organisms as ecosystem engineers. In *Linking species & ecosystems*. Springer, Boston, MA, pp. 141-150.

Leak WB (1985). *Relationships of tree age to diameter in old-growth northern hardwoods and spruce-fir* (Vol. 329). US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

LeopoldL B and Maddock T (1953) The hydraulic geometry of stream channels and some physiographic implications. *Professional Paper 282A* US Geological Survey.

Levey DJ (1988). Tropical wet forest treefall gaps and distributions of understory birds and plants. *Ecology* 69(4):1076-1089.

Liao C, Luo Y, Jiang L, Zhou X, Wu X, Fang C, Chen J and Li B (2007). Invasion of Spartina alterniflora enhanced ecosystem carbon and nitrogen stocks in the Yangtze Estuary, China. *Ecosystems* 10(8):1351-61.

Lincoln R, Boxshall G and Clark P (1998). A dictionary of ecology, evolution, and systematic (2nd ed.). Cambridge University Press, Cambridge, United Kingdom.

Loope LL, Sanchez PG, Tarr PW, Loope WL and Anderson RL (1988) Biological invasions of arid land nature reserves. *Biological Conservation* 44:95–118.

Lutz HJ (1960) Movement of rocks by uprooting of forest trees. *American Journal Science* 258(10):752–56.

Lutz HJ and Griswold FS (1939) The influence of tree roots on soil morphology. *American Journal Science* 237(6):389–400.

MacWilliams ML, Wheaton JM, Pasternack GB, Street RL and Kitanidis PK (2006). Flow convergence routing hypothesis for pool-riffle maintenance in alluvial rivers. *Water Resources Research* 42(10).

Malard F, Mangin A, Uehlinger U and Ward JV (2001). Thermal heterogeneity in the hyporheic zone of a glacial floodplain. *Canadian Journal of Fisheries and Aquatic Sciences* 58(7): 1319-1335.

Marston R A, Girel J, Pautou G, Piegay H, Bravard JP and Arneson C (1995). Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. *Geomorphology* 13(1-4): 121-131.

Martin LL (2006) Effects of Forest and Grass Vegetation on Fluviokarst Hillslope Hydrology Bowman's Bend Kentucky. *PhD Dissertation*, University of Kentucky Lexington KY.

Massong TM and Montgomery DR (2000) Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels. *Geological Society of America Bulletin 112*(4):591-599.

Matthes-Sears U and Larson DW (1995) Rooting characteristics of trees in rock: a study of Thuja occidentalis on cliff faces. *International Journal of Plant Sciences* 156: 679–686.

Matthews B, De Meester L, Jones CG, Ibelings BW, Bouma TJ, Nuutinen V, Van De Koppel J and Odling-Smee J (2014). Under niche construction: an operational bridge between ecology, evolution, and ecosystem science. *Ecological Monographs* 84(2): 245-263.

McBride JR and Strahan J (1984) Establishment and survival of woody riparian species on gravel bars of an intermittent stream. *American Midland Naturalist* 235-245.

McKenney R, Jacobson RB and Wertheimer RC (1995) Woody vegetation and channel morphogenesis in low-gradient gravel-bed streams in the Ozark Plateaus Missouri and Arkansas. *Geomorphology* 13(1-4):175-198.

Meentemeyer RK, Vogler JB and Butler DR (1998). The geomorphic influences of burrowing beavers on streambanks, Bolin Creek, North Carolina. *Zeitschrift fur Geomorphologie* 42: 453-468.

Milan DJ, Heritage GL, Large ARG and Entwistle NS (2010). Mapping hydraulic biotopes using terrestrial laser scan data of water surface properties. *Earth Surface Processes and Landforms* 35(8): 918-931.

Millar RG (2000). Influence of bank vegetation on alluvial channel patterns. *Water Resources Research* 36 (4):1109–1118.

Millar RG (2005). Theoretical regime equations for mobile gravel-bed rivers with stable banks. *Geomorphology* 64 (3–4): 207–220.

