2020

Knickzones in Southwest Pennsylvania Streams Indicate Accelerated Pleistocene Landscape Evolution

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**Knickzones in Southwest Pennsylvania Streams Indicate Accelerated Pleistocene
Landscape Evolution**

Mark D. Swift

**Thesis Submitted to the Eberly College of Arts and Sciences at
West Virginia University**

in partial fulfillment of the requirements for the degree of

**Master of Arts in
Geography**

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**Morgantown, West Virginia
2020**

Keywords: landscape evolution, knickzone, southwest Pennsylvania

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ABSTRACT

Knickzones in Southwest Pennsylvania Streams Indicate Accelerated Pleistocene Landscape Evolution

Mark D. Swift

A set of 22 southwestern Pennsylvania streams flowing into the Monongahela and Ohio rivers with drainage areas ranging from 8 km² to >512 km² exhibit knickzones, when compared to Mackin's (1948) idealized graded stream profile. Watersheds delineated from LiDAR-derived 1 m DEMs were processed using Esri's ArcGIS for Desktop 10.6 to extract stream elevation data used to create stream profiles. These data were exported to MS Excel, where gradients were calculated and compared. This study used a new methodology in which gradient was calculated using incremental measurement distances (d) at every meter along the length of each stream. Profile convexities were identified where downstream reach ($d/2_d$) gradient was greater than upstream reach ($d/2_u$) gradient, and "knickzone extents" were designated where extended stream reaches had downstream gradients $\geq .001$ and ratios of downstream to upstream reach gradients ≥ 1.2 . A selection of stream profiles was plotted using Goldrick and Bishop's (2007) DS profile form, revealing most upper reaches fit the graded stream model, but lower reaches show disequilibrium steepening. Disequilibrium was likely induced by the rerouting of the regional drainage to its present configuration by Pleistocene glaciation, based on strong correlation of knickzones elevations with elevations of Pre-Illinoian and Illinoian terrace features along the main trunk rivers. The best correlation occurred when study area streams were compared by confluence location along the main trunk, possibly due to the lithologic differences in bedrock across the area or due to differences in the evolution of the Allegheny and Monongahela rivers. Although knickzones were assumed to have migrated into study area tributaries from the main

trunk, migration distance appears to be controlled more by lithology or pre-incision topography rather than time elapsed since inducement of disequilibrium.

Acknowledgements

First and foremost, I would like to thank Dr. J. Steven Kite, my thesis advisor, for his keen intelligence, collegial demeanor, and delightful company. He doubled the value of my degree by teaching me some geology along the way and was extremely generous with his time. Many thanks also go to my committee members, Dr. Jamison Conley and Dr. Nicolas Zegre for their teaching and thoughtful comments. Further acknowledgements go to both the Department of Geology and Geography at West Virginia University for their willingness to support a non-traditional student like me, and to the Presidents and Deans of my employer, Washington and Jefferson College, for believing that this was a worthwhile pursuit for a mid-career Professor of Music. I never would have been able to complete this work without the support of my sister, brother-in-law, and nephew in Seattle, whose fast internet connection made it possible for me to access large datasets and whose scientific and editorial knowledge kept me honest. Finally, I would like to thank my mother for her constant encouragement and generosity while I used her home in Virginia as my “retreat” for getting work done, and her patience with long thesis workdays when I could have been celebrating holidays with her.

What makes a river so restful to people is that it doesn't have any doubt—it is sure to get where it is going, and it doesn't want to go anywhere else.

—Hal Boyle

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Chapter 1: Introduction

Southwest Pennsylvania is a region where the topography of rolling hills is widely admired for its aesthetic beauty. The exact processes by which the surface received its contours, however, is still being revealed. The work that has been done in geomorphology of the region has often focused on periglacial deposition, erosion, and mass wasting, and the connection of these processes to fluvial evolution and disequilibrium of the major rivers—Ohio, Allegheny, and Monongahela (Foshay, 1890; White, 1896; Campbell, 1902; Leverett, 1934; Stout et al., 1943; Lessig, 1961, 1963; Clendening et al., 1967; Gillespie and Clendening, 1968; Jacobson, 1985, 1987; Jacobson et al., 1988; Morgan, 1994; Marine, 1997; Hamel and Ferguson, 1999; Hamel and Adams, 2000; Harper, 2000; Marine and Donahue, 2000; Kite and Swift, 2019). The question remains how extensively regional fluvial disequilibrium has altered networks of these rivers' tributaries, with implications for the safety of people and stability of human infrastructure throughout the region.

This thesis presents research on knickzones, or areas of steepening in a stream's gradient, a fluvial morphological characteristic known to be connected with fluvial disequilibrium (Gardner, 1983; Goldrick and Bishop, 1995; Crosby et al., 2005; Crosby and Whipple, 2006; Frankel et al., 2007; Berlin and Anderson, 2007; Harkins et al., 2007; Loget and Driessche, 2009; Gallen et al., 2011; Finnegan, 2013; Gallen et al. 2013; Bressen et al., 2014; Beckers et al., 2015; Gallen and Wegmann, 2015). It looks at whether knickzones exist in streams that flow into the Monongahela and Ohio rivers in southwestern Pennsylvania, and whether those knickzones are pervasive enough across watersheds of different drainage areas and locations to suggest one or more common disequilibrium-inducing events. This study further seeks evidence of whether patterns in knickzone number, location, length, and elevation indicate that they have migrated

upstream after base-level lowering on the Monongahela and Ohio rivers by comparing them with terrace elevations on those rivers. If wide-spread disequilibrium is evident, it will corroborate other research that suggests the entire region in disequilibrium (Kite and Swift, 2019) and may help narrow our understanding of when disequilibrium was induced.

The study area for this research is the area of southwest Pennsylvania bounded by the Ohio and Monongahela rivers in the north and east, the West Virginia state line in the south, and a major drainage divide near the West Virginia border in the west (Table 1, Figure 1).

Western Pennsylvania is part of the Allegheny Plateaus physiographic province (Fenneman, 1928), an ancient Paleozoic continental margin uplifted in the Alleghenian orogeny (Schultz, 1999). The study area can be described as having a substrate of near-horizontal cyclothems of sedimentary bedrock, dissected in a dendritic drainage pattern (Fenneman, 1928; Schultz, 1999). Topographic relief in the region, as defined by Fenneman's seminal work on physiography, is low near the drainage divides, and increasingly moderate as one approaches the major waterways of the Monongahela and Ohio rivers (Fenneman, 1928, 273). The history of continental glaciation proximal to the study area was long ago determined to figure prominently in the surface history of the region (Foshay, 1890; Chamberlain and Leverett, 1894; White 1896; Scranton and Lamb, 1932; Leverett, 1934; Stout and Lamb, 1938; Stout, et al., 1943).

Order south to north	Study area streams	Abbreviation	Distance from Midland, PA (km)	Drainage Area Rank	Drainage Area (km ²)	Drainage Area (mi ²)	Percent urban (%)	Mean Annual Precipitation (cm)
1	Dunkard Creek	D	198	2	603	233.0	1	107
2	Whiteley Creek	WC	187	7	141	54.4	1	104
3	Little Whiteley Creek	LWC	184	16	23	9.0	1	104
4	Muddy Creek	MdC	175	10	82	31.7	3	102
5	Pumpkin Run	PuR	168	19	15	5.8	5	99
6	S. Fork Ten Mile Creek	STM	163	3	515	199.0	3	99
7	N. Fork Ten Mile Creek	NTM	163	5	350	135.0	3	99
8	Fishpot Run	FpR	160	20	13	5.2	11	99
9	Two Mile Run	TmR	152	21	13	4.9	6	99
10	Pike Run	PiR	140	11	74	28.6	6	99
11	Maple Creek	MpC	126	14	26	10.2	11	97
12	Pigeon Creek	PiC	110	6	154	59.6	10	99
13	Mingo Creek	MgC	106	12	57	22.0	6	99
14	Lobbs Run	LoR	98	22	10	3.9	13	97
15	Peters Creek	PeC	90	8	133	51.5	37	99
16	Streets Run	SR	68	15	26	10.1	54	97
17	Saw Mill Run	SMR	57	13	51	19.5	87	97
18	Chartiers Creek	CC	54	1	715	276.0	29	97
19	Montour Run	MR	43	9	95	36.5	33	94
20	Logtown Run	LtR	28	18	16	6.1	58	94
21	Elkhorn Run	EhR	21	17	22	8.5	45	94
22	Raccoon Creek	RC	10	4	477	184.0	9	97

Table 1: Streams included in study, ordered south to north (upstream to downstream), that flow into Monongahela or Ohio rivers (USACE, 2002; USACE, 2006; USGS, 2016). All have drainage areas greater than 8 km².

Figure 1. Map of streams in study area. Smaller streams draining $< 8 \text{ km}^2$ are shown in light blue, and collectively give a sense of the total drainage area of streams in the study area. Streams are grouped by drainage area and their confluence location along three reaches of the Monongahela-Ohio River. Reaches are separated by a star and labeled Upper OH, Lower Mon, Middle Mon, and Upper Mon, which was beyond the scope of the current study. Created using National Hydrology Dataset streamlines in ArcGIS.

Chapter 2: Literature Review

Geologists and geomorphologists determined that glacial advances of the Pleistocene epoch had a profound effect on drainage patterns and topography of a significant portion of the North American continent (Figure 2) over hundreds of thousands or even millions of years and several glacial cycles.

Figure 2. Preglacial regional drainage. Adapted from Hansen (1995) map of east-central U.S. paleo-drainage, showing the traditional interpretation of a west-flowing preglacial Teays River and a northeast-flowing Erigan River, which followed the axis of what is now Lake Erie into the ancestral St. Lawrence River. Much of the former path of the Teays River is deeply buried under thick glacial drift. The northward-flowing Steubenville-Pittsburgh river system, which had flowed into the Erigan River, was blocked by ice sheets and overtopped a drainage divide shared with the Teays/proto-Ohio River basin. Flow was diverted permanently into the proto-Ohio drainage basin, at an undetermined time in the early to middle Pleistocene. Used by permission of Ohio Geologic Survey.

Thus, the following narrative must be understood as a simplified narrative of these events. In western Pennsylvania, Foshay (1890) was the first to publish the idea that the ancestral Steubenville and Pittsburgh rivers flowed northward, as did sections of the ancestral Allegheny River (Figure 3).

Figure 3. Drainage pattern of the Steubenville-Pittsburgh river system and proto-Allegheny rivers before re-routing by glaciation. Map slightly modified from Harper (1997), after Leverett (1934).

(The moniker “Pittsburgh River” first appeared in Scranton and Lamb (1932), and the moniker “Steubenville River” first appeared in Stout and Lamb (1938)). Chamberlain and Leverett (1894), White (1896), Leverett (1934), Fullerton (1986), Jacobson et al. (1988), Morgan (1994), Marine (1997), and Harper (1997, 2000) each contributed to the developing picture of how continental glaciation or glacial outwash (or both) obstructed the northward flow of rivers and created a body of water that covered much of southwestern Pennsylvania and northern West Virginia, named Lake Monongahela by I. C. White (White, 1896, 369) (Figure 4). Due to this blocked drainage, streamflow overtopped low elevation cols near New Martinsville, Ohio, Salem, West Virginia, and possibly Arnold (Lewis County), West Virginia (White, 1896). The west side of the col near Salem, West Virginia has barbed tributaries, evidence of stream piracy possibly initiated by overflow from Lake Monongahela. However, only the col at New Martinsville, Ohio was incised enough to permanently capture the whole upper Ohio River and Monongahela River systems (Foshay, 1890; White, 1896; Leverett, 1934; Jacobson et al., 1988). Leverett (1934) found evidence of another col separating the ancestral Steubenville and Pittsburgh rivers in the vicinity of Midland, Pennsylvania. This col was also breached, connecting the Steubenville and Pittsburgh rivers south of their pre-glacial confluence (Figure 4). In order for overflow from Lake Monongahela to incise the col near Midland, either the impounded drainage on the Steubenville River had a lower surface elevation, or the Steubenville River flow had already been reversed in an earlier episode, else there would not have been sufficient difference in elevation to generate the stream power necessary to incise the Midland col. Once the Midland col was eroded, the entire upper Ohio and Monongahela drainage became part of the Teays or proto-Ohio system (Figure 2), which itself was rerouted by ice sheets to form the modern Ohio River (Hansen, 1995).

