THE ORIGINS OF RAPIDS IN THE LOWER NEW RIVER GORGE, WEST VIRGINIA

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ABSTRACT

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Rapids occur where supercritical flow conditions are present (Kieffer, 1985). Supercritical flow, resulting from a local decrease in stream depth or acceleration in flow, is commonly produced where voluminous surficial deposits or bedrock outcrops constrict the stream channel. Mapping at 1:10,000-scale shows that most rapids in the lower New River Gorge, are a result of surficial deposits, including valley-wall mass movement, tributary debris fans, and alluvium. Few rapids occur at bedrock outcrops.

Half of the rapids are predominantly the result of valley-wall mass movement, including debris flow, rock fall, and debris slide/complex failures. Tributary debris-fan deposits, derived from debris flows along tributary streams, are responsible for five rapids. Bedrock outcrops account for four of the 22 rapids. Alluvial debris bars cause the remaining two rapids.

The distribution of rapids in the lower New River Gorge is comparable to those in other canyons. The Grand Canyon and the lower New River Gorge both reflect the importance of mass-movement deposits in the formation of rapids. However, most rapids in the Grand Canyon are located at tributary debris fans. In contrast, rapids in the lower New River Gorge are located at local mass-movement deposits.

The origin of rapids does not appear to correlate with the difficulty rating. This lack of correlation is most likely a result of the subjective nature of the difficulty class rating.

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Introduction

The New River flows northward through the generally flat-lying Mississippian- and Pennsylvanian-age rocks of the Appalachian Plateau physiographic province in south-central West Virginia. Incision by the New River has formed a deeply dissected landscape known as the New River Gorge. The lower portion of the New River Gorge, between Thurmond and Fayetteville, is home to some of the most challenging whitewater in the country. The origin of the lower New River Gorge rapids has been generalized as primarily a result of the local topography and underlying geology promoting abundant mass-movement phenomena. According to Mills (1990), most rapids in the gorge appear to result from mass movement along the valley walls. In the lower gorge, valley-wall slope and river gradient steepen, and the valley narrows where the New River passes through the resistant New River Formation. These factors result in numerous slope failures that deliver large amounts of quartz conglomeratic sandstone to the river channel. The mass-movement deposits commonly constrict the New River, producing supercritical flow, hence rapids, as the river attempts to adjust to constricting and shallowing conditions within the channel (Mills, 1990).

The general concept of mass-movement-derived rapids, coupled with the presence of a spectacular gorge that exposes up to 490 m of sedimentary rocks, suggests similarity between the lower New River Gorge and other canyon rivers, such as the Grand Canyon. Similar to the Grand Canyon, the bedrock underlying the lower New River Gorge and the presence of rapids has contributed to the local economy, fueling abundant scenic and recreational opportunities. According to New River Gorge National River visitation statistics, 1,240,037 people visited the gorge in 1997. During commercial rafting season between April and October, the gorge's foremost attraction is its whitewater. This whitewater has earned the New River a reputation as one of the three most popular rafting rivers in the East (Armstead, 1982). Therefore, investigation into the rapids of the New River Gorge may present a rare opportunity to highlight a positive outcome of slope instability.

The purpose of this study is to explore the geology resulting in rapids along the New River Gorge National River. A total of 22 rapids, ranging in difficulty class from I through V, between Cunard and Fayette Station, West Virginia, are investigated. The objectives of this study are to: (1) construct a 1:10,000-scale map of near-channel surficial deposits; (2) identify and map the alluvial and colluvial deposits associated with each rapid; (3) use boulder-transport calculations to determine the process that formed tributary-fan deposits associated with major rapids; (4) determine the dominant control on each of the major rapids in the lower New River Gorge; (5) provide a better understanding of the role of mass-movement phenomena in the formation of rapids in the New River Gorge; (6) compare the distribution of rapids along the lower New River Gorge with those of the Grand Canyon and other western river canyons; and (7) test possible correlations between origin and rapid-difficulty rating.

Study Area

Location

This study encompasses an 11 km reach of the New River extending from Cunard to the U.S. Route 19 New River Bridge at Fayette Station (Figure 1). This portion of the New River lies entirely in Fayette County, West Virginia, and within the National Park

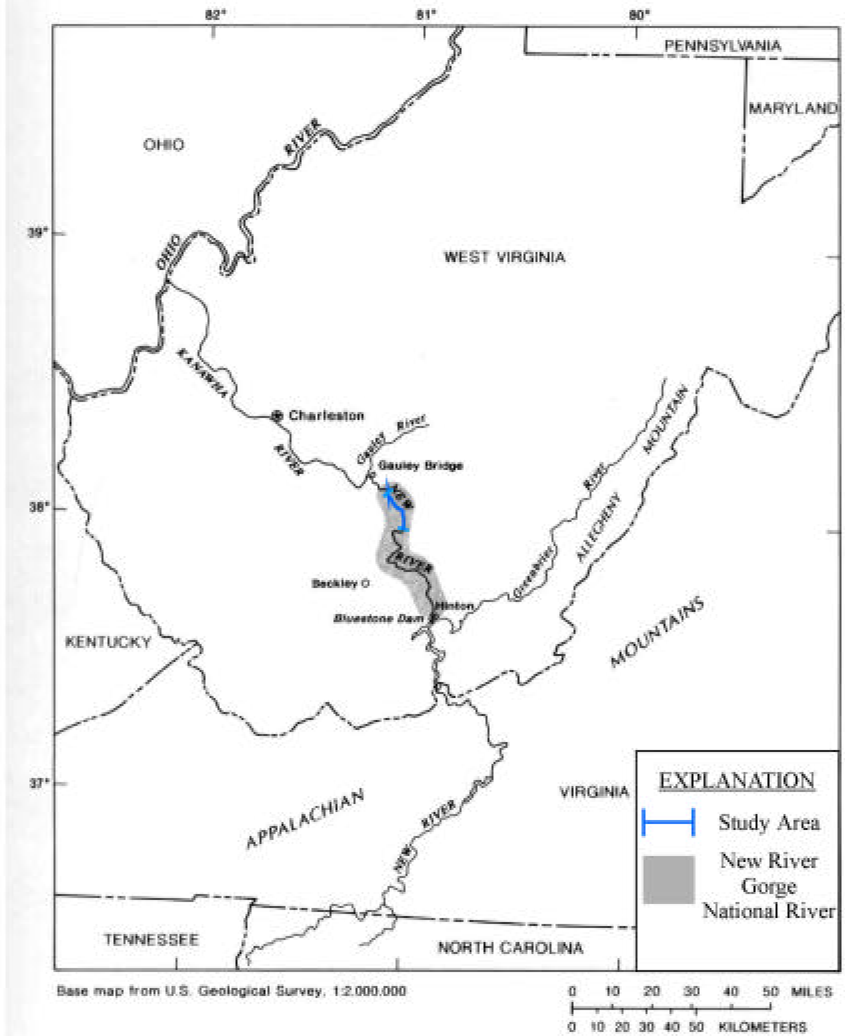


Figure 1: Location of the lower New River Gorge study area. (Modified from Wiley and Cunningham, 1994)

Service lower New River Gorge planning unit. This report herein refers to this area as the lower New River Gorge.

Climate

The New River Gorge has a humid, continental climate (Gorman and Espy, 1975). Annual precipitation averages 127 cm (Gorman and Espy, 1975). Thunderstorms occur 40 to 50 days per year on average, mostly during June and July (Gorman and Espy, 1975). These summer storms are typically limited in extent and produce only local flooding (Summers County Convention and Visitors Bureau, 1998). Heavy rainfall from intense thunderstorms, and rare, large-area, hurricane-related storms can result in flash floods on smaller watersheds and, occasionally, severe floods on the main channel (Gorman and Espy, 1975). Winter climate is mild, although cold waves occur two or three times per year, on average (Gorman and Espy, 1975). Average seasonal snowfall ranges from 76 to 152 cm depending on elevation (Gorman and Espy, 1975). Snowstorms are usually followed by thawing periods, so large-scale spring melts are not a common source of flooding (Gorman and Espy, 1975). However, winter storms often cover the entire drainage basin and can produce the most severe floods (Summers County Convention and Visitors Bureau, 1998).

Structural Geology

The lower New River Gorge is located in the Appalachian Plateau physiographic province, which is characterized by a series of low-amplitude folds (McColloch and others, 1997) (Figure 2). Sedimentary rocks in the study area are nearly horizontal with a regional dip of less than 2 degrees to the northwest (Englund and others, 1977) (Figure 3). The northwest dip increases in magnitude southeasterly to about 5 degrees due to the

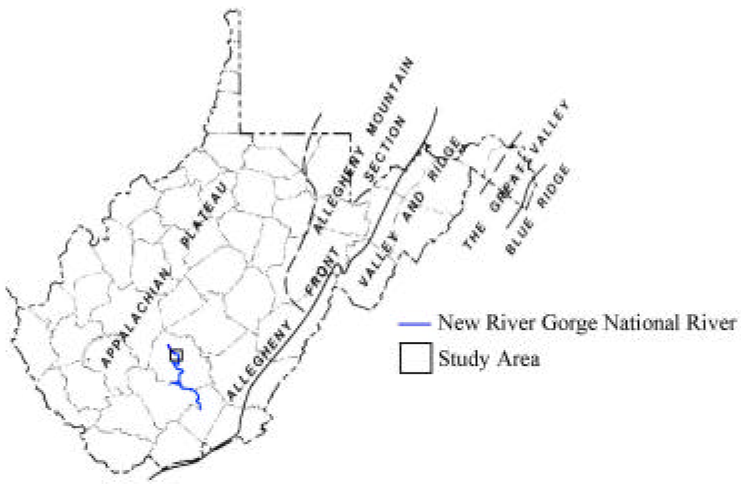


Figure 2: Physiographic provinces of West Virginia. (Modified from West Virginia Geological and Economic Survey, 1969)

