

Abundance, Distribution, and Geometry of Naturally Occurring Macropores in Stream Banks

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Abstract

Preferential flow paths are areas of substantially higher permeability than surrounding media. Macropores and soil pipes are a type of preferential flow path where conduit-like voids in the subsurface are typically greater than three millimeters in diameter. They are known to occur in agricultural and forest soils, often as a result of biological and physical processes. Macropores also exist in stream banks and have the potential to enhance the exchange of water and solutes between the channel and riparian groundwater, yet the geographic distribution of bank macropores is unknown. Here we determined the abundance, distribution, and geometry of naturally occurring surface-connected macropores in the banks of 20 streams across five physiographic provinces in the Eastern United States. We identified a total of 1,748 macropores, which were present in all 20 streams, with 3.8 cm average width, 3.3 cm average height, 11.5 cm average depth, and 27.9 cm average height above water surface elevation. Macropore abundance, distribution and geometry were statistically different between physiographic provinces, stream orders, and soil textures, with the latter being the most important. Macropores tended to be larger and more abundant in soils with a high cohesiveness and a low hydraulic conductivity compared to soils with a low cohesiveness and high hydraulic conductivity. As a result, streams with greater longitudinal heterogeneity of soil texture also had greater heterogeneity of macropore density. However, macropore size and height above baseflow water surface elevation also increased with stream order and therefore stream size. This work represents the first attempt to characterize macropores across a variety of riverine systems and presents evidence that macropores may play an important role in hyporheic exchange within stream banks. These results may have water quality implications, where macropores may enhance hyporheic exchange yet reduce the filtering capacity of riparian buffer zones.

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General Audience Abstract

Preferential flow paths are soil cavities or areas of highly permeable porous media surrounded by media with a significantly lower permeability. Macropores are a type of preferential flow path where conduit-like voids in the subsurface are typically greater than three millimeters in diameter. Their formation is often the result of biological processes, such as animal burrows and plant roots, erosive action in subsurface flow, or cracks in the soil, and can enable rapid movement of water. Macropores are known to exist in stream banks and have the potential to enhance the exchange of water and solutes between the stream channel and riparian groundwater, yet the geographic distribution of bank macropores is unknown. This research examines the distribution, abundance, and geometry of naturally occurring macropores in the banks of 20 streams across five physiographic provinces in the eastern United States. Macropores were present in all 20 streams despite variations in physiographic province, stream order, and soil texture. However, soil texture appeared to have the greatest influence on the distribution, abundance, and geometry of macropores. For example, soils primarily containing silt and clay had more macropores than soils consisting of sand or gravel. We suspect this is due to differences in soil cohesiveness and/or hydraulic conductivity. This work represents the first attempt to characterize macropores across a variety of riverine systems and presents evidence that macropores may play an important role in surface water and groundwater exchange within stream banks. These results may have water quality implications, for example, how macropores affect the pollutant filtering capacity of riparian buffer zones.

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Chapter 1 – Introduction and Literature Review

1.1 Literature Review

Preferential flow paths are areas of high hydraulic conductivity (K) where water and solutes can be transported rapidly through soil or sediment. Macropores or soil pipes, a type of preferential flow pathway, are naturally occurring void spaces in the substrate. When macropores are present in soil, it has been found that macropore flow can be several hundred times more rapid than flow through the soil matrix [Aubertin, 1971]. Due to growing concerns of contaminant discharge and nutrient overloading in riverine systems, it is important to understand how macropores play a role in processing pollutants and nutrients in streambed and stream bank sediments. Such processes may affect pollutant migration down channels through exchange within the hyporheic zone, and from uplands to the channel through effects on transport across the riparian zone.

1.1.1 Hyporheic Exchange

The hyporheic zone is the area beneath and adjacent to stream channels, through which shallow groundwater and surface water interact [Triska *et al.*, 1989]. The rate (Q) of hyporheic exchange can be modeled using Darcy's Law, $Q = KiA$, where Q is the flow rate [L^3/T], K is the hydraulic conductivity [L/T], i is the hydraulic gradient [L/L], and A is the cross-sectional area [L^2]. The transitional nature of the hyporheic zone plays a critical role in mitigating interactions between shallow groundwater and surface water. More processes occur in the hyporheic zone than in surface water or deeper groundwater, such as thermal moderation of surface water, creation of niche aquatic habitat, nutrient cycling, and pollutant attenuation [Allaire-Leung *et al.*, 2000; Brunke and Gonser, 2003]. These processes may be influenced by the presence or absence of macropores in riverine systems.

Because the hyporheic zone within stream banks can fluctuate depending on varying river stages and flow conditions, it is important to understand how macropores may influence their hydrology. Hyporheic zone flow paths can be classified as “lung” model or “gill” model [Sawyer *et al.*, 2009]. The gill model is characterized by steady-state flow from surface water to groundwater and back to surface water. Reach hydrology can be mildly gaining or mildly losing, and gill model exchange is typically present when water levels are relatively constant in streams over a period of time, such as at steady baseflow conditions. Conversely, the lung model entails

exchange that fluctuates temporally between gaining and losing conditions based on fluctuating water levels in the stream, such as following a storm event, snowmelt runoff, tidally influenced riverine systems, or as a downstream result of hydropower peaking [Arntzen *et al.*, 2006; Bianchin *et al.*, 2011; Francis *et al.*, 2010; Loheide and Lundquist, 2009]. Based on findings by Menichino *et al.* [2015a], macropores in stream banks are most likely to occur above baseflow conditions. This indicates that macropores may influence such lung model exchange.

1.1.2 Preferential Flow

Preferential flow refers to rapid movement of water and associated solutes through porous media in regions of significantly higher K compared to the surrounding media. Preferential flow can increase the unidirectional transport of solutes and contaminants from land to water bodies and the bidirectional exchange between channel and stream banks [Allaire *et al.*, 2011]. For example, studies of gravel veins in floodplains and natural levees have shown that high levels of hyporheic exchange occur through areas of high hydraulic conductivity compared to surrounding areas with lower hydraulic conductivity [Zhou *et al.*, 2014; Newman and Keim, 2013; Fox *et al.*, 2011]. Similarly, models have shown that bedforms and meander bends may induce preferential flow paths and increase hyporheic residence times [Stonedahl *et al.*, 2010]. However, hyporheic exchange through preferential flow paths and macropores within stream banks has been relatively little studied.

Macropores or soil pipes are one type of preferential flow. Macropores are large void spaces in soil that are typically greater than 3 mm in diameter [Luxmoore, 1981]. When open to the surface, macropores can be examined with the naked eye. Macropores have been well characterized in fields related to forest hydrology [Aubertin, 1971; Sidle *et al.*, 2001] and agriculture [Allaire *et al.*, 2011]. In these studies, it was found that the soil matrix hydraulic conductivity was almost completely masked by macropore flow, which was several hundred times more rapid. In substrates with substantial preferential flow through macropores, only a small portion of water percolates through the soil matrix, while the large majority of water is transported through preferential flow paths [Hendrickx and Flury, 2001]. However, the characterization of macropores has been relatively absent from stream hydrology literature. As a part of the hyporheic exchange, it is well known that surface water and groundwater can be readily exchanged within the hyporheic zone; however, the mechanisms by which water flows

between streams and their adjacent banks through macropores is poorly understood [Menichino *et al.*, 2015a].

According to Menichino *et al.* [2015a], Menichino *et al.* [2015b], and Menichino *et al.* [2014], the common belief was that hyporheic exchange and hydraulic conductivity of the channel substrate were directly proportional [Azinheira *et al.*, 2014; Hester and Doyle, 2008; Kasahara and Hill, 2007; Storey *et al.*, 2003]. That is, substrates comprised primarily of gravels and cobbles would have higher hyporheic exchange than substrates dominated by silts and clays. However, the presence of macropores in finer grained soils, such as silts and clays, can potentially increase hyporheic exchange. Until a study by Menichino *et al.* [2015a], this hypothesis had not been tested. To better understand the function of the hyporheic zone in riverine systems, it is crucial to understand the exchange processes and physical pathways of surface water and groundwater interaction in macropores.

1.1.3 Macropore Creation Mechanisms

Naturally occurring macropores can be formed through a variety of mechanisms, including animal burrows [Ehlers, 1973; Stone, 1993] plant root decay [Stirzaker *et al.*, 1996], soil piping [Fox *et al.*, 2011; Jones, 1971; Jones and Cottrell, 2007], erosion around hardened structures, and freeze-thaw cycle [Allaire *et al.*, 2011]. Macropores are more likely to occur in soils with high clay content compared to soils with a high sand content [Allaire *et al.*, 2011]. Because clays and silts tend to be more cohesive compared to sands and gravels, macropores may have greater structural integrity in clayey soils than in soils with high sand content [Lal and Shukla, 2004]. Additionally, clay particles can be deposited as clay skins on the side of the macropores, thus possibly increasing their structural integrity and persistence [Aubertin, 1971].

The physical characteristics of macropores, such as their geometry, abundance, and distribution, can vary widely based on soil properties [Beven and Germann, 2013] and creation mechanisms [Holden, 2005; Jones, 1971; Jones and Cottrell, 2007]. However, the breadth of mechanisms by which macropores are created within riverine systems specifically have not been studied. Although previous studies suggest that macropores can be common in specific riverine systems [Menichino *et al.*, 2015a], their broader distribution at regional or continental levels is unknown.

1.1.4 Hydraulic Implications of Macropores in Stream Banks

A practical application of studying macropores is to further understand how water is transported and stored in soils adjacent to streams. According to *Menichino et al.* [2015a], HEC-RAS modeling showed that only 1 to 32% of macropores were inundated by channel water at baseflow conditions; the remaining 99 to 68% of macropores were found above baseflow conditions. Given that these macropores tend to be inundated on a time-dependent basis, this supports the hypothesis that macropores in stream banks may be more influenced by the lung model than gill model. As such, understanding the physical characteristics of macropores (i.e. volume and interconnectivity) can help hydrologists, engineers, ecologists, and geomorphologists understand the transient storage capacity of riverbanks beyond the storage capacity of the stream channel. Quantifying the volume and interconnectedness of macropores in riverine systems may help build more accurate hydrologic models to prepare for and mitigate flood events [*Pinder and Sauer*, 2010].

Another hydrological application is to model the nutrient processing efficiency of natural or constructed riparian zones. Water traveling from uplands to streams is often transported as subsurface flow through pervious substrate. A wealth of studies has shown that riparian buffer zones improve water quality of infiltrated groundwater in uplands before discharging to natural bodies of water [*Anbumozhi et al.*, 2005; *Correll*, 1997; *Osborne and Kovacic*, 1993]. However, the presence of surface-connected macropores may result in preferential flow paths that bypass the infiltrative capacity and nutrient processing capabilities of the riparian zones. Ultimately, this may allow a greater loading of pollutants to pass through the riparian zone than otherwise expected. Conversely, surface-connected macropores in stream banks may serve as a conduit for preferential flow into the banks during high flow events. This may enhance pollutant reducing capabilities of the hyporheic zone and riparian buffers. The implication of these may eventually improve how engineered riparian buffer zones are constructed to better process nutrients and other pollutants.

Some studies have explored how the hyporheic zone affects the transient storage capacity and solute transport capacity of riverine systems [*Morrice et al.*, 1998; *Valett et al.*, 1990]; however, the inclusion of macropores in these processes has been relatively absent from stream literature [*Menichino et al.*, 2014].

1.1.5 Purpose of Study

A study by *Menichino et al.* [2015a] explored the fundamental physical characteristics of surface-connected macropores along streams. The study focused on the abundance, distribution, and geometry of macropores along five second- and third-order streams banks in the Valley and Ridge physiographic province of Virginia. While surface-connected macropores were found along all five streams, the small sample size and area of the study restricted the applicability to other physiographic provinces and stream orders.

The purpose of this study is to expand upon the work done by *Menichino et al.* [2015a]. This research will characterize the geometry, abundance, and distribution of naturally occurring surface-connected macropores in stream banks throughout five physiographic provinces and first through fourth order streams throughout the Eastern United States. Characterizing the physical parameters of macropores will provide a fundamental basis for further investigations of how macropores influence hyporheic exchange in riverine systems. The specific objectives of this study are to:

1. Determine whether or not surface-connected macropores are present in all physiographic provinces and surveyed stream reaches.
2. Qualify and quantify differences in macropore abundance, distribution, and geometry based on physiographic province, stream order, and soil texture.

Characterizing these parameters will provide a fundamental basis for furthering the field of research pertaining to stream hydrology and morphology. Further studies, beyond the scope of this thesis, can build upon these fundamental physical characteristics to parameterize the total volume and interconnectivity of macropores, the spatial-temporal distribution of macropores, how macropores influence hyporheic exchange, and the importance of formation mechanisms of macropores in riverine systems.

1.2 Organization of Thesis

This thesis is organized in a journal article format. The journal article is located in Chapter 2 of this document and will likely be submitted to *Freshwater Science*. The introduction of the journal article is a condensed version of the literature review in this section. The engineering applications and significance of the study are located in Chapter 3. The appendix

contains supporting material, including figures, tables, and results beyond what could be included in the journal article.

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Chapter 2 - Abundance, Distribution, and Geometry of Naturally Occurring Macropores in Stream banks

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2.1 Abstract

Preferential flow paths are areas of substantially higher permeability than surrounding media. Macropores and soil pipes are a type of preferential flow path where conduit-like voids in the subsurface are typically greater than three millimeters in diameter. They are known to occur in agricultural and forest soils, often as a result of biological and physical processes. Macropores also exist in stream banks and have the potential to enhance the exchange of water and solutes between the channel and riparian groundwater, yet the geographic distribution of bank macropores is unknown. Here we determined the abundance, distribution, and geometry of naturally occurring surface-connected macropores in the banks of 20 streams across five physiographic provinces in the Eastern United States. We identified a total of 1,748 macropores, which were present in all 20 streams, with 3.8 cm average width, 3.3 cm average height, 11.5 cm average depth, and 27.9 cm average height above water surface elevation. Macropore abundance, distribution and geometry were statistically different between physiographic provinces, stream orders, and soil textures, with the latter being the most important. Macropores tended to be larger and more abundant in soils with a high cohesiveness and a low hydraulic conductivity compared to soils with a low cohesiveness and high hydraulic conductivity. As a result, streams with greater longitudinal heterogeneity of soil texture also had greater heterogeneity of macropore density. However, macropore size and height above baseflow water surface elevation also increased with stream order and therefore stream size. This work represents the first attempt to characterize macropores across a variety of riverine systems and presents evidence that macropores may play an important role in hyporheic exchange within stream banks. These results may have water quality implications, where macropores may enhance hyporheic exchange yet reduce the filtering capacity of riparian buffer zones.

Keywords: macropore, soil pipes, preferential flow, surface water-groundwater interaction, stream bank hydrology, subsurface flow, hydraulic conductivity, hyporheic zone

2.2 Introduction

The hyporheic zone is the area beneath and adjacent to stream and river channels through which shallow groundwater and surface water interact [Triska *et al.*, 1989]. The transitional nature of the hyporheic zone plays a critical role in mitigating interactions between shallow

groundwater and surface water. A variety of processes occur to a greater extent in the hyporheic zone than in surface water or deeper groundwater, such as thermal moderation of surface water, creation of niche aquatic habitat, nutrient cycling, and pollutant attenuation [Allaire-Leung *et al.*, 2000; Brunke and Gonser, 2003]. Hyporheic zone flow paths can be classified as “lung” model or “gill” model [Sawyer *et al.*, 2009]. The gill model entails steady-state flow from surface water to groundwater and back. Conversely, the lung model entails dynamic exchange that transitions temporally between flow into and out of the banks due to fluctuating water levels in the channel. Lung model exchange is also known as bank storage, and can occur during storm events, snowmelt runoff, tidal cycles, and hydropower peaking [Arntzen *et al.*, 2006; Bianchin *et al.*, 2011; Francis *et al.*, 2010; Loheide and Lundquist, 2009].

Preferential flow in porous media refers to rapid movement of water and associated solutes through regions of significantly higher hydraulic conductivity (K) compared to the surrounding media. Preferential flow can increase both unidirectional transport of solutes and contaminants from land to water bodies and bidirectional hyporheic exchange between channel and stream banks [Allaire *et al.*, 2011]. For example, studies of gravel veins in floodplains and natural levees have shown that high levels of hyporheic exchange occur through areas of high hydraulic conductivity compared to surrounding areas with lower hydraulic conductivity [Zhou *et al.*, 2014; Newman and Keim, 2013; Fox *et al.*, 2011]. Similarly, models have shown that bedforms and meander bends may induce preferential flow paths and increase hyporheic residence times [Stonedahl *et al.*, 2010].