Full extent of Lake Monongahela

Figure 4. Approximate extent of high phases of Lake Monongahela drawn on a 30 m DEM based on modern topography. Study area is entirely within the ancestral Pittsburgh River drainage, east of the breached col near Midland, Pennsylvania. Reconstruction does not include likely isostatic or neotectonic changes in topography.

The Ohio, Monongahela, and Allegheny river valleys have many features that give clues to the evolution of the river system upstream of New Martinsville, including terraces, abandoned meanders, and barbed tributaries, suggesting one or more episodes of incision of the main channels. Early work (Chamberlain and Leverett, 1894; White, 1896) posited that terraces at different elevations must have developed over considerable amounts of time and multiple glacial cycles. Later, Leverett (1934) began to correlate terrace deposits with named glacial episodes of Pre-Illinoian, Illinoian, and Wisconsinan. Lessig (1963), in a study of soils on terraces, noted interbedded layers of paleosols derived from lacustrine and glacial outwash, suggesting a complex picture of deposition of terrace sediments from multiple periods of impoundment, and erosion, incision, and pedogenesis during long interglacial stages. Logic would suggest that episodes of accelerated incision happened during interglacial stages only after streams removed lacustrine and glacial outwash deposits from their beds. There was an early consensus that this process began before the beginning of the Middle Pleistocene (now dated to 780 ka) and continued through Late Pleistocene. In subsequent work, researchers such as Jacobson et al. (1988), Pazzaglia et al. (1998), Pan et al. (2003), and Fuller et al. (2009) have applied modern analytical tools and methods, lending support for the pre-Middle Pleistocene onset interpretation.

Research leading to a geomorphic timeline for the river system has, for the past few decades, focused on terraces and the alluvial and lacustrine deposits resting upon them. If a terrace was blanketed at least partially by lake sediment, then the underlying strath, or bedrock terrace, must have been created prior to the existence of the lake, and by extension prior to the early glaciations. Using these sediment deposits, terrace remnants have been roughly correlated to the cycle of glacial and interglacial periods in this region (Leverett, 1934; Jacobson et al., 1988). The deposits, collectively called the Carmichaels Formation (Campbell, 1902; Kent,

1969a) are found on terraces along the Monongahela River at approximately 70-80 m and 95-105 m above modern riverbed level and in abandoned meanders near Carmichaels, Pennsylvania (Jacobson et al., 1988, 222). Examinations of lacustrine deposits on the high terrace, comprised of finely bedded layers of clay and silt, have provided tantalizing, yet sometimes contradictory, evidence for their age, and by extension the age of the strath terraces on which they rest. Deposits studied by Jacobson et al. (1988) exhibit evidence of deposition of some of the lacustrine sediments during a reversed paleomagnetic chron, the most recent occurring 780 ka. Clendening et al. (1967) and Parsons (1969), in studies of pollens in Lake Monongahela sediment, interpret the ratio of species represented as being indicative of a period of warming, suggesting deposition late in a glacial cycle. Clendening et al. (1967) and Gillespie and Clendening (1968) obtained radiocarbon dates for organic samples in lake deposits ranging from $26,394 \pm 262$ calBP to $\geq 37,267 \pm 1174$ calBP (Stuiver et al., 2020). However, the $\geq 37,267$ calBP date could be much older, but skewed by slight sample contamination or limitations of instrument technology (Gillespie and Clendening, 1968). Kite has hypothesized that the more recent deposits may indicate a later ponding on the terrace, such as a beaver pond (Kite, personal communication, 2016). Marine (1997), attempting to corroborate Jacobson's findings, tested many cores on terraces along the Allegheny and Youghiogheny rivers, but found no samples that had reversed magnetic signatures. More recently, Li (2018) turned to cosmogenic nuclide testing and iron chemistry (FeO / FeD ratio) to date the sediment deposits of the Carmichaels Formation, the results of which are more in line with Jacobson's older dates. The wide range of possible dates suggests the saga of when and how sediments were deposited is complex.

This thesis undertakes a morphological analysis to shed light on the erosional history of the upper Ohio and Monongahela river basins. Instead of looking at the main trunks of the

Monongahela, Allegheny, and Ohio rivers and the features along their valleys, this project examines left bank tributaries, looking downstream, flowing into the Ohio and Monongahela between Pennsylvania's southern border with West Virginia and the remnants of the col at Midland, Pennsylvania (Figure 3 and 4). Incision that left behind terraces and abandoned meanders on the main trunk resulted in a drop in local base level where tributaries joined the rivers, causing disequilibrium steepening of those tributaries, as can be seen in other parts of the world, such as Israel (Bowman et al., 2009) and France (Valla et al., 2010; Larue, 2011). Disequilibrium steepening creates knickpoints and knickzones, or convexities in a stream channel's longitudinal profile, which are known to migrate upstream from their point of origin. This process has been studied extensively in settings of tectonic uplift level (Goldrick and Bishop, 1995; Carretier et al., 2006; Finnegan, 2013; Jiang et al., 2016), but is little studied in the distinctive geologic and geographic setting of southwestern Pennsylvania.

Longitudinal profiles (a.k.a. long profiles or simply profiles) have long been recognized as an important indicator of geomorphic evolution of a landscape, and are often discussed in relationship to the concept of a "graded stream" (Mackin, 1948; Hack, 1957, 1973; Schumm and Lichty, 1965; Gardner, 1983; Chorley, R.J. 2000; Harmar and Clifford, 2006; Phillips and Lutz, 2008). A graded stream is by definition an idealized stream profile and is of fundamental importance to the current study. In theory, streams are graded such that "over a period of years, slope [and channel characteristics are] delicately adjusted to provide, with available discharge. . . just the velocity required for the transportation of the load supplied from the drainage basin" (Mackin, 1948, 471). The profile of a graded stream is thus steeper in its upper reaches and flatter in its lower reaches, with its slope diminishing continually from headwater to base level. Since the concept was proposed by Mackin, many have used it as a model against which actual

stream profiles can be compared to identify other geomorphic processes at work along the channel (Chorley, 2000; Harmar and Clifford, 2006; Phillips and Lutz, 2008). Curve fitting procedures (Hack, 1957; Peckham 2015), in which real streams are shown to somewhat fit mathematical models of a graded stream using relatively simple equations and calculus, work only at certain scales and in certain contexts. As one examines a stream profile at larger map scales, deviations from the best fit curve appear because of many factors (Harmar and Clifford, 2006). Some of these factors result in adjustments to the gradient of the profile in a way that maintains an overall dynamic equilibrium (Schumm and Lichty, 1965). Other factors are indicators of disequilibrium in the development of the profile.

The term “knickzone” is used for an area of steepening in a river’s gradient that does not fit the predicted mathematical curve of a graded stream, regardless of whether it is a product of equilibrium or disequilibrium steepening, and appears as a convexity in the profile. Steepening may occur at many scales and may reflect any gradient on a continuum of shallow to steep. At their most dramatic, end member knickzones indicate waterfalls, where the gradient nears 90°, and are usually termed “knickpoints.” Most research has been connected to these abrupt changes in gradient (Gardner, 1983; Goldrick and Bishop, 1995; Crosby et al., 2005; Crosby and Whipple, 2006; Frankel et al., 2007; Berlin and Anderson, 2007; Harkins et al., 2007; Loget and Driessche, 2009; Gallen et al., 2011; Finnegan, 2013; Gallen et al. 2013; Bressen et al., 2014; Beckers et al., 2015; Gallen and Wegmann, 2015). Knickpoints are obvious features in a stream. But knickzones, because they can exist on a continuum of gradient and scale, may not be apparent to a casual observer. Several studies have been undertaken to develop methods to verify the presence of knickzones (Strahler, 1952; Crosby and Whipple, 2006; Harmar and Clifford, 2006; Gong-Saholiariliva et al., 2011; Yunus et al., 2016; Whipple et al., 2007, cited in Zahra et

al., 2017; Zahra et al., 2017), which is a subtly different undertaking than identifying the morphological characteristics of those knickzones, discussed below.

Brush and Wolman (1960), Begin (1988), Foster and Kelsey (2012), and Stanford et al. (2016) have described how convexities in a streambed migrate in an upstream direction. Reneau (2000), Berlin and Anderson (2007), Hayakawa and Oguchi (2014), DiBiase et al., (2018), and Li (2018) studied how the migratory process may be slowed or accelerated, such as by relatively harder bedrock exposure in the streambed, or where erosion is enhanced by the hydraulic characteristics of the channel. Beckers et al. (2015) found that knickpoints in certain geologic settings can persist in their migration all the way to the head of the stream. Although it is well-established that knickzones in heterogeneous substrates also migrate (Hayakawa and Matsukuna, 2003; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2014), the substrate composition can complicate the pattern of convexity, making the knickzone's upper and lower boundaries difficult to isolate. Gerrard (1988) and Miller (1991) found that knickzone boundaries may be obscured after migrating some distance, and almost unrecognizable by the time they approach the drainage divide. In these ways, both disequilibrium and equilibrium steepening can have similar expression in the same stream profile. Work discussed below describes methods for differentiating between these types of steepening.

Culling (1957a, b) was one of the first to apply the theory of dynamic equilibrium to erosion slopes and stream grade. The underlying factors and processes that drive equilibrium steepening are many (Hack, 1973, 1975; Howard and Kirby, 1983; Goldrick and Bishop, 1995; Pazzaglia et al., 1998; Inoue et al., 2014), and include bed lithology (Goldrick and Bishop, 1995), climate (Roe et al., 2002), seasonal changes in precipitation (Roe et al., 2002), and sediment fluxes within the system (Crosby et al., 2005).

In areas with a heterogeneous bedrock structure, a few minor faults, and low amplitude synclines and anticlines, variability in composition and thickness of stream bed substrate can often result in local areas of steepening that may be related to a disequilibrium-inducing event (Miller, 1991; Wagner et al., 1970; Wohl and Achyuthan, 2002; McCleary et al., 2011; Fedorko and Skema, 2013; Forte et al., 2016). Working in areas with heterogeneous substrate, Dibiase et al. (2018) and Del Vecchio et al. (2018), turned to isotopic analysis to determine erosion rates of a resistant sandstone caprock layer, providing insight into knickpoint migration in central Pennsylvania. It is therefore critical to have an awareness of the geological structure of the region under study.

Regionally, the bedrock of the greater Pittsburgh area was mapped at 1:125,000 scale by Wagner, et al. (1975). Additionally, many 1:24,000 scale geologic maps were created in the 1960s and 1970s providing detail of members within geologic formations for some parts of the study area, including maps by Berryhill (1964a, 1964b), Swanson and Berryhill (1964), Kent (1967), Schweinfurth (1967), Roen et al. (1968), Kent (1969a, 1969b), Roen et al. (1968), Roen (1970), Kent (1971), Roen (1972), and Roen (1973). Geologic columns developed by Harper (2000) and Fedorko and Skema (2011) provide a synopsis of lithological units and their thicknesses in southwestern Pennsylvania. Some geologic formations or members within formations are more resistant than others, potentially causing a lithological control for either equilibrium or disequilibrium steepening.

Goldrick and Bishop (1994, 2007) demonstrated lithologic control of steepening by comparing the elevation of lower order stream knickpoints with the distance from their confluence with higher order streams, based on the underlying principle of Playfair's Law (Niemann et al., 2001), which says a stream and its tributaries must erode at similar rates at their

junction. Additionally, their Distance-Slope (DS) profile form (Goldrick and Bishop, 2007), a refinement of Hack's (1957, 1973) slope-length (SL) profile form, shows that plotting the natural log of the slope against the natural log of the horizontal distance can reveal lithologic steepening. These logarithmic curves, however, do not reveal the specific morphological characteristics of knickzones.

Climate may also play a role in equilibrium steepening and has varied greatly through time in southwest Pennsylvania. However, geographically speaking, the impact of climate variation has been relatively homogeneous over the study area, with a periglacial climate during maximum glacial stages, a humid-temperate climate during peak interglacials, and intermediate climates during the transitional episodes that constitute most of the Quaternary (Parsons, 1969; Sevon, 1993; Fullerton, 1986; Bartsch et al., 2009; Bitting, 2013). In the modern climate, temperatures vary by only 1° C between the northernmost and southernmost parts of the study area (NOAA, 2020), and mean annual rainfall varies by only about 10 cm (4 in) or 10% (USGS, 2016). Regional similarities during past climate regimes were assumed going into this study. Minor variations across the study area were unlikely to have had meaningful impact on the relevant geomorphological processes. However, that does not discount climate as a possible factor if presented with different results between northern and southern areas.