Millar RG and Quick MC (1993). Effect of bank stability on geometry of gravel rivers. *Journal of Hydraulic Engineering* 119 (12): 1343–1363.

Miller JR (1991) The influence of bedrock geology on knickpoint development and channel-bed degradation along downcutting streams in south-central Indiana. *The Journal of Geology* 99(4): 591-605.

Mills LS, Soule ME and Doak DF (1993). The keystone-species concept in ecology and conservation. *BioScience*. 43: 219-224.

Minshall GW, Petersen RC, Cummins KW, Bott TL, Sedell JR, Cushing CE and Vannote RL (1983). Interbiome comparison of stream ecosystem dynamics. *Ecological monographs* 53(1): 1-25.

Montgomery DR (1999). Process domains and the river continuum 1. *Journal of the American Water Resources Association* 35(2): 397-410.

Montgomery DR, Abbe TB and Buffington JM (1996) Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* 381(6583) 587.

Murray AB and Paola C (2003). Modelling the effect of vegetation on channel pattern in bedload rivers. *Earth Surface Processes and Landforms* 28 (2): 131–143.

Nanson GC (1981) New evidence of scroll-bar formation on the Beatton River. *Sedimentology* 28(6): 889-891.

Naylor LA (2005). The contributions of biogeomorphology to the emerging field of geobiology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *219*(1-2): 35-51.

Naylor LA, Coombes MA and Viles HA (2012). Reconceptualising the role of organisms in the erosion of rock coasts: a new model. *Geomorphology 157*: 17-30.

Naylor LA, Viles HA and Carter NEA (2002) Biogeomorphology revisited: looking towards the future. *Geomorphology* 47(1) 3-14.

Newson MD and Newson CL (2000). Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography* 24(2): 195-217.

Nilsson C, Ekblad A, Dynesius M, Backe S, Gardfjell M, Carlberg B, Hellqviist S and Jansson R (1994). A comparison of species richness and traits of riparian plants between a main river channel and its tributaries. *Journal of Ecology* 82: 281-295.

Nilsson C, Grelsson G, Dynesius M, Johansson ME and Sperens U (1991). Small rivers behave like large rivers: effects of postglacial history on plant species richness along riverbanks. *Journal of Biogeography* 18: 533-541.

Nixon ES, Willett RL and Cox PW (1977) Woody vegetation of a virgin forest in an eastern Texas river bottom. *Castanea* 42: 227-236.

Nortcliff S (1978). Soil variability and reconnaissance soil mapping. A statistical study in Norfolk. Journal of Soil science 29(3): 403-418.

Oswalt SN and King SL (2005). Channelization and floodplain forests: impacts of accelerated sedimentation and valley plug formation on floodplain forests of the Middle Fork Forked Deer River, Tennessee, USA. *Forest Ecology and Management* 215(1): 69-83.

Page K and Nanson G (1982) Concave-bank benches and associated floodplain formation. *Earth Surface Processes and Landforms* 7(6): 529-543.

Paine RT (1969). A note on trophic complexity and community stability. *American Naturalist* 103: 91-93.

Paine RT (1995). A conversation on refining the concept of keystone species. *Conservation Biology* 9: 962-964.

Palumbi SR and Freed LA (1988). Agonistic interactions in a keystone predatory starfish. *Ecology* 69(5):1624-1627.

Parola AC, Vesely WS, Croasdaile MA, Hansen C and Jones MS (2007). Geomorphic characteristics of streams in the Bluegrass physiographic region of Kentucky. Kentucky Division of Water: Frankfort, Kentucky, USA.

Parsons M and Thoms MC (2007). Hierarchical patterns of physical–biological associations in river ecosystems. *Geomorphology* 89(1-2): 127-146.

Pawlik Ł (2013) The role of trees in the geomorphic system of forested hillslopes—a review. *Earth-Science Reviews 126*: 250-265.

Pawlik L, Phillips JD and Samonil P (2016) Roots rock and regolith: biomechanical and biochemical weathering by trees and its impact on hillslopes - A critical literature review. *Earth-Science Reviews* 159: 142-159.

