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CHANNEL GEOMETRY AND STRATH LEVELS OF THE POTOMAC RIVER BETWEEN GREAT FALLS, MARYLAND AND HAMPSHIRE, WEST VIRGINIA

by

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ABSTRACT

The channel gradient and strath levels of the Potomac River and most of its North Branch, extending from Hampshire, West Virginia to tidewater in Washington, DC (a distance of 375 km), are examined. In this distance, the river crosses six geological provinces: the Allegheny Plateau, the Valley and Ridge (accounting for about two-thirds of the total distance), the Blue Ridge, the Culpeper Basin, the Piedmont, and the Coastal Plain. The passage from the Allegheny Plateau to the Valley and Ridge coincides with a change of river course from paralleling the structureal trend to athwart the structural trend. The river slope in the Valley and Ridge province is a linear function of the river distance; the profile is well described by a quadratic equation. Several large clusters of meanders occur within this province, but only in specific bedrock formations that include both massive carbonate strata and greywacke-and-shale strata. These meanders, as well as all the larger tributaries to the Potomac River, are deeply entrenched. The pre-entrenchment elevations of the confluences and of the interfluves between meander loops positively correlate with the river distances and define two least-squares straight lines, one for the entire Valley and Ridge province and the other for the reach farther downstream. The slopes of these lines, respectively 0.04% and 0.07%, define the paleoslopes of the pre-entrenchment valley floors. They are not affected by the bedrock, presence of meanders, or entrance of large tributaries. These paleo-slope values are similar to the respective modern reach values; the gentle slope across the modern Culpeper Basin is compensated by steeper slopes in both the Blue Ridge and the Piedmont. The paleoslope for the reach below Harpers Ferry is consistent with the hypothesis that channel downcutting from its "200-ft strath" to its "140-ft strath" (referring to elevations near Great Falls), documented elsewhere, caused the entrenchment. The close agreement of the paleo- and modern slope values in both

reaches shows that the baselevel lowering and entrenchment were not caused by crustal deformation but by either eustatic sealevel drop or epeirogenic uplift. The interfluves of the large meander cluster at Paw Paw, West Virginia are about 250 ft higher than the others and were formed at an earlier time when the Devonian greywacke and shale beds were leveled to a broad flood plain. This event could be coeval with the Miocene-Pliocene fluviatile beds at Tyson's Corner near the Capital Beltway. The Potomac was even then a large river, having a drainage area not significantly smaller than its modern descendant. Fitting the relative sequence of events at different points of the river into a comprehensive chronology, however, is not yet feasible, pending direct determination of exposure and erosion ages for the morphological features.

INTRODUCTION

The Potomac River basin (Figure 1) is nestled in the mid-Atlantic seaboard, and heads near the east front of the Allegheny Plateau in West Virginia (Rodgers, 1965; Stanton, 1993). Unlike its larger neighbour to the north, the Susquehanna basin, the Potomac basin lies entirely beyond the reach of meltwater from Quaternary ice sheets, even though during the Pleistocene the upper reaches of the river basin were probably within a climatic and vegetation zone somewhere between taiga and tundra (Conners, 1986; Delcourt and Delcourt, 1986; Whitehead, 1965; Richards and Judson, 1965; Kutzbach and Wright, 1985). This climatic period may well have coincided with the evolution of much of the Potomac River as reported in this study, though firm geochronologic data are so far unavailable (Zen, 1997). Although much has been written about the geomorphology of the river (e.g.

Reed, 1981; White, 1953; Hack, 1982; Tormey, 1980; Zen, 1997), many puzzles remain. Here, I relate two of these puzzles, the entrenched tributaries and the entrenched meanders, to the geomorphic history of the river valley as deduced from a study of its history below Great Falls.

The river channel between Great Falls and Key Bridge in Arlington, VA is a bedrock gorge, having steep rock walls as much as 80 ft above the channel floor and as much as 60 ft above the water surface at normal flow. This gorge is incised into an abandoned and wide bedrock channel, called the "140-ft strath" (Zen, 1997). That strath has a nearly-horizontal surface and forms much of the Great Falls National Park in Virginia and the area near the Great Falls Tavern Visitor Center (including Olmsted Island, Falls Island, Rocky Island, Sherwin Island, and Bear Island) of the Chesapeake and Ohio Canal (C&O) National Historical Park in Maryland. Below Great Falls, the strath still functions as the flood plain during exceptional floods. Details of the strath levels within the gorge below Great Falls have been described elsewhere (Zen, 1997).

This study uses a system that records river distance with the reference zero-point just downstream from the 14th Street Bridge in Metropolitan Washington DC. All distances are positive in the upstream direction. The river distances are measured along a series of mid-thalweg straight line segments which lie within the modern river channel during normal discharge. The terminations of these segments, or control points (CP), are recorded as latitudes and longitudes reckoned on the basis of the 1927 North American Datum, which is the basis of the U.S. Geological Survey's 1:24,000 topographic maps (see Welch and Homsey, 1997). The precision of my measurement is 0.5 mm on the 1:24,000 scale topographic map, or 12 m on the ground; the ground distance is recorded to the nearest 10 m. The overall accuracy of location is estimated to be about 1 second (about 20 m on the ground; 1 mm map distance = 1 second of longitude or 3/4 second of latitude). The control points, their river distances, and their map locations are given in Appendix 1.

The control point designated in Zen (1997) at +27.78 km, at Memorial Bridge, is now redesignated at river distance 2.22 km, and the zero-point of the old reference system at Gladys Island is now at a whole-number value of 30.00 km. In practical use the control point at Memorial Bridge is the one that matters because it is both the first point in the Coastal Plain and well within the tidewater realm. All my computations terminate there.

THE RIVER CHANNEL

The Modern River Channel

Bedrock Along the Channel The profile of the modern Potomac River, based on water surface elevations, is given as the lowest line in Figure 2. Between Memorial Bridge and the hamlet of Hampshire, WV on the North Branch, where the profile ends, the distance is 371 km and the elevation rise is 1000 ft (Table 1). Within this distance, the river crosses six geological and physiographic provinces. At Memorial Bridge it is within the Coastal Plain. Between Roosevelt Island, just upstream, and Blockhouse Point (a distance of 36 km), it is in the Piedmont; this segment includes the gorge complex (Zen, 1997). Between Blockhouse Point and Point of Rocks (42 km), the river is in the Culpeper Basin of Mesozoic rocks, except for a short distance near Point of Rocks, where a fault block of Lower Paleozoic sedimentary rocks occurs between the Culpeper Basin and the Blue Ridge proper (Cleaves and others, 1968; Burton and others, 1992). The Blue Ridge province extends from Point of Rocks as far as Dam no. 3 of the C&O Canal system just above

Harpers Ferry (22 km). Between Harpers Ferry and Pinto, MD (232 km), the river is in the Valley and Ridge Province. The river follows the boundary of the Allegheny Plateau between Pinto and Keyser, WV (24 km), and is entirely within the Plateau between Keyser and Hampshire, WV (15 km; Schultz and McDowell, 1989).

The 140-ft strath that flanks the gorge below Great Falls is a useful starting point for discussing the channel morphology because this strath merges smoothly into the contemporary Potomac River channel at the Great Falls Water Supply Dam one-half kilometer above Great Falls (Zen, 1997). The pre-gorge morphology and gradient can be confidently traced to Plummers Island just inside the Beltway (I-495) bridge, and with slightly less confidence to High Island near Little Falls, respectively approximately 15 and 10 km above Memorial Bridge.

The 140-ft strath below Great Falls lies entirely on bedrock, whereas above this point and within the Piedmont the channel is partly on bedrock and partly on alluvium. The bedrock consists of schist, quartzite, and meta-greywacke, intercalated with amphibolite and small granitic dikes and plugs.