Macropores or soil pipes are one type of preferential flow where void spaces exist in soil with typically greater than 3 mm diameter [Luxmoore, 1981]. Macropores have been well characterized in forest hydrology [Aubertin, 1971; Sidle *et al.*, 2001] and agriculture [Allaire *et al.*, 2011]. In substrates with substantial preferential flow through macropores, only a small portion of water percolates through the soil matrix, while the large majority of water is transported through preferential flow paths [Hendrickx and Flury, 2001]. A common assumption of hyporheic studies is that exchange flux and substrate matrix hydraulic conductivity are directly proportional [Azinheira *et al.*, 2014; Hester and Doyle, 2008; Kasahara and Hill, 2007; Storey *et al.*, 2003]. This implies that substrates comprised primarily of gravels and cobbles have higher hyporheic exchange than substrates dominated by silts and clays. However, the presence of macropores can increase hyporheic and riparian exchange in finer grained soils Menichino *et*

al. [2015b]; *Menichino et al.* [2015a]; *Menichino et al.* [2014]. *Menichino et al.* [2015a] showed that most (99 to 68%) macropores were found above baseflow conditions. Thus, macropores in stream banks likely influence lung model hyporheic exchange more than gill model. The characterization of macropores has been relatively absent from stream hydrology literature, yet is critical for understanding how macropores affect hyporheic exchange hydrology and in turn pollutant migration processes.

Naturally occurring macropores can be formed through a variety of mechanisms, including animal burrows [*Ehlers*, 1973; *Stone*, 1993], plant root decay [*Stirzaker et al.*, 1996], soil piping [*Fox et al.*, 2011; *Holden*, 2005; *Jones*, 1971; *Jones and Cottrell*, 2007], erosion around hardened structures, and freeze-thaw cycles [*Allaire et al.*, 2011]. Macropores are more likely to occur in soils with high clay content compared to soils with a high sand content [*Allaire et al.*, 2011]. The physical characteristics of macropores, such as their geometry, abundance, and distribution, can vary widely based on soil properties [*Beven and Germann*, 2013] and creation mechanisms. Although previous studies suggest that macropores can be common in specific streams [*Menichino et al.*, 2015a], their broader distribution at regional or continental levels is unknown.

Riparian buffer zones are vegetated areas of land that separate a body of water from an adjacent land use. They occur naturally or are engineered with the expectation that they remove contaminants from groundwater migrating toward receiving water bodies [*Anbumozhi et al.*, 2005; *Correll*, 1997; *Osborne and Kovacic*, 1993]. However, the presence of macropores in riparian soils and stream banks may create preferential flow that bypasses this expected beneficial capacity. Conversely, macropores in stream banks may induce preferential flow into the banks during high flow events. This may enhance the ability of hyporheic restoration approaches to remove pollutants migrating down the channel [*Berg et al.*, 2014]. Knowledge of preferential flow effects could improve how engineered riparian buffer zones and hyporheic restoration are conducted to better process nutrients and other pollutants.

The purpose of this study is to expand upon the work done by *Menichino et al.* [2015a] which studied the abundance, distribution, and geometry of stream bank surface-connected macropores (macropores visible to the naked eye) in five streams in southwest Virginia. While surface-connected macropores were found in all five streams, their geographic scope and range of stream orders were narrow. Here, we survey surface-connected macropores along stream

banks in five physiographic provinces and first through fourth order streams in the Eastern United States. Our objectives were to 1) determine whether surface-connected macropores are present in all physiographic provinces and 2) quantify variation of macropore abundance, distribution, and geometry among physiographic provinces, stream orders, and soil textures. This will provide a fundamental basis for understanding their effects on stream hydrology and water quality.

2.3 Methods

2.3.1 Site Selection

We conducted field surveys in 20 stream reaches in the Eastern United States (Figure 1) from May 2017 through September 2017. We chose field locations (Table 1) primarily based on dominant land cover and stream order. We conducted field surveys in five physiographic provinces (Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain) to capture the potential effects of distinct variations in geology, soil texture, and topography on presence of stream bank macropores. These physiographic provinces can be classified into three regions: mountains (Appalachian Plateau, Valley and Ridge, and Blue Ridge), highlands (Piedmont), and flats (Coastal Plain), with corresponding variations in stream slope. Field sites in Virginia were located in the mountains and the Piedmont physiographic province, while field sites in New Jersey were location in the Coastal Plain (Figure 1). We only surveyed one site in the Valley and Ridge physiographic province since *Menichino et al.* [2015a] had previously surveyed five sites in the Valley and Ridge physiographic province. We chose Coastal Plain sites in New Jersey rather than Virginia due to greater relative abundance of accessible public land.

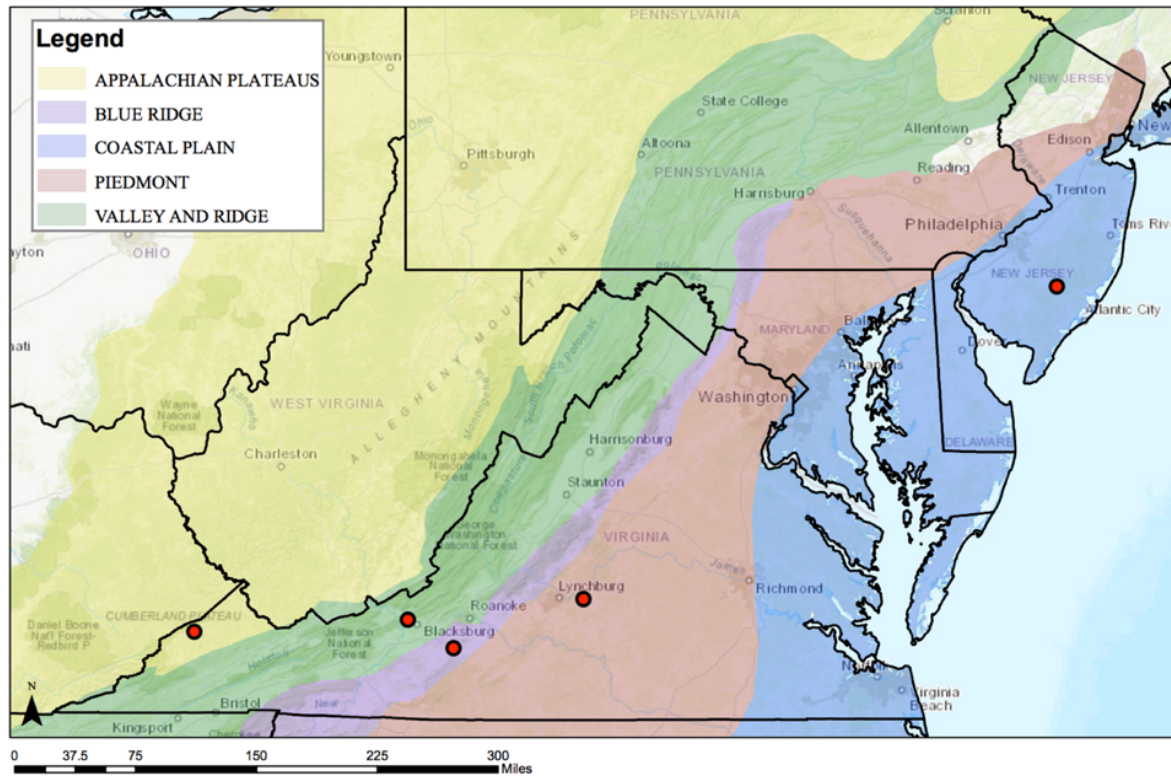


Figure 1: General location of field survey areas across Virginia and New Jersey within their respective physiographic provinces.

Table 1: Stream sites surveyed for naturally occurring macropores. Further data for the Valley and Ridge physiographic province can be found in *Menichino et al.* [2015a].

Physiographic Province	Stream Name	Stream Order	Channel Morphology	Land Cover	Stream Slope [m/m]	Length Completed [m]	Avg. Bank Width [m]	Avg. Bank Height [m]	Latitude [DD]	Longitude [DD]
Blue Ridge	Tributary to Bottom Creek	1	Cascade	Forest	1.1E-01	187.4	3.0	0.4	37.133603	-80.186282
	Little Rock Castle Creek	2	Cascade	Forest	7.6E-02	270.0	5.7	0.8	36.808084	-80.331591
	Bottom Creek	3	Pool Riffle	Forest	7.1E-03	270.0	13.8	3.2	37.131716	-80.181339
Valley and Ridge	Poverty Creek	1	Pool Riffle	Forest	2.2E-02	340.0	5.6	0.6	37.280187	-80.471922
Appalachian Plateau	Little Laurel Creek	1	Cascade / Colluvial	Forest	7.1E-02	226.8	3.8	0.7	37.198378	-82.441470
	Bearpen Creek	2	Bedrock	Forest	1.7E-02	289.0	7.1	1.6	37.198911	-82.479722
	North Fork Pound River	3	Pool Riffle	Forest/ Lawn	1.2E-02	130.0	5.6	1.3	37.100383	-82.679374
	Pound River	4	Pool Riffle	Forest	8.9E-03	234.7	18.2	--	37.192317	-82.457413
Coastal Plain	Arnold Branch	1	Coastal Plain	Forest	5.3E-03	86.0	1.4	0.4	39.646358	-74.503163
	Bispham Mill Creek – Left Branch	2	Coastal Plain	Forest	1.2E-03	251.0	9.0	0.8	39.943616	-74.607815
	Bispham Mill Creek – Right Branch	2	Coastal Plain	Forest	1.2E-03	61.3	5.3	0.6	39.943616	-74.607815
	Greenwood Branch	4	Coastal Plain	Forest	2.4E-04	30.0	9.3	0.9	39.947904	-74.608882
	Wading River	4	Coastal Plain	Forest	1.2E-03	210.0	10.5	0.5	39.660041	-74.525678
Piedmont	Fishpond Creek	1	Pool Riffle	Forest	8.9E-03	234.0	3.9	1.2	37.428128	-78.714824
	Plain Run Branch	1	Pool Riffle	Forest	1.5E-02	324.0	5.4	1.0	37.374845	-78.791569
	Fishpond Creek	2	Pool Riffle	Forest	3.0E-02	178.0	8.9	1.3	37.398832	-78.681420
	North Fork Wolf Creek	2	Pool Riffle	Forest	2.7E-02	342.0	5.7	0.6	37.398919	-78.730660
	Vaughans Creek	3	Dune Ripple	Forest	2.8E-02	245.0	12.3	2.9	37.352168	-78.560220
	Appomattox River	3	Pool Riffle	Forest	6.7E-03	200.0	8.0	2.0	37.382204	-78.787962
	Appomattox River	4	Pool Riffle	Forest	6.4E-03	156.6	20.0	6.2	37.358853	-78.555310

Macropore abundance and characteristics depend on soil characteristics [Menichino *et al.*, 2015a], which in turn vary geographically. Soil texture (the relative amounts of clay, silt, and sand) can be used as a rough proxy for soil cohesion [Lal and Shukla, 2004] and soil hydraulic conductivity [NRCS, n.d.]. Soils with high clay and silt content have a higher cohesion, and therefore a higher stability [Lal and Shukla, 2004; Menichino *et al.*, 2015a] than soils predominated by sands and gravels. Because of this, we expected macropores to be more abundant, wider, taller, and deeper in clayey and silty soils (low K) compared to sandy, organic, and gravelly soils (high K).

Both the Appalachian Plateau and Valley and Ridge consist of sedimentary rocks such as sandstone, limestone, and shale. Mountain ridges tend to be sandy (sandstone parent material), while valley floors tend to be silty and clayey (limestone and shale parent material). We therefore expected to find more macropores in the valley floors compared to higher on ridges. The Blue Ridge consists of sedimentary and igneous rock [Baker, 2000; DCR, 2016], stony soils, high amounts of crystalline substrates, and substantial colluvium on steep hill slopes. We therefore expected fewer macropores in this province. The Piedmont is dominated by igneous and metamorphic rocks such as gneiss, schist, and granite, and soils have a high clay content [Baker, 2000; DCR, 2016]. Because soils range from clayey to sandy loam and are often deep, we expected a high number of macropores. The Coastal Plain tends to consist of unconsolidated sediment deposits with thick sandy surfaces; however, some areas of the Coastal Plain can be very clayey [Baker, 2000; DCR, 2016]. Our field studies for this physiographic province were conducted around the New Jersey Pine Barrens, which has a high presence of sand and organic substrate, with very little clay or silt. Due to the high amount of sand and organic substrate, we expected few macropores there.

We chose first through fourth order streams [McKay *et al.*, 2012; Strahler, 1952] as a proxy for stream width, depth, and discharge to see how flow conditions affect macropore characteristics. Avoiding streams larger than fourth order allowed us to complete stream surveys on foot without the need for watercraft. In some physiographic provinces, certain stream orders were unavailable. For example, in the Blue Ridge Mountains, only first through third order streams were available, due to the narrowness of the province. Additionally, even if some stream orders were physically present in physiographic provinces, they were sometimes inaccessible due to logistical constraints (e.g. on private land or inaccessible by car). In all, we surveyed six first-

order streams, six second-order streams, four third-order streams, and four fourth-order streams for a total of 20 streams (Table 1). Eight streams were in the mountains, seven in the Piedmont, and five in the Coastal Plain.

Other factors potentially influencing macropore variability include channel slope and land cover. Channel slope affects channel flow conditions which may affect macropores, although the effect of slope on the variability of macropore characteristics has not been studied. We determined approximate channel slope for each stream based on 1:24,000 USGS topographic maps and by using Google Earth Pro (7.3.1.4507). Land cover may also affect macropores, which have been observed in agricultural lands [Allaire *et al.*, 2011] and forested soils [Aubertin, 1971; Sidle *et al.*, 2001]. We chose only undisturbed stream reaches with forested riparian zones, as designated by the National Land Cover Database [Homer *et al.*, 2015]. This limits such variability in our data set and is appropriate for an initial benchmark study of this kind. All field sites had forested riparian zones except one (North Fork of Pound River), which was partially forested and partially mowed field. Finally, we chose field sites based on ease of access (i.e. near a road accessible by car, on public land, and within close proximity to other field locations to minimize travel time). We identified public land using Google Maps and maps from Virginia State Parks, New Jersey Division of Parks and Forestry, U.S. Forest Service, U.S. National Park Service, and The Nature Conservancy.

2.3.2 Field Measurements

Our field measurement techniques were similar to Menichino *et al.* [2015a]. We characterized surface-connected macropores along only one stream bank at each site. This assumed the other bank had similar land cover characteristics and increased the total number of streams we could visit. We scheduled field surveys during baseflow to enhance site access and to compare the measurement of macropore height relative to the baseflow water surface elevation. We determined baseflow occurrence qualitatively by waiting a minimum of four days after a rain event.

We split each stream into a short reach upstream of a long reach, which respectively measured twenty and forty times the average bankfull width. We completed the short-reach survey first, then completed the long reach where feasible. Exceptions occurred, for example, where stream depth got too deep to continue on foot, a survey site encroached on private land, or

the overall survey time exceeded four hours.

We determined bankfull width and height within the short reach of each stream using a 100-meter measuring tape using commonly accepted bankfull indicators [Harrelson *et al.*, 1994; McCandless, 2003; Menichino *et al.*, 2015a; Rosgen, 1996]. In streams with a pool-riffle morphology [Montgomery and Buffington, 1997], we measured bankfull width and height at the mid-section of the riffles. We averaged three bankfull width and height measurements to obtain an average bankfull width and height.

We determined the number and longitudinal position of the macropores within the short and long reaches using a 100-meter measuring tape with 5.0 cm accuracy (Figure 2A). We used the longitudinal measurements to determine macropore interspacing and distribution throughout the reaches.

Within the short reach, we measured the macropore height relative to the water surface elevation (WSEL), macropore opening width, macropore opening height, depth into bank, and horizontal angle. First, we measured the height of the bottom of the macropore opening relative to the WSEL (Figure 2B) with a modified measuring stick with 0.5 cm intervals. Macropores above the WSEL were positive, while macropores below WSEL were negative. We then measured the macropore opening width (Figure 2C) and opening height (Figure 2D) at their widest points. Next, we measured macropore depth (Figure 2E) by inserting the modified measuring stick into the macropore as far as possible. This straight-line distance therefore did not account for additional macropore length beyond bends. Lastly, we determined macropore angle of orientation based on the horizontal angle perpendicular to the direction of in-channel flow. We measured the angle by inserting the measuring stick and using a protractor with five degree intervals (Figure 2F). Macropores oriented perpendicular to the direction of flow had an angle value of zero, while macropores oriented downstream had negative angles and those oriented upstream had positive angles. We did not measure the vertical angle of orientation.

Lastly, we determined the dominant soil texture surrounding each macropore. We manipulated a wet, golf ball-size soil sample to estimate the ratio of clay, sand, and silt content from soil flexibility, stickiness, and graininess using the NRCS Guide to Texture by Feel [adopted from Thien, 1979]. We then analyzed the proportion of gravel and organic material in bank substrate qualitatively. We did this every ten meters, or when there was an apparent visual

change in the soil texture. We noted which macropores were in the various soil texture classifications.