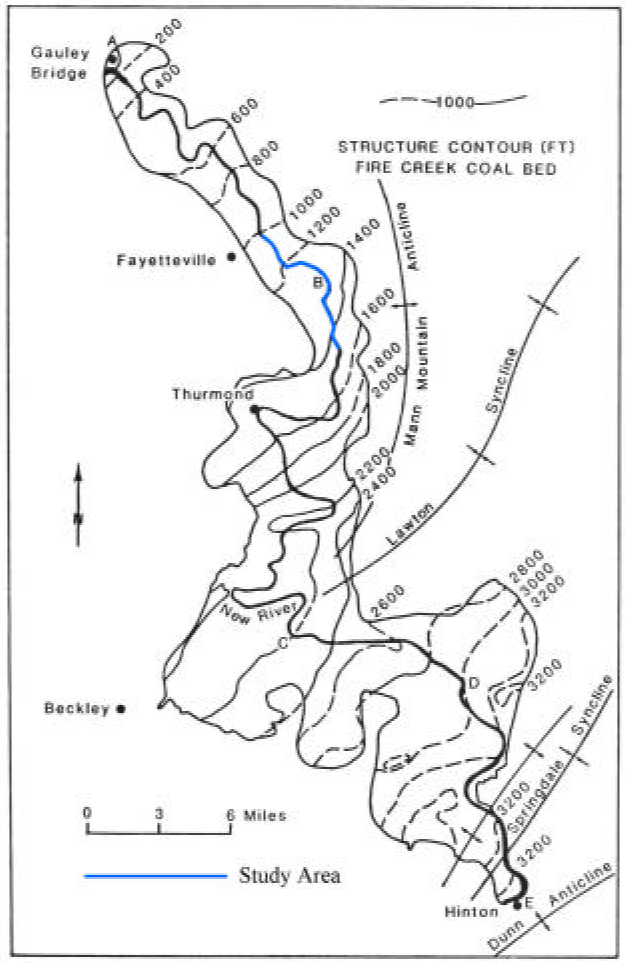


Figure 3: Structure contour map of New River Gorge based on the bottom of the Fire Creek Coal. (Modified from Englund and others, 1982)

proximity of the western limb of the Mann Mountain anticline. Faulting is minimal and has only a minor effect on the topography (Mills, 1990). Jointing is generally widely spaced, trending northwest and northeast (Hennen and others, 1919) with a local influence on topography.

Bedrock Stratigraphy

Three major stratigraphic units occur in the study area (Figure 4). The youngest stratigraphic unit is the Lower Pennsylvanian New River Formation (Figure 5), which generally consists of argillaceous to clean sandstones, siltstones, shales, conglomerates, underclays, and coals (Hennen and others, 1919). Arndt and others (1979) estimated the New River Formation to be 277 m thick in the gorge near Fayetteville. The great cliffs along the valley walls of the New River are formed from the quartz sandstones and conglomerates of the Nuttall, Guyandot, and Raleigh members, which comprise approximately 65 to 75 percent of the New River Formation. The Nuttall Member forms the canyon rim in the northern portion of the study area. The pronounced cliff beneath the rim is formed by the Guyandot Member, which is underlain by the cliff-forming upper and lower Raleigh members (Hennen and others, 1919). The Pineville Sandstone Member, beneath the Raleigh members, also produces a cliff near river level in the southern portion of the study area. The topographic expression of these sandstones varies as they grade laterally from quartzose in the northwest to argillaceous in the southeast (Hennen and others, 1919). The Sewell and Fire Creek coal members of the New River Formation are the only minable coals within the gorge area (McColloch and others, 1997).

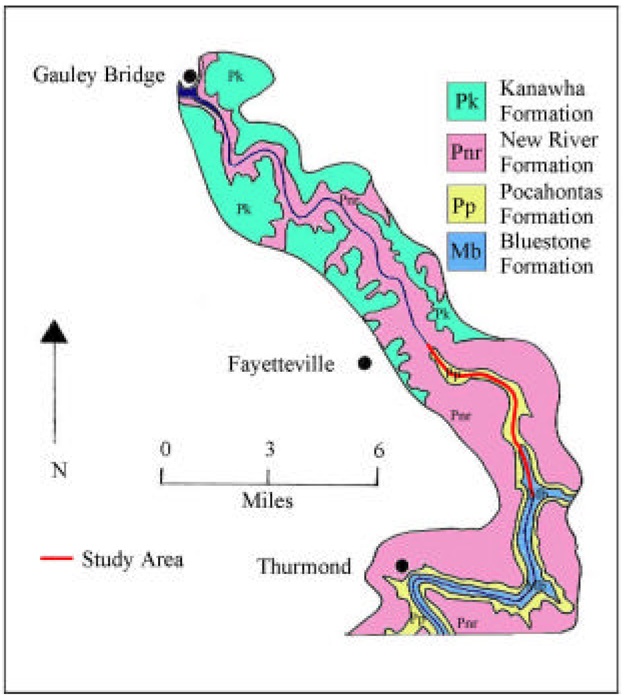


Figure 4: Geologic map of the lower New River Gorge. (Modified from Englund and others, 1982)

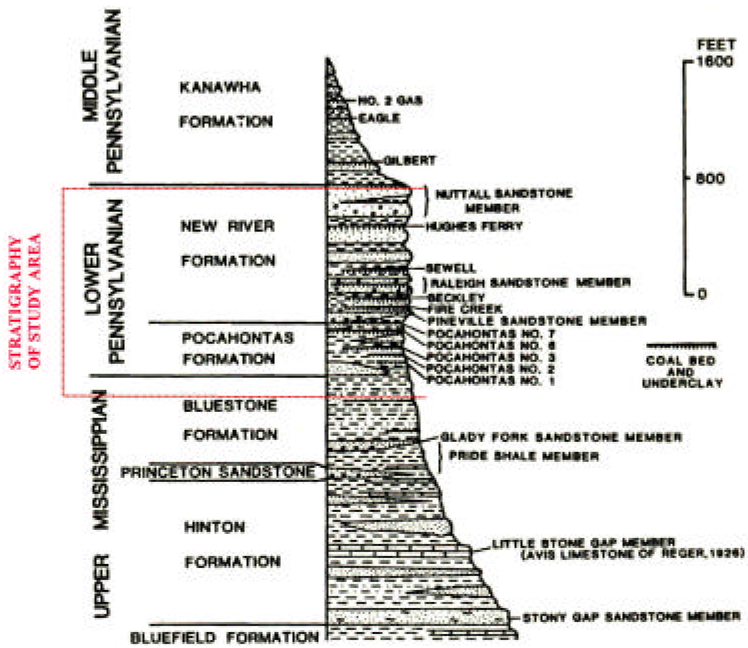


Figure 5: Generalized columnar section of bedrock exposed in the New River Gorge. Stratigraphy exposed in the study area is highlighted. (Modified from Englund and others, 1982)

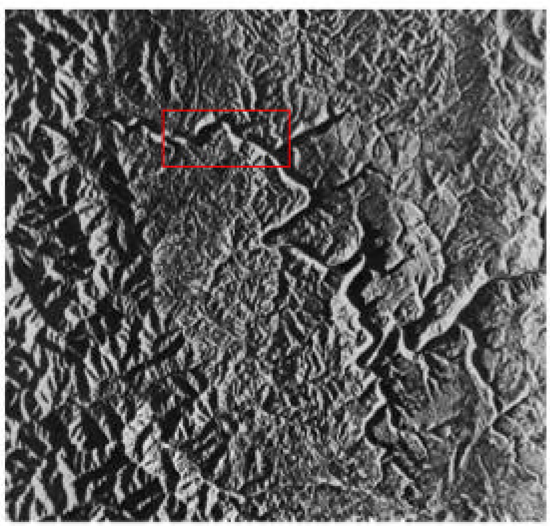
The Pocahontas Formation unconformably underlies the New River Formation (Figure 5). This formation primarily consists of argillaceous subgreywacke sandstones, shales, coals, and underclays (Hennen and others, 1919). The Pocahontas is intermediate in terms of erosion resistance. Sandstone comprises 70 percent of this terrestrial, coal-bearing formation, whereas siltstone, shale, and underclay combined make up 28 percent (Englund and others, 1982). Coal seams account for the remaining 2 percent of the formation. The maximum thickness of 122 m in the southeastern part of the gorge thins to the northwest due to an erosional unconformity (Englund and others, 1982).

The Upper Mississippian Bluestone Formation is the oldest exposed rock unit in the lower gorge (Figure 5). The exposed portion of this formation crops out in the southernmost part of the study area near Manns Creek. This upper portion includes an unnamed member consisting of shales and siltstones (Englund and others, 1982). The silty, ripple-bedded to coarse conglomeratic sandstone of the Glady Fork is the only resistant member; hence, the formation is relatively weak in resisting erosion.

Surficial Geology

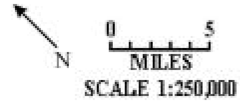
The topography of the lower gorge is comprised of numerous ridges, side slopes, hollows, noses, and footslopes with virtually no bottomland along the valley axes (terminology after Hack and Goodlett, 1960) (Figure 6). Noses and ridges are areas in which the contours are convex outward. These areas are the driest in the gorge because runoff tends to diverge downslope. Side slopes represent areas where topographic contour lines are straight. In general, slopes tend to be steeper where there is more sandstone (Outerbridge, 1986). Hollows are areas of concentration of drainage lines where topographic contour lines are concave outward. In these areas, the amount of

A



B

Figure 6: Topography of the lower New River Gorge: (A) Beauty Mountain overlook of Keeneys rapids; (B) Side-looking airborne radar (SLAR) image of New River Gorge with approximate study area shown. (Modified from Lessing, 1986)



moisture and colluvium are highest. The increased colluvium and moisture, coupled with the steep slopes, result in numerous debris-flow deposits at the base of hollows. Hollows include all topographic lows, parallel to the downslope direction, that lack an intermittent or perennial stream. Footslopes are transitional areas between the side slope and the bottomland. In the study area, footslopes are comprised mostly of mass-movement deposits. Human activity has also produced a footslope in a few localities.