Pettit NE and Naiman RJ (2005) Flood-deposited wood debris and its contribution to heterogeneity and regeneration in a semi-arid riparian landscape. *Oecologia* 145(3): 434-444.

Phillips JD (1986). Spatial analysis of shoreline erosion, Delaware Bay, New Jersey. *Annals of the Association of American Geographers* 76(1): 50-62.

Phillips JD (1999). Earth surface systems. Blackwell, Oxford, UK.

Phillips JD (2004). Independence, contingency, and scale linkage in physical geography. In: E. Sheppard and R. B. McMaster (eds.), *Scale and Geographic Inquiry: Nature, Society, and Method*, 86-100. Wiley-Blackwell, New Jersey, USA.

Phillips JD (2006). Deterministic chaos and historical geomorphology: a review and look forward. *Geomorphology* 76(1): 109-121.

Phillips JD (2012). Synchronization and scale in geomorphic systems. *Geomorphology* 137(1): 150-158.

Phillips JD (2015) Hillslope Degradation by Trees in Central Kentucky. (Available at: https://www.researchgate.net/profile/Jonathan_Phillips4/publication/279189727_Hillslope_Degradation_by_Trees_in_Central_Kentucky/links/558d4de008ae18cfc19e1d62/Hillslope-Degradation-by-Trees-in-Central-Kentucky.pdf)

Phillips JD (2015). Badass geomorphology. *Earth Surface Processes and Landforms* 40(1): 22-33.

Phillips JD (2016) Biogeomorphology and contingent ecosystem engineering in karst landscapes. *Progress in Physical Geography* 40(4): 503-526.

Phillips JD (2016). Vanishing point: Scale independence in geomorphological hierarchies. *Geomorphology* 266:66-74.

Phillips JD (2017). Geomorphic and hydraulic unit richness and complexity in a coastal plain river. *Earth Surface Processes and Landforms* 42(15): 2623-2639.

Phillips JD (2018). Self-limited biogeomorphic ecosystem engineering in epikarst soils. *Physical Geography* 39(4): 304-328.

Phillips JD and Lorz C (2008) Origins and implications of soil layering. *Earth-Science Reviews* 89(3): 144-155.

Phillips JD and Lutz JD (2008). Profile convexities in bedrock and alluvial streams. *Geomorphology* 102(3): 554-566.

Phillips JD and Marion DA (2004) Pedological memory in forest soil development. *Forest Ecology and Management 188*(1): 363-380.

Phillips JD and Marion DA (2005) Biomechanical effects lithological variations and local pedodiversity in some forest soils of Arkansas. *Geoderma* 124: 73–89.

Phillips JD and Marion DA (2006) The biomechanical effects of trees on soils and regoliths: beyond treethrow. *Annals of the Association of American Geographers* 96: 233–247.

Phillips JD and Walls MD (2004). Flow partitioning and unstable divergence in fluviokarst evolution in central Kentucky. Nonlinear Processes in *Geophysics* 11(3): 371-381.

Phillips JD, Marion DA and Turkington AV (2008) Pedologic and geomorphic impacts of a tornado blowdown event in a mixed pine-hardwood forest. *Catena* 75: 278–287.

Phillips JD, Martin LL, Nordberg VG and Andrews WA (2004). Divergent evolution in fluviokarst landscapes of central Kentucky. *Earth Surface Processes and Landforms* 29(7): 799-819.

Phillips JD, Šamonil P, Pawlik L, Trochta J and Daněk P (2017) Domination of hillslope denudation by tree uprooting in an old-growth forest. *Geomorphology* 276: 27-36.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE and Stromberg JC (1997) The natural flow regime. *BioScience* 47(11): 769-784.

Pollen-Bankhead N and Simon A (2010). Hydrologic and hydraulic effects of riparian root networks on streambank stability: is mechanical root-reinforcement the whole story? *Geomorphology* 116 (3–4): 353–362.

Polvi LE, Wohl E and Merritt DM (2014) Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms 39*(9):1245-1258.