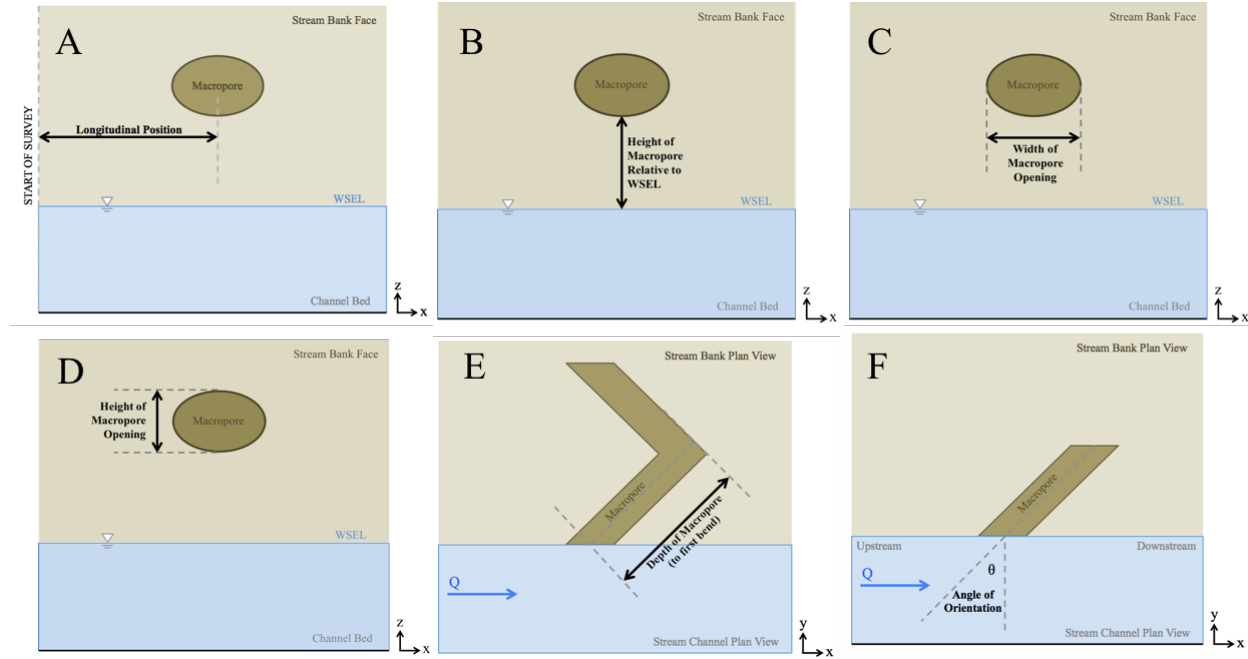


Figure 2: Measurement approach for macropore longitudinal position (A), height relative to WSEL (B), opening width (C), opening height (D), depth (E), and horizontal angle (F). For orientation, z is the vertical direction, x is parallel to the direction of flow, and y is perpendicular to the face of the stream bank.

2.3.3 Data Analysis

We calculated average macropore dimensions (height relative to WSEL, opening width, opening height, depth, horizontal angle, and interspacing) for each physiographic province, stream order, and dominant soil texture. We ran regressions of macropore dimensions against stream order and soil texture. We ranked streams by stream order and soil texture hydraulic conductivity from low to high values, which allowed for linear regression relationships to be analyzed. We then performed single-factor Analysis of Variance (ANOVA) tests ($\alpha = 0.05$) to determine statistical differences of the mean macropore dimensions between stream orders, between physiographic provinces, and between different soil texture classifications. We determined the interspacing of macropores based on the horizontal distance between adjacent macropores. We analyzed macropore interspacing at the reach scale to show the relative

distribution of macropores between different soil texture classifications, and analyzed macropore interspacing at the soil texture scale to show the average interspacing within each soil texture classification.

In order to find the opening area of each macropore, we assumed all macropores were ellipsoid in shape. We calculated the macropore opening area by using the formula for the area of an ellipsoid, the opening width, and the opening height of each macropore (Equation 1).

$$\text{Opening area} = \pi * \frac{\text{Opening Width}}{2} * \frac{\text{Opening Height}}{2} \quad \text{Equation 1}$$

We then calculated the mean effective opening area by dividing the sum of the macropores opening areas by the area of the stream bank within each soil texture.

2.4 Results

Surface-connected macropores were a widespread phenomenon, being present in all 20 streams despite variations in physiographic province, stream order, and soil texture. As observed in a prior study [Menichino *et al.*, 2015a], their formation was often the result of biological processes such as animal burrows and plant roots (Figure 3A-C), erosive action in subsurface flow (Figure 3D), or cracks in the soil (Figure 3E).

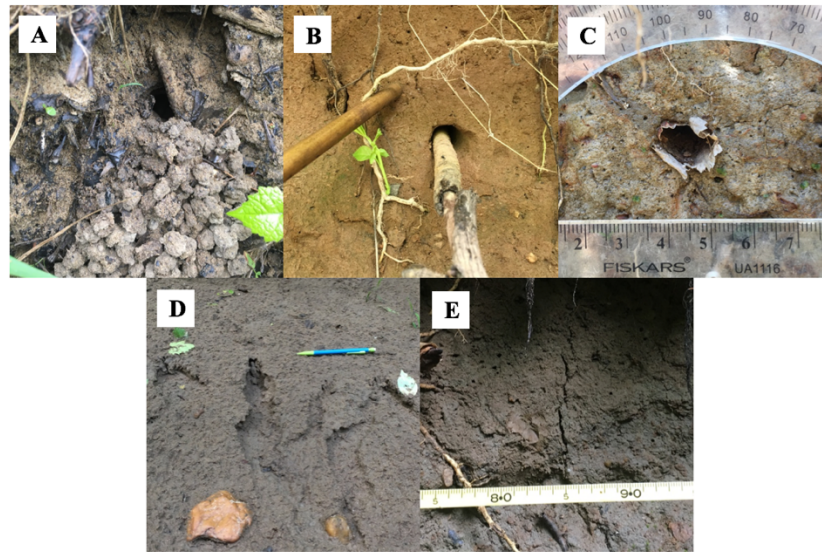


Figure 3: Various formation mechanisms of macropores observed in the field. Animal burrows (A – notice the excavated material below the macropore opening), live roots (B), decaying roots (C), hydraulic seepage (D), and cracks within the soil (E).

Macropores were also observed in a variety of bank substrates and soil textures (Figure 4). Consistent with the findings by *Menichino et al.* [2015a], some macropores were observed in substrates containing sand and gravel; however, most macropores were found in substrates with a higher cohesiveness, such as silts and clays. As we discuss further in the discussion, this was likely because macropores can retain their shape more persistently in soils with a high cohesiveness.

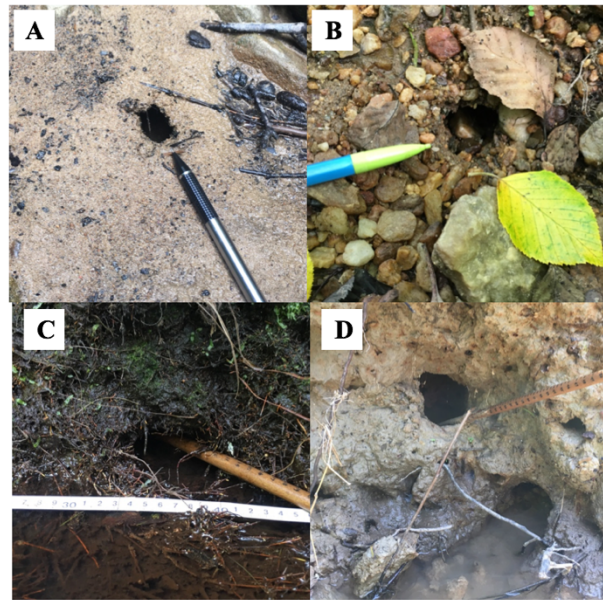


Figure 4: Macropores were observed in a variety of soil textures as estimated by *Thien* [1979]. Panels A through D show macropores in sand, gravel, organic material, and silty clay, respectively.

2.4.1 Overall Macropore Geometry

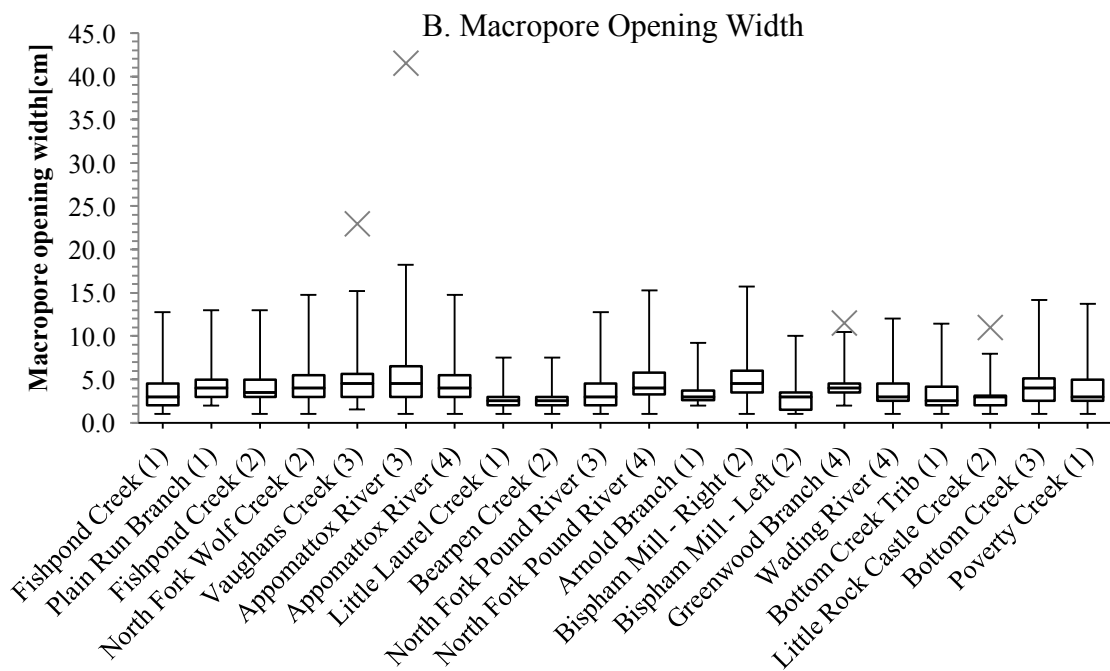
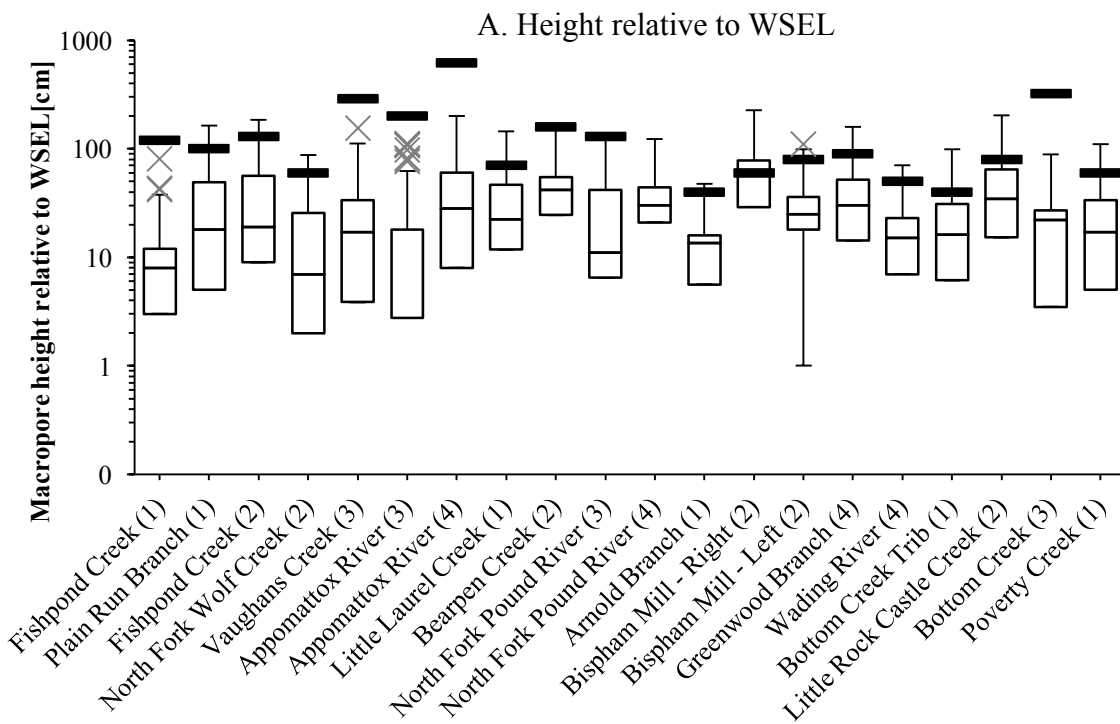
We surveyed a total of 1,748 surface-connected macropores across all 20 streams (Table 2). Most macropores were below the average bankfull elevation (Figure 5A). Interestingly, only 3.2% of the surveyed macropores were below the WSEL (i.e. baseflow conditions) during our field surveys (Table 2; North Fork Wolf Creek was omitted from that statistic since it was the only stream surveyed above baseflow conditions). Macropores thus tend to be present above the baseflow WSEL and below bankfull elevation., consistent with *Menichino et al.* [2015a].

Macropores openings across all sites were on average slightly wider than they were tall at 3.8 cm and 3.3 cm, respectively (Table 2; Figure 5BC). The average depth of the macropores to

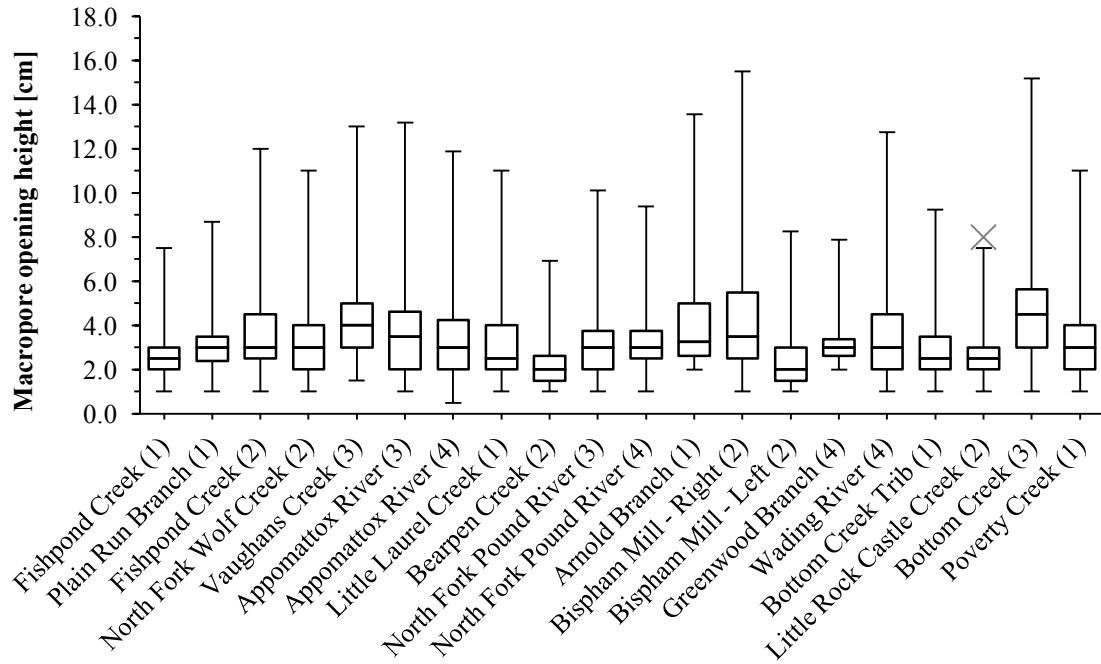
the first bend was 11.5 cm across all surveyed sites (Table 2; Figure 5D). Macropores had an inconsistent longitudinal distribution within most reaches, as indicated by the high number of outliers within each data set (Figure 5E). This suggests another controlling factor that varies within each reach (e.g., soil texture, see Section 2.4.4 below). Across all streams, macropores faced upstream, downstream, and perpendicular to the direction of in-channel flow (Figure 5F).

Table 2: Macropore data on all 20 streams surveyed. Values at bottom of table in bold are column sums, italics are column averages. Further data for the Valley and Ridge physiographic province can be found in *Menichino et al. [2015a]*.