The gorge's topography promotes accumulation of numerous colluvial and, to a lesser degree, alluvial deposits along the main channel of the New River. Locally, the Mississippian and Pennsylvanian bedrock in the gorge is covered by surficial deposits. In general, colluvium is thickest on the lower slopes and thinnest near hilltops and on steep slopes. The thick colluvial deposits along the lower New River can be described based on Varnes' (1978) classification of mass movement. This classification and nomenclature gives primary consideration to the type of movement and secondary consideration to the type of material (Table 1).

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				PREDOMINANTLY COARSE	PREDOMINANTLY FINE
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
SLIDES	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
		MANY UNITS	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow	Debris flow	Earth flow
			(deep creep)	(soil creep)	
COMPLEX			Combination of two or more principal types of movement		

Table 1: Classification of mass movements (From Varnes, 1978)

The types of mass movement in the lower New River Gorge are predominantly rock fall, rock topple, debris slide, debris flow, or complex (Figure 7). Rock fall, similar

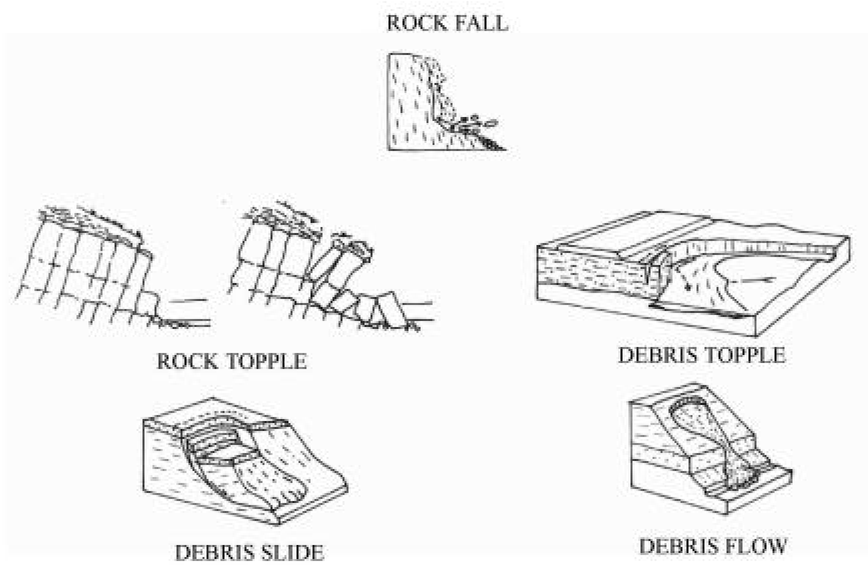


Figure 7: Generalized block diagrams illustrating common types of mass movement in the study area. (Modified from Varnes, 1978)

to topple, refers to individual, large, detached rock masses that move down steep slopes or cliffs with little or no shear displacement. Rock falls travel a considerable part of their distance through the air by free fall with subsequent bouncing or rolling. Topple describes an overturning movement about a pivot point. Rock topples commonly transform into falls or slides. A slide refers to shear displacement of a detached mass that remains in constant sliding contact with the underlying, stable, slope materials. Natural and human-induced sliding results in numerous broad, hummocky deposits creating gentle footslopes within the study area. Debris flow is a form of mass movement in which coarse material, fine-grained matrix, liquid, and gas flow together as a viscous slurry. The speed of debris flow can range from rapid to slow. These deposits have a distinct bouldery lobate fan shape with a noticeably coarser snout. Although the matrix eventually erodes out of these deposits due to subsequent flooding, the larger boulders and fan shape usually remain (Mills, 1990). Complex mass movement refers to any combination of two or more principal types of movement.

The narrow valley produced as the New River passes through the resistant New River Formation does not promote the development of alluvial landforms. Gravel and sand bars are the most common alluvial deposits. Other alluvial features result from the reworking and weathering of colluvial material. These deposits, locally referred to as rock gardens and debris bars, resemble alluvial point and diagonal bars along the main channel. The canyon floor is so narrow that it is completely occupied by the main channel and a floodplain landform is not distinguishable at a stage of 0 m or higher on the Fayette Station gage.

Hydrology

General

The New River flows generally northward a distance of approximately 483 km from its headwaters near the summit of the Blue Ridge in western North Carolina to the town of Gauley Bridge, West Virginia, where it joins the Gauley River to form the Kanawha River (McColloch and others, 1997). The New River flows through the New River Gorge National River Park between Hinton and Fayetteville, West Virginia. The free-flowing New River drops 229 m in the 85 km reach along this section which is bounded by the Bluestone Dam to the south and by Hawks Nest Lake to the north (National Park Service, 1996) (Figure 8). The New River in the park is characterized as a pool-and-riffle stream that becomes narrower, steeper, and deeper in the downstream direction as the Nuttall Member of the New River Formation becomes the canyon rim (Wiley and Cunningham, 1994).

Water flow within the gorge has been regulated since completion of Bluestone Dam by the U.S. Army Corps of Engineers in January 1949. The Bluestone Dam serves as part of the flood control system for the New, Kanawha, Ohio and Mississippi rivers. It has a flood control storage capacity of approximately 7.40×10^8 m^3 (Summers County Convention and Visitors Bureau, 1998). Since this dam was completed, the New River discharge through the gorge has been limited to less than 1,841 m^3/s on the Hinton gage station (Stanley, 1999). Along the study section, the New River has an annual mean discharge of 211 m^3/s and the average gradient is 0.0023 (Davidson and others, 1996). In general, maximum discharges occur in March, whereas the minimum discharges occur in September (McColloch and others, 1997).

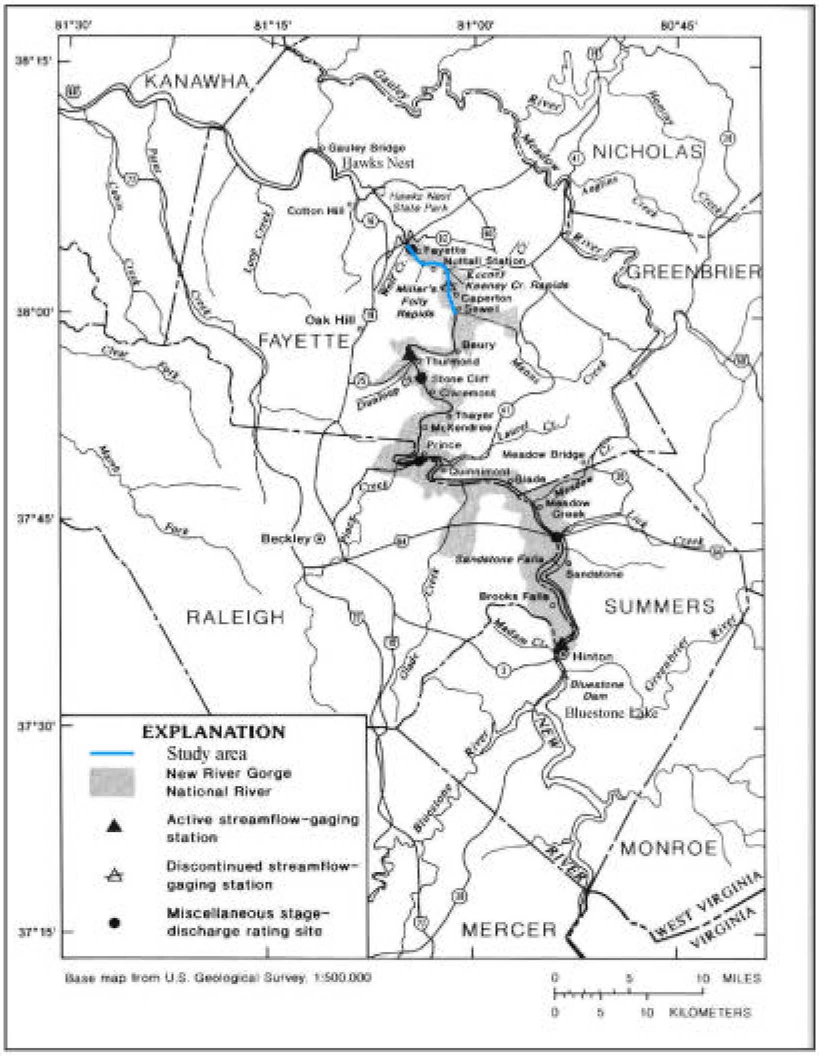


Figure 8: Location of gaging stations and dams along New River Gorge. (Modified from Wiley and Cunningham, 1994)

Figure 8 shows the streamflow-gaging stations along the New River Gorge National River. The Hinton station has been maintained since June 1936 (Ward and others, 1999). The instantaneous peak flow for the period of record at this station was 6,967 m^3/s on August 15, 1940 (Ward and others, 1999). The Thurmond station has been maintained since February 1981 (Ward and others, 1999). The instantaneous peak flow for the period of record at this station was 2,832 m^3/s on January 20, 1996 (Ward and others, 1999). A station located at Caperton is no longer active (Wiley and Appel, 1989). Another station was maintained periodically at Fayette Station between 1878 and 1916, where a staff gage is painted on the upstream side of the left bank pier of the Highway 82 bridge (Wiley and Cunningham, 1994). Table 2 lists the rating table for the Fayette Station gage.

Gage Level	Stream Flow	
ft	ft^3/s	m^3/s
-2	1,072	30
-1	1,704	48
0	2,440	68
1	3,352	94
2	4,436	124
3	5,820	163
4	7,550	211
5	9,550	267
6	11,400	319
7	14,100	395
8	17,200	482
9	20,200	566
10	23,800	666
11	26,800	750
12	30,000	840

Table 2: Rating table, Fayette Station gage (Modified from Davidson and others, 1996)

The 10- and 100-year flood discharges of unregulated flow were estimated to be 4,903 m^3/s and 9,862 m^3/s, respectively, prior to regulation by the Bluestone Dam (Mills, 1990). The largest recorded floods occurred in 1878 and 1940. The 1878 flood had an estimated discharge of 8,785 m^3/s on the Fayette Station gage (Mills, 1990). The 1940 flood had an estimated instantaneous peak flow of 6,967 m^3/s on the Hinton gage (Ward and others, 1999).