The role of sediment in stream profile development and incision is particularly well-studied, and the flux of sediment through a stream has an important role in maintaining dynamic equilibrium in the overall incision rate. Bedrock erosion is closely tied to sediment flux in semi-alluvial channels and in bedrock channels (Langbein and Leopold, 1964; Howard, 1980; Sklar and Dietrich, 1998; Golden and Springer, 2006; Wohl and David, 2008; Goode and Wohl, 2010; Hassan and Zimmerman, 2012; Meshkova et al., 2012; Turowski, 2012; Schroeder et al., 2015).

A stream bed may not incise into bedrock without an adequate sediment transport capacity to remove material from the system (Taylor and Kite, 2006; Bartsch et al., 2009; Inoue et al., 2014). This factor is particularly important in the study area during glaciations because outwash sediment load on the Allegheny River or its predecessors may have led to higher incision rates than would have occurred on the unglaciated ancestral Monongahela River. Aggradation, including legacy sediments of the Anthropocene, may obscure earlier bedrock erosion (Walter and Merritts, 2008; James, 2013).

Sediment transport and incision are often tied to stream power, a variable extremely well-represented in the literature, although scholars still do not fully understand how stream power is connected to channel evolution and morphology (Hancock et al., 1998; Pazzaglia et al., 1998; Sklar and Dietrich, 1998; Whipple and Tucker, 1999; Allen et al., 2002; García et al., 2004; Golden and Spring, 2006; Jain et al., 2006; Berlin et al., 2007; Parker et al. 2014; Beckers et al., 2015). Reneau (2000) and Crosby et al. (2005) have suggested that below a certain threshold of drainage area, there is not enough stream power for knickpoints to propagate up through a stream system, and, consequently, may get permanently arrested on hard bedrock, confounding any further attempt to tie them to a specific disequilibrium-inducing past event. Given these multiple factors, it is unsurprising that the size of knickzones in tributary profiles are both large and small, and in some cases, appear nested within larger knickzones.

The present study is not focused on the fluvial processes that create the knickzones, but rather the identification and comparison of patterns in knickzones across watersheds. Still, there are important insights to gain from the literature because of the direct connections between drainage area, stream power, sediment supply, and incision rates.

Knickzones and knickpoints created by an abrupt change in base level are considered “disequilibrium steepening,” such as would occur after initiation by eustasy, accelerated downstream incision or tectonic uplift. While disequilibrium knickpoint retreat in horizontally-bedded sedimentary rock was recognized more than a century ago in a study of Niagara Falls by Gilbert and Hall (1907), such studies focus on how undercutting of a massive, resistant cap rock maintain a retreating near-vertical knickpoint (Gardner, 1983; Tinkler et al., 1994). Articles that examine sedimentary geologies in connection to disequilibrium steepening (Philbrick, 1974; Gardner, 1983; Frankel et al., 2007; Hattanji et al., 2014) cite few profile studies in their own literature reviews dealing specifically with streams cutting through sedimentary bedrock with varied bed thickness and erosional resistance. Disequilibrium steepening in varied sedimentary bedrock settings with a resistant caprock has been taken up relatively recently by Del Vecchio et al. (2015) and DiBiase (2018) using isotopic analysis of ^{10}Be and ^{16}Al .

Isostatic depression and rebound may also play a role in knickzone formation, changing the base level or mimicking tectonic uplift (Reusser, 2002; Reusser et al., 2006; Stanford et al., 2016). Based on work done in New England by Hooke and Ridge (2016), the average gradient within 100 km of the Laurentian ice margin could be have been isostatically depressed 50 m/100 km or 0.05% more than baseline. In a study of glacioisostasy in the eastern part of Pennsylvania, Ruesser (2006) provided evidence in the Susquehanna River that an isostatic fore-bulge existed some 150 km south of the Wisconsin glacial margin, a result similar to findings in Hooke and Ridge (2016). That said, the uplift of the forebulge analyzed by Hooke and Ridge (2016) is only about 10% as great as the depth of the depression at the glacial margin. It is logical to construe that the directional orientation of streams must be nearly perpendicular to the directional orientation of isostasy-induced changes in gradient for isostasy to fully affect stream gradients.

Most studies of true knickzones caused by disequilibrium steepening are focused in steep terrain. In turn, many of these studies are focused on knickpoints caused by tectonic uplift or eustasy that created a change in base level (Merritts and Vincent, 1989; Merritts et al., 1994; Pazzaglia et al., 1998; Carretier et al., 2006). A further subset of studies involves stream systems in hard and homogeneous bedrock environments (Tanaka et al., 1993; Gardner, 1983; Gallen et al., 2011, 2013; Gallen and Wegman, 2015). Several studies of knickpoints focus instead on base-level fall caused by non-tectonic and non-eustatic processes (Berlin et al., 2007; Bowman et al., 2009; Storz-Peretz et al., 2011).

Studies focused on disequilibrium knickzones, *per se*, have taken place in steep landscapes such as the mountains of Japan (Hayakawa and Oguchi, 2006, 2009), the French Prealps (Liébault et al., 2002), the Blue Mountains of Australia (Goldrick and Bishop, 1995), the French Massif Central (Larue, 2011), the Baetic Mountains of Spain (García et al., 2004), and the Coastal Range of northern California (Foster and Kelsey, 2012). Very few studies focus on knickzones of shallow gradient, perhaps due to an assumed gradual change in base-level (Carretier et al., 2006; Belmont, 2011), or the absence of DEMs (Digital Elevation Models) with resolution adequate for analysis.

Downstream of knickzones, terrace features are commonly evident, which provide evidence of past stream morphology, and provide support for a time-delimited (disequilibrium) event. Many researchers focus on these landforms rather than channel features (Seidl and Dietrich, 1992; Pazzaglia et al., 1998; Pazzaglia, 2013; Liang et al., 2015). While terrace studies are focused on the results of past processes, channel studies are often focused more on the dynamic processes at work in the moment.

Incision waves that cause convexities in more homogeneous bedrock geologies have been modeled with success, both in laboratory and field, by Begin (1988), Berlin and Anderson (2007), and Gallen et al. (2013). These studies are perhaps more numerous because the homogeneity of the substrate removes many complexities or “muddiness” in the data presented by heterogeneous bedrock. In some settings and conditions, convexities often “recline” or “lay back” into milder gradients as they migrate upstream (Rich, 1938; Gardner, 1983). When the setting contains inter-bedded cyclothems of shale, limestone, sandstone, siltstone, mudstone, and coal as found in the Dunkard, Monongahela, Conemaugh, and Allegheny groups of western Pennsylvania, convexities may vary according to the bedding and thickness of relatively resistant strata as compared to weaker strata (Berryhill and Swanson, 1962; Berryhill et al., 1971; Gerrard, 1988; Miller, J.R., 1991; Fedorko and Skema, 2013) (Figure 5).

Figure 5. Small lithologic knickpoint (limestone bed in the Redstone Member of the Pittsburgh Formation) along Mingo Creek, Nottingham Township, Pennsylvania.

Additionally, the distance between convexities may become foreshortened, resulting in a single convexity, as observed in the sedimentary rock dominated landscapes of western Virginia (Harbor et al., 2005).

An on-going challenge in the study of knickzones is the determination of their salient morphological characteristics, not just their presence. Important morphological characteristics of knickzones identified in the literature include the elevation, height, and length of knickzones (García et al., 2004; Hayakawa and Oguchi, 2006; Hayakawa and Oguchi, 2009; Hayakawa and Oguchi, 2014; Zahra et al., 2017), the correlation of knickzone crest elevation and terrace elevations (Seidl and Dietrich, 1992; Pazzaglia et al., 1998; Zaprowski et al., 2001; Davis et al., 2009; Foster and Kelsey, 2012; Finnegan, 2013; Pazzaglia, 2013), and the correlation across watersheds of normalized stream distance of knickzones from the confluence of the tributary with the trunk channel (Hayakawa and Matsukura, 2003; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2006; Loget and Driessche, 2009; Hayakawa and Oguchi, 2014).

Because actual stream profiles can be difficult to analyze because of many contributing variables, researchers have developed methods and procedures for identifying knickzone parameters. Zahra et al. (2017), while acknowledging that a typical method for locating knickzones has traditionally been through visual inspection of the profile, sought to build upon recent attempts to quantify an extraction process. They reviewed the most effective methods developed for GIS identification and analysis of knickzone characteristics across large areas that included multiple watersheds. These methods included the Stream Profiler Tool (SPT) developed by Whipple et al. (2007), the GIS-Knickfinder (GKF) developed by Rengers (2012; as cited in Zahra et al. [2017]), and the SAKE method, developed by Hayakawa and Oguchi (2006), and refined by Hayakawa and Oguchi (2009). The latter investigatory duo's most recent

approach, presented by Zahra et al. (2017), and called Knickzone Extraction Toolkit (KET), borrowed from or followed procedures similar to earlier methods.

Commonalities to all the aforementioned knickzone-determination studies include: (1) focus on mountainous terrains with relatively large gradients, (2) the use of 10 m (or coarser) resolution DEMs, appropriate for the topography being studied, and (3) use of vector or raster datasets that could be processed by GIS software in a reasonable amount of time. The SPT method (Whipple et al., 2007) still required a visual demarcation of knickzones. GKF, SAKE, and KET could “automatically” extract knickzones, but required the investigator to establish thresholds for what “counts” as a knickzone. Importantly, when Zahra et al. (2017) compared all four methods’ effectiveness for identifying knickzones in the same geographic locale, they rarely coincided in location or even in recognition of the existence of a knickzone. By adjusting threshold values, there was more coincidence between methods, but rarely more than 70%.

The most recent and refined quantitative approach to knickzone extraction is the Knickzone Extraction Toolkit (KET) created by Tuba Zahra and Yuichi Hayakawa (Zahra et al., 2017) as part of the HDTopography Project for use with GIS software. It is a refinement of the methods presented in Hayakawa and Oguchi (2006, 2009), which provide a more straightforward explanation of the process. These methods calculate and create a raster for the relative steepness index (R_d) along a stream profile based on parameters input by the user to determine the scale of analysis. The scale of analysis is essentially a user-determined incremental measurement distance (d) used to calculate gradient at a point along the stream (G_d).

$$G_d = \frac{e_2 - e_1}{d}$$

where e_2 is the elevation $d/2$ upstream and e_1 is the elevation $d/2$ downstream. Shorter measurement distances reveal more detail in local gradients, whereas longer measurement

distances show trend gradients. R_d quantifies the comparison of local and trend gradients to extract knickzones (Hayakawa and Oguchi, 2006, 2009). Higher values for R_d represent locally steeper segments of stream, while lower values for R_d represent shallower segments of stream. Knickzones are then identified in the tool by providing a threshold value for R_d , and a minimum distance of stream to be considered. Hayakawa and Oguchi (2006, 2009) used the standard deviation of R_d to arrive at an objective threshold value for knickzone determination.

A different kind of disequilibrium is brought about by human interaction with watersheds. Anthropogenic influences often obscure naturally produced river features in some watersheds (Allen et al., 2002; Wampler, 2005; Bitting, 2013; James, 2013) and include (1) stream channelization and diversion for placement of residential areas, industry, roads, and railroads; (2) subsidence of stream reaches due to undermining; (3) complete destruction of stream reaches for the purpose of strip mining or mine waste storage; (4) increase in bedload from mining and other sediment sources; (5) alterations to discharge quantity and velocity due to land cover change. Channelization, particularly, is an important consideration, because the change in gradient from removal of meanders overshadows subtle, natural changes in stream gradient in a migrating knickzone, at least over relatively short measurement distances (Landemaine et al., 2015). Remote sensing and GIS software tools, when used with datasets showing roads, railroads, land use, and other landscape features, have aided in the spatial analysis of channel morphology and human-stream interfaces (Karwan et al., 2001; Wampler, 2004; Price and Lee, 2006; Pechenick et al., 2014).