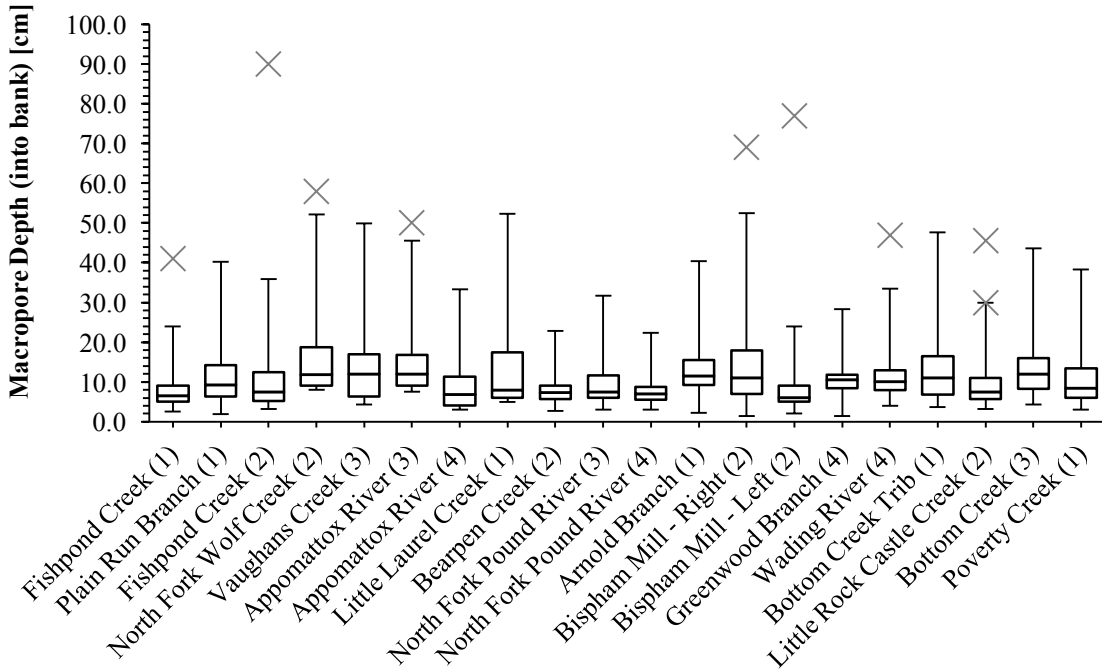
Physiographic Province	Stream Name	Stream Order	# Macropores in Short Reach	# Macropores in Long Reach	Avg. Height Above WSEL [cm]	Avg. Opening Width [cm]	Avg. Opening Height [cm]	Avg. Macropore Depth [cm]	# Macropores Below WSEL
Blue Ridge	Tributary to Bottom Creek	1	28	96	19.0	3.2	2.9	12.6	0
	Little Rock Castle Creek	2	68	68	40.0	3.0	2.8	9.3	0
	Bottom Creek	3	24	0	23.2	4.1	4.4	12.5	2
Valley and Ridge	Poverty Creek	1	69	148	20.3	3.8	3.1	9.9	4
Appalachian Plateau	Little Laurel Creek	1	46	32	32.6	2.8	2.8	11.9	0
	Bearpen Creek	2	24	12	40.4	2.5	2.3	8.0	0
	North Fork Pound River	3	35	0	32.6	2.8	2.8	11.9	1
	Pound River	4	27	0	24.6	3.3	2.9	9.2	0
Coastal Plain	Arnold Branch	1	10	11	61.0	4.9	4.2	15.1	0
	Bispham Mill Creek – Left Branch	2	19	12	31.7	2.6	2.3	10.7	0
	Bispham Mill Creek – Right Branch	2	21	0	41.5	4.9	3.3	11.7	0
	Greenwood Branch	4	8	0	14.3	3.4	4.0	15.0	0
	Wading River	4	45	23	16.5	3.5	3.6	11.8	2
Piedmont	Fishpond Creek	1	37	38	38.4	4.4	3.5	9.0	0
	Plain Run Branch	1	36	56	26.8	4.3	3.0	11.7	0
	Fishpond Creek	2	111	0	22.0	4.9	4.4	12.7	0
	North Fork Wolf Creek	2	54	116	15.5	4.3	3.3	14.6	6
	Vaughans Creek	3	84	0	11.1	3.4	2.5	8.3	10
	Appomattox River	3	100	138	33.5	4.0	3.6	9.8	29
	Appomattox River	4	152	0	13.0	5.0	3.7	13.8	3
			998	750	27.9	3.8	3.3	<i>11.5</i>	57



C. Macropore Opening Height



D. Macropore Depth



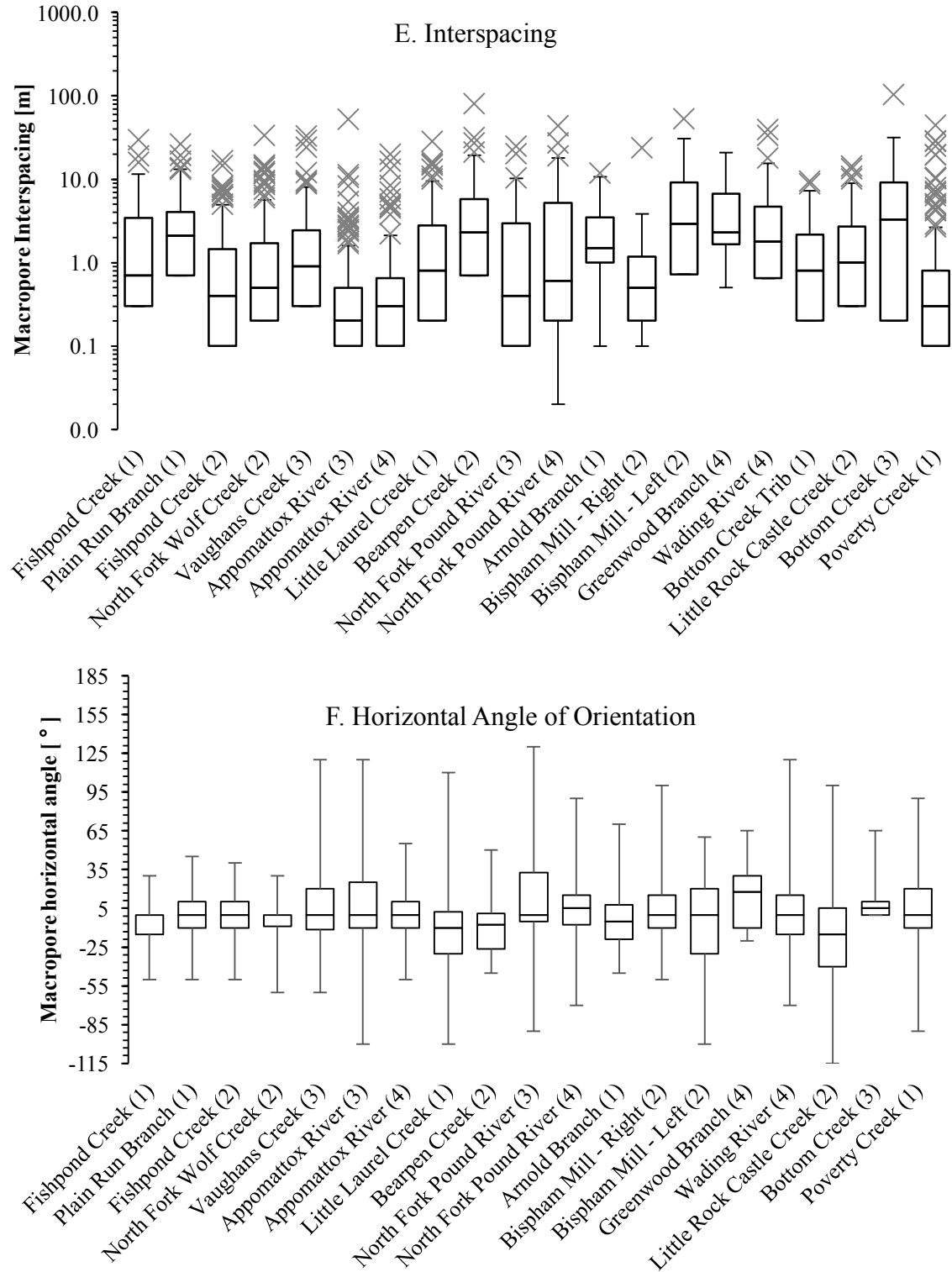


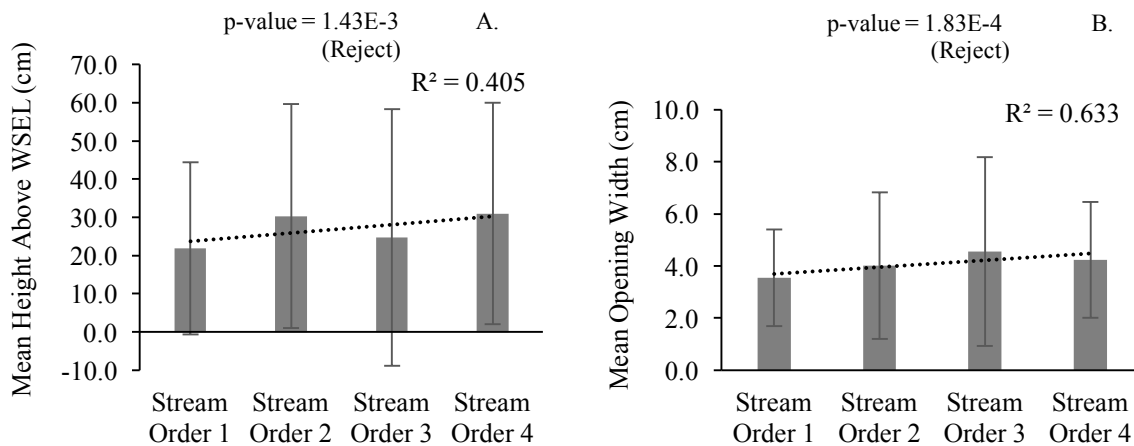
Figure 5: Boxplot of measured macropore dimensions: height relative to WSEL (A), opening width (B), opening height (C), macropore depth (D), interspacing (E), and horizontal angle (F). Lines in boxes are medians, box ends are quartiles and whiskers show 1.5x the interquartile

range. Outliers, indicated by crosses, are measurements that fall outside of the 1.5x interquartile range. X-axis indicates stream name with stream order in parenthesis. Note that for panel A, the solid rectangular bars indicate average bankfull elevation.

2.4.2 Macropore Characteristics Based on Stream Order

According to single-factor ANOVA, mean macropore height relative to WSEL, opening width, opening height, depth to first bend, and horizontal angle of orientation vary significantly between stream orders (Figure 6, $p < 0.05$). By contrast, macropore interspacing ($p = 0.87$) does not significantly differ between stream orders at that level of statistical significance.

According to regression, mean macropore height relative to WSEL, opening width, and opening height all increase with increasing stream order (Figure 6ABC, $R^2=0.41$, 0.63 , and 0.71 , respectively). The average depth of macropores to first bend decreased as stream order increased (Figure 6D), but the trend was negligible ($R^2 = 0.01$). The average horizontal angle of orientation of the macropore openings in the banks shifted from facing downstream (negative value) in stream orders one and two to facing upstream (positive value) in stream orders three and four (Figure 6E, $R^2=0.34$), but the low R^2 indicates considerable noise in this trend.



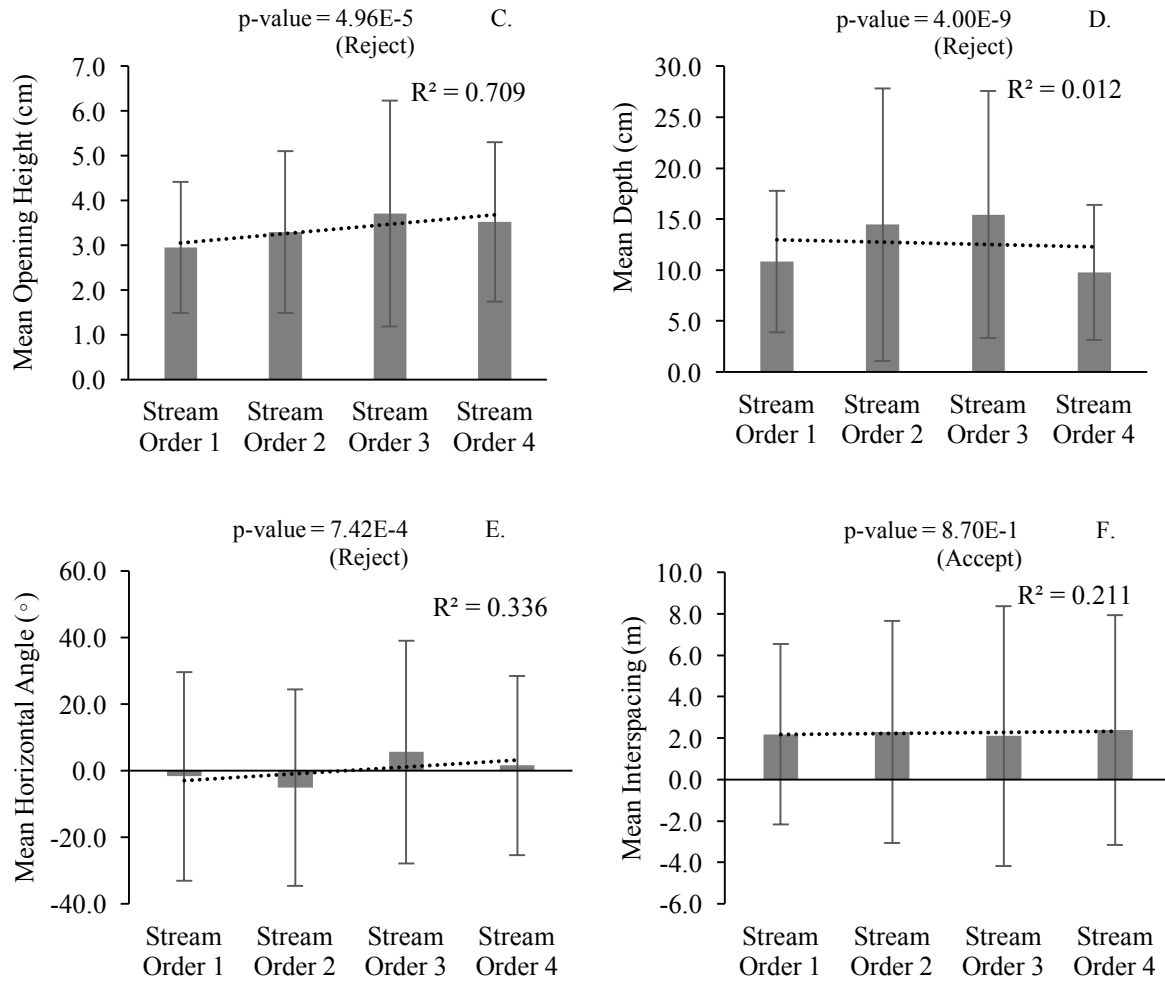


Figure 6: Averages of measured macropore dimensions with standard deviations grouped by stream order. P-values are based on a single factor ANOVA test with a 95 percent confidence interval ($\alpha = 0.05$), and determines whether the null hypothesis is accepted or rejected based on the means between groups. The null hypothesis states that measured macropore dimensions are not significantly different between stream orders. Trend lines and R^2 values are from a separate regression analysis. Note that this analysis includes data from the Valley and Ridge physiographic province from *Menichino et al.* [2015a].

2.4.3 Macropore Characteristics Based on Physiographic Province

According to single-factor ANOVA, mean height relative to WSEL, opening width, opening height, depth, horizontal angle, and interspacing vary significantly between physiographic provinces (Figure 7, $p < 0.05$).