The Culpeper Basin contains unmetamorphosed sandstone, shale, mudstone, basalt and diabase sill, but the resistant igneous rocks are not important along the river (Burton and others, 1992). Midway across the basin older rocks closely approach the river from the Maryland side (Cleaves and others, 1968), but they are not recorded on the Virginia bank (Burton and others, 1992) so presumably do not affect the river channel.

The next geological province upstream is the Blue Ridge, consisting of a core of upper Middle Proterozoic ("Grenvillian") basement rocks flanked by Upper Proterozoic sedimentary and volcanic rocks, which in turn are flanked by Lower Cambrian sedimentary rocks. Among the latter, the basal

Weverton Quartzite forms high ridges both at Point of Rocks (Catoctin Mountains) and below Harpers Ferry (South Mountain, Elk Ridge; Loudoun Heights and Maryland Heights). The Weverton causes nickpoints in the channel that controls the river gradient. The overlying Harpers Formation, containing significant quartzite beds, and, on the west side, the next younger Antietam Quartzite also contribute to the river gradient, although in a more subdued manner than does the Weverton. For the purpose of this study, the western boundary of the Blue Ridge is identified with Dam no. 3 above Harpers Ferry, coinciding with the contact between the Harpers Formation and the Antietam Quartzite (Nickelsen, 1956).

Within the Valley and Ridge, the river channel, in an upstream direction, traverses first through Cambrian and Ordovician rocks dominated by carbonate but including the shale bed of the overlying Martinsburg Formation, then through younger formations dominated by Upper Devonian clastic units. Above Keyser, West Virginia, the channel is in Carboniferous clastic strata.

Gradients of the Modern River To discuss the modern gradient, we must first consider the effect on gradient estimation of the dams on the river.

The C&O Canal had seven water-intake dams, numbered consecutively in an upstream direction. Because the dams were designed to divert water to feed the canal locks, they were located near the top of steep natural grades. Dam no. 1 at Little Falls is in the Potomac gorge and does not concern us here. Dam no. 2, at the boundary between the Piedmont and the Culpeper Basin, was originally 4 ft high (Hahn, 1992, p. 52) but has been reduced by erosion (Davies, 1989). Dam no. 3, just above Harpers Ferry and at the boundary between the Blue Ridge and the Valley and Ridge provinces, was originally about 1 m high but has been breached. It does not seriously impede gradient estimation.

Dams 4 through 8 are within the Valley and Ridge. Dam no. 4 is discussed in Appendix 2. Dam no. 5 near the confluence of Little Conococheague Creek poses no difficulty in the reconstruction of the original channel gradient. Dam no. 6, above the confluence of Cacapon River, has been reduced to rubble (Hahn, 1992, p. 182). Dam no. 7 was never built (Stanton, 1993, p. 16). Dam no. 8 just below Wills Creek was destroyed in 1958 (Hahn, 1992, p. 222).

In addition to the C&O Canal dams, the Great Falls Water Intake Dam above Great Falls is discussed below. A power plant dam in Williamsport (near CP129, river distance 160.9 km), and a dam near Potomac Park upstream from Cumberland (CP354, river distance 326.5 km), are in the middle of long reaches and do not affect the gradient estimate.

From Dam no. 2 at Blockhouse Point downstream to the south end of Gladys Island, where the influence of inpoundment at the Great Falls Water Intake Dam begins, the average water surface gradient is 0.08% (22 ft in 8.8 km; Table 2). From Dam no. 2 to the summit of Plummers Island, following the 140-ft strath, the gradient is 0.07% (51 ft in 22 km); to the summit of High Island (52 ft in 28 km) it is 0.06%. Although these figures may be slightly high because the layer of water at Plummers and High Islands is not included, the gradient estimate should be good to $\pm$0.01%. The modern overall gradient between Dam no. 2 and tidewater, including Great Falls, is 0.13% (156 ft in 35.3 km).

Dam no. 2 still interferes with estimating the natural slope across the Culpeper Basin. However, even the maximum estimate, obtained by taking the pre-dam water surface to the base of the dam, is only 0.02% (29 ft in 42 km), just 30% of the slope within the Piedmont. The channel within the Culpeper Basin is largely alluvium-floored and contains many large aggradational islands, but no meander loop.

From Point of Rocks to Dam no. 3 near Harpers Ferry, the channel traverses across the Blue Ridge anticlinorium in a bedrock channel of low sinuosity, has many rapids, and a gradient of 0.09% (63 ft in 22 km).

The overall gradient between Dam no. 3 and Gladys Island (a drop of 114 ft in 72 km of river distance) is 0.05%. From Dam no. 3 to Plummers Island (84 km of river distance), the gradient is 0.06% (Table 2), the higher value reflecting the reduced role of the Culpeper Basin. This value is the appropriate one for later comparison with their ancient counterparts.

Between Dam no. 3 and Pinto, MD on the North Branch, the river is in the Valley and Ridge province. The channel is partly bedrock-floored. For purpose of discussion, I distinguish three reaches. In an upstream direction (Table 2), the first reach extends from Dam no. 3 to the junction of the North and South Branches at Oldtown, and has a gradient of 0.04%[1].

The second reach extends from Oldtown along the North Branch to Wills Creek in the city of Cumberland, MD. Here is the upstream terminus not only of the C&O Canal, but of a river flowing athwart the geological structures. The gradient of this reach is 0.07%. The combined gradient of the two reaches is just under 0.05%. These values may be compared with the smoothed slopes based on fitting the data to one-parameter equations (Appendix 2).

Within both reaches, the river has several clusters of entrenched meanders (Table 3; see below). Removal of this sinuosity (i.e. substituting the along-thalweg distances by the straight-line distances

[1]At Green Springs Run (river distance 184 km) near McCoy Ferry, the predominantly Cambro-Ordovician carbonate-rich bedrock yields, in an upstream direction, to a Middle to Upper Devonian, predominantly clastic bedrock sequence, but this change does not appear to affect the river gradient.

from the beginning to the end of each meander cluster) could increase the gradient by as much as 0.02% (Table 2, *italics*), but this procedure is probably not justified because, the meanders being deeply entrenched, the modern river gradients were not responding to a meandering regime.

The third reach of the North Branch extends upstream from the junction with Wills Creek, where North Branch turns abruptly southward to follow the breached Wills Mountain anticline. Between Pinto, MD and Keyser, WV the river tracks the boundary with the Allegheny Plateau (Schultze and McDowell, 1989; Cleaves and others, 1968; Cardwell and others, 1968). From Wills Creek to Keyser the river gradient is a steep 0.15% (200 ft in 42 km).

At Keyser, the North Branch makes another right-angle turn, temporarily becomes a transverse stream again, and enters the Allegheny Plateau. At Westernport, MD it makes a third right-angle turn, and follows the Georges Creek syncline southward. The gradient within this reach is 0.44% (elevation drop of 200 ft in 14 km). My profile ends at the hamlet of Hampshire, WV, just above Westernport, where the 1,000 ft contour line crosses the channel. In the next 20 kilometer or so of river distance above this point the average gradient exceeds 0.7% and entrenchments cannot be firmly defined; the river is no longer suitable for my inquiry.

The overall gradient from Hampshire to tidewater is 0.08%.

Figure 3 plots the modern gradients (*s*) of the river taken in 3 km increments between Memorial Bridge and Hampshire. The plot shows several prominent spikes. In an upstream direction, the first pair of spikes (*s* about 0.2%) is caused by Little Falls and Dam no. 1, but does not affect the discussion of the pre-gorge channel. Likewise, the spikes at Great Falls and Mather Gorge (*s* as much as 0.71%) do not concern us here.