GIS tools complement, and in some instances, may supplant the traditional quantitative tools used to measure and describe stream morphology (Whipple et al., 2007). Hypsometric or slope-area analysis (Strahler, 1952), slope-length (SL) analysis (Hack, 1973), stream order-

magnitude analysis (Flint, 1974), distance-slope (DS) analysis (Goldrick and Bishop, 2007), and analysis of topographic relief (Gallen et al., 2011, 2013; Gallen and Wegmann, 2015) have all been used to describe slope characteristics, connecting drainage area, discharge, and stream length to stream gradient, as well as to identify knickpoints on relatively high-gradient streams. DEMs with 3 m, 5 m, 10 m, and 30 m resolution have been used in regional studies (Goldrick and Bishop, 1995; Troiani et al., 2014) and mountainous areas (Lin and Oguchi, 2006). For steep streams, it has been demonstrated that 3 m DEMs are as accurate as 1 m DEMs (Schroeder et al., 2015), but 1 m DEMs provides a higher precision (Foster and Kelsey, 2012).

Chapter 3: Methodology

For this study, it was assumed the lower gradient streams and subtle changes in gradient in knickzones of Monongahela-Ohio River tributaries require higher resolution elevation data for meaningful analysis. The PAMAP Project (Pennsylvania Bureau of Geologic Survey, no date) acquired LiDAR across southwestern Pennsylvania in 2006. The high resolution 1 m (nominal) DEMs derived from this project were essential to extracting knickzones along the relatively shallow gradient streams of the region (Appendix 1.a).

Unfortunately, 1 m DEMs are of such high resolution that it was impossible to create a map of the whole region and apply the methods used by Hayakawa and Oguchi in their work in Japan with 50 m resolution DEMs (Hayakawa and Oguchi, 2009, 29). Additionally, 1 m resolution DEMs required extremely intensive computation, even after division of the study area into the individual watersheds identified for this project (Appendix 1.b).

The National Hydrologic Database (NHDB) vector-based dataset was used to delineate watersheds (USDA-NRCS et al., 2017). Then, a separate DEM map for spatial analysis of each watershed was created by identifying the DEM tiles, each 10,000 by 10,000 ft (3048 by 3048 m), contained within each watershed and masking the mosaic DEM used the NHDB lines. (Figure 6). In cases where a smaller watershed was not already established as a NHDB hydrological unit, spatial analysis hydrology tools were used to delineate watersheds. The difference in the two methods was negligible in terms of the resulting drainage characteristics of the watershed.

The typical steps required to create a stream network using ArcGIS for Desktop 10.6 include: (1) fill pits so that there are no internally draining areas, (2) establish the flow direction for every pixel, (3) run the flow accumulation tool wherein pixels with the highest accumulation become those that represent streams, (4) derive the stream raster with a conditional statement

after deciding what accumulation value would represent a true “stream”, (5) convert the raster to vector lines, (6) use the 3D analyst tools to create a table of elevations of each pixel under the vector line.

Figure 6. Screenshot of PAMAP DEM mosaic masked by NHDM watershed boundary for Mingo Creek.

Published DEMs with resolution coarser than 1 m typically have been pre-processed to remove human structures such as bridges and buildings. The PAMAP 1 m DEM had been minimally processed before publication. Only the largest LiDAR-blocking objects on the landscapes, such as high bridges, had been removed. Smaller bridges and culverts were not removed. Running the standard “fill all pits” process resulted in areas upstream of these blockages being altered to create virtual “lakes” as much as 30 m deep and many km² in area. Thus, completing the process in the typical way defeated the purpose of the using a high-resolution DEM in the first place.

To rectify these issues, this investigator employed two steps of pre-processing the DEMs: filling small pits (4 ft or less) and then using a raster editing tool (ARIS™ Grid and Raster Editor) to remove stream blockages that created larger “pits” to re-create the natural connectivity within the main channel of the stream. A fill value of 4 ft was chosen through process of trial and error. Filling pits of only 4 ft deep or less appeared to be enough to create connectivity in a channel crossed by a driveway over a 24-inch culvert, but not so much that the gradient of the channel was significantly affected over distances more than 100 m in length. The areas affected by the fill process were verified using ArcGIS “Minus” tool that compares the elevation values of the original DEM to the filled DEM.

After filling ≤ 4 ft pits, symbology was used to reveal points in the stream network where accumulation values were interrupted by blockages. Typically, there were 25 to 30 structures crossing the channels in each watershed that needed to be dealt with using DEM editing software. A by-product of filling pits was the conversion of pixel elevation values to integer feet. By symbolizing elevations with unique color values, it was possible to identify the precise structures that blocked connectivity in the stream network and the lowest elevations representing the stream itself. For technical reasons, two passes were required, one where a “channel” was cut to the elevation of the stream, and another where pixels bordering that cut were set at an elevation of 1 ft higher than the stream (Figure 7). The values for stream elevation in these cuts was determined by comparing the elevation just upstream and downstream of the blockage. If the difference in elevation between those two locations was 1 ft, then the lower elevation was used for the elevation of the cut channel. If the elevation difference was 2 ft, then an intermediate value was used, and so on. In some few cases, long distances of culverted stream

necessitated estimation of a range of values for the culverted section. Also, in some locations, artificial “pits” or errors in the DEM raster had to be filled manually.

Figure 7. Sample of DEM editing process. Pixel colors uniquely represent each 1 ft (0.3048 m) elevation value.

By this process, the investigator was able to generate a stream raster for main channels connected from their headwaters to their confluence with the Monongahela or Ohio rivers, preserving accurate stream elevation values within an approximate 4 ft window. This process was completed only on the longest flow path in each watershed, and this longest path was used for analysis (Hack, 1973). Nevertheless, obvious large obstructions were removed from other parts of the stream network to be able to show a more visually appealing network on maps of the watersheds. Complete connectivity for the broader stream network outside of the longest path of

the main channel was created by filling all pits in the traditional method *after* the main channel was fully connected and major sub-tributary obstructions were removed.

After connectivity was established, an accumulation value threshold of 16,000 pixels was chosen to determine the headwaters of streams (Appendix 1.c). Then, converting the stream network raster to vector environment, stream segments were uniquely numbered (using the Stream Link tool) and symbolized according to their unique value. Using a SQL statement, the segments comprising the longest path were extracted and combined into one single line segment with the ArcGIS Dissolve tool. Finally, this longest path was used to create a 3D line with an accompanying table that contained fields for (1) integer stream distance (Objectid) from the headwater, (2) horizontal distance under the 3D line, also from the headwater, and (3) stream elevation values in ft. The table was then exported to Microsoft® Excel®.

All subsequent computational work was done in Excel. Each row or record of the spreadsheet represented 1 m of stream length (Table 2). Columns A, B, and D contained the original data imported from ArcGIS. The remainder of the columns contained data computed in the spreadsheet. Because elevation values were derived from the average LiDAR “bare earth” value in each m², they contained significant “noise” that required smoothing. This was accomplished by rounding the elevation down to the nearest integer value. Next, these values were converted to m by multiplying the value in ft by .3048. At this point, the elevation data required a further degree of “smoothing” because remnant edge effects and vegetation, especially in wetlands, caused some downstream elevation values to be erroneously higher than upstream values. In these cases, cell values were changed manually to match the lowest elevation occurring upstream of the erroneous values.

Column	Value
A	Stream Distance (m) imported from ArcGIS
B	Horizontal distance (m) imported from ArcGIS
C	Normalized Horizontal Distance from headwater (%)
D	Elevation (ft) imported from ArcGIS
E	Elevation (Column D) rounded down to nearest integer (ft)
F	Elevation (Column E) converted to m
G	Elevation (Column F) with .0001 decrease per row if unchanged from previous row
H	Normalized Elevation (Column G) from highest point (%)
I	Gradient at point for $d = 200$ (upstream $d/2 = 100$, downstream $d/2 = 100$) (m/m)
J	Gradient of downstream reach $d/2_d = 100$ (m/m)
K	Absolute difference in gradient between upstream and downstream reach for $d/2 = 100$ (m/m)
L	Ratio of lower reach gradient to upper reach gradient for $d/2 = 100$ (dimensionless)
M	Gradient at point for $d = 300$ (upstream $d/2 = 150$, downstream $d/2 = 150$) (m/m)
N	Gradient of downstream reach $d/2_d = 150$ (m/m)
O	Absolute difference in gradient between upstream and downstream reach for $d/2 = 150$ (m/m)
P	Ratio of lower reach gradient to upper reach gradient for $d/2 = 150$ (dimensionless)
...	(d increment of 100 continues until reaching $d = 1000$)
AO	Gradient at point for $d = 1000$ (upstream $d/2 = 500$, downstream $d/2 = 500$) (m/ m)
AP	Gradient of downstream reach $d/2_d = 500$ (m/m)
AQ	Absolute difference in gradient between upstream and downstream reach for $d/2 = 500$ (m/m)
AR	Ratio of lower reach gradient to upper reach gradient for $d/2 = 500$ (dimensionless)
AS	Gradient at point for $d = 2000$ (upstream $d/2 = 1000$, downstream $d/2 = 1000$) (m/ m)
AT	Gradient of downstream reach $d/2_d = 1000$ (m/m)
AU	Absolute difference in gradient between upstream and downstream reach for $d/2 = 1000$ (m/m)
AV	Ratio of lower reach gradient to upper reach gradient for $d/2 = 1000$ (dimensionless)
...	(d increment of 1000 continues until reaching $d = 10,000$)
BY	Gradient at point for $d = 10,000$ (upstream $d/2 = 5000$, downstream $d/2 = 5000$) (m/ m)
BZ	Gradient of downstream reach $d/2_d = 5000$ (m/m)

Table 2: Column header descriptions for Microsoft Excel computational spreadsheet. These include data for stream distance, horizontal distance, elevation, and related data for each 1 m interval of stream length (A through H), and gradient computations for each measurement distance (I through EV). One spreadsheet row was generated for each m of stream length.

(continued next page)

Column	Value
CA	Absolute difference in gradient between upstream and downstream reach for $d/2 = 5000$ (m/m)
CB	Ratio of lower reach gradient to upper reach gradient for $d/2 = 5000$ (dimensionless)
CC	Gradient at point for $d = 12,000$ (upstream $d/2 = 6000$, downstream $d/2 = 6000$) (m/ m)
CD	Gradient of downstream reach $d/2_d = 6000$ (m/m)
CE	Absolute difference in gradient between upstream and downstream reach for $d/2 = 6000$ (m/m)
CF	Ratio of lower reach gradient to upper reach gradient for $d/2 = 6000$ (dimensionless)
...	(d increment of 2000 continues until reaching $d = 20,000$)
CS	Gradient at point for $d = 20,000$ (upstream $d/2 = 10,000$, downstream $d/2 = 10,000$) (m/ m)
CT	Gradient of downstream reach $d/2_d = 10,000$ (m/m)
CU	Absolute difference in gradient between upstream and downstream reach for $d/2 = 10,000$ (m/m)
CV	Ratio of lower reach gradient to upper reach gradient for $d/2 = 10,000$ (dimensionless)
CW	Gradient at point for $d = 24,000$ (upstream $d/2 = 12,000$, downstream $d/2 = 12,000$) (m/ m)
CX	Gradient of downstream reach $d/2_d = 12,000$ (m/m)
CY	Absolute difference in gradient between upstream and downstream reach for $d/2 = 12,000$ (m/m)
CZ	Ratio of lower reach gradient to upper reach gradient for $d/2 = 12,000$ (dimensionless)
...	(d increment of 4000 continues until reaching $d = 72,000$)
ES	Gradient at point for $d = 72,000$ (upstream $d/2 = 36,000$, downstream $d/2 = 36,000$) (m/ m)
ET	Gradient of downstream reach $d/2_d = 36,000$ (m/m)
EU	Absolute difference in gradient between upstream and downstream reach for $d/2 = 36,000$ (m/m)
EV	Ratio of lower reach gradient to upper reach gradient for $d/2 = 36,000$ (dimensionless)

Table 2, continued from previous page.

Finally, the elevation of each row was adjusted to decrease by a miniscule amount (.00001 m) if its value was the same as the previous row to avoid a “divide by zero” error in comparison of downstream and upstream gradients, such as when the upstream gradient was comprised entirely of a pool with no appreciable change in elevation.