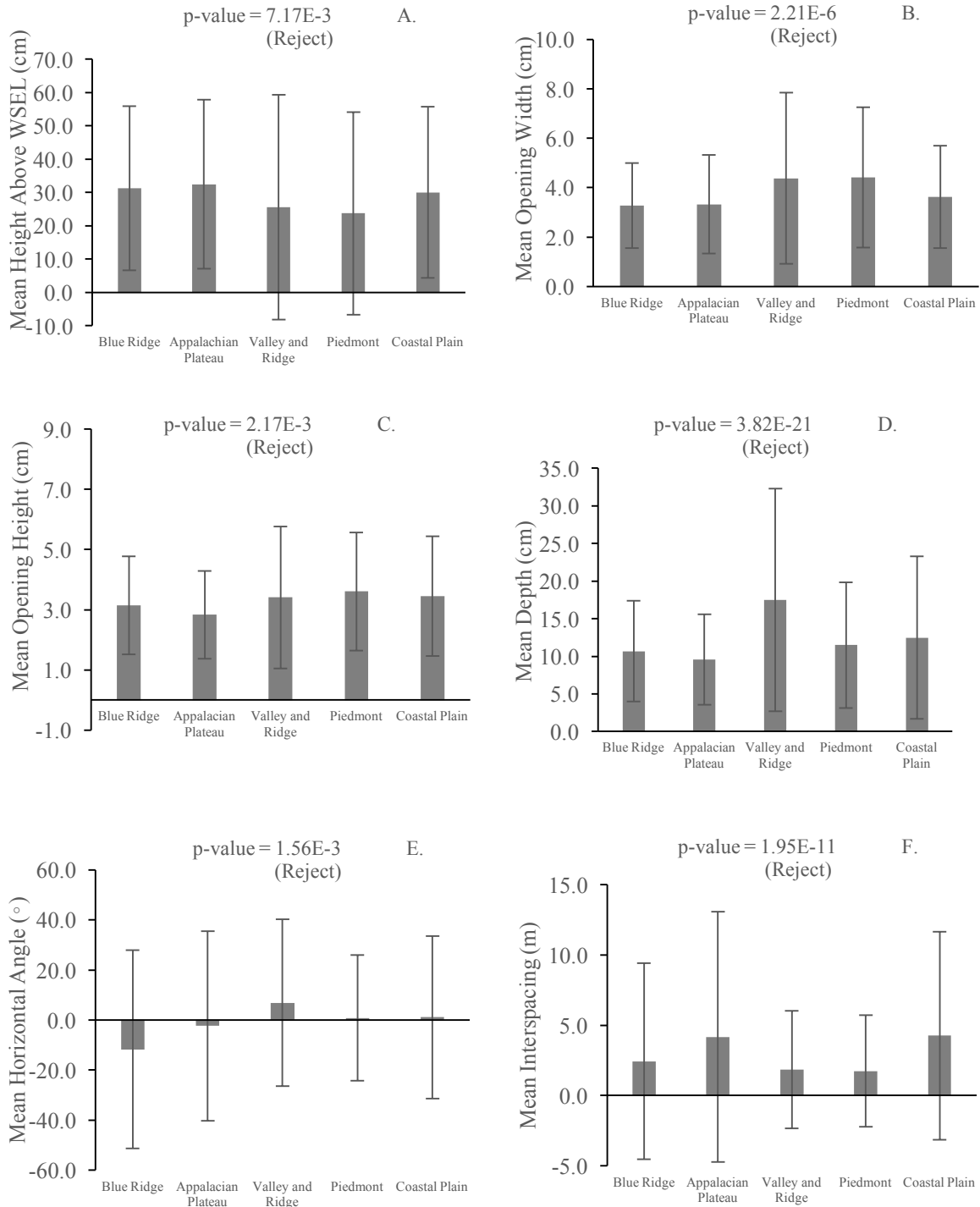


Figure 7: Averages of measured macropore dimensions with standard deviations grouped by physiographic province. P-values are based on a single factor ANOVA test with a 95 percent confidence interval ($\alpha = 0.05$), and determines whether the null hypothesis is accepted or rejected. The null hypothesis states that measured macropore dimensions are not significantly

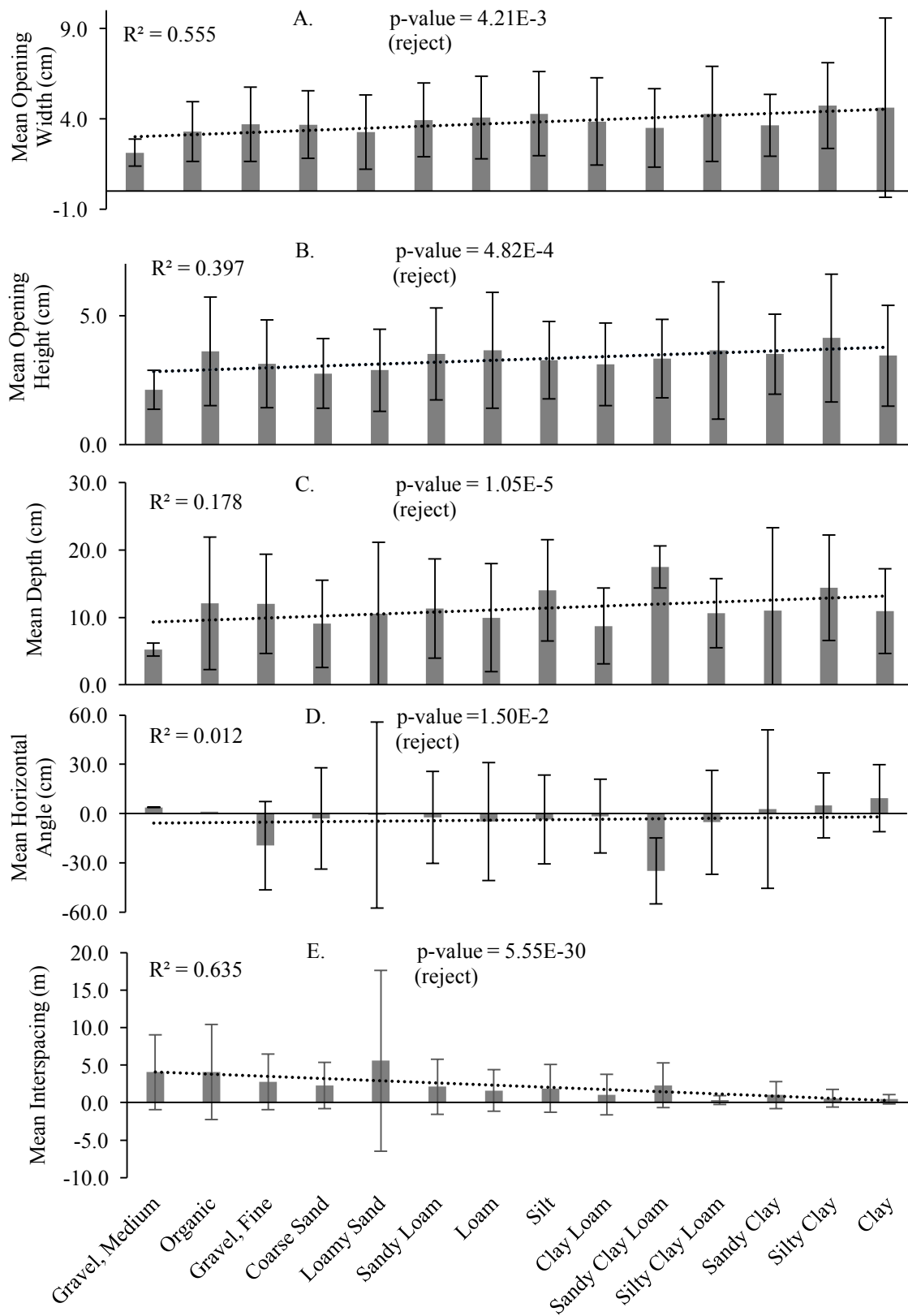
different between physiographic provinces. Note that this analysis includes data from the Valley and Ridge physiographic province from *Menichino et al.* [2015a].

2.4.4 Macropore Characteristics Based on Soil Texture

According to single-factor ANOVA, mean opening width, open height, horizontal angle, and interspacing all vary significantly between physiographic provinces (Figure 8, $p < 0.05$). According to regression, mean opening width, opening height, and depth of the macropores increase with decreasing soil hydraulic conductivity (Figure 8ABC, $R^2=0.56, 0.40$, and 0.18 respectively). This means that macropores in soils primarily containing silt and clay tended to be wider, taller, and deeper than macropores in soils consisting of sand, gravel, or organic material, although the R^2 values are fairly low. This is possibly due to differences in soil cohesiveness and/or hydraulic conductivity. Lastly, the interspacing of the macropores decreased with decreasing soil conductivity (Figure 8E, $R^2 = 0.64$). This indicates that soil textures with a higher hydraulic conductivity are more likely to have macropores spaced farther apart, while soil textures with a lower hydraulic conductivity are more likely to have macropores spaced closer together. This is possibly because soils with a lower hydraulic conductivity, such as silts and clays, are more cohesive, therefore potentially increasing the persistence and longevity of macropores. We further discuss the role of soil cohesion and hydraulic conductivity in the discussion section.

The effective opening area ranged from 0.0087% to 0.21% across all observed soil textures (Figure 8F). The linear regression line in shows that the average effective opening area increases with increasing soil K . However, the low R^2 value ($R^2 = 0.291$) indicates considerable noise in this trend. The p-value from the single-factor ANOVA shows that the mean effective opening area does not significantly differ between soil textures.

The reason why the analysis of macropore height relative to WSEL is not included in this soil texture analysis is that soil texture differed vertically along the banks. Including the analysis of macropore height relative to WSEL in this section would have assumed that soil texture was vertically uniform along the bank, which we did not find to be the case.



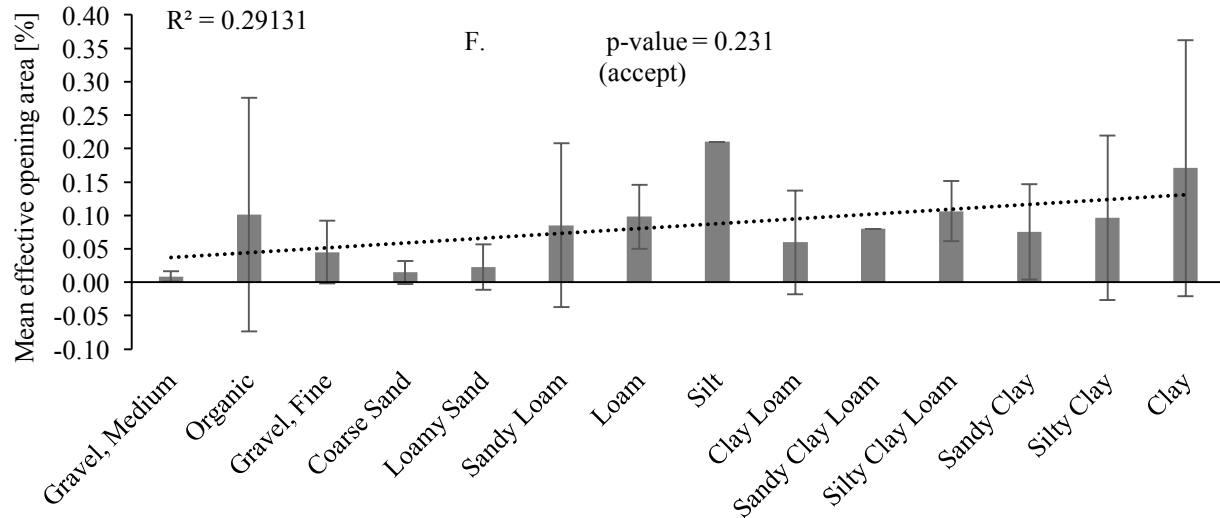


Figure 8: Average measured dimensions of macropores with standard deviations based on NRCS soil textures [Thien, 1979]. Soil texture categories are ordered along the x-axis by approximate saturated hydraulic conductivity, with highest at left and lowest at right (Table 3). P-values are based on a single factor ANOVA test with a 95 percent confidence interval ($\alpha = 0.05$), and determines whether the null hypothesis is accepted or rejected. The null hypothesis for each analysis (A through F) states that the averages of the measured macropore dimensions do not significantly differ based on soil texture. Note that these results do not include data collected in the Valley and Ridge physiographic province by Menichino *et al.* [2015a].

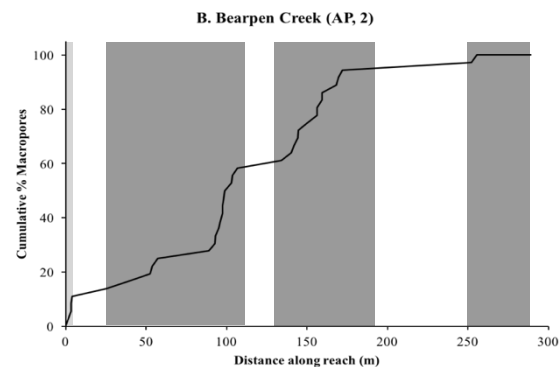
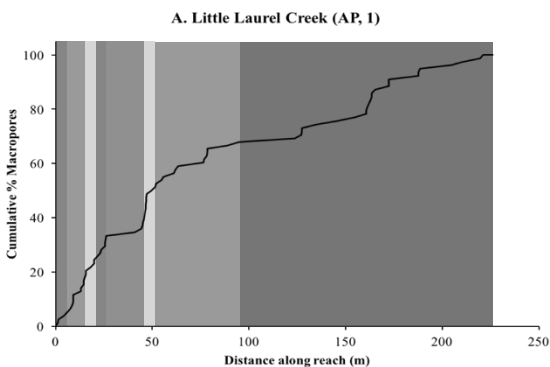
Macropore longitudinal distribution appears to be associated with hydraulic conductivity (Table 3) specific to variations in soil texture (Figure 9). In general, there tended to be fewer macropores in soils with a high hydraulic conductivity (dark shades of grey) and more macropores in soils with a lower hydraulic conductivity (light shades of grey). Note that bedrock had the lowest hydraulic conductivity (color shade = white) in this analysis, and had little to no presence of macropores. We did not investigate bedrock fracturing or fissures.

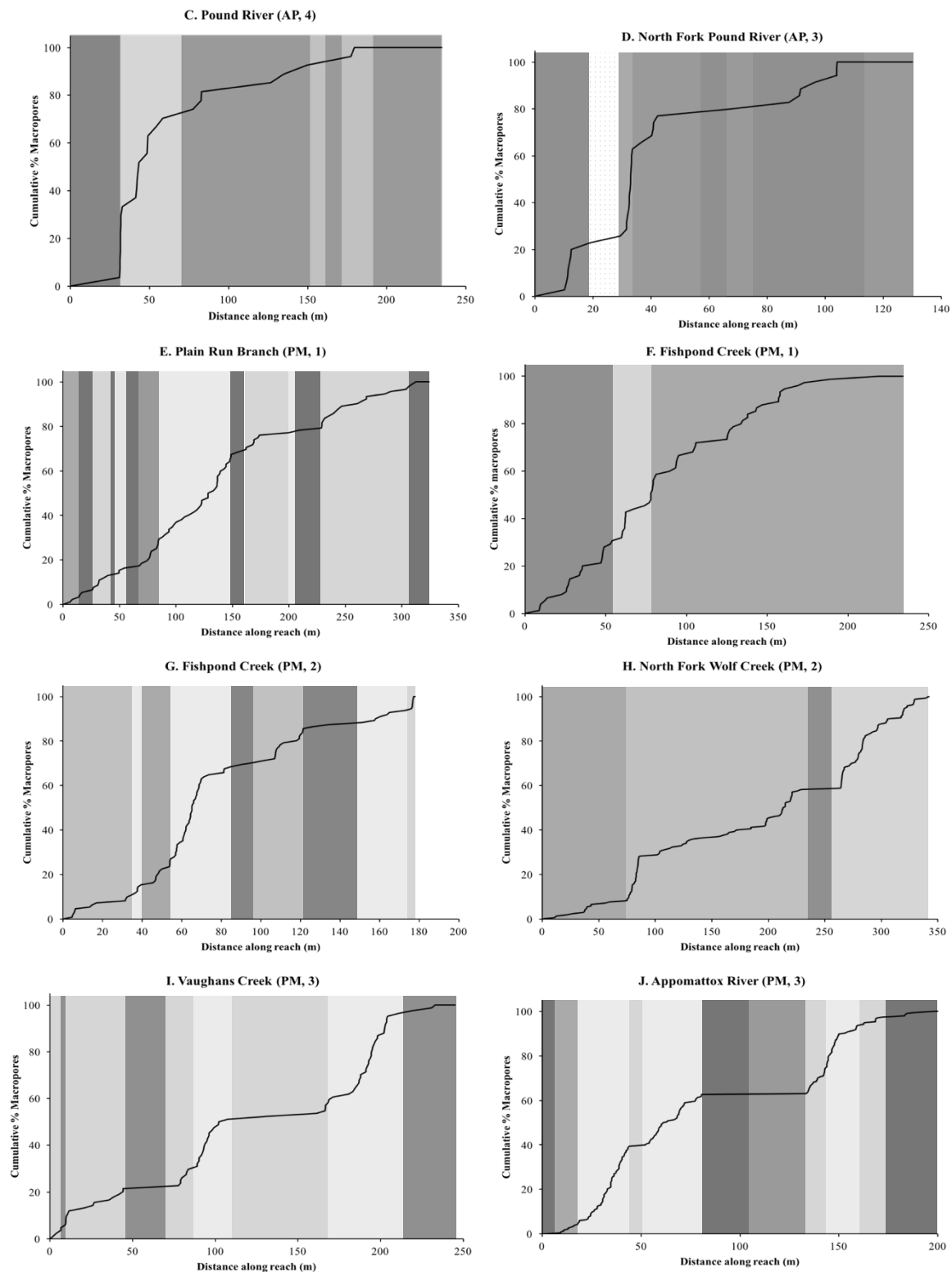
Soil texture affected how evenly or unevenly macropores were distributed (Figure 9). For example, in Bottom Creek Tributary (Figure 9M), there was only one dominant soil type, and macropores were evenly distributed throughout. Conversely, macropores in the Appomattox River (Figure 9K) were the most densely distributed in clay loam, less present in sandy loam, and the least present in coarse sand. This pattern of macropores being the most densely