The spike of 0.12% at Dam no. 2 reflects the effect of that dam. The spikes within the Blue Ridge province largely reflect the natural river gradient, although the highest value ($s = 0.33\%$) does include the effect of Dam no. 3. The spike, $s = 0.16\%$, between meander Clusters 2 and 3 near Sherpherdstown, is caused by Dam no. 4 and is examined in detail in Appendix 2.

Straths of the Potomac River

Although the 140-ft strath merges upstream with the modern channel, it is not the oldest channel; two higher and presumably older levels have been recognized (Zen, 1997). The best evidence for the lower of these levels, called the "155-ft" strath, is a series of trimmed spurs near Blockhouse Point. The spurs are transverse ridges athwart the steep, straight, river-cut channel bank that share a common sharp base, separated from one another by small ravines. The trimmed spurs occur within both the Culpeper Basin and the Piedmont, with a barely discernible paleoslope change across this boundary (Zen, 1997).

The higher of the two older straths is a "200-ft" strath. At Glade Hill within the Great Falls National Park, it is recorded by a deposit of large boulders capping the hill at that elevation. The field evidence and significance of this boulder bed in the history of the river was discussed in Zen (1997; see also Figure 2) and will be summarized later.

Yet even the 200-ft strath was not the most ancient record of a fluviatile environment within the Potomac River basin. At Gantt Hill and Freedom Hill near Tyson's Corner within the Piedmont province, fluviatile deposits at an elevation of about 450 ft span the Miocene-Pliocene transition

(Darton, 1951; Zen, 1997). As of 1984, the hills topped off at about 500 ft, but they are being destroyed by urban sprawl. By contrast, the 200-ft strath could be contemporaneous with the 300-350-ft upland surface on which Gantt and Freedom Hills sit as monadnocks.

ENTRENCHED MEANDERS AND TRIBUTARIES ON THE POTOMAC RIVER

The Entrenched Meanders

The Potomac River has no meander, modern or entrenched, between Harpers Ferry and the Coastal Plain; not even in the Culpeper Basin dominated by easily eroded sedimentary rocks. In contrast, immediately upon entering the Valley and Ridge, the channel contains entrenched meanders (Table 3); their location apparently determined by sufficient thicknesses of favourable bedrock lithology. For ease of discussion I consign the meanders to nine clusters. Proceeding in an upstream direction, Cluster 1 is just above Dam no. 3, where the river leaves the resistant Antietam Quartzite and enters the Lower Cambrian Tomstown Dolomite, consisting of between 200-1,000 ft of dolostone and limestone (Cleaves and others, 1968). Between control points 68-77, over a distance of 8 river km and 6 straight-line km, the channel sinuosity is only 1.4 (Table 3), barely qualifying as "meandering" (Leopold, Wolman, and Miller, 1964, p. 295).

Meander Clusters 2, 3, 5, and 6, are all within Lower Ordovician (Beekmantown) carbonate formations (Cleaves and others, 1968). Cluster 2 is well formed in the Conococheague Formation (1600-1900 ft of mostly limestone), and is between control points 82-102, a distance of just over 16 river km and a straight-line distance of nearly 7.5 km, for a sinuosity of 2.2. Cluster 3, between control points 108-120, covers over 11 km of river distance and just over 4 km of straight line distance, for a sinuosity of 2.6. It overlies the Rockdale Formation, 1700-2500 ft of dolostone and dolomitic limestone that lies above the Conococheague (Cleaves and others, 1968).

Cluster 4, between control points 121-127, is a single large loop, having a river distance of 6.7 km and a straight line distance of 3.6 km for a sinuosity of 1.9. This loop is developed on the Ordovician Martinsburg Formation, 2000-2500 ft of shale and siltstone (Cleaves and others, 1968). Though clastic, the Martinsburg appears to favour meanders as it hosts the splendid and high-sinuosity meanders of the Opequan Creek and the Cocococheague Creek, both tributaries to the Potomac, and the even more magnificent meander loops of the Conodoguinet Creek, a tributary of the Susquehanna River that shares the same lowland valley with the Conococheague. For the Conococheague, the width of the meander belt is coextensive with the outcrop width of the formation. Though the Potomac itself can claim only a single loop over the Martinsburg Formation, the loop does span the entire outcrop width.

Cluster 5, between control points 134-139, covers 3.6 km of river distance and 2.3 km of straight line distances, for a sinuosity of 1.6. Cluster 6, between control points 140-151, covers a river distance of 9.7 km and a straightline distance of 2.4 km for a sinuosity of 4.0. Cluster 5 is in the Rockdale Formation again, and Cluster 6 is in the Conococheague again. The massive carbonate units clearly favour meanders; comparison of the geologic map with meander locations shows that large meanders resulted wherever the river encounters sufficient widths of these formations.

Cluster 7, between control points 191-230, is a very long stretch of meanders having large amplitudes and wave lengths (both ca. 5 km), over a river distance of 31.9 km and a straight line distance of 11.5 km, for a sinuosity of 2.8. This cluster of magnificent meanders below Paw Paw challenged the builders of railroads and the C&O Canal, and will be discussed again. Cluster 8, between control points 230-249, covers a river distance of 9.8 km and a straight line distance of 4.3 km for a sinuosity of 2.3. Although contiguous, the two clusters are separately treated because Cluster 8 has smaller amplitude and wave length (ca. 2 km) and much lower interfluve elevations (i.e. land elevation between successive meander loops); they have different morphological histories. Both clusters are on Upper Devonian units assigned by Cleaves and others (1968; "Dch" on their map) to the Chemung Formation, 2000-3000 ft of greywacke, siltstone, and shale, the Brallier Formation, 1700-2000 ft of shale and siltstone, and the thinner Harrell Shale. These formations also host the meanders on the Cacapon River and the Little Cacapon River (Cardwell and others, 1968).

Cluster 9, between control points 292-322, covers a river distance of 13.3 km and a straight line distance of 4.3 km, for a sinuosity of 3.1. This cluster of two sweeping loops occurs just below Cumberland and is developed in Dch again.

The development of large meanders within Devonian greywackes and shales is puzzling. One might expect massive carbonate formations to host meanders because these rocks are readily eroded in temperate climate, but one hardly expects mixtures of shale, siltstone, and greywacke to do so. Yet the correlation of location of meander clusters with stratigraphic units makes that inference compelling.

The Entrenched Tributaries

Tributaries streams join the Potomac River at entrenched confluences, showing incision of many tens of feet. This relation is ubiquitous within my study area irrespective of the bedrock. Below Great Falls, such entrenchment could be explained at least partly by the formation of the gorge (Zen,

1997) leading to the development of hanging valleys and to nickpoint retreat in the tributaries; for example, the entrenchment of the lower 60 feet or so of the Difficult Run valley can be so explained (Zen, 1997). This explanation cannot apply upstream from Great Falls.

The locations of confluences of the large tributaries and many, though not all, of the smaller tributaries to the Potomac River above Great Falls are marked along the base of Figure 2. For ease of discussion, these tributaries may be put in three size groups. The first are the small, kilometer-long gullies. The second are creeks tens of kilometers long. The third are large rivers including Monocacy River, Shenandoah River, Conococheague Creek, Cacapon River, and South Branch of the Potomac. Gullies shorter than ca. 1 km are ignored because they may be too young to shed light on the geomorphic history.

For the small, km-long gullies, identification of a former confluence level on the topographic map is commonly fairly straightforward because their slopes are typically steep just above the confluence, but flatten shortly upstream with a sharp nickpoint. The elevation of the nickpoint is taken as the former confluence elevation, no correction being made for the short projection downstream to the confluence points. The error of estimation of the former confluence elevation is probably no more than the contour interval of the map (either 10 or 20 ft).