Columns were then added for each row to calculate normalized horizontal distance (percent distance from headwater to mouth) and normalized elevation (percent elevation change from highest to lowest elevation within the watershed). Additional columns were used to compute gradient-related values for every row, including calculations for: (1) gradient over the given measurement distance (d) determined by dividing difference in elevation from $d/2$ upstream to $d/2$ downstream; (2) gradient of the lower reach, i.e., from the point of measurement to $d/2$ downstream; (3) the absolute difference in gradient between downstream reach and upstream reach; (4) the ratio of the downstream reach gradient to the upstream reach gradient. Importantly, instead of computing gradient at fixed intervals along the streams, gradient was computed at every meter along the length of the stream.

Because, in general, shorter streams have higher gradients and longer streams have lower gradients, the measurement distance (d) used to compute gradient was increased incrementally as watershed size increased (Table 3). The increment was 100 m between $d = 200$ m and $d = 1000$ m. Increments of 1000 m were used between $d = 1000$ m and 10,000 m. Increments of 2000 m were used between $d = 10,000$ and 20,000 m. Finally, increments of 4000 m were used between $d = 20,000$ m and 72,000 m, the highest measurement distance used in determining gradient. For each measurement distance (d), the relevant values for determining knickzones involved a comparison of downstream reach ($d/2_d$) and the upstream reach ($d/2_u$).

<i>d</i>	LoR	TmR	FpR	PuR	LtR	EhR	LWC	SR	MpC	SMR	MgC
200	M	M	M	M	M	M					
300	M	M	M	M	M	M					
400	M	M	M	M	M	M	M	M	M		
500	M	M	M	M	M	M	M	M	M	M	M
600	M	M	M	M	M	M	M	M	M	M	M
700	M	M	M	M	M	M	M	M	M	M	M
800	M	M	M	M	M	M	M	M	M	M	M
900	M	M	M	M	M	M	M	M	M	M	M
1000	K	K	K	K	K	K	M	M	M	M	M
2000	K	K	K	K	K	K	K	M	M	M	M
3000	x	K	K	K	K	K	K	K	K	M	M
4000	x	K	K	K	(k)	K	K	K	K	K	M
5000	x	K	K	K	(k)	K	K	x	K	K	K
6000	x	K	K	K	(k)	K	K	x	K	K	K
7000	x	(k)	K	K	x	K	K	x	K	K	K
8000	x	x	(k)	K	x	K	K	x	K	K	K
9000		x	x	K	x	K	K	x	K	K	K
10000				K	x	K	K	x	K	K	K
12000									K	K	K
14000										x	K
16000										x	K
18000										x	(k)
20000											(k)
24000											
28000											
32000											
36000											
40000											
44000											
48000											
52000											
56000											

Table 3. Measurement distances used to identify knickzones in study streams. Stream abbreviations are given Table 1. Explanation of table symbols:

K = knickzone extents exist with at least one row above thresholds of slope $\geq .001$ and ratio value ≥ 1.20

(k) = knickzone extents exist but all rows are below thresholds of slope $\geq .001$ and ratio ≥ 1.20

x = knickzone extents were searched for, but do not exist at this measurement distance

M = knickzone extents exist with at least one row above thresholds of slope $\geq .001$ and ratio value ≥ 1.20 , but measurement distance is too short to reveal meaningful results; none of this data appears in profiles, maps, or charts

empty cell = for lower *d*, upstream reach gradient is near 0, skewing ratio of downstream to upstream gradients; for upper *d*, stream length does not allow for a comparison of reaches *d*/2 in length

(continued next page)

d	PIR	MdC	MR	PeC	WC	PiC	NTM	RC	STM	D	CC
200											
300											
400											
500											
600	M										
700	M										
800	M										
900	M	M	M	M							
1000	M	M	M	M							
2000	M	M	M	M	M	M					
3000	M	M	M	M	M	M					
4000	M	M	M	M	M	M					M
5000	M	M	M	M	M	M					M
6000	K	M	M	M	M	M					M
7000	K	M	K	K	M	M	M	M	M	M	M
8000	K	K	K	K	M	M	M	M	M	M	M
9000	K	K	K	K	K	K	M	M	M	M	M
10000	K	K	K	K	K	K	M	M	M	M	M
12000	K	K	K	K	K	K	M	M	M	M	M
14000	K	K	K	K	K	K	M	M	M	M	M
16000	K	K	K	K	K	K	M	M	M	M	M
18000	K	K	K	(k)	K	K	K	M	M	M	M
20000	(k)	K	(k)	(k)	K	K	K	K	M	K	M
24000	x	K	(k)	x	K	K	K	K	K	K	M
28000		K	x	x	K	K	K	K	K	K	M
32000		K	x	x	K	K	K	K	K	K	M
36000					K	K	K	K	K	K	M
40000					K	K	K	K	K	K	K
44000					K	x	K	K	K	K	K
48000							K	(k)	K	K	K
52000							K	(k)	K	K	K
56000							K	(k)	K	K	K
60000							(k)	(k)	(k)	K	K
64000							x	x	x	x	x
68000										x	x
72000										x	x

Table 3, continued from previous page.

The last record for each stream is at its confluence with the Monongahela or Ohio River, which necessarily serves as base level because locks and dams on the main trunk rivers obscure pre-industrial river elevations. Rather than truncating the process at $d/2$ from the mouth of each

stream, I virtually extended the length of the streams in the spreadsheets by 50% beyond their mouth with the elevation value of each row decreasing by 0.00001 m, a rough approximation of modern navigational pool gradients. This artificial extension allowed knickzones to be identified closer to the mouths of the streams than would be possible if the knickzone calculations had to end at $d/2$ upstream of the mouth. However, it must be noted that the nearly-flat elevation of the virtual main trunk, as well as the lowest reaches of some streams due to backwater from the main trunk pool, eventually causes the downstream reach gradient to become concave, i.e., not a knickzone, while in actuality, the stream profile might continue its convex shape closer to the mouth of the stream or even to the main trunk itself (Appendix 1.d).

Unlike other studies where gradient was “sampled” at established increments of stream length, these results show that there were long sections of stream where, at each meter of stream length, the downstream reach’s gradient was greater than the upstream reach’s gradient (Appendix 1.e). These consecutive rows, termed “knickzone extents,” are the features represented visually, both in profile and map planform views.

Knickzone extents were numerous, but often with extremely small downstream to upstream ratios that reflected the “bumpiness” of the profiles and noise in the data. It was necessary to establish a threshold below which the knickzone extents would be excluded from the primary analysis. Knickzone extents at applicable measurement distances were each scanned to find the point with the highest ratio value between downstream and upstream gradients, or points of maximum difference (PMD). Values ≥ 1.20 (hereafter, written simply as 1.2) for these PMD were one part of the threshold determining whether the knickzone extent would be included on profile and map visualizations of the streams (Appendix 1.f, 1.g). The other threshold component was a downstream reach absolute gradient value $\geq .001$. This approach

was fundamentally different from Hayakawa and Oguchi (2006, 2009), which used the standard deviation of the relative steepness of local to trend gradients (R_d) to arrive at an objective threshold value for knickzone determination.

I created a new Excel sheet for each measurement distance into which I recorded the data for each knickzone extent: (1) from- and to- stream distance, (2) from- and to- horizontal distance, (3) from- and to- normalized horizontal distance, (4) from- and to- elevation, (5) from- and to- normalized elevation, and the (6) stream distance, (7) horizontal distance, (8) normalized distance, (9) elevation, and (10) normalized elevation values at the PMD of each knickzone extent, plus the (11) absolute gradient and (12) gradient ratio at the PMD. At longer measurement distances, there were fewer knickzone extents. As measurement distances became shorter, the number of knickzone extents increased, until at very short distances (less than 1000 m for small watershed streams) there were so many as to become “noise” in the data, i.e., small lithologic knickpoints, sediment bars, human infrastructure, and remnants of the ArcGIS Fill process. Consequently, knickzones extents were excluded for measurement distances less than 1000 m for small (8-32 km²) watersheds, less than 10,000 m for medium (32-256 km²) watersheds, and less than 20,000 for large (>256 km²) watersheds.

Knickzone extents at all applicable measurement distances were charted for each stream in planform and profile views by using the ArcGIS tool “Generate Points” to create numbered vertices along the stream line that corresponded to the to- and from- horizontal distance for each knickzone extent (Appendix 1.h).

Chapter 4: Results

The study area was delimited as left-bank (facing downstream) tributaries of the Monongahela and Ohio rivers between the West Virginia state line on Pennsylvania's southern border and a major drainage divide near the West Virginia border in the west, encompassing parts of Greene, Washington, Allegheny, and Beaver counties. The two combined rivers have 198 km (123 mi) of stream length within the study area (Figure 1), entirely within previously delineated boundaries of Lake Monongahela. LiDAR-based DEMs with nominal 1 m horizontal resolution derived from PAMAP LiDAR missions in 2006 were available for the entire study area.

Thirty-four streams were identified in the study area using StreamStats online tools (U.S. Geological Survey, 2016). Only 22 streams with drainage area of 8 km² and greater, up to the largest watershed of 715 km² (276 mi²) were used (Figure 8). The presence of terrace remnants in these watersheds was an indicator that the channel had incised and abandoned its former floodplain, a possible indicator of disequilibrium steepening and channel evolution going back to the middle Pleistocene. Streams smaller than 8 km² drainage area were excluded because visual inspection on topographic maps revealed no terrace remnants to suggest disequilibrium steepening. Moreover, anthropogenic alteration of the landscape has had a disproportionately large impact on smaller areas, making data derived from these streams unreliable.

Profiles of all 22 tributary streams were created and analyzed for knickzones. The investigator hypothesized that drainage area, location along the main trunk, and geologic substrate could each have something to do with where knickzones appear in the tributaries. Geologic substrate and location turned out to be related, with older bedrock along the valley

bottom in the downstream direction, except for the except for the uppermost 13 km of the middle Monongahela reach.

Figure 8. Streams in study area, grouped by drainage area. See Figure 1 for stream locations.

The results were then compared across the study area according to the location of their confluence with the main trunk rivers, as well as their drainage area and measurement distance used for analysis, in order to identify similarities in landscape evolution and provide more evidence of fluvial changes connected to the rearrangement of continental drainage.

Sorted by drainage area, streams could be conveniently grouped according to powers of 2 (2^n) (Figure 8). Five streams drain greater than $256 (2^8) \text{ km}^2$, the smallest of which is more than twice the size of the sixth largest watershed. Eight streams drain between $32 (2^5)$ and $256 (2^8) \text{ km}^2$, the smallest of which is nearly twice the size of the next largest watershed flowing directly into the Monongahela. Nine streams with evidence of terraces fall between $8 (2^3)$ and $32 (2^5) \text{ km}^2$. The five largest watersheds all have sub-tributaries greater than $32 (2^5) \text{ km}^2$ with their own well-developed floodplains and terraces. Although large sub-tributaries were not analyzed in the present study, they are fruitful territory for future research.

Among the five largest watersheds, North Fork Ten Mile Creek and South Fork Ten Mile Creek were counted separately because the confluence of these two forks to form Tenmile Creek is only 5 km upstream of its confluence with the Monongahela River, a planform unlike any other in the study area. More importantly, the Carmichaels Formation (Jacobson et al., 1988) forms an arc suggestive of a paleo-channel diverging from the Monongahela River upstream of the Tenmile confluence and returning to the Monongahela through the lower reaches of Tenmile Creek (Figure 9). If South Fork Tenmile Creek and North Fork Tenmile Creek emptied independently into the paleo Pittsburgh River, their knickzone development would also have been independent of each other.

Figure 9. Map of Carmichaels Formation in the vicinity of Tenmile Creek, southwestern PA. The Carmichaels Formation provides evidence that lower reaches of Tenmile Creek were part of a large paleo-meander of the ancient Pittsburgh River. Image was compiled from parts of the geologic maps of Mather Quadrangle (Kent, 1969b) (left) and Carmichaels Quadrangle, (Kent, 1969a) (right).