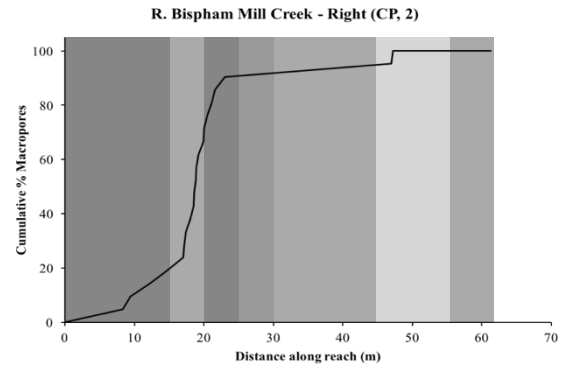
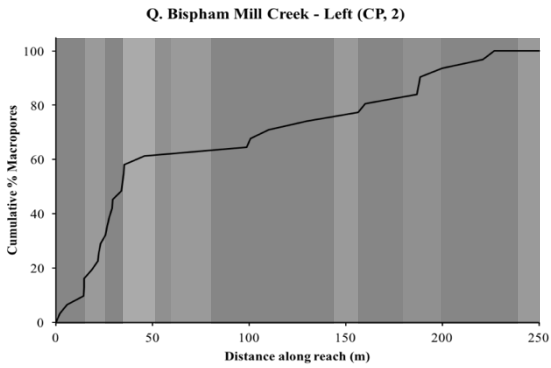
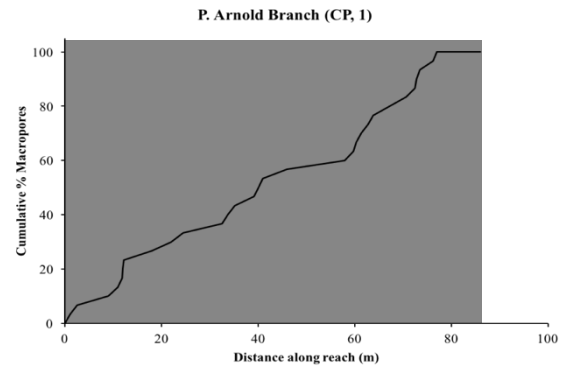
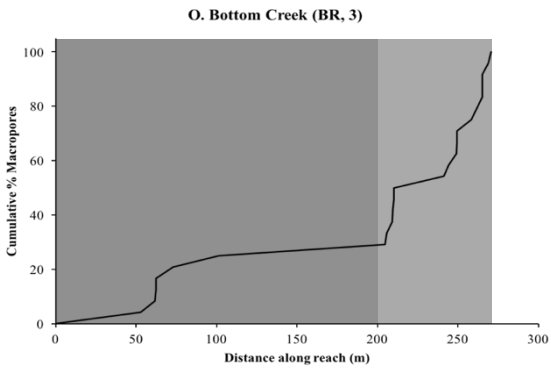
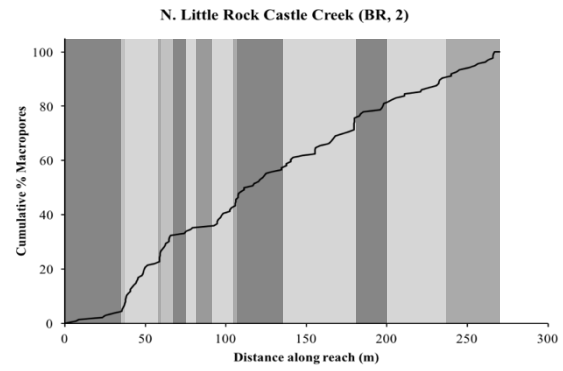
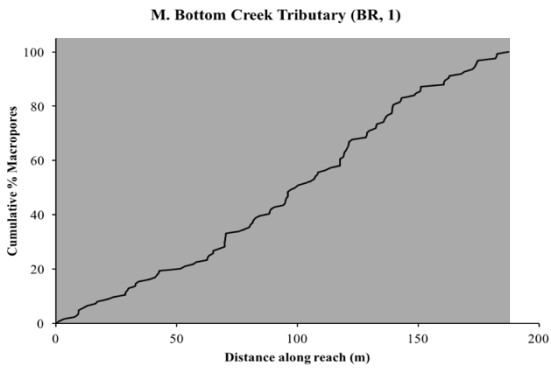
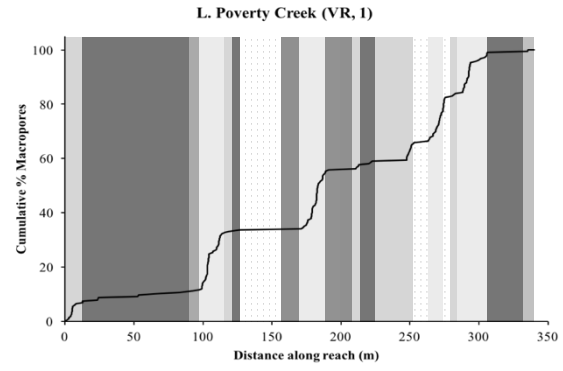
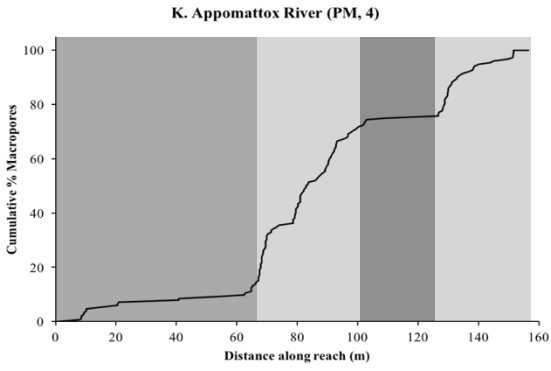
distributed in soils with a low hydraulic conductivity was observed in the majority of streams (e.g., Figure 9B, C, G, H, I, J, K, L, O, and R), but not all (e.g., Figure 9A, D, F, N, Q, T).

Table 3: Soil textures and respective ranges of saturated soil hydraulic conductivity values. Hydraulic conductivity values are from the NRCS Saturated Hydraulic Conductivity in Relation to Soil Texture [NRCS, n.d.] except for organic substrate [Caron *et al.*, 2015] and bedrock [Gupta, 2008]. “Obstruction” refers to areas that could not be surveyed for practical reasons (e.g. presence of a bridge, too deep to survey, logjam, vegetation too dense, etc.). Grayscale shades correspond with shades presented in Figure 9.

NRCS Soil Texture	Saturated Hydraulic Conductivity [m/day]	
Gravel, Coarse	1000	8600
Gravel, medium	20	1000
Organic	43.2	302.4
Gravel, fine	20.0	50.0
Coarse Sand	0.51	
Loamy Sand	0.15	0.51
Sandy Loam	0.05	0.15
Loam	0.02	0.05
Silty Loam	0.02	0.05
Silt	0.02	0.05
Clay Loam	0.01	0.02
Sandy Clay Loam	0.01	0.02
Silty Clay Loam	0.01	0.02
Sandy Clay	0.002	0.005
Silty Clay	0.002	0.005
Clay	0.002	0.00
Bedrock (Sandstone)	1.00E-06	3.0
Obstruction	N/A	N/A







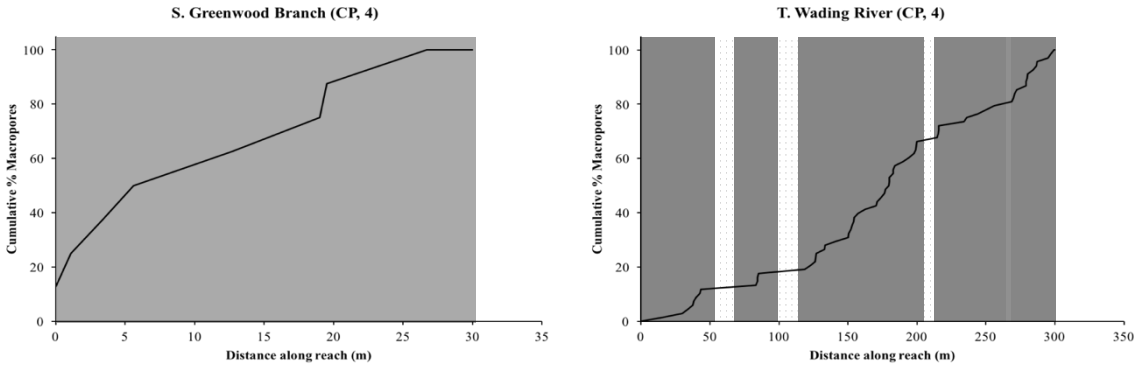


Figure 9: Longitudinal cumulative distribution of macropores along the length of the surveyed reaches overlain on a color schematic of the saturated hydraulic conductivity of dominant soil textures found in each reach. Graph titles indicate stream name, physiographic province (AP = Appalachian Plateau; PM = Piedmont; CP = Coastal Plain; VR = Valley and Ridge; BR = Blue Ridge), and stream order.

2.5 Discussion

2.5.1 Macropore Distribution, Abundance, and Geometry

Our results show that surface-connected macropores are a widespread phenomenon in a variety of physiographic provinces, stream orders, and soil textures, confirming the hypotheses of *Menichino et al.* [2015a]. They are formed through a variety of biotic and abiotic creation mechanisms. While our study only focused on Eastern U.S. states, we also expect macropores to be widespread beyond our geographic scope assuming similar geology, geomorphology, soil texture, and creation mechanisms. This is an important subject of future research. Similarly, we studied streams with forested riparian zones, so future studies of riverine macropores in streams with other riparian or watershed land covers (e.g. agriculture and urban) are recommended.

Most macropores were above baseflow water surface elevation, but below bankfull elevation. Additionally, macropore openings tended to be slightly wider than they were tall. These findings were consistent with the findings from *Menichino et al.* [2015a]. We found that macropores were most abundant in soils with a low hydraulic conductivity, but only in half of our stream reaches. Other factors may be important in the remaining streams, such as whether the observed macropores were on the inside or outside of a meander bend, the hillslope gradient adjacent to the stream bank, channel slope, the hydraulic gradient of the water table within the

stream bank, soil compaction, bulk density, etc. An interesting anomaly in our observations was that macropores in loamy sand, with a relatively moderate hydraulic conductivity, had an average interspacing substantially greater than macropores in substrates with a higher hydraulic conductivity such as coarse sand and gravel (Figure 8E). We were not sure why loamy sand had a high interspacing and fell outside of the trend seen in all other observed soil textures.

Because we measured macropore depth using a straight inflexible dowel, our methodology likely underestimated the true depth. We suspect that the true macropore depths were likely greater than those observed in the field, possibly due to the heterogeneous nature of stream banks and tortuous nature of macropores. Developing methods to accurately assess the likely tortuous nature of macropores is recommended, such as using a flexible endoscope or other nondestructive technique [Stewart *et al.*, 2014]. Additionally, due to logistical constraints, we were only able to observe macropores once at each site. We recommend that future studies examine the persistence of macropores over a long period of time with multiple visits to the same field sites.

2.5.2 Effect of Stream Order, Physiographic Province, and Soil Texture

Surface-connected macropores tended to be wider, taller, have a higher height above the WSEL, and be angled more upstream at higher stream orders (Figure 6). A possible explanation is that higher stream order typically denotes larger watershed area and in-channel flow rate [Strahler, 1957], which in turn could increase macropore dimensions due to higher channel velocities and hence erosion, presence of larger aquatic organisms, etc. Macropores also tended to be higher on the stream bank with increasing stream order (Figure 6A). A possible explanation is that bank heights usually increase with increasing stream order and basin area [Keaton *et al.*, 2005]; therefore, there is more vertical area for macropores to form. Another explanation is that as flow increases with stream order, vertical distribution of erosive forces and habitat may also increase.

Surface-connected macropores were ubiquitous across all physiographic provinces. While macropore dimensions were statistically different between physiographic provinces (Figure 7), differences in dominant soil texture seemed to have a greater influence on the overall macropore geometry rather than the physiographic province itself. This relationship was apparent when comparing physiographic provinces with their expected soil textures. For example, we

observed that high amounts of clay were present in the Piedmont and Valley and Ridge physiographic provinces, consistent with literature [Baker, 2000; DCR, 2016]. The high amount of clay, a highly cohesive substrate [Lal and Shukla, 2004], yielded macropores that were taller and wider than macropores in soil textures that were less cohesive (Figure 8). Additionally, differences in soil texture may influence the effective areas of macropores (Figure 8F); however, we cannot definitively draw a direct correlation between the two since the R^2 value is quite low. Additionally, spatial heterogeneity of soil texture vertically across the stream bank profile may affect our results, which we did not account for. Conversely, the Coastal Plain physiographic province had high amounts of porous sand, remnants of sediment deposition from varying prehistoric sea levels [Baker, 2000; DCR, 2016]. We observed a fewer percentage of macropores compared to the total stream length surveyed in the Coastal Plain, which was apparent in the large interspacing between macropores in this physiographic province (Figure 7F).

2.5.3 Hydrologic Implications of Macropore Characteristics

Macropores have been shown to substantially affect hydrology in whatever hydrologic system they are present. Agricultural and forest hydrology studies in particular have extensively documented how macropores influence subsurface transport of nutrients and pollutants. In agricultural applications, it was found that phosphorous was transported faster in soils with macropores compared to soils without macropores [Tebbetts and Moore, 2017], and that macropores could transport solutes from farmland to bodies of water [Allaire et al., 2011]. Furthermore, it was suggested that increased macropore interconnectivity may significantly increase transport time [Allaire-Leung et al., 2000]. In forest hydrology applications, it was also found that the presence of macropores increased subsurface water and solute transport several hundred-fold, compared to soils without macropores [Aubertin, 1971; Sidle et al., 2001]. Given that macropores tend to increase subsurface transport in other applications, it is imperative to study how macropores influence solute and contaminant transport between riverine systems and their surrounding land.

Macropores are preferential flow paths that may act as conduits between floodplains, riparian buffer zones, and stream channels. The presence of surface-connected macropores may have substantial hydrologic implications in riverine systems. This bears emphasis given our finding that macropores are likely ubiquitous throughout large areas of the Eastern United States.

Such hydrologic effects can be divided up based on flow processes and locations including 1) flow from uplands through riparian zone or floodplain groundwater to the channel, and 2) bidirectional (typically lung model) hyporheic exchange between the channel and riparian zone or floodplain groundwater.

A wealth of studies has shown that riparian buffer zones improve water quality of polluted groundwater migrating from infiltration locations in the uplands toward discharge locations along natural water bodies [Anbumozhi *et al.*, 2005; Correll, 1997; Osborne and Kovacic, 1993]. However, the presence of surface-connected macropores may result in preferential flow paths that bypass the pollutant mitigating capabilities of riparian zones by reducing the residence time within these areas [Fuchs *et al.*, 2009]. While the effect of macropores and soils pipes in particular have not received much attention in this particular context, the more general topic of preferential flow has been studied in riparian zones and floodplain groundwater [Fuchs *et al.*, 2009; Heeren *et al.*, 2009; Newman and Keim, 2013; Zhou *et al.*, 2014]. Those studies have shown that flow in buried gravel bars in floodplains, through preferential flow in natural riverine levees, and through bedforms and meander bends can transport solutes much faster than would be expected based on the texture of the surrounding soil matrix. Ultimately, this may allow a greater loading of pollutants to pass through the riparian zone than otherwise expected. We recommend future studies that model the nutrient processing efficiency of natural or constructed riparian zones taking the presence of macropores into consideration.

In terms of bidirectional hyporheic exchange, submerged macropores may enhance lung model exchange during flood events [Sawyer *et al.*, 2009; Menichino *et al.*, 2015b]. When macropores are inundated on a temporally limited basis, the depth at which stream water penetrates the flood plain or riparian buffer zone may increase, thus increasing the area and rates of exchange at which the riparian zone can attenuate and process pollutants [Newman and Keim, 2013]. The implication of this may eventually improve how engineered riparian buffer zones are constructed to better process nutrients and other pollutants.

This may have implications at larger spatial scales. According to Menichino *et al.* [2015a]; Menichino *et al.* [2015b]; Menichino *et al.* [2014], a common belief is that hyporheic exchange and hydraulic conductivity of the channel substrate are directly proportional [Azinheira *et al.*, 2014; Hester and Doyle, 2008; Kasahara and Hill, 2007; Storey *et al.*, 2003]. That is,

substrates comprised primarily of gravels and cobbles have higher hyporheic exchange than substrates dominated by silts and clays. However, the presence of macropores in finer grained soils, such as silts and clays, has the potential to increase hyporheic exchange in such areas, broadening the geographic area in which significant hyporheic exchange occurs. A study by *Menichino et al.* [2015a] tested this hypothesis and found that macropores increased hydraulic conductivity in fine grained-soils. Our results qualitatively supported this finding. We recommend further studies to quantify the effects of macropores on hydraulic conductivity in fine-grained soils.