Tributaries tens of km long are numerous, especially in the Valley and Ridge province. Those shown on Figure 2 are a fairly representative lot. Estimating former confluence elevation of these streams is less accurate than for the small gullies because the nickpoints are harder to identify and because greater stream power can cause more obliteration of the pre-entrenchment landform.

However, remnant terraces and valley floors, as well as sharp truncations at base of spurs (and top of slipslopes) that indicate the limit of a strath, allow the former strath elevations to be estimated, within an uncertainty of no more than two contour intervals.

Considerable uncertainty attends estimation of the former confluence elevations for the large tributary rivers because these rivers have caused considerable landform modification since entrenchment. Shenandoah River, one of the larger, typifies the challenge. Some terrace levels above its confluence at Harpers Ferry are useful, as is an abandoned channel at Snyder Hill at 430 ft. However, the uncertain correction for the former gradient of these rivers over long distances add to the problem; for the Snyders Hill gap, I used a former gradient of 0.06% over a distance of 10 km. The Monocacy River valley has preserved terraces and/or straths which are more readily identifiable. Reconstruction of the strath level of Conococheague Creek is easy because, flowing within the Ordovician Martinsburg Formation, the river has developed magnificent meanders (see discussion of meander Cluster 4) and their interfluve elevations were useful proxy estimators for the amount of entrenchment.

Deciphering Former Potomac River Channel Levels

The former levels of tributary streams near its confluence to the Potomac River are read off the topographic maps; repeat readings are separately recorded. For the confluence of Catoctin Creek (Maryland), corroboration was obtained by the presence at the confluence of an abandoned meander bend of the Potomac River (Scott Southworth, oral communication, July 1996). These estimates are shown separately in Figure 2 and in Appendix 2.

The former channel levels of the Potomac also can be directly read from the interfluve elevations of entrenched meanders. These features are identified on topographic maps as extensive flat areas that locally may contain small closed depressions and/or minor channels. Exceptionally, these areas contain prominences interpreted as paleoislands that hint at even earlier history. This procedure meets no difficulty in the meander clusters within the Cambrian and Ordovician carbonate bedrock units. The interfluve for the single meander loop within the Martinsburg Formation is of questionable reliability because it stands alone, even though the interfluve is extensive and has the appearance of a dissected "plateau". The estimated elevation, 540 ft, is too high when compared to the levels for for the interfluves within the lower reaches of Conococheague Creek just upstream, developed within the same bedrock unit.

With this exception, the elevations within the Ordovician bedrock belts are mutually consistent, and gradually increase upstream (Figure 2). In contrast, within the Devonian bedrock reach, the interfluves for meander Cluster 7 - the spectacular, deeply entrenched meander loops near Paw Paw- have been deeply dissected; moreover, they are well over 300 ft above the modern river level, rather than 100-140 ft as is common for the other meander clusters. As the elevations of Cluster 7 are consistent from one interfluve to the next, they presumably record a real, albeit older part of the channel history than that recorded in the Beekmantown terrain. I will discussed it later.

The interfluves of Cluster 8 are at about 600 ft, 100 ft above river level and nearly 200 ft lower than those of the contiguous and downstream Cluster 7. These lower interfluve elevations are corroborated by the presence of a large (ca. 4 km amplitude) abandoned horseshoe valley just above the village of Paw Paw, now occupied by Reckley Flats and Pursalane Run. The valley has a flat valley floor at 640 ft. This horseshoe valley is continued in an upstream direction to an abandoned meander bend (elevation 640 ft)just east of the hamlet of Little Cacapon, and in a downstream direction with another abandoned meander loop that sweeps behind Bevan Hill in the town of Paw Paw; the total amplitude of the reconstructed meander loop is about 5 km and modern river shortcuts these loops (Figure 4). Farther downstream and within the entrenched channel of Cluster 7, this ca. 600-ft elevation defines the upper elevations of smooth slopes against escarpments showing trimmed spurs, as well as nickpoints along narrow tributaries (Devil's Alley, Roby Hollow, Tunnel Hollow).

South Branch of the Potomac River, near its confluence with North Branch, shows terraces and slip slopes having about 60-100 feet relief. These terraces surround isolated higher interfluves about 200 ft above river level, as does Cluster 7. Farther upstream along the South Branch, alluvial deposits in abandoned meander loops and horseshoe valleys record river levels (Froelich and others, 1992) 60-120 ft above the modern river, that record intermediate steps of the entrenchment process. Though I have not examined these data, they seem to form a consistent set.

Interpreting the Elevations of the Entrenched Tributaries and Meanders

Downstream from Harpers Ferry My interpretation of the elevations of the entrenched meanders of Potomac River, and of the entrenched tributaries and their own entrenched meanders, is built on the relations found in the Great Falls area (Zen, 1997).

Glade Hill, located in the Great Falls National Park in Virginia, is a flat-topped hill, unusual for the Piedmont; its uppermost 10 ft is mantled by an unconsolidated deposit of channel boulders. The contact is at 200 ft elevation, and the hill rises 60 ft above the 140-ft strath (the modern channel above Great Falls) which surrounds it on all sides.

The boulder bed overlies unweathered schist of the Piedmont (see Reed, 1981; Reed and others, 1980; Southworth and others, 1996; Drake and Lee, 1989). The well-rounded boulders are as much as 2.3 m in maximum diameter and 1.5 m in intermediate diameter, and consist exclusively (n=280) of quartzite and quartz-rich arkose that lithically best match rocks of the Lower Cambrian Weverton Formation found on the west flank of the Blue Ridge anticlinorium at Harpers Ferry. The river distances from Glade Hill to Harpers Ferry is 73 km. Because there are no remnants of boulders that can be assigned to Piedmont rocks, the boulders must have been carried to Glade Hill by an ancient Potomac River in one or a few floods (Zen, 1997), presumably over a short time interval.

Hydraulic calculations for boulder transport serve to constrain the channel slope (assumed to be same as the energy slope) from the source area to Glade Hill to between 0.05% and 0.08% (Zen, 1997). This range agrees well with a least-squares fitted paleoslope of 0.07%, based on entrenchment and field data (Appendix 3). For comparison, the slope of the modern river channel within the Piedmont is 0.08%; the paleoslope for the 140-ft strath is about 0.06-0.07% (Table 2).

If the paleoslope upstream from Glade Hill were much lower, the boulders would have been trapped in their downstream passage. They might be re-mobilized, but the chances for a monomictic boulder bed would have been reduced. Thus I infer that the modern 3-4 fold slope decrease between the Blue Ridge province and the Culpeper Basin (Figure 3) did not exist then. This agrees with the fact that for the 155-ft strath, the slope was nearly identical on either side of the Culpeper Basin-Piedmont boundary near Blockhouse Point (Zen, 1997, figure 10). The paleo-Potomac River had a different geometry than it does today.

Might the boulders have been transported even with a slope decrease by compensatory changes in the other hydraulic parameters? Such parameters would be: channel roughness (unit stream power increasing as the square of Manning's n), water depth (unit stream power increasing approximately linearly); current speed (unit stream power increasing as the cube of speed), or possibly large-scale increase in turbulence. A gentle slope is not likely to beget greater turbulence. The roughness was unlikely to be greater in the Culpeper Basin than in the Blue Ridge. Water depth in the Culpeper Basin was likely no greater than in the Blue Ridge because the channel was at least as wide in the former. Thus, a decrease in channel slope would *not*, for a given discharge, lead to increased stream power. I thus rule out significant stream gradient reversal during the transportation of the boulders of Glade Hill.

The modern channel from Glade Hill to Harpers Ferry has a slope of 0.05% and is free of meanders. This slope is same as the model-inferred minimum slope and less than the field-based estimate of paleoslope. Therefore, I conclude that the 60-ft elevation difference at Glade Hill between the 200-ft strath and the 140-ft strath was maintained as far as Harpers Ferry. If the paleoslope was steeper at 0.07%, the elevation difference between the two straths would become greater in the upstream direction.