Rapids

Whitewater normally begins just north of Thurmond, where rapids of varying heights and combinations range from class I to V. For the purposes of this study, whitewater is defined as flow having rapids with assigned difficulty ratings. Rapids occur where supercritical flow conditions are present. Supercritical flow conditions are defined by a Froude number greater than one (Kieffer, 1985). The Froude number, which is the ratio of mean flow velocity to critical velocity, is given by the equation:

(1) $$Fr = u/(gD)^{0.5}$$

where u is mean flow velocity, g is acceleration due to gravity, and D is mean depth of flow. Supercritical flow conditions generally occur where stream depth decreases locally or flow is accelerated (Kieffer, 1985).

There are 20 major rapids widely recognized and rated as a result of supercritical flow conditions along the lower New River Gorge (Table 3).

Rapid Name	AKA*	Class
Pinball	Big Baloney	II
Upper Railroad	U. Tressle	III
Lower Railroad	L. Tressle	IV
Swimmers	Catfish Rock	II
Stripper Hole	Warm Ups	II-III
Ender Waves	Warm Ups	II-III
McCabes	Warm Ups	II-III
Corkscrew	Warm Ups	II-III
Upper Keeney	Whale Rock	III-IV
Middle Keeney		V
Lower Keeney		V
Dudley's Dip		IV
Double Z	Sunset	V
Turtle Rock	Hook 99	III
Greyhound Bus Stopper		III
Upper Kaymoor	U. Tipple	II
Lower Kaymoor	L. Tipple	III
Millers Follies	Undercut Rock	V
Thread the Needle	Pick a Slot	I
Fayette Station	Wolf Creek	IV

*AKA (also known as): Some rapids are known by additional names.

Table 3: Major rapids of the lower New River Gorge (Compiled from Scott, 1985, and Miller, 1998)

Two of the 20 rapids, Upper Railroad and Millers Follies, are further subdivided into two parts for this study. The locations of all 22 rapids are shown in Figure 9. Rapids are rated based on the International Scale of River Difficulty (Table 4).

Class	Level	Description
I	Easy	small regular waves, clear passages
II	Novice	small drops, clear passages, routes obvious
III	Intermediate	moderate and irregular waves,
		some maneuvering necessary
IV	Advanced	large irregular waves, faster water,
		calls for precise maneuvering
V	Expert	long distances, powerful and violent water, heavily obstructed
		riverbed, complex and powerful maneuvering necessary
VI	Extreme	unpredictable, dangerous, very severe consequences of errors,
		for experts only, utmost limit of navigability

Table 4: International Scale of River Difficulty (Modified from Davidson and others, 1996)

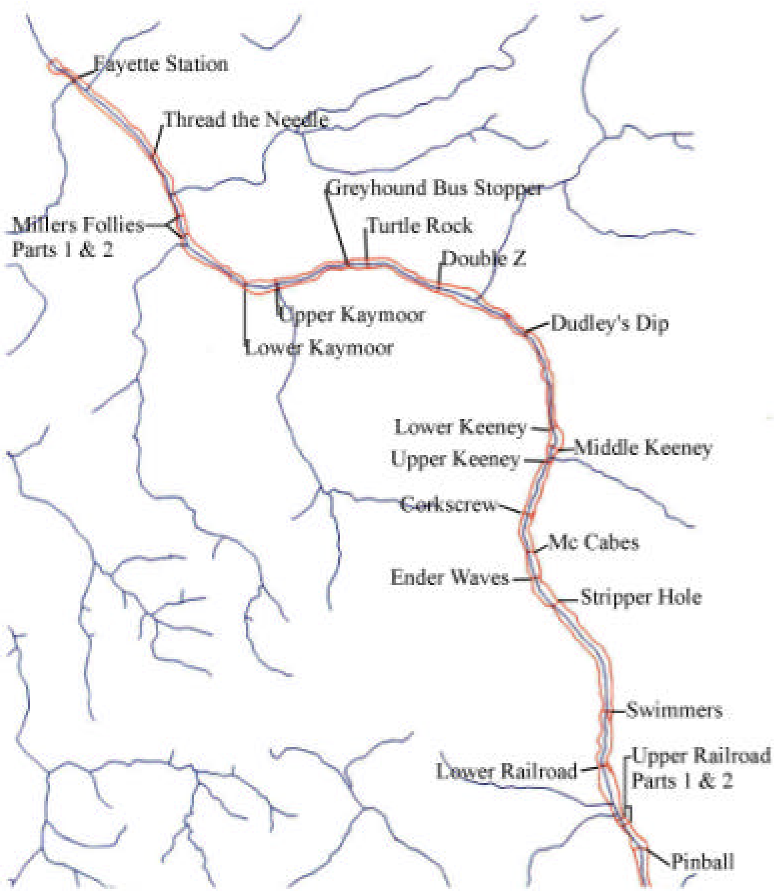


Figure 9: Location of rapids.

This widely accepted classification system is based on the amount of boating skill necessary to navigate, presence of riverbed obstructions such as trees and undercut rocks, stream hydrology, rapid length, ease of rescue, and degree of accessibility.

Rapid difficulty ratings are subjective because they reflect normal stage, conditions and surroundings. The rapid classifications listed in Table 3 are based on water levels between 0 to 3 ft on the Fayette Station gage (79 to 178 m^3/s). Fluctuations in stage, drowned trees, and geological disturbances can alter the rapid rating because they have an effect on flow regime. Different rapids respond differently to changes in flow. Both high or low flow, for example, can enhance or diminish the existence of a rapid. At higher levels, Upper, Middle, and Lower Keeney rapids merge to become a single Keeney rapid (class V-VI), and create a much longer rapid and more difficult rafting situation (Grove and others, 1995) (Figure 9). The waves and holes of Lower Keeney Rapid are most dynamic at water levels of 1 ft and begin to wash out, or approach subcritical conditions, at levels of 2 ft and above on the Fayette Station gage (Grove and others, 1995). Rocks can also become exposed as stage changes the amount of supercritical flow present (Armstead, 1982). Mills (1990) stated that the rating of rapids generally increases with steeper gradients, narrower channel widths, and larger boulders. Therefore, geomorphic factors, such as flooding and the type of mass movement delivering the boulders, may affect the difficulty of rapids.

Previous Work

There have been several reports pertaining to the geomorphology of the New River Gorge. Outerbridge (1986) described the Logan Plateau physiographic region of the Appalachian Plateau of West Virginia, Kentucky, Virginia, and Tennessee.

According to Outerbridge, landslide debris is the dominant surficial deposit on hillslopes. Landslides are further defined as mostly debris flows and debris avalanches with minimal slumping. Torrential thunderstorms during spring and summer are identified as the most common trigger of debris avalanches and debris flows. Outerbridge also stated that most streams in this region flow on bedrock. Sandstone ledges crop out in stream bottoms. Sediment enters streams from creep, landslides, and to a lesser degree, strip-mine runoff. Outerbridge suggested erosion rates of 100 m/ma for subgraywacke sandstone, siltstone, shale, and coal, and 10 m/ma for quartz sandstone.

Davies and Ohlmacher (1977) produced a 1:50,000-scale landslide map and brief discussion of mass-movement activity within the New River Gorge. The landslide map included recent slides, older slides, debris avalanches, rock falls, and earth flows from surface mines. Davies and Ohlmacher found numerous older slides throughout the gorge that show no sign of historical movement. Most historical slides in this area have moved slowly and have not involved bedrock. Accelerated movement and resultant debris flows or rock falls only occur when activity, such as mining, logging, or road construction, alter the slope. Davies and Ohlamcher also referred to "debris avalanches," as evidenced by steep-sided valleys with nearly uniform gradient from rim of upland to the valley floor. However, true debris avalanches are characterized by the presence of a skim zone where the main body of the moving material loses contact with the slope (Orme, 1987). Skim zones have not been identified in the New River Gorge, so "debris flow" is a more appropriate term for this type of failure. Debris flows have not been widely documented in this area (Davies and Ohlmacher, 1977). However, most of the hundreds of hollows along the walls of the New River Gorge are potential sources of debris flows during times of very heavy rainfall. Old debris flows are evidenced by massive fan-shaped mounds of poorly sorted debris that are not graded to the New River. Rock falls, on the other hand, are common in most of the field area where the massive New River sandstones form the cap rock and steep faces along the gorge. Mass movement in the lower gorge ranges in age from prehistoric (prior to settlement around the late 1800's) to currently active.

Remo (1999) produced a 1:24,000-scale mass-movement deposit map and discussion of geologic controls on mass-movement in the New River Gorge. The mass-movement deposit map included prehistoric and historic debris flows, debris slides, rock falls, complex failures, and spoil slides/flows from surface mines. Bedrock lithology was found to be an important factor in affecting the size, texture, preservation potential, and type of mass-movement deposit. Joints, both stress-release and tectonic, affected mass movement in the gorge by controlling ground-water flow, providing planes of weakness for failure to occur, and providing zones of weakness that may aid in the development of hollows and colluvial materials along the gorge walls. Tectonic joints and lineaments appeared to have no direct effect on the orientation or location of mass movement deposits except for their indirect effect on the trend of the New River. Remo also suggested modern-day mass-movement rates of 36 to 72 m/ma, based on the volume of mass-movement deposits on abandoned road and railroad grades, and the three formations in the middle and upper gorge. Unexpectedly, these mass-movement denudation rates were unexpectedly found to be similar to the regional denudation and downcutting rates.

Mills (1990) has written the only geomorphological study of the rapids in the New River Gorge, which examined the geologic and topographic controls on the rapids.

According to Mills, most rapids in the gorge result from mass movement from the gorge walls. Mills also identified that only 20 out of 58 rapids in the entire New River Gorge are associated with debris-flow deposits located near tributary mouths. Mills concluded that supercritical flow and rapids are produced as the river attempts to adjust to constricting and shallowing conditions within the channel.