Poole GC (2002). Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. *Freshwater Biology* 47(4): 641–660.

Power ME, Tilman D, Estes JA, Menge BA, Bond WJ, Mills LS, Daily G, Castilla JC, Lubchenco J and Paine RT (1996). Challenges in the quest for keystones: identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. *BioScience* 46(8):609-20.

Reuter H, Jopp F, Blanco-Moreno JM, Damgaard C, Matsinos Y and DeAngelis DL (2010). Ecological hierarchies and self-organisation–Pattern analysis, modelling and process integration across scales. *Basic and Applied Ecology* 11(7): 572-581.

Rice S (2016). Sampling in Geography. In: Clifford N, Cope M, Gillespie T, French S, *Key methods in geography*. Sage, California.

Rice SP, Greenwood MT and Joyce CB (2001). Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. *Canadian Journal of Fisheries and Aquatic Sciences* 58(4): 824-840.

Rittle AM (2015) Ecohydraulic Investigation of Diatoms in a Bedrock-Controlled Stream. *MS Thesis*, University of Kentucky Lexington KY.

Roering JJ, Schmidt KM, Stock JD, Dietrich WE and Montgomery DR (2003) Shallow landsliding root reinforcement and the spatial distribution of trees in the Oregon Coast Range. *Canadian Geotechnical Journal* 40: 237–253.

Rosenfeld JS (2002). Functional redundancy in ecology and conservation. *Oikos* 98(1):156-62.

Rosenfeld JS, Post J, Robins G and Hatfield T (2007). Hydraulic geometry as a physical template for the River Continuum: application to optimal flows and longitudinal trends in salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences* 64(5): 755-767.

Ruesink JL, Lenihan HS, Trimble AC, Heiman KW, Micheli F, Byers JE and Kay MC. (2005). Introduction of non-native oysters: ecosystem effects and restoration implications. *Annual Review of Ecology, Evolution, and Systematics* 15(36): 643-89.

Russo JP and Fox JF (2010). A Model of Surface Fine Grained Laminae, Streambed and Streambank Processes Applicable to the Watershed Scale, *World Environmental and Water Resources Congress 2010: Challenges of Change*, 1893-1904.

Šamonil P, Král K and Hort L (2010) The role of tree uprooting in soil formation: A critical literature review. *Geoderma* 157: 65–79.

Schaetzl RJ, Burns SF, Johnson DL and Small TW (1989) Tree uprooting: review of impacts on forest ecology. *Vegetation* 79:165–176.

Schumm SA (1977) The Fluvial System. John Wiley and Sons, New York.

Schumm SA (2007) River variability and complexity. Cambridge University Press, New York.

Schumm SA and Chorley RJ (1983) Geomorphic controls on the management of nuclear waste. *US Nuclear Regulatory Commission NUREG/CR-3276*, Washington DC.

Schwarz C, Gourgue O, Van Belzen J, Zhu Z, Bouma TJ, Van De Koppel J, Ruessink G, Claude N and Temmerman S (2018). Self-organization of a biogeomorphic landscape controlled by plant life-history traits. *Nature Geoscience 11*(9): 672.

Shafroth PB, Auble GT, Stromberg JC and Patten DT (1998). Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona. *Wetlands 18*(4):577-590.

Shepherd RG and Ellis BN (1997). Leonardo da Vinci's tree and the law of channel widths–combining quantitative geomorphology and art in education. *Journal of Geoscience Education* 45(5): 425-427.

Sherman DJ (1995). Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geology* 124: 339–349.

Shoffner D and Royall D (2008). Hydraulic habitat composition and diversity in rural and urban stream reaches of the North Carolina Piedmont (USA). *River Research and Applications* 24(8): 1082-1103.

Shouse M (2014). Biomechanical effects of trees and soil thickness in the cumberland plateau. PhD Dissertation. Department of Geography, University of Kentucky, Lexington, KY. (URL: https://uknowledge.uky.edu/geography_etds/25).