Bedrock in the region is generally horizontal or gently folded, interbedded sandstone, limestone, shale, coal, mudstone, and claystone, of varying thickness and erodibility. Streams in the study area traverse lithologies ranging (top to bottom) from the Washington and Waynesburg formations of the Dunkard Group, the Uniontown and Pittsburgh formations of the Monongahela

Group, the Casselman and Glenshaw formations of the Conemaugh Group, and the Allegheny Formation. Detailed geologic maps of many of the watersheds were available to help identify bedrock units (Berryhill, 1964a, 1964b; Berryhill and Schweinfurth, 1964; Swanson and Berryhill, 1964; Kent, 1967; Schweinfurth, 1967; Roen et al., 1968; Kent, 1969a, 1969b; Roen et al., 1968; Roen, 1970; Kent, 1971; Roen, 1972; Roen, 1973; Kohl and Briggs, 1975; Wagner, et al., 1975).

Moving from downstream to upstream in the study area, the lower reaches of Raccoon Creek, Elkhorn Run, and Logtown Run are underlain by bedrock of the Allegheny Formation, resistant to erosion because of its 48% sandstone content (Macrostat, 2020). Montour Run is underlain mostly by the relatively resistant limestone (39%) bedrock substrate of the Glenshaw Formation (Macrostat, 2020). Chartiers Creek, Saw Mill Run, and Streets Run have Glenshaw Formation bedrock in their lower reaches, and much less resistant Casselman Formation in their mid- and upper reaches, including about 45% claystone red beds (Macrostat, 2020). Peters Creek, Lobbs Run, Maple Creek, and Pike Run are underlain by the Casselman Formation for most of their length, while a syncline puts the intervening Mingo Creek and Pigeon Creek channels mostly into the overlying Monongahela Group, containing some 34% resistant strata of limestone and sandstone (Roen et al., 1968; Macrostat, 2020). The remainder of study streams, from Two Mile Run upstream to Dunkard Creek, have bedrock of the Monongahela Group (Macrostat, 2020), except for the lowest 5-10 km of Dunkard Creek, which is in the Casselman Formation (Kent, 1973; Macrostat, 2020).

Land use is generally rural, except for watersheds in Pittsburgh and its suburbs (Table 1). Of the five largest streams, four are less than 10% urbanized (U.S. Geological Survey, 2016). Chartiers Creek, at 29% urban, had the most potential for anthropogenic masking of natural

stream features, and its profile must be interpreted with these alterations in mind. Six of the 17 mid-size and small watersheds were urbanized to some degree. However, only one watershed, Streets Run, was so altered as to require its omission from comparison with other streams. Its profile and planform map are included among the collection of all stream profiles and maps in Appendix 2.

As discussed in the Introduction, regional land cover and precipitation during the glacial periods would have been different from current conditions, generating different stream flow, erosion, and sediment transport. It was assumed for the purpose of this study that the difference in these two variables between northern and southern portions of the study area was small and therefore was not factored into my analysis (Table 1). However, a large area of the ice sheet to the north may have released meltwater, sediment, or even cataclysmic jökulhlaups into the proto-Allegheny River, resulting in a different gradient profile in the upper Ohio River reach of the study area.

Glacial isostatic depression, attendant forebulge, and post-glacial rebound were recognized as important factors in knickzone genesis and distribution, and may have been critical in the successful breach and incision of the New Martinsville, West Virginia, and Midland, Pennsylvania, cols instead of the Salem, West Virginia, col (Kite, personal communication, 2020). Tills dated to Wisconsinan, Illinoian, and pre-Illinoian glaciations suggest that the glacial margin in each of these cycles was oriented northeast-southwest, with the mass of the lobe of the ice sheet to the north-northwest (Shepps, et al., 1959; Sevon, et al., 1999). The literature suggests that at its most recent glacial maximum, the northern- and westernmost part of the study area would have been within 25 km (15 mi) of the terminus of the Late Wisconsinan Laurentide ice sheet (Shepps et al., 1959; Sevon et al., 1999). The pre-Illinoian terminus is thought to have been

as far south as the bend in the modern Ohio River (Sevon et al., 1999) and, using research from eastern Pennsylvania and New England as analogs (Reusser et al., 2006; Hooke and Ridge, 2016), an attendant forebulge would have been approximately 150-165 km south-east of the margin at its glacial maximum. The controlling northward-trending main stem of the Pittsburgh River likely would have been in an area steepened by isostatic depression, possibly lowered as much as 56 m from today's elevation at the Illinoian ice margin, assuming that Late Wisconsin Glacial Lake Hitchcock lake levels in New England were analogous to a much older Lake Monongahela (Hooke and Ridge, 2016; Kite, personal communication, 2020). However, during one or more of the glacial cycles, the area is known to have been inundated by Lake Monongahela, prior to major stream incision. During and after glacial retreat and before crust fully rebounded is posited here as the best estimate for the timing of channel incision and terrace abandonment. Although only 1 to 5 of the twenty-two streams used in comparisons were oriented in the north-south direction most susceptible to significant gradient changes related to isostasy, the incision wave begun on the main stem would have worked its way up these stream valleys.

A preliminary analysis of long profiles was accomplished by creating log-log plots using the distance-slope (DS) method developed by Goldrick and Bishop (2007) (Figure 10, 11, Appendix 4). The measure is designed to reveal when a profile deviates from the graded form, which appears as a straight line, and whether the deviation is caused by lithology or disequilibrium steepening. The logarithmic curves, however, do not reveal the specific morphological characteristics of knickzones.

Figure 10. DS Plot (after Goldrick and Bishop, 2007) for South Fork Tenmile Creek, $d = 7000$

Figure 11. DS Plot (after Goldrick and Bishop, 2007) for Mingo Creek, $d = 1000$

In every study stream, the results of a meter by meter comparison of downstream gradient to upstream gradient at all measurement distances revealed a significant pattern. Unlike other studies where gradient was “sampled” at established intervals or steps through the stream, these results show that there were long sections of stream where at every consecutive point, the downstream reach’s gradient was greater than the upstream reach’s gradient. These consecutive rows that I call a “knickzone extent” are the features represented visually, both in profile and map planform views (Figures 12-19, Appendix 2). Although this method does not conform to prior research methodology, it has the advantage of revealing broader and continuous trends in the profile.

Figures 12, 14, 16, 18 contain profiles of three illustrative streams, representing a large-, middle-, and small-sized drainage area, plus one outlier. Each profile x-axis is scaled to include the full length of the given stream. Each y-axis is scaled to show the entire elevation change from headwater to mouth of the given stream. Vertical exaggerations, not standardized across charts, are extreme in every case, as one might expect when the range of the y-axis is approximately 120 m (400 ft) but the x-axis range is anywhere from 8000 m to 80,000 m. The extreme vertical exaggeration allows the reader to see convexities in the profiles that are otherwise nearly invisible. Illustrated underneath each profile (black line), knickzone extents at the longest measurement distances used to calculate gradient are represented by the widest swaths of color and are overlain by narrower swaths representing shorter measurement distances. To discern the area covered by the longest measurement distance knickzone extents, one must look for their representative color along the edges of the color swaths.

Figure 12. North Fork Tenmile Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 13. North Fork Tenmile Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 14. Muddy Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 15. Muddy Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 16. Little Whiteley Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 17. Little Whiteley Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 18. Raccoon Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figure 19. Raccoon Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Figures 13, 15, 17, 19 contain maps of the same watersheds as Figures 12, 14, 16, 18. Each map shows the planform view of the study stream, as well as the network of tributaries of that stream. The scale of each map is different, depending on the size of the watershed, and can be discerned by looking at the scale bar. Knickzone extents at all relevant measurement distances are drawn on the maps to show their location within the watershed. Color swaths are used in the same way as the profiles, with swaths representing longer measurement distances partially obscured by swaths representing shorter measurement distances.

Knickzone extents above the established threshold were compared in three ways to look for patterns: (1) by gradient measurement distance, (2) by watershed size—large, middle, and small, and (3) by where they connect with the main trunk in the study area—upper Ohio River, lower Monongahela River, or middle Monongahela (Figures 20 – 26). On these charts, the y-axis represents the absolute elevation, while the x-axis represents the normalized (%) distance from the headwater of the stream. A straight line is drawn between the uppermost point to the lowest point of each knickzone extent. A trendline is included that represents all the data in each chart. Figures 27 and 28 combine the trendlines for where they connect with the main trunk and the trendlines for watershed size, respectively.

Figure 20. Knickzone extent graphical comparison chart for $d = 6000$ m. Streams with knickzone extents above the ratio and downstream gradient threshold include Elkhorn Run, Saw Mill Run, Mingo Creek, Maple Creek, Pike Run, Two Mile Run, Fishpot Run, Pumpkin Run, and Little Whiteley Creek.

Figure 21. Knickzone extent comparison of elevation ranges for large drainage area streams, including Raccoon Creek, Chartiers Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, and Dunkard Creek.

Figure 22. Knickzone extent comparison of elevation ranges for midsize drainage area streams, including Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Pigeon Creek, Pike Run, Muddy Creek, and Whiteley Creek.

Figure 23. Knickzone extent comparison of elevation ranges for midsize drainage area streams, including Elkhorn Run, Logtown Run, Streets Run, Lobbs Run, Maple Creek, Two Mile Run, Fishpot Run, Pumpkin Run, and Little Whiteley Creek.

Figure 24. Knickzone extent comparison of elevation ranges for upper Ohio River streams, including Raccoon Creek, Elkhorn Run, Logtown Run, Montour Run, Chartiers Creek, and Saw Mill Run.

Figure 25. Knickzone extent comparison of elevation ranges for lower Monongahela streams, including Peters Creek, Lobbs Run, Mingo Creek, Pigeon Creek, Maple Creek, Pike Run, Two Mile Run, and Fishpot Run.

Figure 26. Knickzone extent comparison of elevation ranges for upper Monongahela streams, including North Fork Tenmile Creek, South Fork Tenmile Creek, Pumpkin Run, Muddy Creek, Little Whiteley Creek, Whiteley Creek, and Dunkard Creek.

Figure 27. Knickzone extent elevation range trendlines by drainage area. Large and medium size watersheds have similar elevation ranges, suggesting the size of the watershed does not control knickzone migration rates. One outlier knickzone in one small watershed extent the small watershed trendline to a higher elevation.

Figure 28. Knickzone extent elevation range trendlines by location of confluence with the Ohio-Monongahela. The farther upstream on the Ohio-Monongahela, the higher the elevation ranges of knickzones in tributaries, suggesting a connection to Monongahela terrace elevations. (One outlier knickzone in one lower Monongahela stream causes the trendlines for middle and upper Monongahela to cross.)

Table 4 shows the correlation coefficient (r^2) values when comparing streams at each measurement distance for the purpose of revealing whether incision waves display periodicity. The specific streams included can be found in Table 3. Analysis included 36 measurement distances. One is presented here as a sample (Figure 20); the rest are included in Appendix 3.

Measurement Distance	Number of Streams Analyzed at this Measurement Distance	Correlation (r^2) of relative location of upper and lower bounds of all knickzone extents at given d
$d = 60,000$	2	.97
$d = 56,000$	4	.77
$d = 52,000$	3	.97
$d = 48,000$	4	.81
$d = 44,000$	6	.64
$d = 40,000$	6	.69
$d = 36,000$	6	.71
$d = 32,000$	7	.70
$d = 28,000$	7	.75
$d = 24,000$	7	.79
$d = 20,000$	6	.76
$d = 18,000$	6	.73
$d = 16,000$	8	.73
$d = 14,000$	7	.69
$d = 12,000$	10	.67
$d = 10,000$	12	.71
$d = 9000$	12	.65
$d = 8000$	10	.71
$d = 7000$	10	.78
$d = 6000$	9	.87
$d = 5000$	8	.86
$d = 4000$	7	.87
$d = 3000$	8	.88
$d = 2000$	7	.74
$d = 1000$	6	.89
	Mean 7.2	Mean = .77

Table 4. Statistical correlation of knickzone extents for study-area streams, sorted by measurement length used to calculate gradient. For specific streams analyzed at each d , see Table 3. Regression analysis was conducted on the relative point locations (x = normalized horizontal distance from stream mouth, y = normalized elevation) of the upper and lower bounds of all stream knickzone extents appearing at each measurement distance. Charts at each distance can be found in Appendix 3 and a sample is provided in Figure 20.