The presence of macropores in riverine systems may also influence transient storage in stream banks during high flow events [*Arntzen et al.*, 2006; *Francis et al.*, 2010; *Sawyer et al.*, 2009; *Loheide and Lundquist*, 2009]. As such, understanding the physical characteristics of macropores (i.e. volume and interconnectivity) can deepen our understanding of the transient storage capacity of stream banks beyond the storage capacity of the stream channel.

2.6 Conclusions

We surveyed twenty streams across a range of stream orders and physiographic provinces for surface-connected macropores. We found that surface-connected macropores were widespread and abundant geomorphic features along all survey reaches. We found that macropores in fluvial systems were created through a variety of mechanisms and formed in a range of soil textures.

While there was a direct, positive correlation between the size of macropores and stream order, we surmised that the largest influence on macropore geometry, distribution, and abundance was the dominant soil texture, with highly cohesive soils having larger and more abundant macropores than soils with a low cohesiveness. Macropores tended to be more abundant in soils with a high cohesiveness and a low hydraulic conductivity compared to soils with a low cohesiveness and high hydraulic conductivity.

Macropores in stream banks may significantly influence hyporheic exchange and transient storage. They may bypass the water quality benefits of riparian buffer zones, but may enhance access of channel water to beneficial hyporheic reactions, particularly during large flow events.

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Chapter 3 – Engineering Applications

3.1 Applications to Improve Pollutant Attenuation in Riparian Buffer Zones

Macropores are preferential flow paths that may act as conduits between floodplain, riparian buffer zones, and streams. The presence of surface-connected macropores may have substantial hydrologic implications in riverine systems. This is particularly true given that we have determined that such macropores are likely ubiquitous throughout larger areas of the Eastern United States. Depending on hydraulic conductivity (K), and the presence of macropores within the soil matrix, residence times may vary, which may affect how well riparian zones attenuate and process pollutants and nutrients. Ultimately, this may allow a greater loading of pollutants to pass through the riparian zone than otherwise expected.

Agricultural and forest hydrology studies have extensively documented how macropores influence subsurface transport of nutrients and pollutants. In agricultural applications, it was found that phosphorous was transported faster in soils with macropores compared to soils without macropores [Tebbetts and Moore, 2017], and that macropores could rapidly transport solutes from farmland to bodies of water [Allaire *et al.*, 2011]. Furthermore, increased macropore interconnectivity may significantly decrease transport time [Allaire-Leung *et al.*, 2000]. In forest hydrology, the presence of macropores increased subsurface water and solute transport several hundred-fold, compared to soils without macropores [Aubertin, 1971].

A wealth of studies has shown that riparian buffer zones improve water quality of infiltrated groundwater in uplands before discharging to natural bodies of water [Anbumozhi *et al.*, 2005; Correll, 1997; Osborne and Kovacic, 1993]. However, the presence of surface-connected macropores may result in preferential flow paths that bypass the infiltrative capacity and nutrient processing capabilities of riparian zones by reducing the residence time within these areas [Fuchs *et al.*, 2009]. Given that macropores tend to increase subsurface transport in other applications, we recommend that future studies examine the direct effects macropores have on pollutant loading in riverine systems. Riparian buffer recommendations may need to be updated depending on the presence or absence of macropores. Areas with more macropores may need to specify greater riparian buffer width requirements. Alternatively, efforts could be made to locate and block bypassing macropores. Yet the active nature of the biological agents that create macropores means that maintenance would be required.

Interestingly, a stream bank that we surveyed at Bottom Creek had recently undergone substantial bank stabilization, although the date of the bank stabilization was unknown. The substrate along the stabilized bank was primarily coarse sand, which differed from other unaltered banks along the stream, which were mostly loam and sandy loam. We were not sure if the coarse sand in the stabilized section was native to the area or if it had been brought in externally. However, we noticed that very few macropores existed within the stabilized area (only six macropores within a 200 m reach), while many macropores existed along the unaltered portions of the stream bank. We surmised that the absence of macropores in the altered bank may be due to differing factors: that the stabilization efforts had occurred fairly recently not allowing time for macropores to form, that the coarse substrate was not cohesive enough to form persistent macropores, or a combination. This observation should open dialogue as to how macropores may affect stream restoration efforts along stream banks, including bank stabilization and the construction of riparian buffer zones. Since macropores have the potential to transport significantly more runoff from upland to nearby bodies of water, and that macropores tend to be more persistent in soils with a high cohesiveness, the choice of soil substrate used for river engineering may significantly affect the nutrient processing capabilities of constructed areas. The implication of this may eventually improve how engineered riparian buffer zones are constructed to better process nutrients and other pollutants. We recommend that future studies model the nutrient processing efficiency of natural or constructed riparian zones taking soil texture and the presence of macropores into consideration.

3.2 Modeling the Transient Storage Capabilities of Macropores

The presence of macropores may also influence transient storage in stream banks during high flow events [Arntzen *et al.*, 2006; Francis *et al.*, 2010; Sawyer *et al.*, 2009; Loheide and Lundquist, 2009]. As such, understanding the physical characteristics of macropores (i.e. volume and interconnectivity) can deepen our understanding of the transient storage capacity of stream banks beyond the storage capacity of the stream channel. Should the volume and interconnectivity of macropore networks be sufficiently large, macropores may help increase transient storage within stream banks, thus progressively decreasing the magnitude of the floodwave hydrograph downstream. This may have real-world implications for attenuating floods in riverine systems. Modeling the transient storage capabilities of macropores in stream

banks may help build more accurate hydrologic models to prepare for and mitigate flood events [Pinder and Sauer, 2010].

3.3 References

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Appendix A: Experimental Field Measurements

A.1 Measurement of Macropores

Once we arrived at our selected field site, took GPS coordinates of the survey starting location using a Garmin GPS unit (Figure A-1).



Figure A-1: Handheld Garmin Montana 680t Handheld GPS Unit (Source: www.garmin.com)

Starting at the beginning of the survey reach, we measured the average bankfull width at three consecutive bankfull indicators. For pool-riffle morphology, we measured bankfull width at the middle of three consecutive riffles using a 100 m open reel tape measure (Figure A-2).



Figure A-2: 100 m open reel measuring tape (Source: www.championsports.com)

In the same location as where we measured the bankfull width, we then measured bankfull elevation from the water surface elevation to the top of the bank, not from the thalweg to the top of the bank. We opted not to measure the bank elevation from the thalweg since we were primarily concerned with macropores above baseflow conditions. The baseflow water surface elevation became our datum for all surveys.

Using the average of the three measured bankfull widths, we then determined the length of the short reach (20x bankfull width), followed by a long reach (40x bankfull width) (Figure A-3).

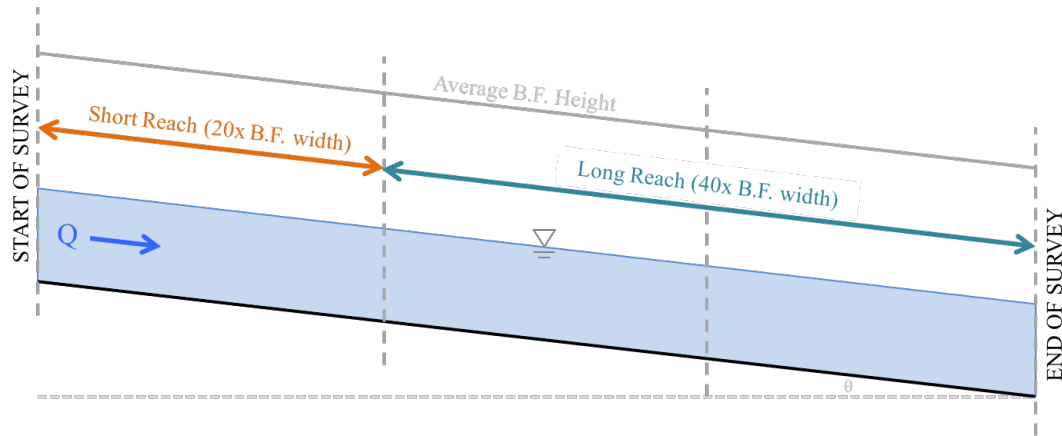


Figure A-3: Profile view of survey reach including short and long reaches.

Within the short reach, we measured the following macropores characteristics, which are detailed in Figure A-4:

1. Longitudinal position (100 m open reel measuring tape)
2. Elevation above baseflow conditions (modified wooden dowel)
3. Macropore height (modified wooden dowel)
4. Macropore width (modified wooden dowel)
5. Macropore depth into bank (modified wooden dowel) (Figure A-5)
6. Macropore angle to normal of water surface (protractor) (Figure A-6)

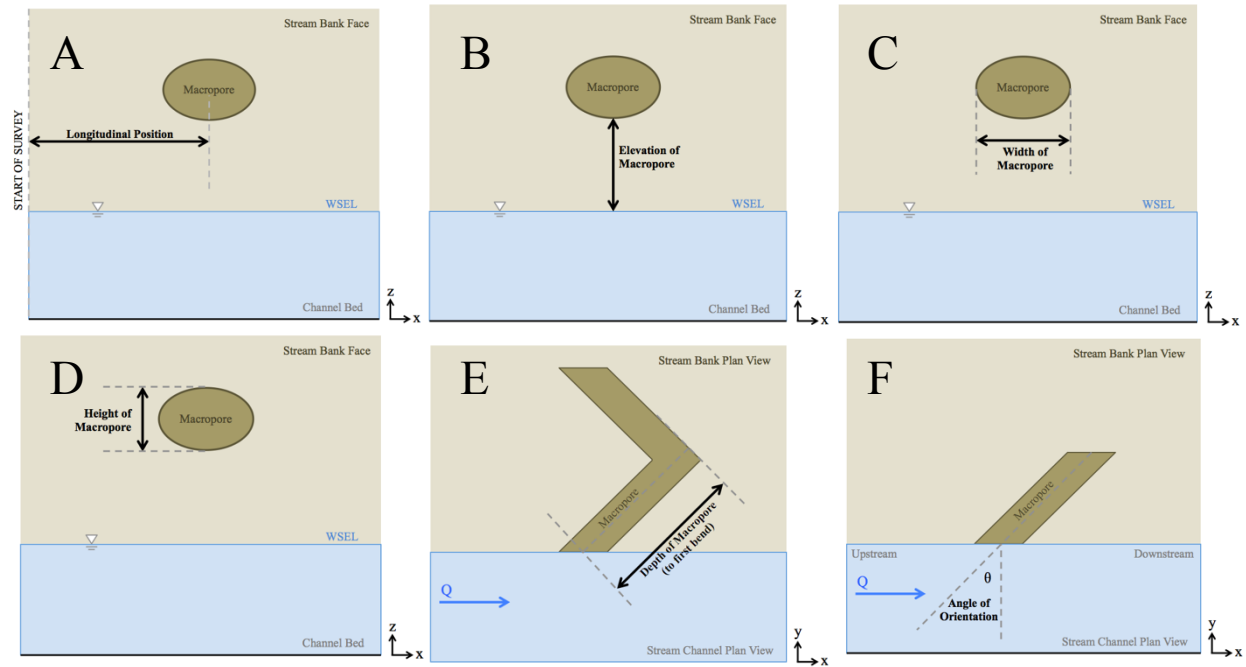


Figure A-4: Pictographic details of macropore measurements



Figure A-5: Depth measurement of macropore using a modified wooden dowel with 0.5 cm increments. The same dowel was used to measure macropore elevation, width, and height.



Figure A-6: Protractor used for horizontal angle measurements. Note that this figure only shows the protractor used, not the procedure used for measuring the horizontal angle.

Within the long reach, we only counted the number of macropores we observed and recorded their longitudinal position using the 100 m open reel measuring tape (Figure A-7).



Figure A-7: Example of longitudinal position measurement (macropore is at 30.5 m)

Within both the short and long reaches we recorded the soil texture using the Soil Texture by Feel Flow Chart as provided by NRCS adopted from *Thien* [1971] (Figure A-8). We tested the soil every 10 meters or when there was a distinctive change in soil texture.

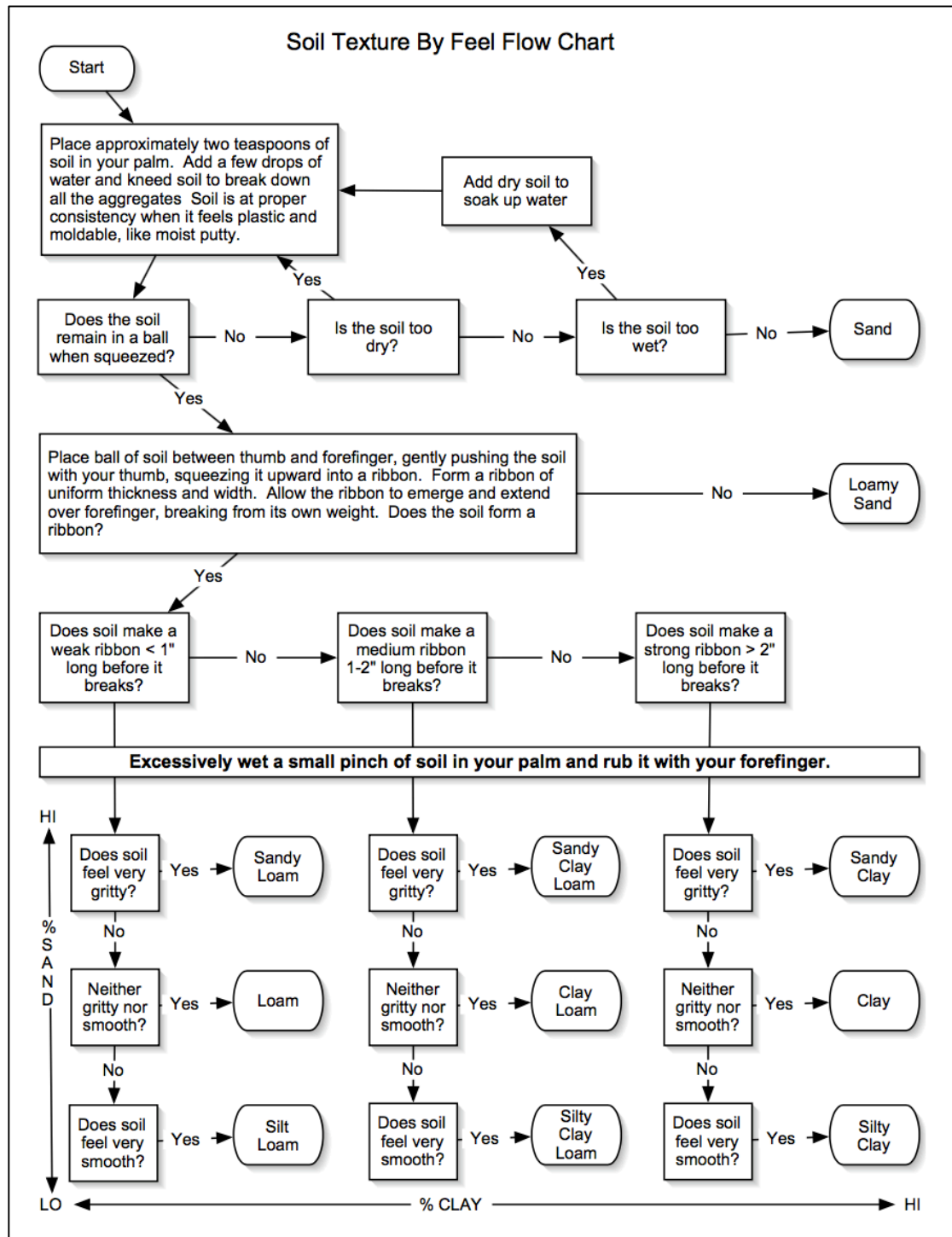


Figure A-8: NRCS Soil Texture by Feel Flow Chart (adopted from *Thien* [1979])

#	STATION (cm)	ELEVATION (cm)	WIDTH (cm)	HEIGHT (cm)	DEPTH (cm)	ANGLE (°)
1	8.8	3.5	7.0	3.5	6.5	0
2	9.2	17.0	5.0	4.0	8.5	-10
3	9.6	17.0	4.0	3.0	11.0	0
4	12.3	1.0	4.0	2.5	4.5	-60
5	14.0	8.5	2.5	2.5	4.0	+5
6	22.7	43.0	6.0	5.0	6.0	0
7	25.5	3.0	10.0	3.0	20.5	-50
8	25.8	2.5	2.5	2.0	6.0	-15
9	26.6	2.5	3.0	3.0	10.0	+30
10	27.2	2.5	4.5	2.0	8.0	-10
11	27.9	1.5	1.0	2.0	4.5	-20
12	33.7	3.0	4.5	2.5	6.0	-15
13	34.2	3.0	1.5	1.5	5.0	-20
14	35.4	0	5.5	2.5	5.5	0
15	35.5	8.0	2.0	2.0	7.0	-10
16	47.0	3.5	4.0	4.0	4.5	-10
17	47.7	5.0	5.0	2.0	7.0	0
18	48.0	8.0	4.5	3.0	16.0	-20
19	48.2	7.5	2.5	2.5	14.0	+15
20	48.4	10.0	3.5	2.5	5.0	+10
21	48.9	10.0	2.5	2.0	8.0	-10
22	52.8	23.0	4.5	5.5	2.5	+10
23	54.0	81.0	4.5	3.0	9.0	0
24	59.8	7.0	3.0	2.0	12.0	0

SOIL
CREATION
MATCH:

SANDY
LOAM/
COARSE
SAND *

PHOTO ID

* PHOTO AT
START

DATE: 06/07/2017

START: 13:00

END: 15:15

PROVINCE: PIEDMONT

GPS: 37.428128, -78.714824

STREAM NAME: FISHPOND CREEK

ORDER: 1

LANDCOVER: FOREST

ABW: 3.9 m

ABH: 1.23 m
S: 78 m
L: 234 m

MORPHOLOGY: POOL RIFFLE

BASEFLOW: YES

SLOPE:

SIDE RIVER: LEFT

CITY

LOAM

W

H

3.7

1.15

4.1

1.35

3.9

1.20

Rite in the Rain

A.2 Field Methodology Recommendations for Future Studies

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Figure A-10: Depstech flexible endoscope. (Photo source: www.depstech.com)

Appendix B: NHDPlus V2 Stream Order Data

NHDPlus Version 2 is a hydrologic geo-spatial framework developed by the US EPA and US Geological Survey and incorporates data from the National Hydrography Dataset (NHD), National Elevation Dataset (NED), and the Watershed Boundary Dataset (WBD). We gathered stream order data using NHDPlus V2, [McKay *et al.*, 2012], which is based on a modified version of the *Strahler* [1952] stream order methodology.