Shouse M and Phillips JD (2016) Soil deepening by trees and the effects of parent material. *Geomorphology* 269: 1-7.

Sigafoos RS (1961) Vegetation in relation to flood frequency near Washington DC. *US Geological Survey Professional Paper* 424: 248-249

Small TW, Schaetzl RJ and Brixie JM (1990) Redistribution and mixing of soil gravels by tree uprooting. *The Professional Geographer* 42: 445–457.

Smiley Jr, PC and Dibble ED (2005). Implications of a hierarchical relationship among channel form, instream habitat, and stream communities for restoration of channelized streams. *Hydrobiologia* 548(1): 279-292.

Sparks TN, Dever GR and Anderson WH (2001). Geologic Map of the Harrodsburg 30 × 60 minute Quadrangle, Central Kentucky. Kentucky Geological Survey.

Stallins JA (2005). Stability domains in barrier island dune systems. *Ecological Complexity* 2(4): 410-430.

Stallins JA (2006). Geomorphology and ecology: unifying themes for complex systems in biogeomorphology. *Geomorphology* 77: 207–216.

Statzner B and Higler B (1985). Questions and comments on the river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 42(5): 1038-1044.

Statzner B and Higler B (1986). Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. *Freshwater biology* 16(1): 127-139.

Steiger J, Tabacchi E, Dufour S, Corenblit D and Peiry JL (2005) Hydrogeomorphic processes affecting riparian habitat within alluvial channel–floodplain river systems: a review for the temperate zone. *River Research and Applications* 21(7): 719-737.

Stoddart DR (1969). Ecology and morphology of recent coral reefs. *Biological Reviews* 44(4): 433-498.

Stoffel M and Wilford DJ (2012) Hydrogeomorphic processes and vegetation: disturbance process histories dependencies and interactions. *Earth Surface Processes and Landforms* 37(1): 9-22.

Stotts S, O'Neal MA and Pizzuto JE (2015). Observations of riparian tree geometry and bank characteristics along a bank stability gradient at the South River, VA. *River research and applications* 31(6):747-54.

Stream Systems Technology Center (2002). Identifying Bankfull Stage in Forested Streams in the Eastern United States. U.S. Department of Agriculture Forest Service.

Tabacchi E, Lambs L, Guilloy H, Planty-Tabacchi AM, Muller E and Decamps H (2000) Impacts of riparian vegetation on hydrological processes. *Hydrological processes* 14(16-17): 2959-2976.

Tabacchi E, Planty-Tabacchi AM, Roques L and Nadal E (2005) Seed inputs in riparian zones: implications for plant invasion. *River Research and Applications* 21: 299–313.

Tal M and Paola C (2007). Dynamic single-thread channels maintained by the interaction of flow and vegetation. *Geology* 35(4): 347–350.

Tal M and Paola C (2010). Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms* 35 (9): 1014–1028.

Tal M, Gran K, Murray AB, Paola C and Hicks DM (2004). Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. *Riparian vegetation and fluvial geomorphology* 8:43-58.

Tang ZC and Kozlowski TT (1982). Physiological, morphological, and growth responses of *Platanus occidentalis* seedlings to flooding. *Plant and Soil* 66: 243-255.

Teller JT and Goldthwait RP (1991). The old Kentucky River; a major tributary to the Teays River. *Geological Society of America* 258: 29–42.

Thompson A (1986). Secondary flows and the pool-riffle unit: A case study of the processes of meander development. *Earth Surface Processes and Landforms* 11: 631-641.

Thompson DM (2006). The role of vortex shedding in the scour of pools. *Advances in Water Resources 29*(2):121-129.

Thomson JR, Taylor MP, Fryirs KA and Brierley GJ (2001). A geomorphological framework for river characterization and habitat assessment. *Aquatic Conservation: Marine and Freshwater Ecosystems* 11(5): 373-389.

Thorne C (1990) Effects of vegetation on river bank erosion and stability, Wiley, UK.

Thorp JH, Thoms MC and Delong MD (2010) The riverine ecosystem synthesis: toward conceptual cohesiveness in river science. Elsevier, Boston, USA.