Numerous USGS reports have provided excellent hydraulic data on the New River and its tributaries. Wiley and Appel (1989) included information on gaging stations, rating curves, water-surface and stream-bed profiles, and channel cross sections along the New River Gorge National River. Wiley (1994) provided estimates of the frequency and magnitude of flooding for selected reaches of five streams tributary to the New River. Wiley and Cunningham (1994) presented flood-frequency discharges, water-surface elevations, and cross-sectional velocities that constitute flood characteristics for the New River between Hinton and Fayette, West Virginia.

Reports conducted along other river canyons also provided theories on the genesis and characteristics of rapids that may prove applicable to the New River in the lower gorge. Powell’s research along the Colorado River (1895) first suggested that rapids form where tributary streams or mass-movement processes deposit clasts in the main channel. Many subsequent authors have agreed with this general idea.

Dolan and others (1978) presented evidence that most rapids along the 450 km course of the Colorado River in the Grand Canyon are associated with structurally controlled tributaries. These tributaries, having steeper gradients and larger clast transporting capabilities, produce debris fans that partially obstruct the main channel, thus producing rapids. The spacing of rapids along the canyon varies with variations in the regional and local fracture patterns and stratigraphy as well as the number of tributaries present. Graf (1979) found most rapids in the Grand Canyon to be associated with tributary-mouth and mass-movement sites. Thus, these rapids are relict geomorphic features that are either unchanging or are accumulating debris from tributary sources. Webb and others (1988,1989) have also demonstrated that tributary fans, emplaced mainly by debris flows, result in the formation of rapids.

Similar to the studies on the Colorado River in the Grand Canyon, Liquori (1994) suggested the importance of rock-fall deposits in the development of rapids along the Gunnison River in western Colorado. Liquori distinguished rock-fall deposits from debris-flow deposits based on their greater tendency to protrude into the channel and greater cross-sectional resistance to channel flow.

Leopold created a fourfold classification system of waves in rapids based on hydraulic form (Figure 10):

- waves below large rocks or outcrops;
- deep-water waves caused by flow convergence;
- waves and riffles in shallow water; and
- waves in deep, high-velocity water.

Kieffer (1985), in hydraulic studies on the waves of major Colorado River rapids, identified three major causes of waves within rapids:

- substantial obstacles in the bed, such as rocks;
- converging or irregular shoreline, or a strong eddy that acts as an effective shoreline; and
- contraction and expansion of flow as it goes through a channel of varying cross-sectional area.

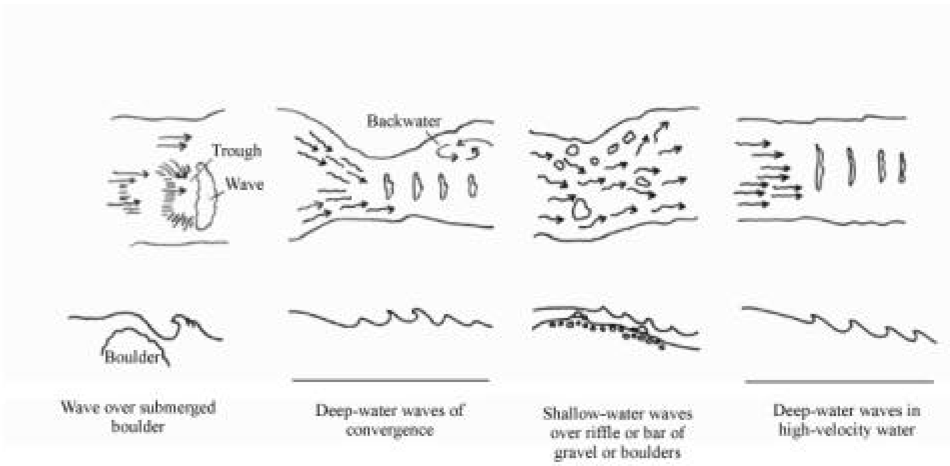


Figure 10: Diagrams showing four types of water waves in rapids. Upper sketches show a plan view of the river; lower sketches indicate the inferred relation of waves to the bed configuration. (From Leopold, 1969)

Kieffer also identified constriction ratios at debris fans ranging from 0.3 to 0.7.

Kieffer concluded rapids form when supercritical flow is reached. After rapids form, they may evolve into two parts: the intact debris-flow deposit, and the rock garden below it which consists of reworked debris. Webb and others (1989) have also identified rock gardens or debris bars downstream from pre-existing rapids or debris-flow fans as possible rapid causes. Melis and others (1993) also discussed eddy zones that form downstream of most debris fans and promote deposition of fine-grained sand bars.

Methodology

This field-based study investigated the origin of rapids along the lower New River Gorge between Cunard and Fayette Station, West Virginia. A total of 22 rapids were identified (Figure 9). Observations and measurements were taken from river level, from the rim of the gorge, from personal aircraft flyovers, and vertical and oblique aerial photos. The majority of field work was completed between July and August 1998, when the river level ranged between 0 m and 1 m on the Fayette Station gage.

Bedrock geology and hydraulic characteristics of the study area were obtained from geologic maps by Englund and others (1977) and reports by Hennen and others (1919), Wiley and others (1989), and Wiley (1994). Rapid names, locations, difficulty ratings, and other important features were obtained from whitewater scouting maps constructed at a river level of 1.5 m on the Fayette Station gage (Rathnow, 1986) and by consultation with local river guides. Mills (1990) noted additional morphologic data including stream gradient, stream width, valley width, stream constriction at tributary mouths, and rapids.

USGS 1:80,000-scale aerial photos (taken in April 1977), low-altitude oblique aerial photos (taken from a private aircraft on July 10th and August 3rd, 1998), and standard 1:24,000-scale topographic maps were used to plot the position of each rapid and to delineate near-channel surface features and landform units. Landforms were verified based on the field recognition of blocky, lobate fan deposits, chutes, alluvial features such as floodplains, gravel and sand bars, isolated boulders, bedrock outcrops, and hummocky topography. Comparison with historic photographs was made to more accurately verify the type of landform.

A 1:10,000-scale map was constructed to show the distribution of surficial deposits in relation to the main stream channel. These near-channel deposits include valley-wall mass-movement deposits, tributary-fan deposits, alluvial deposits, and bedrock outcrops. Although it is difficult to represent individual hydraulic characteristics of rapids at this scale, the main landforms and their relationship to rapid formation can be successfully illustrated. Once the map was complete, map units were described and general conclusions were made on the origin of each rapid. A total of seven different types of surficial deposits were identified in association with major rapids along the lower New River Gorge.

Six of eight tributary fans associated with rapids were analyzed further to determine whether deposits in the fans have an alluvial or colluvial origin. These tributary fans were selected based on the field recognition of large, predominantly coarse, bouldery fan deposits adjacent to the tributary mouth. Regression equations by Williams (1983) and Knox (1988) allowed the calculation of competent flow depth based on maximum boulder size and stream gradient. For each of the six tributary fans, the intermediate axes of the five largest boulders were identified and measured in the field. The method of measuring the five largest boulders for paleohydraulic reconstruction has been successfully used by Costa (1983) on the Colorado Front Range. Therefore, discharges determined by this competence method can be used as a maximum flow value. Stream gradients were determined from 1:24,000-scale topographic maps. Tributary drainage-basin divides were drawn on a 1:24,000-scale topographic map and drainage-basin areas were determined using a point-counting method devised by the Pennsylvania Geological Survey (Wells, 1972). This method has been used for area measurement by the West Virginia Geological and Economic Survey and differs from planimeter measurements by less than 4 percent (McClelland, 1999). The area calculations were then checked using a compensating polar planimeter. Drainage-basin area also was compared to a set of partial area calculations by Wiley (1994) and outdated area calculations (prior to publication of 1:24,000-scale maps) by Hennen and others (1919). Historical peak flood estimates were calculated based on the relationship between peak discharges and drainage area for small streams (Runner, 1980). Competent flow depth based on boulder-transport calculations was compared to estimated historical flood depths to evaluate the origin of these six tributary-fan deposits.

Map Units

At 1:10,000 scale, eight different types of mappable landforms adjacent to the New River can be resolved within the study area (Figure 11). These landforms can be divided into four main categories including valley-wall mass-movement deposits, tributary-fan deposits, alluvial deposits, and bedrock outcrops.

Valley-wall Mass-movement Deposits

Most boulders along the valley floor were delivered by natural or human-induced mass movement from the valley wall, particularly by debris flows and debris slides. These valley-wall deposits occur along the footslope at the base of hollows where no mappable tributary stream is present (Figure 11). These deposits have debris-flow, debris-slide, rock-fall, or complex mass-movement origins (Table 5).

Origin	Number of Units
debris flow	43
debris slide/complex	11
rock fall	3

Table 5: Origin and number of valley-wall mass-movement deposits

Debris-flow origin is reflected by a distinct fan shape with a bouldery snout and a proximal source hollow. Rock-fall deposits, although often incorporated in many other deposits, are identified by the presence of large, isolated boulders. Debris-slide deposits are generally broad, hummocky features. Debris-slide deposits are grouped with complex deposits in this study because failures from multiple sources also may result in broad hummocky features. In general, the term “complex” is used when there are distinguishable, multiple failure events or evidence of more than one mode of movement.

Tributary-fan Deposits

Alluvial and colluvial processes from tributaries also result in deposition of fans along the valley bottom. Tributary-fan deposits are associated with perennial streams. Five of the eight tributaries in the study area have mappable fan deposits that greatly constrict the flow of the New River. Another tributary fan at Coal Run, is not directly associated with a rapid; however, a coarse fan deposit suggests a colluvial origin.

Boulder Transport Calculations

Tributary fans associated with rapids and Coal Run were further analyzed to differentiate between alluvial or debris-flow origin. A tentative determination was obtained by applying regression equations by Williams (1983) and Knox (1988) to estimate competent flow depths from maximum boulder size and stream gradient. Williams (1983) developed a regression equation:

(2) $$D=0.000114d^{1.15}\,S^{-0.62}$$

where D is competent flow depth in m, d is clast intermediate axis in mm, and S is an approximation of the energy slope.