Upstream from Harpers Ferry Within the Valley and Ridge province, estimation of the paleoslope of the Potomac is complicated by the meanders. Using the straightline distances (Table 2), that is, removing the sinuosity, would increase the apparent gradients by as much as 0.02%. Figure 2 displays only the actual modern river distances; however, the data of Table 3 allow estimations that take into account the meander sinuosity.

The modern river slope is slightly over 0.04% between Harpers Ferry and Oldtown, where South Branch and North Branch combine, and 0.07% between Oldtown and Wills Creek, where the North

Branch turns to follow the Wills Mountain anticline. The combined slope for the two reaches is 0.05%. This value is to be compared with the 0.04% paleoslope, based on entrenchments (see below; also Figures 2 and 5) within the same combined reach.

Restored Paleo-gradients Figure 2 shows my estimates of the entrenchments of the tributaries of the Potomac River, including the South Branch, at their confluence with the Potomac. These estimated elevations, each with an assigned uncertainty of 2 contour intervals (40 ft), are plotted against the river distance. Also shown are three reference lines, representing slopes of 0.05%, 0.06%, and 0.07%, that converge on Glade Hill. The amount of entrenchment is consistent with the proposition that downcutting from the 200-ft strath to the 140-ft strath explains the 60-110 feet of entrenchment of the tributaries within this reach of the Potomac River.

A statistical restoration of the gradient is obtained by using least-squares linear regression. This is done in two separate segments. The dataset for the segment between Glade Hill and Harpers Ferry (Appendix 3) includes both entrenched confluences and field data on the Glade Hill boulder bed and the abandoned channel at Snyder Hill. The regressed equation is

$H = 142.8 + 2.206\, \underline{d}, (r^2 = 0.93; n = 24)$

where H = elevation in feet and $\underline{d}$ = river distance in km. The slope, 0.07% (2.206/3281), agrees well with the field-based slope estimate within the limits of uncertainty. The predicted channel elevation at the boundary of the Valley and Ridge province (river distance 102 km) is 368 ft. The validity of the result depends on the assumption that all entrenchment data belong to a single isochron (Zen, 1997); it also depend on all the data having a central tendency. The "central tendency" surely applies to repeated readings of the same confluence, but cannot be assured beyond that point.

Between Harpers Ferry and Pinto, MD, all within the Valley and Ridge province, the least-squares straightline includes all the points except the meander interfluves higher than 700 ft, for reasons discussed elsewhere in this report. The data are given in Appendix 3 and the regression equation (elevation in feet and river distance in km) is

$H = 246.2 + 1.306\underline{d}, (r^2 = 0.89; n = 66)$

and the slope is 0.04% (1.306/3281). The two equations are linear rather than quadratic in elevation, contrary to my fitting of the modern channel (see below); however, nothing more is justified by the data. Note also that there is a discrepancy of 11 ft for the predicted strath elevation at the position of the *modern* boundary between the Blue Ridge and the Valley and Ridge provinces - the upstream equation gives 379 ft whereas the downstream equation gives 368 ft. Inasmuch as the contour interval is 20 ft and my estimated uncertainty of each elevation value is 40 ft, I consider the discrepancy to be acceptable, and infer that the two equations describe a single strath with a slope change at 102 km.

My reconstruction is consistent with the data of Froelich and others (1992), who reported the results of coring high-level terrace deposits on the North Branch and the South Branch of the Potomac, and on the tributaries including the Cacapon. The drill sites were in abandoned horseshoe bends above modern river level. Froelich and others (1992) interpreted the core data as recording several ancient river levels that ranged from a few tens to as much as 120 ft above the modern channel. Site #6, on the North Branch just below Keyser, is plotted on Figure 2. Here the river is at 770 ft and the terrace deposits, resting on bedrock, is between 810 ft and 850 ft, consistent with, though not demanded by the data on entrenchments of tributaries nearby.

THE PUZZLE OF MEANDER CLUSTER 7 NEAR PAW PAW

The meander loops of Cluster 7 downstream of Paw Paw deviates from the above interpretations because the elevations of their interfluves cluster around 750 ft and 850 ft, 300-400 feet above the modern river level, in contrast to the elevations of interfluves for the other clusters, about 150 ft above the river (Figures 2 and 5). When the channel was at the level of the lower set of interfluves, the meanders of Cluster 7 were already entrenched by a couple hundred feet. These meander loops also have unusually large amplitude and wavelength, each about 5 km. The abandoned meander loop that now occupies Reckley Flats and the valley of Pursalane Run (Figure 4) is of the same amplitude.

The consistent elevations of the interfluves of Cluster 7 (Appendix 3, part C) suggest that they are remnants of one or more yet older straths. Two explanations are possible for the large meander amplitude (though not the large wavelength). The first explanation is that the amplitude was inherited from the highest channel level; if so. it may record greater paleo-discharge, caused either by larger watershed area or by a different climate (here called the "static entrenchment model; see Leopold, Wolman, and Miller, 1964). The second hypothesis (Karen Prestegaard, 1997, oral commun.), posits that the river continued to erode into the concave bank at the prows of meander loops during downcutting, thereby enlarging the amplitude (the "slipslope model"). If true, the large amplitude is a later modification of the original meander system, and provides no information on the paleo flux. These two hypotheses may be discriminated by the landform because the "static entrenchment" model predicts tableland interfluves dropping off abruptly near the modern river whereas the "slipslope" model predicts extensive development of inclined hillslopes.

Such an examination (Appendix 4) shows that the amplitude of the Cluster 7 meanders was largely inherited from the highest strath level, with only minor increase through erosion of the concave bank (commonly likely less than 10% of the total; in the worst case, less than 20%). This conclusion justifies using the amplitude to estimate the paleo-flux. Based on the meander amplitude, the paleo-drainage area at this point was 1-2 x 10^4 km^2, and the mean annual discharge was several thousand cfs (Leopold, Wolman and Miller, 1964, Figure 7-48 and Table 7-13). For comparison, the modern Potomac above and including meander Cluster 7 has a drainage area just under 1 x 10^4 km^2, and the mean flux from October 1 1994 to September 30 1995 at the U.S.G.S. gaging station at Paw Paw was 2480 cfs. The ancient Potomac was not a mountain torrent but a large river, powerful enough to sweep out a broad floodplain and to form a large-amplitude meander belt from the locally coarse clastic bedrock. It also seems reasonable to infer that the drainage divide between the Potomac and the Mississippi River systems was not much farther eastward than where it is now (see Harbor, 1996).

We do not know the age of this ancient strath; I can only speculate. If the ancient river had a gradient typical of the modern Potomac downstream from Wills Creek, 0.05%, and if the river distance between Cluster 7 and Cabin John Bridge on the Capital Beltway was equal to its modern value (about 250 km), then a channel at 850 ft (the higher of two concentrations of interfluve elevations for Cluster 7 and the interfluve at the junction with South Branch; see Appendix 4 and Figure 2 and Figure 8) would be at about 450 ft near Cabin John Bridge. Cabin John Bridge is a few km north of Tyson's Corner, where the Miocene-Pliocene fluviatile beds are preserved at an elevation of 430-470 ft (Figure 5; Darton, 1951; Zen, 1997). The 850-ft strath of Cluster 7 and the unconformity at Tyson's Corner may have the same origin.