Tickner DP, Angold PG, Gurnell AM and Mountford JO (2001) Riparian plant invasions: hydrogeomorphological control and ecological impacts. *Progress in Physical Geography* 25(1): 22-52.

Tiner RW (2016). Wetland indicators: A guide to wetland formation, identification, delineation, classification, and mapping. Boca Raton, FL: CRC Press.

Tinkler K and Wohl E (1998) A primer on bedrock channels In: Tinkler K and Wohl E (Eds) *Rivers over rock: Fluvial processes in bedrock channels*, 1-18. Washington DC, American Geophysical Union.

Tinkler KJ and Parish J (1998) Recent adjustments to the long profile of Cooksville Creek an urbanized bedrock channel in Mississauga Ontario In: Tinkler K and Wohl E (Eds) *Rivers over rock: Fluvial processes in bedrock channels*, 167-187. Washington DC, American Geophysical Union.

Tockner K and Stanford JA (2002) Riverine flood plains: present state and future trends. *Environmental Conservation* 29(3): 308-330.

Townsend CR (1989). The patch dynamics concept of stream community ecology. *Journal of the North American Benthological Society* 8(1): 36-50.

Townsend CR (1996). Concepts in river ecology: pattern and process in the catchment hierarchy. *Large Rivers* 3-21.

Trimble SW (1997) Stream channel erosion and change resulting from riparian forests. *Geology* 25(5): 467-469.

Tsujimoto T (1999) Fluvial processes in streams with vegetation. *Journal of hydraulic research* 37(6): .789-803

Tsukahara H and Kozlowski TT (1985). Importance of adventitious roots to growth of flooded *Platanus occidentalis* seedlings. *Plant and Soil* 88: 123-132.

Van Breemen N (1995). How Sphagnum bogs down other plants. *Trends in ecology & evolution* 10(7): 270-275.

Van Dyke C (2016) Nature's complex flume—Using a diagnostic state-and-transition framework to understand post-restoration channel adjustment of the Clark Fork River Montana. *Geomorphology* 254: 1-15.

Vander Zanden MJ, Casselman JM and Rasmussen JB (1999). Stable isotope evidence for the food web consequences of species invasions in lakes. *Nature* 401:464–67.

Vannote RL, Minshall GW, Cummins KW, Sedell JR and Cushing CE (1980). The river continuum concept. *Canadian journal of fisheries and aquatic sciences* 37(1): 130-137.

Vaughn DM (1990) Flood dynamics of a concrete-lined urban stream in Kansas City Missouri. *Earth Surface Processes and Landforms* 15(6): 525-537.

Viles HA (1988). Biogeomorphology. Blackwell, Oxford, UK.

Viles HA, Naylor LA, Carter NEA and Chaput D (2008) Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. *Earth Surface Processes and Landforms* 33(9): 1419-1435.

Vitousek PM (1990) Biological invasions and ecosystem process: towards an integration of population biology and ecosystem studies. *Oikos* 57: 7–13.

Wang Q, An SQ, Ma ZJ, Zhao B, Chen JK and Li B (2006). Invasive Spartina alterniflora: biology, ecology and management. *Journal of Systematics and Evolution* 44:559–88.

Ward JV, Tockner K, Arscott DB and Claret C (2002) Riverine landscape diversity. *Freshwater Biology* 47(4): 517-539.

Ward JW and Stanford JA (1983). Intermediate-disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. In: T.D. Fontaine and S.M. Bartell (eds.), *Dynamics of lotic ecosystems*, 347- 356. Ann Arbor Science Publishers, Ann Arbor MI, USA.

Whipple KX (2004) Bedrock rivers and the geomorphology of active orogens. *Annual Review of Earth and Planetary Sciences* 32: 151-185.

Whipple KX, Hancock GS and Anderson RS (2000) River incision into bedrock: Mechanics and relative efficacy of plucking abrasion and cavitation. *Geological Society of America Bulletin* 112(3): 490-503.