Knox (1988) developed a similar regression equation:

(3) $$D=0.0001d^{1.21}\,S^{-0.57}$$

using the same variables as Williams (1983).

The five largest boulders of each fan were identified and measured in the field (Table 6). Stream gradients were determined from 1:24,000-scale topographic maps (Table 7). Competent flow depths were calculated using equations 2 and 3. Competent discharges, D_C, were then calculated using the (Ritter, 1986) equation:

(4) $$D_C = A_{sc}\,V$$

where A_{sc} is channel cross-sectional area in m^2, and V is velocity in m/s (Table 8). Channel cross-sections were constructed from 1:24,000-scale topographic maps. The approximate stream channel area, A_{sc}, is equal to:

(5) $$A_{sc}= L \times W$$

Table 6: Data from five largest boulders at selected tributary fans

Location	Boulder 1	Boulder 2	Boulder 3	Boulder 4	Boulder 5	Mean
	(m)	(m)	(m)	(m)	(m)	(m)
Manns Creek						
axis X	3.07	3.99	3.25	4.50	2.97	3.56
axis Y	3.07	3.45	1.96	2.21	2.69	2.68
axis Z	1.88	2.64	1.30	1.68	1.60	1.82
Coal Run						
axis X	1.65	2.34	2.69	2.01	2.11	2.16
axis Y	0.99	1.02	1.68	1.35	1.42	1.29
axis Z	0.69	0.79	1.04	0.79	1.02	0.86
Keeneys Creek						
axis X	4.70	3.94	2.92	4.72	3.12	3.88
axis Y	4.30	2.54	2.62	3.45	2.57	3.10
axis Z	2.15	2.51	2.08	1.40	1.73	1.97
Craig Branch						
axis X	3.53	2.03	2.44	1.88	1.90	2.36
axis Y	1.73	0.97	0.97	1.78	0.97	1.28
axis Z	1.04	0.69	0.74	0.97	0.74	0.83
Butcher Branch						
axis X	4.70	6.10	12.12	7.70	6.30	7.38
axis Y	4.01	4.34	10.85	4.77	4.62	5.72
axis Z	2.54	2.21	1.60	1.93	1.96	2.05
Wolf Creek						
axis X	4.11	5.94	4.01	4.83	4.60	4.70
axis Y	2.41	4.90	2.79	2.16	3.45	3.14
axis Z	1.45	1.68	1.83	1.57	1.02	1.51

Table 7: Competent flow depth (D) required to move a clast with intermediate diameter (d) and approximate energy slope (S) based on equations by Williams (1983) and Knox (1988)

Tributary	Rapid Present	Upper Stream Elevation	Lower Stream Elevation	Rise	Run	S	d*	D Williams	D Knox
		(ft)	(ft)	(ft)	(ft)		(mm)	(m)	(m)
Manns Creek	Y	1100	1000	100	2375.00	0.04	1820	4.56	5.36
Coal Run	N	1510	1000	510	3280.83	0.16	860	0.86	1.03
Keeneys Creek	Y	1400	1000	400	3280.83	0.12	1970	2.58	3.22
Craig Branch	Y	1860	1000	860	3280.83	0.26	830	0.59	0.73
Butcher Branch	Y	1820	920	900	3280.83	0.27	2050	1.64	2.13
Wolf Creek	Y	1400	920	480	3280.83	0.15	1510	1.70	2.10

*d is based on mean axis Z of five largest boulders from Table 6.

Table 8: Competent discharge (Qc) based on competent flow depth (D) from Knox (1988) equation and velocity (V) from the Manning equation

Tributary	Width (W)	Length (D)	X-Sectional Area (A)	Velocity (V)	(Qc)
	(m)	(m)	(m^2)	(m/s)	(m^3/s)
Manns Creek	21.3	5.4	114.3	12.3	1407.0
Coal Run	7.6	1.0	7.8	8.1	63.7
Keeneys Creek	12.2	3.2	39.2	15.2	594.0
Craig Branch	15.2	0.7	11.1	8.3	92.0
Butcher Branch	17.5	2.1	37.2	17.2	641.5
Wolf Creek	15.2	2.1	32.0	12.7	407.8

where L is length or stream depth, and W is channel width (Ritter, 1986). The competent flow depths were used with the channel cross-sections to determine flow. Velocity, V, was calculated based on the Manning equation:

$$V=(1.49/n)(R^{2/3}S^{1/2}) \qquad (6)$$

where R is the hydraulic radius (approximately equal to the competent flow depth), S is slope, and n is a roughness coefficient (Morisawa, 1968). A 0.05 value for n is representative of a mountain stream with no channel vegetation, steep banks, and a bed of cobbles and large boulders (Morisawa, 1968).

Competent discharge was compared with peak discharge estimates for the 100-year and 500-year flood frequencies. Since historical stream-flow data did not exist for all six tributaries, the peak discharge was estimated based on drainage basin area (Table 9), and following a method developed for unregulated, virtually natural streams in West Virginia that have drainage areas between 0.3 and 2,000 mi^2 (0.8 and 5,180 km^2) (Runner, 1980). Both the graphical and formula approach of this method were used to ensure accuracy. For example, the 100-year discharge for Wolf Creek at Fayette Station, with a

drainage area of 16.2 mi^2 (41.9 km^2), was calculated from the equation:

$$Q_{100}=437A^{0.719} \qquad (7)$$

$$Q_{100}=437x16.2^{0.719}$$

$$Q_{100}=3237 \text{ ft}^3/\text{s } (92 \text{ m}^3/\text{s})$$

The 100-year discharge of Wolf Creek was estimated graphically as 92 m^3/s (Figure 12). Table 10 lists the 100-year and 500-year peak discharge estimates in comparison to the competent discharges for boulder transport.

Table 9: Drainage basin area estimates for selected tributaries based on compensating polar planimeter measurements (cpp) and point-counting method (pcm)*

Tributary / Subbasin	# CPP Units**	CPP Area (km^2)	CPP Area (mi^2)	# Points	PCM Area (km^2)	PCM Area (mi^2)	Difference (mi^2)
Manns Creek	23087.0	114.9	44.4	3479	116.3	44.9	-0.5
Fayetteville	582.5	2.9	1.1	87	2.9	1.1	0.0
Winona	5003.5	24.9	9.6	751	25.1	9.7	-0.1
Danese 1	2653.5	13.2	5.1	405	13.5	5.2	-0.1
Danese 2	6134.0	30.5	11.8	921	30.8	11.9	-0.1
Danese 3	2983.0	14.9	5.7	450	15.0	5.8	-0.1
Rainelle 1	4684.5	23.3	9.0	706	23.6	9.1	-0.1
Rainelle 2	1046.0	5.2	2.0	159	5.3	2.1	0.0
Coal Run	1842.5	9.2	3.5	280	9.4	3.6	-0.1
Fayetteville	725.0	3.6	1.4	116	3.9	1.5	-0.1
Thurmond	1117.5	5.6	2.1	164	5.5	2.1	0.0
Keeneys Creek	4620.0	23.0	8.9	696	23.3	9.0	-0.1
Fayetteville	1339.0	6.7	2.6	201	6.7	2.6	0.0
Winona	3281.0	16.3	6.3	495	16.6	6.4	-0.1
Craig Branch	828.5	4.1	1.6	128	4.3	1.7	-0.1
Butcher Branch	619.0	3.1	1.2	99	3.3	1.3	-0.1
Wolf Creek	9023.0	44.9	17.3	1255	42.0	16.2	1.1
Fayetteville	6121.0	30.5	11.8	815	27.3	10.5	1.2
Thurmond	926.0	4.6	1.8	144	4.8	1.9	-0.1
Beckwith	614.0	3.1	1.2	47	1.6	0.6	0.6
Beckwith	1417.5	7.1	2.7	220	7.4	2.8	-0.1
Oak Hill	190.5	0.9	0.4	29	1.0	0.4	0.0

*Highlighted section shows total area values for each tributary.

**1 CPP Unit = 53590.57 ft^2

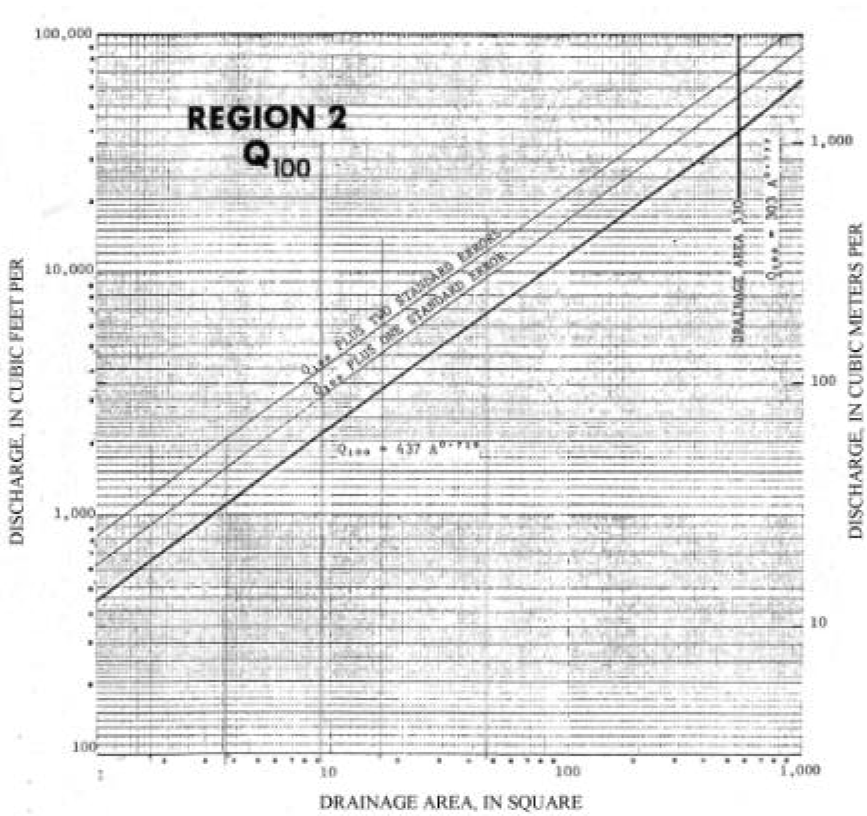


Figure 12: Relation of 100-year peak discharge to drainage area (Q100) in Region 2. (From Runner, 1980)