Table 5 shows the correlation coefficient (r^2) when streams are compared by similar drainage areas (Figures 21-23, 27), with area ranges as described at the beginning of this chapter and in Figure 7, for the purpose of determining whether knickzone migration rates are similar or different based on stream discharge (as a proxy for stream power). Data points for all measurement distances are included for each stream on their respective charts.

Watershed Size	Number of Streams Included	Correlation coefficient (r^2) of Knickzone Extent Upper and Lower Bounds
> 256 km ²	5	.80
32 km ² to 256 km ²	8	.68
8 km ² to 32 km ²	8	.83

Table 5: Statistical correlation of knickzone extents at all gradient measurement distances for streams of similar drainage area.

Table 6 shows the correlation coefficient (r^2) when comparing by location within the study area according to their confluence with the main trunk (Figures 24-26, 28).

Confluence Location	Number of Streams Included	Correlation coefficient (r^2) of Knickzone Extent Upper and Lower Bounds
upper Ohio River	6	.95
lower Monongahela River	8	.86
middle Monongahela River	7	.87

Table 6. Statistical correlation of knickzone extents at all gradient measurement distances for streams whose mouths lie the same reach of the main Monongahela-Ohio trunk stream. The upper Monongahela reach is located in West Virginia, beyond the limits of study.

The upper Ohio River tributaries include those downstream of the confluence of the Allegheny and Monongahela rivers at Pittsburgh. This boundary was chosen because Leverett (1934) and Jacobson et al. (1988) posited it as the location of an Illinoian glacial outwash dam formed by sediments brought down the Allegheny River, which may have effectively separated the fluvial evolution below and above that point. The upper Ohio River tributaries includes Raccoon Creek,

Elkhorn Run, Logtown Run, Montour Run, Chartiers Creek, and Saw Mill Run. The lower Monongahela River tributaries include those entering the Monongahela River between Pittsburgh and Tenmile Creek, including Peters Creek, Lobbs Run, Mingo Creek, Pigeon Creek, Maple Creek, Pike Run, Two Mile Run, and Fishpot Run. The middle Monongahela River tributaries include those entering the Monongahela River upstream and inclusive of Tenmile Creek, including North Fork Tenmile Creek, South Fork Tenmile Creek, Pumpkin Run, Muddy Creek, Little Whiteley Creek, Whiteley Creek, and Dunkard Creek. Data points for all measurement distances are included for each stream on their respective charts.

Chapter 5: Discussion

The profiles of streams in the study area display complex and chaotic combinations of knickzones and knickpoints traditionally conceptualized as rapids or waterfalls of varying lengths and heights. Although I expected that small-scale transient features on the landscape would be revealed by shorter reach measurement lengths for calculating gradient, I did not expect small-scale transient features to impact gradients calculated with longer measurement distances. As it turned out, even for the shortest streams, calculating gradient using < 1000 m distance lengths was unproductive. At $d < 1000$ m, the number of knickzone extents became so numerous it was clear that the many factors identified in the literature review as causes of “equilibrium steepening” were at work, such as sediment fluxes, lithologic changes in bedded bedrock, and manmade structures. It is also likely that knickzone migration is locally “hung up” on resistant rock lithologies, creating frequent small knickpoints that had oversized impact on gradient measurements in otherwise shallow stream reaches. Additionally, some small virtual knickpoints were created by the ArcGIS Spatial Analyst “Fill” procedure used to gain connectivity through the main channel. Errors in the DEM, however, are unlikely to be apparent in the data, because they were manually corrected along the main channel in DEM preparation by the investigator, hence, it is very unlikely that DEM errors account for the inefficacy of measuring gradient at shorter measurement distances.

Although one would not normally consider a change of gradient measured across 1000 m as “abrupt,” the overall gradients of the studied streams are generally so shallow that even a minor break in elevation can have an outsized impact on the gradient value even at longer measurement distances. A “traditional” knickzone or knickpoint gradient, visible as stream features such as rapids and waterfalls, might be measured over tens or, at most, hundreds of

meters in this region. Knickzones indicating regional disequilibrium are not visible as discrete features, but rather are formed from an aggregate of features across long reaches of stream. They required much longer measurement distances for calculating gradient, up to 50% of the length of the streams.

The DS Plots created for South Fork Tenmile Creek ($d = 7000$) (Figure 10) and Mingo Creek ($d = 1000$) (Figure 11) are good examples of a pattern similar to that discussed by Goldrick and Bishop (2007) as indicative of disequilibrium steepening. When the natural log of the stream gradient is plotted against the natural log of the distance, a graded stream should appear as a straight line. Each of these streams matches the expectations of a graded stream downstream to a point. Below that point, a chaotic pattern above and below the expected straight line suggest disequilibrium steepening, as indicated in the figures. The mid-section of the DS Plot for Mingo Creek (Figure 11), however, also resembles what would be expected of a lithologic knickzone, according to the model provided by Goldrick and Bishop (2007), with a roughly linear offset section suggestive of a reach with sustained steeper gradient. Field observations corroborate such an interpretation. Whether lithological or disequilibrium steepening, the overall picture is one of significantly steeper gradients in the lower reaches of streams throughout the study area. Additional DS Plots for streams across the study area can be found in Appendix 4 for comparison.

The profile shapes and knickzone extent arrangement presented in Figures 12, 14, and 16 are representative of what is found across different size watersheds across the study area (Appendix 2). In comparing them, streams exhibit two shared characteristics. First, knickzone extents overlap for applicable measurement distances on reaches with lower reach/upper reach gradient ratios of ≥ 1.2 , and a lower reach gradient of at least 0.001. Their overlapping nature suggests

that although convexities are of different lengths and magnitudes, the aggregate of these convexities, derived from using very long gradient measurement distances, reveal continuous steepening in the area of the profile curve where a graded stream profile would show the opposite: continuous shallowing. Separate smaller convexities can be considered “local ornaments” representing bigger picture processes. At relatively shorter measurement distances where there is more than one knickzone extent, one upstream and one downstream (Figure 12, $d \leq 28,000$ m), the profile could be interpreted as two separate migrating incision waves. In both cases, the higher gradient is the cumulative influence of many short knickzones and low-relief knickpoints.

Second, in Figures 12, 14, and 16, the locations of the knickzone extents are similar within the length of the stream. Some variation does exist among other stream profiles (Appendix 2), perhaps caused by differences in overall lithologic resistance of the different formations in which the channels are situated. For example, in Raccoon Creek (Figure 18), prominent knickzone extents are far downstream. The streambed in that reach lies within the highly resistant Allegheny Formation, which suggests possible lithologic control. An alternative explanation is that Raccoon Creek had a drainage history that differed from other study streams, possibly linked to an abandoned middle Pleistocene outlet, as evidenced by large areas of alluvial Carmichaels Formation deposits across the divide separating Raccoon Creek and Logtown Run (Wagner, 1975). In such a scenario, the lower portion of Raccoon Creek would be an artifact of more recent stream piracy. Two lesser upstream knickzones do fall in elevation and distance ranges comparable to other streams.

The knickzone extents are depicted on the maps of individual watersheds (Figures 13, 15, 17, 19). Muddy Creek (Figure 15) and Little Whiteley Creek (Figure 17), which are located

spatially on either side of a high point in a high level paleo-meander of the Monongahela River, are the only planforms studied where the shape of the watershed itself, a relict of the paleo-meander, is connected to where knickzones appear. Otherwise, the planforms of longest paths have no apparent bearing on the location of knickzone extents within the lengths of the streams, with the possible exception of Raccoon Creek, which itself may be rerouted from a paleo-channel.

Most of the stream profile evidence points to a single disequilibrium-inducing event, posited as the rerouting of paleo-Pittsburgh River to its modern course as the Ohio River. It would seem that even if there were separate disequilibrium inducing events across the Pleistocene, such as an earlier capture of the Steubenville River across the New Martinsville col and a significantly later removal of the Midland col, the geologic complexity of the region obfuscates any attempt to separate out those events based on an analysis the distance their incision waves have moved up through stream systems. What might have begun as a discernable knickpoint or knickzone on the main trunk seems to have either reclined into a much longer and invisible knickzone or been interrupted and foreshortened by significantly harder rock strata.

Elevation tells a different story, however. With the exception of streams at the lower end of the study area that are dominated by the Allegheny and Glenshaw formations, knickzone extents fit remarkably well within the bounds of the Monongahela-Ohio terraces most associated with upper, pre-Illinoian and lower, Illinoian Carmichaels Formation deposits (Jacobson et al., 1988) (Figures 24 – 26, 28) and tied to rerouting of the ancient Pittsburgh River to the present Ohio River course. The correlation (r^2) of the bounds of knickzone extent elevations of streams grouped by the location (Table 6) is remarkably high for geodata. In contrast, there is not as much correlation based on drainage area (Table 5). These results can be interpreted as evidence

that area, as a proxy for stream discharge and erosive force, is not as much a factor as geographic location, a proxy for bedrock geology in the study area. Correlation of knickzone extent bounds based on measurement distance (Table 4) is also not as strong. Only regular frequencies of incision waves in streams across the study area would have caused knickzone extents to correlate based on measurement distance. The complex configuration of each study stream's geographic orientation, planform, and bedrock characteristics, combined with irregular timing of disequilibrium-inducing events, support irregularity rather than regularity in the frequencies of incision waves.

Chapter 6: Conclusion

PAMAP 1 m DEMs with 18-36 cm (8-15 in) vertical resolution accuracy allowed this study to be undertaken in a geographic setting unsuitable for analysis at coarser horizontal and vertical resolution. Spatial analysis using 1 m DEMs was effective in extracting knickzones in relatively shallow stream systems but required delicate and skillful work with the data to get meaningful results. The benefit of using PAMAP's 1 DEM product was diminished because they were not pre-processed, their native unit of measurement was in imperial units, and they were computationally intensive when spatially analyzed with GIS across large areas.

This study identified steeper trend gradients through the identification of "knickzone extents," reaches where, at every meter of stream, a given distance downstream was steeper than the same distance upstream. This method was more useful in the given study area than other methods because other methods were developed to identify visible knickzone and knickpoint features. The visible features in the study area were low relief, nested, and of varying amplitudes, and individually said little about trend gradients. With a careful calibration of threshold values, the methodology revealed broader steepening trends in studied watersheds.

An early hypothesis was that watershed size, as a proxy for discharge, would lead to knickzone being located at proportional distances from the mouths of streams due to knickzone migration, and that distance would provide evidence of time elapsed since initiation of steepening in the main trunk. Evidence presented here suggested lithology was a more likely controlling factor, and that elevation of steepened reaches rather than distance was the key to connecting stream profiles to terraces, and by extension, glacial rerouting of rivers.

The evidence presented in this research supports the conclusion that all tributaries in the region are in a state of disequilibrium and that this disequilibrium is related to the rerouting of a

vast drainage area to the present route of the Ohio River. For much of their headwater reaches, the longitudinal profiles were what one would expect of a graded stream, with a trend of gradients decreasing downstream. Between the elevations of 300 m and 230 m, the streams became increasingly steeper, and correlated well across the study area with terrace elevations on the main trunk rivers (Figure 28).

There are real world consequences for humans and human infrastructure near a channel with increased downstream gradients, especially in modern times when suburban sprawl has resulted in deforestation and large areas paved over with impervious surfaces. Episodes of high precipitation result in rapid run-off and a higher peak in the flood hydrograph of the main channel, a phenomenon known as “flashiness.” As the peak of the flood passes through relatively shallow gradient upper- to mid-reaches of stream, the stream’s stage rises quickly and it escapes its banks, possibly inundating surrounding properties. When the flood wave arrives at the ever-steepening knickzone extent, its velocity increases. In the formula for total stream power, $\Omega = \rho g Q S$, where ρ is the density of water, g is gravitational acceleration, Q is discharge (m^3/s) and S is stream gradient, the combination of increased Q and S dramatically intensify the power the stream has to entrain and transport sediment and erode its banks and bed. Destabilization of stream banks also can destabilize adjacent slopes, causing landslides. Field examinations of streams in the study area reveal plentiful examples of mass wasting that further increase bedload. Given the increased bedload, it seems counterintuitive that one also finds plentiful reaches with bedrock beds. It speaks to just how steep these reaches of stream are, where discharge velocity is enough to regularly scour the bed clean of its sediments.