Wicander R and Wood GD (1981). Systematics and biostratigraphy of the organic walled microphytoplankton from the Middle Devonian (Givetian) Silica Formation, Ohio, USA. No. 8. American Association of Stratigraphic Palynologists Foundation.

Wiens JA (2002). Riverine landscapes: taking landscape ecology into the water. *Freshwater biology* 47(4): 501-515.

Wilkinson MT, Richards PJ and Humphreys GS (2009) Breaking ground: pedological geological and ecological implications of soil bioturbation. *Earth-Science Reviews* 97(1): 257-272.

Wohl E (2013) Floodplains and wood. *Earth-Science Reviews* 123: 194-212.

Wohl E and Scott DN (2017) Wood and sediment storage and dynamics in river corridors. *Earth Surface Processes and Landforms* 42(1): 5-23.

Wohl E and Ikeda H (1998) Patterns of bedrock channel erosion on the Boso Peninsula Japan. *The Journal of Geology* 106(3): 331-346.

Wohl EE and Merritt DM (2001). Bedrock channel morphology. *Geological Society of America Bulletin* 113(9): 1205-1212.

Wohl EE, Greenbaum N, Schick AP and Baker VR (1994). Controls on bedrock channel incision along Nahal Paran, Israel. *Earth Surface Processes and Landforms* 19(1): 1-13.

Wohl EE, Thompson DM and Miller AJ (1999). Canyons with undulating walls. *Geological Society of America Bulletin* 111(7): 949-959.

Woodhouse WW (1982). Coastal sand dunes of the United States. In: Lewis, R.R. (Ed.), *Creation and Restoration of Coastal Plant Communities.* CRC Press, Boca Raton, Florida. 1–44.

Wright JP and Jones CG (2006). The concept of organisms as ecosystem engineers ten years on: progress, limitations, and challenges. *BioScience 56*(3): 203-209.

Yanosky TM (1982) Effects of flooding upon woody vegetation along parts of the Potomac River flood plain. *United States Geological Survey Professional Paper 1206.*

Yatsu E (1988) The nature of weathering: an introduction Sozosha, Tokyo, Japan.

Ziemer RR (1981) The role of vegetation in the stability of forested slopes. *Proceedings of the International Union of Forestry Research Organizations XVII World Congress 6–17 September 1981, Kyoto Japan,* vol I: 297–308.

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RESEARCH PUBLICATIONS

- **Jerin, T.**, and Phillips, J. (2020). Biogeomorphic Keystones and Equivalents: Examples from a Bedrock Stream. *Earth surface processes and landforms*. DOI: 10.1002/esp.4853 (in press).

- Ishtiaque, A., Masrur, A., Rabby, Y.W., **Jerin, T**., and Dewan, A. (2020). Remote Sensing-Based Research for Monitoring Progress towards SDG 15 in Bangladesh: A Review. Remote Sensing, 12 (4), 691.

- **Jerin, T**. (2019). Biogeomorphic effects of woody vegetation on bedrock streams. *Progress in Physical Geography: Earth and Environment*, 43 (6), 777 – 800.

- **Jerin, T**., and Phillips, J. (2017). Local efficiency in fluvial systems: Lessons from Icicle Bend. *Geomorphology*, 282, 119–130.

- **Jerin, T.** and Rahman, M.M. (2015). Groundwater Depletion in Dhaka City, Bangladesh: A spatio-temporal analysis. *Oriental Geographer,* 56, 25-42.

MANUSCRIPT IN REVISION/UNDER REVIEW/IN PREPARATION

- Van Dyke, C., **Jerin, T**., Albright, N. and Blandford, B. (2020). Rapid Diagnostic Framework for Assessing Bridge and Culvert Sensitivity to Hydraulic Forcings. *Natural Hazards Review* (in revision).

- **Jerin, T.** (2020). Scale associated coupling between channel morphology and riparian vegetation in a bedrock controlled stream. *Geomorphology* (under review).

AWARDS AND FELLOWSHIPS

- Research fellowship, Spring 2019. Department of Geography, University of Kentucky.
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