Table 10: 100-year and 500-year flood peak discharge estimates (Q_{100} and Q_{500}, respectively) based on Runner, 1980 in comparison to the competent discharges (Qc) for boulder transport along selected tributaries*

100 Year Flood Peak Estimates (Q_{100})

Tributary	Area	Equation			Graph			Q_{100} Avg	Q_{100} Avg	Max Q_{100}	Qc
	PCM	Q100	Q100+1SE	Q100+2SE	Q100	Q100+1SE	Q100+2SE	all 6	all 6		Knox, 1988
	(mi^2)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(m^3/s)	(m^3/s)	(m^3/s)
Manns Creek	44.9	6737	9701	12665	6900	9500	12250	9625	273	359	1407
Coal Run	3.6	1098	1581	2064	1100	1550	2050	1574	45	58	64
Keeneys Creek	9.0	2121	3055	3988	2150	3090	3950	3059	87	113	594
Craig Branch	1.7	640	922	1203	640	900	1200	917	26	34	92
Butcher Branch	1.3	528	760	992	530	755	980	757	21	28	642
Wolf Creek	16.2	3237	4661	6085	3250	4600	6050	4647	132	172	408

500 Year Flood Peak Estimates (Q_{500})

Tributary	Area	Equation			Graph			Q_{500} Avg	Q_{500} Avg	Max Q_{500}	Qc
	PCM	Q500	Q500+1SE	Q500+2SE	Q500	Q500+1SE	Q500+2SE	all 6	all 6		Knox, 1988
	(mi^2)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(m^3/s)	(m^3/s)	(m^3/s)
Manns Creek	44.9	9338	14007	18677	9200	14250	18600	14012	397	529	1407
Coal Run	3.6	1641	2462	3282	1550	2500	3375	2468	70	96	64
Keeneys Creek	9.0	3086	4628	6171	3100	4700	6400	4681	133	181	594
Craig Branch	1.7	979	1468	1957	na	1460	1950	1563	44	55	92
Butcher Branch	1.3	814	1220	1627	na	1220	1610	1298	37	46	642
Wolf Creek	16.2	4626	6939	9252	4600	7250	9400	7011	199	266	408

* Highlighted cells indicate that the competent flow required to move the largest boulders as part of tributary stream flow is possible during a 500-year flood on Coal Run.

The boulder-transport calculations suggest it is unlikely that the largest boulders on any of the five fans associated with rapids have been moved solely by tributary stream flow. The 500-year discharge estimates of Coal Run indicate the possibility of an alluvial origin (Table 10). However, due to close proximity to a railroad tressle and associated human impact in addition to field interpretation of morphology, this deposit is also considered unlikely to have been moved solely by tributary flow. Therefore, all six of the tributary-fan deposits are probably derived from mass-movement mechanisms. Due to the colluvial material and shape of the deposit, these tributary-fan deposits are interpreted to be the result of debris flows and are referred to herein as tributary debris-fan deposits.

Alluvial Deposits

Although the narrowness of the New River valley does not promote the development of many alluvial landforms, some small alluvial deposits were mapped within the study area (Figure 11). These deposits include sand bars, diagonal bars, debris bars, and alluvial tributary fans. The 14 mappable sand bars within the study area are associated with slackwater. Slackwater conditions are typically a result of obstacles within the main channel. The sudden channel expansion and rapid deceleration of flow associated with such obstructions induces the recirculating-eddy systems and results in deposition of fine-grained sand-bar deposits.

A few gravel-to-boulder bars occur in the study area, mostly in the southern portion, upstream from where the Nuttall Member of the New River Formation forms the canyon rim. These deposits are identified as diagonal bars, but are not mappable at the 1:10,000 scale used for this project.

Prominent debris bars form downstream from tributary fans and other valley-wall mass-movement deposits. These debris bars are similar to the debris-flow deposit and rock garden rapids identified in the Grand Canyon by Kieffer (1985). Debris bars consist of fluvially reworked boulders from previously existing mass-movement deposits. In the study area, three debris bars appear as blocky, scattered, larger-grained deposits that only slightly resemble typical alluvial features.

There are two alluvial tributary fans associated with Short Creek and Fern Creek. These deposits are finer grained than mass-movement deposits and do not significantly constrict the main channel.

Bedrock Outcrops / Ledges

Resistant sandstone members of the Pocahontas and Bluestone formations are exposed at or near river level along a few sections of the study area. Bedrock outcrops are only mappable at three locations along the stream bank. At these locations, bedrock outcrops appear to constrict the channel, resulting in supercritical flow and rapids. At two other localities, submerged bedrock outcrops are inferred based on the recognition of shallow flow over a visible ledge-like feature or linear drop across the main channel.

The Origins of Rapids

Mapping of near-channel, surficial deposits has revealed that the rapids are created by an obstruction of the main channel resulting in supercritical flow. The most common causes of channel obstruction are surficial deposits along the valley wall that protrude into the main channel. These deposits generally result from colluvial processes, including rock falls, debris flows, and debris slide/complex slope failures. Tributary debris-fan deposits also create rapids along the lower New River. In the southernmost portion of the study area, alluvial deposits within the main channel help create riffles and, in some cases, rapids. These alluvial deposits can be in the form of sand and gravel bars or debris bars. In a few cases, resistant bedrock outcrops in the river channel aid in constriction, producing similar supercritical flow conditions.

Many rapids result from a combination of surficial deposits. In most cases, surficial deposits from both sides of the valley wall contribute to the formation of major rapids. Table 11 lists the dominant deposit responsible for the formation of the rapid, as well as any other influential factors.

Valley-wall Mass-movement Deposits

The most important cause of major rapids on the lower New River is the presence of mass-movement deposits derived from the valley wall altering flow. Valley-wall mass-movement deposits create 11 of the 22 rapids by obstructing or constricting the width and depth of the main channel. As water flows over the mass-movement deposits within the main channel, the New River flow becomes supercritical because the concentration of water mass with decreased depth requires an increase in velocity. The supercritical flow characteristic of rapids also results where these deposits constrict the width of the main channel.

Valley-wall debris-flow deposits influence the origin of eight of the 22 rapids in the lower gorge. In six of these eight rapids, the presence of a debris-flow deposit is the dominant feature involved in the formation of the rapid (Table 11). Upper Keeney Rapid is the best example of a debris-flow deposit creating a major rapid, as shown in Figure 13.

Figure 13: Upper Keeney Rapid, unrelated to any tributary mouth, caused by a debris-flow deposit along the valley wall.

Debris-slide and complex deposits influence the origin of five of the 22 rapids (Table 11). In four of these five rapids, the presence of a debris-slide/complex deposit is the dominant feature involved in the formation of the rapids. Double Z Rapid is the best example of a debris-slide/complex deposit creating a major rapid (Figure 14).

Table 11: Origin of rapids along the lower New River Gorge

Rapid Name	Dominant Origin	Secondary Origin
Pinball	tributary debris fan from Manns Creek	
Upper Railroad Pt 1	inferred bedrock outcrop	alluvial gravel-bar deposit, valley-wall debris-slide/complex
Upper Railroad Pt 2	debris bar	tributary debris fan from Coal Run, valley-wall debris-slide/complex
Lower Railroad	bedrock outcrop	valley-wall debris-flow deposit
Swimmers	debris bar	valley-wall debris-flow deposit
Stripper Hole	valley-wall debris-flow deposit	alluvial gravel-bar deposit
Ender Waves	valley-wall debris-flow deposit	alluvial gravel-bar deposit
McCabes	valley-wall debris-slide/complex deposit	
Corkscrew	valley-wall debris-slide/complex deposit	alluvial gravel-bar deposit
Upper Keeney	valley-wall debris-flow deposit	tributary debris fan from Keeneys Creek
Middle Keeney	tributary debris fan from Keeneys Creek	
Lower Keeney	bedrock outcrop	valley-wall debris-flow deposit
Dudley's Dip	valley-wall debris-flow deposit	valley-wall debris-slide/complex deposit
Double Z	valley-wall debris-slide/complex deposit	
Turtle Rock	valley-wall debris-slide/complex deposit	
Greyhound Bus Stopper	inferred bedrock outcrop	valley-wall debris-flow and debris-slide/complex deposits
Upper Kaymoor	tributary debris fan from Butchers Branch	valley-wall rock-fall deposit
Lower Kaymoor	valley-wall debris-slide/complex deposit	valley-wall debris-flow deposit
Millers Follies Pt 1	tributary debris fan from Craig Branch	valley-wall rock-fall deposit
Millers Follies Pt 2	valley-wall debris-flow deposit	
Thread the Needle	valley-wall rock-fall deposit	valley-wall debris-flow deposit
Fayette Station	tributary debris fan from Wolf Creek	

Figure 14: Double Z Rapid caused by large complex failure deposits on both sides of the stream channel.

Figure 15: Thread the Needle Rapid created by the presence of large block rock-fall deposits within the main channel.

Since rock falls are commonly incorporated into, or concealed by, other deposits, the role of rock falls in creating rapids is unclear. Rock-fall deposits clearly influence the origin of two of the 22 major rapids (Table 11). Thread the Needle Rapid is the only location where large, isolated boulders have fallen directly into the river channel and dominantly resulted in rapids (Figure 15). In general, rock-fall deposits more commonly armor the slopes along the river margin rather than protrude into the center of the river channel.

Tributary Debris-fan Deposits

Many rapids are a result of large bouldery fan deposits caused by steep-gradient tributaries of the New River. The tributary debris-fan deposits associated with rapids result from debris-flow events. Flow becomes supercritical and rapids are produced as the river attempts to adjust to the constricting and shallowing conditions created by the protrusion of the tributary fans into the channel. Tributary debris-fan deposits are dominantly involved in the origin of five of the 22 rapids (Table 11). Fayette Station Rapid is the best example of a tributary debris-fan deposit creating a major rapid (Figure 16).