The close similarity between the paleo river gradients and those of the youngest pre-gorge channel (= the modern channel above Great Falls) allows us to place an upper bound to crustal tilting or warping during this time interval by attributing the slightly higher paleo-gradient downstream from Harpers Ferry to differential uplift. This upper bound for differential uplift is 50 feet (a gradient difference of 0.02% over a distance of about 70 km), located at or near the boundary between the Blue Ridge and Valley and Ridge provinces. However, it seems equally plausible to attribute the down-stream gradient increase to the bedrock contrast at this boundary, such that downcutting from the 200-ft strath to the 140-ft strath allowed a nickpoint to be established here. Upstream from this point, the gradient remained largely unaffected; indeed the close fit of the river profile to a simple quadratic equation rules out nickpoints over a distance of 170 km. Downstream from river distance 161 km, nickpoints can be identified at the boundary of the Blue Ridge and Valley and Ridge provinces and at the boundary of the Culpeper Basin and the Piedmont.

The absence of significant crustal warping or tilting means that the principal cause for the entrenchment and downcutting must have been epeirogenic uplift and/or eustatic sealevel change, and that the depressed slope across the Culpeper Basin was a later development. Although large meanders developed early in the Valley and Ridge province, in the downstream provinces they never developed, not even in the soft sedimentary rocks of the Culpeper Basin. Instead, during that period, the river channel within the Culpeper Basin maintained open, straight reaches with sweeping bends, and a gradient equal to the gradients in both the adjoining provinces of crystalline rocks, in striking contrast to its modern descendant.

SOME CHRONOLOGICAL ILLS

Unfortunately, few reliable chronological controls, be they isotopic, stratigraphic, or even archaeological, exist to permit correlation of morphological events along the length of the Potomac River. Here, I can only attempt to summarize what have been reported, and to evaluate my hypothesis in their light.

At the downstream end, the Miocene-Pliocene fluviatile beds at ca. 450-ft level at Tyson's Corner provides an age limit. This is so because the 200-ft strath in the Great Falls National Park is nested within the 300-ft upland surface, and this surface in turn resulted from a ca. 40-m denudation that reduced the Tyson's Corner site of deposition after an unknown time lapse (see Zen, 1997). Pavich (1986) and Pavich and others (1985) suggested a landform denudation rate of about 8 m/m.y. since the Tyson's Corner deposition to which they assigned a 10 Ma age. When that age is changed to ca. 5 Ma to agree with a 5.3 Ma age for the Miocene-Pliocene boundary (Palmer, 1983), the rate is doubled to about 16 m/m.y. and the upland surface would be formed at an age no older than 2.5 Ma (assuming immediate erosion of the Tyson's Corner bed after deposition). The 200-ft strath can be no older; I surmise its age to be around 2 Ma.

The 200-ft strath is succeeded first by the 155-ft strath (Zen, 1997), then by the 140-ft strath which is the modern channel upstream from Great Falls. The 140-ft strath preceded the formation of the Potomac River gorge complex, which must have taken some time. Peaty material from this level has yielded ^{14}C dates of about ten thousand years (Reed, 1981), but this age refers to the growth of plants after the channel was formed. Other considerations are that the feldspar in arkosic layers within boulders of the Glade Hill boulder beds is but weakly altered, and that the boulder bed rests on saprolite-free crystalline bedrock (Zen, 1997). These bits of information collectively suggest that the 200-ft strath is younger than 1 Ma, but the 140-ft strath is older than 0.01 Ma.

Froelich and others (1992) discussed the age of the cored alluvial deposits near Keyser, WV. Radiocarbon dates from samples collected within the modern alluvial material from the Potomac and Shenandoah drainage systems[2] suggested to them that "the principal alluvial floodplain of the Potomac River and its main tributaries, which enclose dissected remnants of at least two low-lying terraces, is mainly Holocene in age" (1992, p. 15). They further stated that "by using an average rate of modern-day erosion and landscape denudation of 40 mm per 1000 years [40 m/m.y.] (Hack, 1980) and calculating local elevation differences between the modern floodplain and the base of the terrace deposits, relative age can be estimated"; these local ages range from 110 k.y. to about 560 k.y., with even older ages associated with high level deposits. Site #6 was assigned an age of 373 k.y.[3]

As discussed earlier, the positions of the terrace deposits permit their correlation with the 200-ft strath near Great Falls. Because these deposits are within meander loops cut into the upland surface, the downcutting was by a river and its rate is likely faster than the rate of general landform lowering as reported by Pavich (1986). Based on ^{14}C dating and artefacts, Froelich and others (1992, p. 15) inferred that the modern channel was formed during the Holocene (about 0.01 Ma). Both "ages" -

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[2]Froelich and others (1992) cited 2170±180 yr BP near Petersburg and 7060±230 yr BP near Moorefield, both on the South Branch, and 9310 yr BP in the Shendandoah Valley.

[3]Note, however, that Hack's (1980) proposed rate is a rough estimate based on data from different places in the eastern North American seaboard, covering different age spans, for different processes and using different proxy indicators.

about 0.4 Ma for the terrace deposit and 0.01 Ma for the modern river which is the 140-ft strath below Great Falls - are consistent with the "ages" developed down river. The average downcutting rate of 40 m/m.y. is reasonably close to the rate of 27.3$\pm$4.5 m/m.y. for the downcutting of New River in southwest Virginia, based on ^{10}Be and ^{26}Al decay (Granger and others, 1997), in the same general geographical and climatic zone.

The chronological relations for Cluster 7 below Paw Paw must somehow fit into the scheme. Whereas correlation of the highest, 850-ft strath to the Miocene-Pliocene deposit at Tyson's Corner, of the 600-ft straths, interfluves, and nickpoints and the terrace deposit at Site #6 (Froelich and others, 1992) to the 200-ft strath, and of the modern channel level to the 140-ft strath (and to the modern channel at Site #6), are relatively consistent, assignment of ages is more troublesome.

At Glade Hill, the 200-ft strath seems to belong toward the young end of the sequence of events. At Paw Paw, its correlative 600-ft strath is only 5/8 of the way of downcutting from the oldest strath to the modern river, so an age assignment of less than 0.5 Ma, suggested for Site #6 and for Glade Hill seems far-fetched (for Cluster 7, the 750-ft strath, not noted at Tyson's Corner or Great Falls, *could*, without introducing extra inconsistency, record a strath developed on the 300-ft upland level). The landform denudation rate of 16 m/m.y., applied to the reduction from the 850-ft to the 600-ft levels at Cluster 7 (even assuming initiation of downcutting at 5 Ma), would make the latter strath modern, obviously impossible. On the other hand, Granger and others (1997) gave a range of downcutting rates, 20 m/m.y. minimum, 27.3 m/m.y. preferred, and 30 m/m.y. maximum; these rates give lapse times respectively of 3.8 m.y., 2.8 m.y., and 2.5 m.y., and ages of 1.2 Ma, 2.2 Ma, and 2.5 Ma. A faster downcutting from the 600-ft strath to the modern level at 450 ft, perhaps spurred by the Quaternary climate, could accommodate the age constraints and explain the removal of bedrock in the Culpeper Basin leading to the reduction of its interval slope. While the numbers seems plausible, they are entirely speculative and fail to allow for the time required for the nickpoint retreat to migrate from Great Falls to this site. Finally, can different uplift rates at different times and places be reconciled with an hypothesis that the uplift was not accompanied by crustal deformation?

One obviously way out is that my correlations are wrong, but that too is speculation. To resolve the dilemma, we need reliable age data. What does seem firm, however, is that the morphological relations of the Potomac River all the way from tidewater to the Allegheny Plateau are no older than the latest Tertiary, and much of it likely Quaternary, during periods of glaciation when the climate was wetter, when vegetation was more sparse, and when frozen ground must have persisted longer during the winter season, forcing all the precipitation into river flow, thus enhancing downcutting and erosion.