B.1 How to Download NHDPlus V2 Stream Order Data

- Ensure that you have at least ten to 20 gigabytes of free space on your computer, external hard drive, or USB before doing the following. Documentation for the NHDPlus V2 dataset is found at: ftp://ftp.horizon-systems.com/NHDplus/NHDPlusV21/Documentation/NHDPlusV2_User_Guide.pdf
- Navigate to: http://www.horizon-systems.com/NHDPlus/NHDPlusV2_data.php
- Select your region(s) of choice (Figure B-1). We used data from the following regions for our study: Mid Atlantic (02), South Atlantic North (03N), Ohio (05), and Tennessee (06).

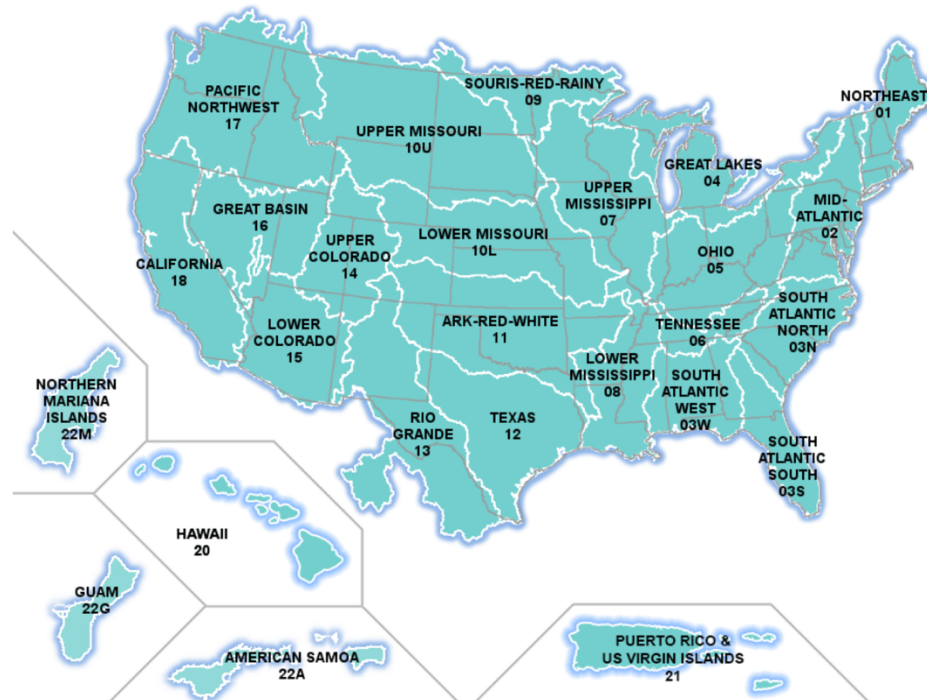


Figure B-1: Snapshot of NHDPlus V2 U.S. regions (Source: www.horizon-systems.com)

- For your selected region(s), download all of the corresponding FTP files (Figure B-2). Note that the data files are compressed using 7-Zip, a file compression software. You may need to download a zipping software to unzip the “.7z” files.

HTTP Download	FTP Download	File Name
HTTP	FTP	0release_notes_VPU02.pdf
HTTP	FTP	NHDPlusV21_MA_02_02a_CatSeed_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02a_FdrFac_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02a_FdrNull_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02a_FilledAreas_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02a_Hydrodem_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02a_NEDSnapshot_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02b_CatSeed_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02b_FdrFac_01.7z
HTTP	FTP	NHDPlusV21_MA_02_02b_FdrNull_01.7z

Figure B-2: Example of some of the requisite NHDPlus V2 FTP files are boxed in red. Note that you will need all of the FTP files associated with a given region, not just the ones boxed in red. (Source: www.horizon-systems.com)

B.2 Inserting NHDPlus V2 Stream Order Data to ESRI ArcMap

- Once all of your files are unzipped, open a blank map in ESRI ArcMap.
- Add the NHDSnapshot/NHDFlowline.shp file to ArcMap and join with the NHDPlusAttributes/PlusFlowlineVAA.dbf database. The result will enable you to extract stream order for all streams in the NHD. See Figure B-3 for Stroubles Creek just outside of Blacksburg town limits (target stream is highlighted in green).

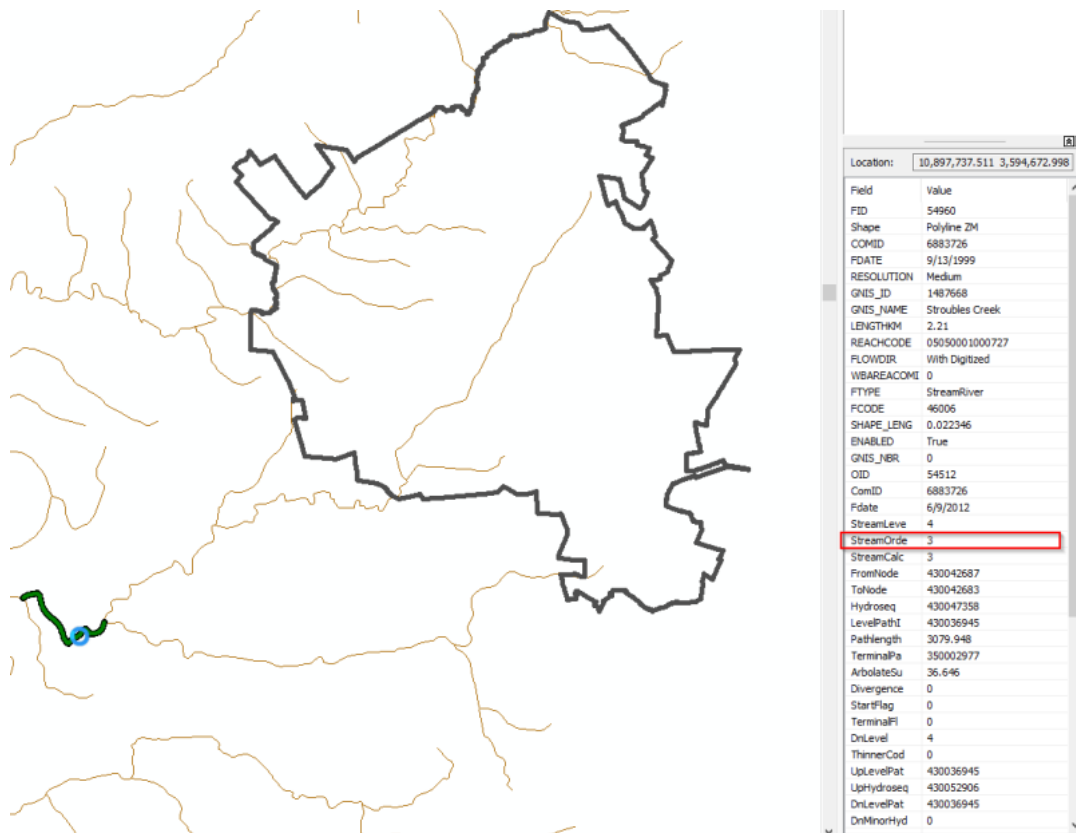


Figure B-3: Example of ESRI ArcMap *.mxd* file with NHDPlus V2 stream order data.

- Ensure that your stream order shapefiles are in an appropriate and consistent projection within the map.
- You may also add a base layer to your ArcMap *.mxd* file for better orientation. We displayed each of the stream orders in different colors to easily differentiate between them. We also added stream order number labels (Figure B-4) or stream name labels (Figure B-5) to the map for easy orientation while out in the field.

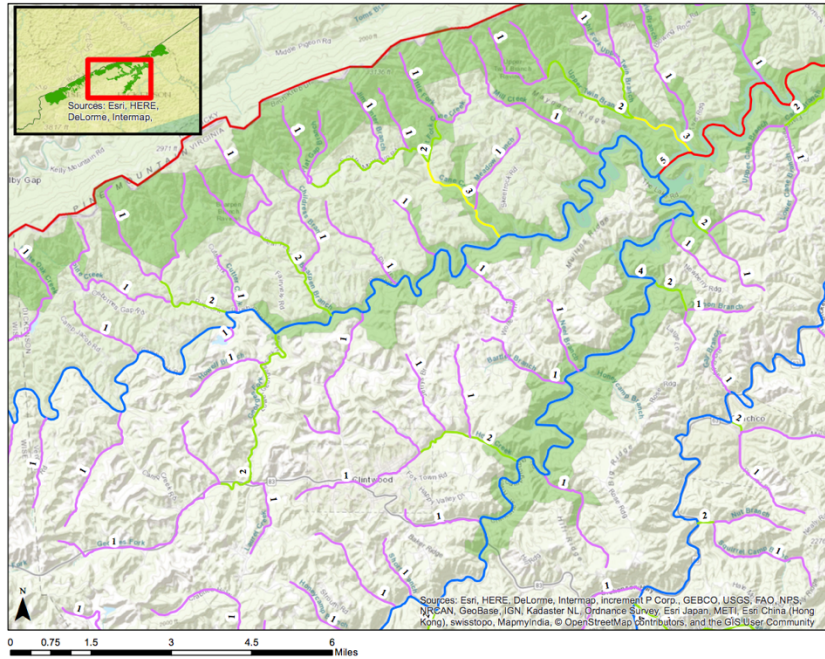


Figure B-4: Example of NHDPlus V2 stream order data with stream order number labels overlain on a base map layer in ArcGIS.

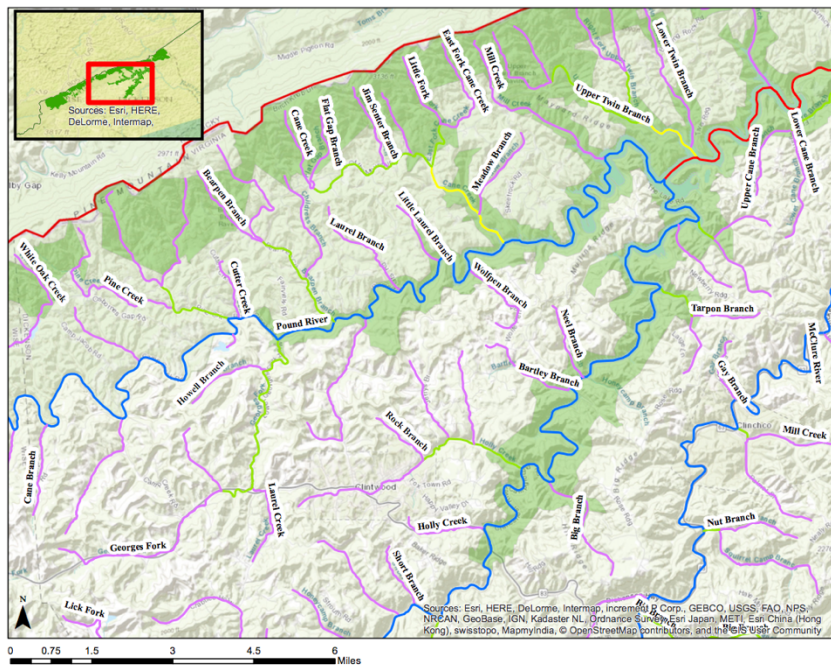


Figure B-5: Example of NHDPlus V2 stream order data with stream name labels overlain on a base map layer in ArcGIS.

Appendix C: Additional Data

We analyzed some data that was not suitable for including in the main journal article; however, we found it important enough to include here in the appendices for future studies. T-test p-values give further insight into statistical differences that ANOVA statistical analysis alone cannot detail.

Table C-1 shows two-tail p-values to determine statistical differences in the measured dimensions of macropores between physiographic province combinations (BR = Blue Ridge; AP = Appalachian Plateau; PM = Piedmont; CP = Coastal Plain; VR = Valley and Ridge). An f-test was used to determine if variances were equal or unequal for each of the combinations. If $F < F_{crit}$ then variances were equal; If $F > F_{crit}$ then variances were unequal. The result of the f-test determined which t-test to run (equal vs. unequal). To account for a Type 1 error in the t-test, the alpha value was the 95% confidence (0.05) divided by the number of groups (6 in this case), so, $\alpha = 0.00833$. The p-values displayed show the result of each two-tailed t-test. Values in bold are considered statistically significant, while unbolded values are not significantly significant.

Table C-1: T-test p-values based on all possible physiographic province combinations.

Physiographic Province Combinations	Elevation	Width	Height	Depth	Angle	Interspacing
BR + AP	7.06E-01	8.55E-01	1.18E-01	1.80E-01	7.98E-02	3.06E-02
VR + AP	1.96E-02	5.76E-07	1.49E-01	1.47E-13	2.02E-03	1.85E-01
PM + BR	4.70E-03	5.43E-08	8.02E-03	2.62E-01	4.93E-03	1.06E-01
CP + BR	7.09E-01	1.75E-01	2.15E-01	1.40E-01	1.52E-02	1.15E-02
VR + AP	1.96E-02	5.27E-06	7.10E-04	5.65E-20	8.89E-02	1.05E-03
PM + AP	9.40E-04	8.17E-07	1.27E-06	3.73E-03	3.73E-01	5.37E-04
CP + AP	4.63E-01	2.52E-01	9.01E-03	1.44E-02	4.52E-01	9.23E-01
VR + PM	4.07E-01	8.67E-01	1.64E-01	2.15E-15	1.46E-01	5.93E-01
VR + CP	1.63E-01	2.85E-03	8.76E-01	6.13E-05	2.57E-01	1.44E-04
PM + CP	2.83E-02	1.17E-03	4.40E-01	3.80E-01	9.16E-01	5.92E-05

Table C-2 shows two-tail p-values to determine statistical differences in the measured dimensions of macropores between all possible stream order combinations (1 = Strahler stream order 1; 2 = Strahler stream order 2; 3 = Strahler stream order 3; 4 = Strahler stream order 4). An

f-test was used to determine if variances were equal or unequal for each of the combinations. If $F < F_{crit}$ then variances were equal; If $F > F_{crit}$ then variances were unequal. The result of the f-test determined which t-test to run (equal vs. unequal). To account for a Type 1 error in the t-test, the alpha value was the 95% confidence (0.05) divided by the number of groups (4 in this case), so, $\alpha = 0.0125$. The p-values displayed show the result of each two-tailed t-test. Values in bold are considered statistically significant, while unbolded values are not significantly significant.

Table C-2: T-test p-values based on all possible Strahler stream order combinations.

Stream Order Combinations	Elevation	Width	Height	Depth	Angle	Interspacing
1 + 2	1.36E-04	5.91E-03	8.65E-03	1.10E-06	2.16E-01	6.64E-01
2 + 3	1.28E-02	8.44E-03	4.30E-03	2.29E-01	1.25E-04	5.58E-01
3 + 4	3.22E-02	2.04E-01	3.31E-01	4.22E-12	2.02E-01	5.02E-01
1 + 3	1.94E-01	1.42E-06	1.21E-06	9.94E-10	2.11E-02	8.08E-01
1 + 4	1.74E-03	2.07E-03	1.84E-03	1.33E-01	3.02E-01	5.81E-01
2 + 4	8.18E-01	3.77E-01	1.88E-01	5.66E-09	2.15E-02	8.00E-01