Alluvial Deposits

Along most river systems, small or large, gravel accumulations tend to produce roughly regularly spaced riffles or rapids (Leopold, 1969). Along the narrow main channel of the lower New River Gorge, only a few rapids result from such alluvial deposits. Alluvial-deposit rapids only occur in the southern portion of the study area,

Figure 16: Fayette Station Rapid caused by convergence where a debris fan from Wolf Creek tributary enters on the left bank in the downstream direction.

Figure 17: McCabes Rapid caused by partial reworking of debris-flow deposit on right valley wall resulting in the formation of a debris-bar deposit.

upstream from where the Nuttall Sandstone Member forms the canyon rim. These alluvial deposits are subdivided into gravel-to-boulder-sized bars and debris bars. Only four of the 22 major rapids are influenced by the presence of gravel-to-boulder-sized alluvial deposits (Table 11). No major rapids are solely created by alluvial bars in the lower New River Gorge.

Debris bars, also referred to as rock gardens, occur as prominent features within the main channel, resulting in the formation of rapids. Of the 22 major rapids, three are influenced by the presence of debris bars (Table 11). In two of these three rapids, the debris-bar deposit is dominantly involved in the formation of the rapids. McCabes Rapid is the best example of a debris-bar deposit origin (Figure 17).

Bedrock Outcrop / Ledges

Shallowing conditions associated with resistant bedrock outcrops along the stream channel bottom produce rapids in the study area as well as in many other eastern rivers. Along the lower New River Gorge, there are only three locations where bedrock outcrops are observable along the banks of the river channel (Figure 11). In these areas, the locally resistant channel bottom creates shallow and accelerated flow conditions. Downstream, a ledge-like feature is produced as the river channel cuts beneath the resistant sandstone unit into a weaker, typically shaley, unit. Lower Railroad and Lower Keeney rapids are dominantly created by visible bedrock outcrops.

In some cases, bedrock outcrop is completely submerged by current flow conditions or covered by surficial deposits. In two areas, a ledge-like feature similar to those associated with visible bedrock outcrops can be identified from aerial photos of the river channel and stream-profile data. In both of these areas, the presence of a bedrock outcrop within the main channel is inferred. Upper Railroad Part 1 and Greyhound Bus Stopper rapids are dominantly created by inferred bedrock outcrops (Table 11). Greyhound Bus Stopper Rapid is the best example of this origin type (Figure 18).

Difficulty Rating vs. Rapid Origin

Difficulty rating and dominant origin were compared for each of the 22 rapids to determine whether the origin of rapids is associated with their difficulty rating (Table 12).

Difficulty Rating*	**I**	**II**	**III**	**IV**	**V**
# of valley-wall debris-fan origins		1	2	2	1
# of valley-wall debris-slides/complex origins			3		1
# of valley-wall rock-fall origins	1				
# of tributary debris-fan origins		2		1	2
# of alluvial debris-bar origins			2		
# of bedrock outcrop origins			2	1	1

*Difficulty rating refers to the highest class rating when a class range is given.

Table 12: Difficulty Rating vs. Rapid Origin

Although there is no perfect correlation and the sample size in each class is very small, some general conclusions can be made. The majority of the most difficult rapids, class V and IV, are a result of mass-movement deposits from the valley wall and tributaries. Valley-wall mass-movement deposits also account for the majority of class III rapids. Alluvial debris bars and bedrock outcrops are equally responsible for the remainder of class III rapids. The easiest rapids, class I-II, have too few examples to relate to any specific type of deposit.

Mills (1990) determined that boulder size and flow velocity most directly affect rapid difficulty rating. Mills hypothesized about the importance of valley-wall mass movement and regional verses local influences on rapid difficulty rating. Mills found channel-narrowing ratios at rapids were higher and more variable in the lower gorge than the Grand Canyon, suggesting mass movement from valley walls for rapid formation may

Figure 18: Greyhound Bus Stopper Rapid caused primarily by shallowing where a resistant sandstone crops out at river level along the stream channel.

be more important in the lower gorge. Mills also suggested that regional influences, such as general downstream narrowing of the channel due to changes in lithology, may contribute more to the difficulty rating than local influences, such as type of deposit.

In general, the low correlation between rapid difficulty rating and any single type of origin supports Mills' (1990) hypothesis, suggesting a greater importance of the regional rather than local influences. These findings contrast with work by Webb and others (1989), which found that the difficulty ratings of rapids on the Colorado River are primarily controlled by local factors such as size of boulders, history of debris flow, and channel constrictions. The strongest controlling factor on rapid difficulty in the New River Gorge is lithology, which is evidenced by all of the most difficult rapids being located downstream from where the massive Nuttall Member of the New River Formation forms the canyon rim. However, this hypothesis could not be fully tested since the field area is located almost entirely within this condition.

The subjective nature of rapid difficulty ratings is another possible reason for the low correlation between origin and rapid difficulty rating. Difficulty ratings do change with changes in stage, conditions, and surroundings. Therefore, investigations conducted at different water levels are likely to yield different difficulty ratings.

Summary

The geology of the New River Gorge creates not only breathtaking scenery and recreation but also an ideal location to research the origins of major rapids along an eastern river canyon. Mapping at 1:10,000 along an 11 km reach of the lower New River Gorge shows that surficial deposits and, to a lesser degree, bedrock outcrops are responsible for the formation of 22 major rapids. The surficial geology map units include valley-wall mass-movement deposits, tributary-fan deposits, alluvial deposits, and bedrock outcrops. This study also shows that most of the major rapids have more than one type of deposit contributing to their configuration. Such complex origin is a result of multiple deposits from both of the valley side walls and, in some cases, the stream channel. Therefore, the six types of rapid origins identified by this study were based on the surficial deposit dominant in creating supercritical flow conditions.

Half of the 22 rapids are dominated by valley-wall mass-movement deposits constricting the channel. In six of these rapids, the mass-movement deposits have been delivered to the valley floor by debris flows. Most of the remainder of valley-wall mass-movement deposits are delivered to the valley floor by debris slide and complex failures. Only one rock-fall deposit results in the formation of rapids.

Tributary debris fans are the second most common type of rapid-forming deposits. Of the 22 rapids, five are created by tributary debris fans. Application of paleohydraulic equations indicates that these tributary fans are created by debris flows rather than typical alluvial processes.

Alluvial deposits and bedrock outcrops are almost equally uncommon as causes in the formation of rapids along the lower New River Gorge. Alluvial debris bars influence the formation of three rapids, but they are the dominant deposit responsible for creating only two rapids. Visible and inferred bedrock outcrops are responsible for the formation of four rapids.

Conclusion

The hydraulic features of the rapids of the lower New River Gorge predominantly reflect a dynamic equilibrium between the flow in the New River channel and mass-movement phenomena from valley walls and tributaries. Most rapids, 16 of 22, are the result of the local topography and underlying geology promoting abundant mass-movement. Therefore, the origins of rapids in the lower New River Gorge provide an ideal location to test many existing theories on the hydraulics of western river canyons, and apply them more broadly to eastern rivers.

This study concludes that the rapids of the lower New River Gorge are similar to those of the Colorado River in the Grand Canyon (Powell, 1895; Dolan and others, 1978; Graf, 1979; Webb and others, 1988, 1989; Melis and others, 1993), as well as numerous other western canyon rivers (Liquori, 1994), because they reflect the great importance of mass-movement deposits, specifically tributary debris fans, in the formation of rapids.

This study also supported similar findings on the hydrologic characteristics of waves associated with rapids in western canyon rivers (Leopold, 1969; Kieffer, 1985) Rapids with an alluvial debris-bar origin tend to have waves and riffles in shallower water. Deep-water waves caused by flow convergence are common in rapids originated from tributary debris fans. In two of the three locations with visible bedrock outcrop, there are waves and rapids present. Large rocks also commonly result in the formation of rapids in the lower New River Gorge. The major causes of waves within rapids are the presence of substantial obstacles in the bed, such as rocks, converging or irregular shoreline due to the presence of surficial deposits, and contraction and expansion of flow as it goes through a channel of varying cross-sectional area due to changes in bedrock lithology.

Future Research

The successful application of hydraulic principles developed in canyons of the western United States to an eastern canyon river suggests that valley geometry is as important to rapid formation as locational factors such as climate and bedrock. Future research on the origins of rapids may strengthen this correlation between eastern and western canyon rivers, as well as examine the potential of a worldwide application of all canyon river hydrological theories.

This study also indirectly emphasized the great impact small tributary streams can have on the hydraulics of large rivers. Therefore, any conditions that may affect the fluvial geomorphology of these tributaries, such as large-scale land disturbances, are of great hydrologic significance. Future research into drainage-altering practices, such as those related to logging and coal mining, would be of importance to understanding stream environments throughout the basin.

Lastly, Davies and Ohlmacher (1977) generalized that the rapids of the New River Gorge and underlying deposits creating them are in equilibrium with pre-dam discharges and stable under present flow conditions since they were largely created in prehistoric times. However, as the channel configurations of rivers continue to gradually change over time, configurations of their rapids are also likely to change. Melis and others (1993) investigated the role of debris flows in creating tributary-fan rapids with respect to regulated flow conditions along the Colorado River. Melis and others (1993) found that, prior to regulation by the Glen Canyon Dam, the severity of rapids was limited by the frequent reworking of sediments by large floods. Graf (1979) also suggested that future theories of rapid genesis in canyons should be based on the operation of the river system as a whole and account for the effects of climatic and hydrologic conditions that have recurrence intervals greater than 100 years. Therefore, any investigation into the stability or increased severity of rapids along the New River Gorge, or any other controlled canyon river, would be of interest.

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Appendix

Figure 11: Surficial geology map of near-channel deposits and bedrock outcrops in the lower New River Gorge, West Virginia

Figure 11: Surficial geology map of near-channel deposits and bedrock outcrops in the lower New River Gorge, West Virginia.