A pattern of flooding and its effects are borne out by decades of news reports in the region along these tributaries. In some areas, whole neighborhoods are inundated by slowly

rising waters. In other areas, flash floods wash away roads, bridges, and vehicles. Human infrastructure near hillslopes are at risk from mass wasting. As unlikely as it would seem, glacial events of tens and hundreds of thousands of years ago continue have relevance today.

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Appendix 1: Methodological explanatory notes

- a. The DEM was delineated in the imperial unit of ft. Horizontal resolution in the PAMAP DEM product was defined as 3.2 ft and described in documentation as “1 m equivalent” (Pennsylvania Bureau of Geologic Survey, no date, 7), although 1 m is more nearly equal to 3.28084 ft. DEM elevation values were also given in ft. This thesis used the PAMAP nomenclature by referring to the smallest unit of horizontal measurement as 1 m. However, the vertical measurements were converted more accurately and precisely by dividing values by 0.3048.
- b. The largest watershed that could be processed without a computer crash was South Fork Tenmile Creek. In that case, the combined steps for running the hydrology spatial analysis tools required about 48 hours of computation time. In the case of the two largest watersheds in the region, Dunkard Creek and Chartiers Creek, sub-watersheds had to be analyzed, with their data combined at a later stage.
- c. It was decided that a single accumulation value should be used for all drainage areas. The headwater accumulation value of 16,000 m² represents a semi-circle with a radius of approximately 100 m, an area of advective accumulation of water that realistically could incise into the earth’s surface over time, given the average precipitation and slope of headwater areas (Montgomery and Dietrich, 1988). It should be noted, however, that this value was ultimately chosen because it provided an intermediate value between too few network branches in small watersheds and too many network branches in large watersheds. For example, in the large watersheds, smaller accumulation values resulted in drainage ditches appearing as streams and even caused some sections of stream to appear braided. In small watersheds, larger accumulation values left out small ravines.

- d. The extension of stream profiles using a 0.00001 gradient beyond their mouth approximated the modern main-stem gradients in navigational pools under most flow conditions. However, this gradient was too shallow to precisely simulate main stem gradients over the long-term knickzone history. After completing stream analysis, and in the process of writing this thesis, it came to the investigator's attention that gradient on the Ohio River between Midland and Pittsburgh before construction of the navigational lock and dam system was approximately 0.0002, 20 times greater than what was used in gradient calculations in the spreadsheets. Between Pittsburgh and the mouth of Dunkard Creek, the pre-lock and dam gradient was approximately 0.0001, or 10 times greater than what was used in gradient calculations in the spreadsheets. The discrepancy between what was used for calculating knickzone extents and conditions prior to navigational dams could mean that knickzone extents could extend farther downstream than shown. However, it must be kept in mind that the threshold for knickzone extents was a gradient of at least 0.001, five to ten times greater than the gradients of the main trunk rivers. For this reason, the investigator believes correcting the error would not materially alter the results of the study.
- e. If a knickzone was separated from another knickzone by 3 spreadsheet rows or fewer, they were combined into the same knickzone extent. If a knickzone extent was 3 spreadsheet rows or fewer, they were omitted.
- f. Although there were sometimes more than one location in the knickzone extent with approximately the same maximum value, I used the Excel formula "`=Max(...)`" displayed with six decimal places to identify the single greatest value.

- g. Only knickzone extents with a PMD ratio ≥ 1.2 were charted because that threshold was empirically found to exist in the longest knickzone extents which provided the clearest representation of where downstream reaches were steeper than upstream reaches across many measurement distances. However, there are other possible knickzones with less convexity on streams at all measurement distances that fell below threshold criteria.

Figure 29 presents one example of a scatter graph showing the magnitude of PMDs in all knickzone extents as a function of the distance of the PMD from the mouth of the stream.

Figure 29. Mingo Creek: Ratio of distance from mouth for all points of maximum difference (PMD) for all knickzone extents, including those with ratios >1 and <1.2 .

It must be kept in mind that knickzone extents were a wide variety of lengths, yet that length is not represented in the chart symbology. To maintain the appearance of streams flowing from left to right on the graphs, the mouth of the stream remains on the right, but

starts with 0, i.e., the x-axis is reversed. The y-axis is the ratio of lower to upper reach minus 1, in logarithmic format. The ratio threshold used for maps and profiles is shown as a black line across the chart. Many or most of these low ratio PMDs are artifacts of minor manmade or lithologic knickpoints (e.g., Figure 5) that individually represent “noise” in the data.

- h. Dunkard Creek was excluded from the maps because of the complexities of stitching together the separate sub-watersheds along with the knickzone extents.

Appendix 2: Stream profiles and watershed maps not included as figures in Chapter 4, arranged in upstream to downstream order

If inserted in upstream to downstream order, the profiles and maps in Chapter 4 would occur as follows: Little Whiteley Creek (figures 16-17) and Muddy Creek (figures 13-14) would appear after 2.c, North Fork Tenmile Creek (figures 12-13) would appear after 2.g, and Raccoon Creek (figures 18-19) would appear after 2.ii.

There is no knickzone extent watershed map for Dunkard Creek because of the complexities of stitching together the separate sub-watersheds along with the knickzone extents.

- Dunkard Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 . (There is no knickzone extent watershed map for Dunkard Creek.)

- b. Whiteley Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- c. Whiteley Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- d. Pumpkin Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- e. Pumpkin Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- f. South Fork Tenmile Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- g. South Fork Tenmile Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- h. Fishpot Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- i. Fishpot Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- j. Two Mile Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- k. Two Mile Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

1. Pike Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- m. Pike Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- n. Maple Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- o. Maple Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- p. Pigeon Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- q. Pigeon Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- r. Mingo Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .
- s. Mingo Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- t. Lobbs Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- u. Lobbs Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- v. Peters Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u \geq 1.2$).

- w. Peters Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u \geq 1.2$).

- x. Streets Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- y. Streets Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- z. Saw Mill Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

- aa. Saw Mill Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

bb. Chartiers Creek profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

cc. Chartiers Creek watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

dd. Montour Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u \geq 1.2$)

ee. Montour Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u \geq 1.2$).

ff. Logtown Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

gg. Logtown Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

hh. Elkhorn Run profile and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

ii. Logtown Run watershed and knickzone extents with downstream reach ($d/2_d$) gradient $\geq .001$ and ratio of downstream reach to upstream reach ($d/2_d:d/2_u$) ≥ 1.2 .

Appendix 3: Graphical comparisons of knickzones on different streams at each gradient measurement distance

- a. Knickzone Extent Graphical Comparison Chart for $d = 60,000$ m. Of all streams analyzed, only South Fork Tenmile Creek and Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- b. Knickzone Extent Graphical Comparison Chart for $d = 56,000$ m. Of all streams analyzed, only Chartiers Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, and Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds..

- c. Knickzone Extent Graphical Comparison Chart for $d = 52,000$ m. Of all streams analyzed, only North Fork Tenmile Creek, South Fork Tenmile Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- d. Knickzone Extent Graphical Comparison Chart for $d = 48,000$ m. Of all streams analyzed, only Chartiers Creek, South Fork Tenmile Creek, North Fork Tenmile Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- e. Knickzone Extent Graphical Comparison Chart for $d = 44,000$ m. Of all streams analyzed, only Raccoon Creek, Chartiers Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- f. Knickzone Extent Graphical Comparison Chart for $d = 40,000$ m. Of all streams analyzed, only Raccoon Creek, Chartiers Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- g.
- h. Knickzone Extent Graphical Comparison Chart for $d = 40,000$ m. Of all streams analyzed, only Raccoon Creek, Chartiers Creek, Pigeon Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- i. Knickzone Extent Graphical Comparison Chart for $d = 36,000$ m. Of all streams analyzed, only Raccoon Creek, Pigeon Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- j. Knickzone Extent Graphical Comparison Chart for $d = 32,000$ m. Of all streams analyzed, only Raccoon Creek, Pigeon Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Muddy Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- k. Knickzone Extent Graphical Comparison Chart for $d = 28,000$ m. Of all streams analyzed, only Raccoon Creek, Pigeon Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Muddy Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- l. Knickzone Extent Graphical Comparison Chart for $d = 24,000$ m. Of all streams analyzed, only Raccoon Creek, Pigeon Creek, North Fork Tenmile Creek, South Fork Tenmile Creek, Muddy Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- m. Knickzone Extent Graphical Comparison Chart for $d = 20,000$ m. Of all streams analyzed, only Raccoon Creek, Pigeon Creek, North Fork Tenmile Creek, Muddy Creek, Whiteley Creek, Dunkard Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- n. Knickzone Extent Graphical Comparison Chart for $d = 18,000$ m. Of all streams analyzed, only Montour Run, Pigeon Creek, Pike Run, Muddy Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- o. Knickzone Extent Graphical Comparison Chart for $d = 16,000$ m. Of all streams analyzed, only Montour Run, Peters Creek, Mingo Creek, Pigeon Creek, Pike Run, North Fork Tenmile Creek, Muddy Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- p. Knickzone Extent Graphical Comparison Chart for $d = 14,000$ m. Of all streams analyzed, only Montour Run, Peters Creek, Mingo Creek, Pigeon Creek, Pike Run, Muddy Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- q. Knickzone Extent Graphical Comparison Chart for $d = 12,000$ m. Of all streams analyzed, only Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Pigeon Creek, Pike Run, Muddy Creek, Little Whiteley Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- r. Knickzone Extent Graphical Comparison Chart for $d = 10,000$ m. Of all streams analyzed, only Elkhorn Run, Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Pigeon Creek, Maple Creek, Pike Run, Muddy Creek, Little Whiteley Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- s. Knickzone Extent Graphical Comparison Chart for $d = 9000$ m. Of all streams analyzed, only Elkhorn Run, Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Pigeon Creek, Maple Creek, Pike Run, Pumpkin Run, Muddy Creek, Little Whiteley Creek, Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- t. Knickszone Extent Graphical Comparison Chart for $d = 8000$ m. Of all the streams analyzed, only Elkhorn Run, Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Maple Creek, Pike Run, Pumpkin Run, Muddy Creek, Little Whiteley Creek have knickszone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- u. Knickszone Extent Graphical Comparison Chart for $d = 7000$ m. Of all the streams analyzed, only Elkhorn Run, Montour Run, Saw Mill Run, Peters Creek, Mingo Creek, Maple Creek, Pike Run, Fishpot Run, Pumpkin Run, Little Whiteley Creek have knickszone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- v. (Knickzone Extent Graphical Comparison Chart for $d = 6000$ m is Figure 18.) Knickzone Extent Graphical Comparison Chart for $d = 5000$ m. Of all streams analyzed, only Elkhorn Run, Saw Mill Run, Mingo Creek, Maple Creek, Two Mile Run, Fishpot Run, Pumpkin Run, Little Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- w. Knickzone Extent Graphical Comparison Chart for $d = 4000$ m. Of all streams analyzed, only Elkhorn Run, Saw Mill Run, Maple Creek, Two Mile Run, Fishpot Run, Pumpkin Run, Little Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- x. Knickzone Extent Graphical Comparison Chart for $d = 3000$ m. Of all streams analyzed, only Elkhorn Run, Logtown Run, Maple Creek, Two Mile Run, Fishpot Run, Pumpkin Run, Little Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- y. Knickzone Extent Graphical Comparison Chart for $d = 2000$ m. Of all streams analyzed, only Elkhorn Run, Logtown Run, Lobbs Run, Two Mile Run, Fishpot Run, Pumpkin Run, Little Whiteley Creek have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

- z. Knickzone Extent Graphical Comparison Chart for $d = 1000$ m. Of all streams analyzed, only Elkhorn Run, Logtown Run, Lobbs Run, Two Mile Run, Fishpot Run, Pumpkin Run have knickzone extents meeting the ≥ 1.2 downstream/upstream gradient ratio and the ≥ 0.001 downstream gradient thresholds.

Appendix 4: Additional DS Plots

- a. DS Plot for Montour Run, $d = 3000$. Shape of plot suggests change in lithology in middle reaches and disequilibrium steepening in lower reaches.

- b. DS Plot for Peters Creek , $d = 3000$. Shape of plot suggests change in lithology in middle reaches and disequilibrium steepening in lower reaches.

- c. DS Plot for Whiteley Creek, $d = 5000$. Shape likely is connected to lower reaches of Whiteley Creek being in a paleo-meander of the Monongahela River.