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Figure Captions

Figure 1. The Potomac River Basin, modified from Grover, 1937. Heavy dashed lines, boundaries of geological provinces. Dash-double dot line, limits of the Potomac river basin. Light lines, rivers and shore line. AP, Allegheny Plateau; VR, Valley and Ridge province. BR, Blue Ridge province. CB, Culpeper Basin. GB, Gettysburg Basin. Pd, Piedmont. CP, Coastal Plain. Numbers refer to water bodies: 1, North Branch, Potomac River. 2, Wills Creek. 3, Evitts Creek. 4, Patterson Creek. 5, South Branch, Potomac River. 6, North Fork, South Branch. 7, South Fork, South Branch. 8. Town Creek. 9, Cacapon River. 10, Licking Creek. 11, Back Creek. 12, Shenandoah River. 13, North Fork, Shenandoah River. 14, South Fork, Shenandoah River. 15, Conococheague Creek. 16, Antietam Creek. 17, Catoctin Creek (Virginia). 18, Catoctin Creek (Maryland). 19, Monocacy River. 20, Goose Creek. 21, Seneca Creek. 22, Difficult Run. 23, Rock Creek. 24, Anacostia River. 25, Patuxent River. 26, Patapsco River. 27, Chesapeake Bay. Letters refer to places: An, Annapolis, MD. BP, Blockhouse Point, MD. Bm, Baltimore, MD. Cb, Cumberland, MD. DC, Washington, DC. Gb, Gettysburg, PA. Fd, Frederick, MD. FR, Front Royal, VA. GF, Great Falls, MD. HF, Harpers Ferry, WV. Hg, Hagerstown, MD. Hk, Hancock, MD. Hm, Hampshire, WV. Ks, Keyser, WV. Lb, Leesburg, VA. Ot, Oldtown, MD. Pb, Petersburg, WV. PP, Paw Paw, WV. PR, Point of Rocks, MD. Pt, Pinto, MD. St, Staunton, VA. TC, Tyson's Corner, VA. Wp, Williamsport, MD. Ws, Westernport, MD.

Figure 2. Potomac River profile. Horizontal river distance in kilometers; elevation above sealevel in feet. Names of USGS 1:24,000 scale, 7-1/2 minute quadrangles, are shown in abbreviations at outside of top edge; see Appendix 1 for full names. Boundaries of major geological provinces are marked in upper part of diagram, as follows: CP, coastal plain; Pd, Piedmont; CB, Culpeper Basin; BR, Blue Ridge; VR, Valley and Ridge; AP, Allegheny Plateau. Control points of mid-thalweg lines shown at inside of top edge; for details, see Appendix 1. Confluence locations of tributary streams shown at the bottom edge. Numbered dams are those of the Chesapeake and Ohio Canal system (see Hahn, 1992). Vertical I-beam symbols: estimated elevations (and uncertainties) of tributary streams before entrenchment; multiple symbols refer to separate estimates. Horizontal bars terminated by vertical lines: estimated elevations for interfluves of entrenched meander loops; height of terminal lines gives estimated uncertainties. Crosses: other indicators of strath levels (see text and Appendix 3). Horizontal lines with arrows at ends: extent of major meander loops. The three lines radiating in an upstream direction from Glade Hill have slopes of 0.05%, 0.06%, and 0.07%; (see text). The "entrenched tributary" symbol at Blockhouse Point (37.5 km) comprises four similar values in four adjacent ravines. The cross-bar symbol at 18 km refers to the Miocene-Pliocene unconformity at Tyson's Corner. The three sites between river distances 355 km and 360 km include drill site 6 of Froelich and others (1992) near Keyser, WV; they are not used in the least-squares regression. Vertical exaggeration, 328 X.

Figure 3. Interval gradients of the Potomac River taken at 3 km intervals and based on the river profile of Figure 2.

Figure 4. The horseshoe valley of Pursalane Run and Reckley Flat, which is an abandoned meander loop having floor elevation of 640 ft. Notice that this abandoned channel formerly continued in an upstream direction to an abandoned meander bend southeast of the hamlet of Little Cacaponm and in a downstream direction to another meander bend behind Bevan Hill, Paw Paw. The modern channel cuts across these loops. From the U.S. Geological Survey topographic quadrangle maps for Oldtown (MD-WV, western part) and Paw Paw (WV-MD, eastern part), scale 1:24,000.

Figure 5. Synoptic profiles of the modern and restored Potomac River, plotting river distance against channel elevation. The modern river (shown in upright triangles) is based on U.S. Geological Survey topographic maps (scale 1:24,000). The solid line segments along this profile are the profiles fitted by equations (Appendix 2): quadratic above river distance 161 km, and straight line below that point. The quadratic fit begins to deviate from the actual elevations above Pinto, MD, and differs radically from the actual elevations above Keyser, WV, within the Allegheny Plateau. The two inverted triangles (lower right corner of diagram) are the strath-based extensions of river elevations at the summit of Plummers Island and at High Island. The two long dashed lines are the least-squares straight line fits to the entrenchment data of Appendix 3; circles, entrenchment of tributaries, crosses, meander interfluves (midpoints of relevant river distances are used in the fitting; see top of diagram), six-pointed stars, strath levels. The data points are same as shown in Figure 2 but without the estimated uncertainties. Squares, high-level meander interfluve between the confluence of South Branch and the lower end of meander cluster; the point at the right is the fluviatile deposit near Tyson's Corner. Major tributaries and geological provincial boundaries are shown at the base. Vertical exaggeration, 984 X.

Figure 6. The interval gradient of the modern river (x 10^4) of the Potomac River from river distance 102 km (Dam no. 3) to 373 km (Hampshire, WV). The slope is assumed constant below distance 160.9 km so as to remove the effect of Dam no. 4. Above that point, three fitted curves are shown: solid line, exponential fit. Dashed line, linear fit; both to distance 317 km (Wills Creek) only. Dotted line, exponential fit to Hampshire. Plotted points are the interpolated slopes for data compartments that contain the contour-line crossings of the river as far as Wills Creek, but the entire data set above that point. Inset shows the relation to Wills Creek in greater detail, and includes the entire dataset.

Figure 7. River profile (h) fitted by integrating the slope data. The profile below river distance 160.9 km corresponds to a constant slope of 0.032%; above that river distance the profiles are fitted to an elevation of 340 ft at 160.9 km. Solid line, exponential fit; dashed line, quadratic fit derived from the linear slope fit. As in Figure 6, the data points are for where the contour lines crossed the river. Inset shows the residuals for the several fits: crosses for the quadratic fit and circles for the exponential fit. See Table A2-1 for details.

Figure 8. Topographic map of parts of the Paw Paw and Artemis 7-1/2 minute quadrangles, U.S. Geological Survey, showing the meanders of Cluster 7. Solid lines locate the profiles shown in Figure 9; dashed lines, connecting the prows of adjacent meander loops, limit the profiles.

Figure 9. Interfluve elevations for the five meanders of Cluster 7 between Paw Paw, WV and Little Orleans, MD, based on U.S. Geological Survey topographic quadrangle map, Paw Paw sheet, scale 1:24,000, revised, 1974. See Appendix 4 for discussion for the procedure of data derivation. The individual meander loops are arranged so the modern river starts from a common point; profiles 1, 3, and 5 have polarity opposite to that of profiles 2 and 4. Symbol with "s" notation indicate the elevation refers to the shoulder, not the top, of a hill. (A), elevations as read off the map. (B), elevations adjusted so that the river level of successive loops are brought to a common value, that of the Little Orleans loop. Numbers along the horizontal axis denote the successive 300-m strips, as explained in Appendix 4. Where several symbols from different profiles are located side by side, they share the same elevation and would be superimposed. From downstream to upstream: plus, Little Orleans loop; circle, Beanpatch Hollow loop; triangle, Green Ridge loop; cross, Jerome loop; square, Tunnel Hollow loop. Note that a "valley" in a profile does not record the elevations of valley floors but rather the highest elevation within that strip.

Figure A1-1 Index map of the quadrangles cited in Appendix 1, from U.S. Geological Survey index to topographic and other map coverage, Maryland, Delaware, and District of Columbia, map 38076-MI-99X, 1 sheet. The numbers within a quadrangle are proxies for the quadrangle names, listed in Appendix 1.

Table Captions

Table 1. Elevation of the normal Potomac River water surface along its river distance, based on USGS 1:24,000 topographic quadrangle maps and used to define the water-surface profile of Figure 2.

Table 2. Longitudinal gradients of the Potomac River from Hampshire, West Virginia to Memorial Bridge (between Washington DC and Arlington, Virginia), disaggregated according to the geological provinces. See "notes" for details.

Table 3. Data on meander clusters of the Potomac River and the correlation of their location with the bedrock formations. For interfluve elevations within a given cluster, see text.

Table A2-1. Data used for equation fitting, test of goodness of fit, and the fitted equations.

Appendix Captions

Appendix 1 Location description, latitude, and longitude of control points for the mid-thalweg line, the topographic quadrangles, and confluences of tributaries that coincide with control points. The relevant pieces of the U.S. Geological Survey topographic quadrangle maps, scale 1:24,000, as well as an index map of the quadrangle locations, are part of this Appendix.

Appendix 2 Fitting of river slope data within the Valley and Ridge province (Dam no. 3 to Wills Creek) to simple equations; integration of the equations to obtain elevations; discussions.

Appendix 3 (A), field data on Glade Hill boulder bed at Glade Hill and McPherson Circle, and map data on tributary confluence entrenchment within the Piedmont, Culpeper Basin, and Blue Ridge provinces, used for least-squares fit of paleochannel profile. (B), map data on meander entrenchment and tributary confluence entrenchment within the Valley and Ridge province, used for least-squares fit of paleochannel profile. (C), map and field data for the high-level interfluves at junction of South Branch and at Cluster 7; the Miocene-Pliocene unconformity at Tyson's Corner.

Appendix 4 Information on strath levels of the meander loops of Cluster 7 below Paw Paw.

Table 1. Elevation of Potomac River water surface along its river distance, based on USGS 1:24,000 topographic quadrangle maps and used to define the water-surface profile of Figure 2.

Elevation above sealevel, feet	Distance from zero point, km (last digit = 10 meters)
000	0.00
000	2.22
010	5.16
020	11.65
030	12.03 (at 12.53, Little Falls Dam)
040	14.47
050	19.27
060	20.71
070	24.27
080	25.91
090	29.96
100	26.29
110	26.33
120	26.37
130	26.49
140	26.86
150	27.10 (top of dam, 6-10 ft high)
160	32.40
170	36.62
180	38.68
190	64.16
200	74.14
220	90.84
240	98.46
260	100.39
280	113.86
300	134.61
320	136.57
340	160.93
360	183.98
380	210.30
400	215.64
420	227.12
440	238.28
460	250.98
480	261.59
500	270.86

520	280.10
540	292.34
560	300.83
580	307.58
600	316.55
620	323.63
640	331.06
660	337.21
680	341.85
700	345.29
720	348.75
740	351.74
760	354.16
780	357.65
800	359.10
820	361.52
840	362.77
860	364.59
880	365.93
900	367.09
920	368.81
940	369.49
960	370.93
980	372.10
1000	372.83

Table 2 Cumulative and interval river gradients

Geological Province	Interval distance, km	Elevation difference, ft	Slope, %
	1. Individual Provinces		
Piedmont (Pd)	8.8-0 = 8.8	178-156 = 22	0.08
*Piedmont	21.8-0 = 21.8	178-126 = 52	0.07
Mesozoic (Mz)	50.5-8.8 = 41.7	207-178 = 29	0.02
Blue Ridge (BR)	72-50.5 = 21.5	270-207 = 63	0.09
Valley & Ridge overall (VR)	329-72 = 257	800-270 = 530	0.06
	193	*530*	*0.08*
	213		0.08
Allegheny Plateau (AP)	343-329 = 14	1000-800 = 200	0.44
	2. Valley and Ridge Details		
BR boundary to Oldtown (N and S Branch junction)	252-72 = 180	522-270 = 252	0.04
	125		*0.06*
	145		0.05
Oldtown to Wills Creek junction	287-252 = 35	600-522 = 78	0.07
	26		*0.09*
BR boundary to Wills Creek	287-72 = 215	600-270 = 330	0.05
Wills Creek junction to Keyser, WV	329-287 = 42	800-600 = 200	0.15
	3. Cumulative Gradients		
Pd+Mz	50.5	51	0.03
*Pd+Mz	63.5	81	0.04
Mz+BR	63.2	92	0.04
BR+VR	278.5	593	0.07
	214.5		*0.08*
	234.5		0.08
VR+AP	271	730	0.08

Pd+Mz+BR	72	114	0.05
*Pd+Mz+BR	84	144	0.06
Mz+BR+VR	320	622	0.06
	256		*0.07*
	276		0.07
BR+VR+AP	293	949	0.10
Overall	343	844	0.08
	279		*0.09*
	299		0.09

Note. Figures in *italics* are the distances and gradients that would obtain if the sinuosities of the meander clusters within the reaches of concern (Table 3) are removed and the river distances are substituted by straight line distances. Figures <u>underscored</u> are the distances and gradients that would obtain if the effect of Cluster 7 of Table 3 is not included in the appropriate recomputation (see text for discussion). Downstream termination of gradient calculations for the Piedmont is at river distance 30.00 km (south end of Gladys Island), except that entries preceded by an asterisk (*) refer to computations for downstream termination at the summit of Plummers Island.

Table 3 Major meanders and their sinuosities

Cluster	Quadrangle name	Between points	River Distance, km	Straight Distance, km	Sinuo-sity	Forma-tion
1	Harpers Ferry/ Charles-town/ Keedys-ville/ Shepherds-town	77-68 = 8.05	78.99-70.94	5.93	1.36	Ꞓt
2	Shepherds-town	102-82	102.86-86.69 = 16.17	7.44	2.17	OꞒc
3	Williams-port	120-108	119.79-108.58 = 11.21	4.32	2.59	Orr
4	Williams-port/ Hedges-ville	127-120	127.18-120.53 = 6.65	3.60	1.85	Om
5	Hedges-ville	139-134	139.44-135.88 = 3.56	2.28	1.56	Orr
6	Hedges-ville	151-140	152.14-142.49 = 9.65	2.40	4.02	OꞒc
7	Paw Paw	230-191	230.34-198.49 = 31.85	11.52	2.76	Dch
8	Paw Paw	240-230	240.18-230.34 = 9.84	4.32	2.28	Dch
9	Cresaptown/ Cumberland/ Evitts Creek/ Patterson Creek	322-293	282.85-269.56 = 13.29	4.32	3.08	Dch
Total of Column			110.27	46.13		

Table 3, continued

Formation Designations

Dch, Upper Devonian, Chemung group ("Chemung", Parkhead (uncertain), Brallier, Harrell fms) total about 6000 ft, shale, siltstone, sandstone, greywacke, conglomerate

Om, Upper-Middle Ordovician, Martinsburg Formation, 2000-2500 ft, shale, siltstone, fissile shale (lower part), greywacke (upper part)

Orr, Lower Ordovician (Beekmantown), Rockdale Fm, 1700-2500 ft, dolostone and dolomitic limestone

OЄc: Lower Ordovician (Beekmantown), Conococheague Fm, 1600-1900 ft, limestone

Єt, Cambrian, Tomstown Fm, 200-1000 ft, dolostone and limestone

Table A2-1 Parameters from fitting gradient data and for integrated river profile

$\underline{d}$, km	h_{obs}	$\hat{h}$	$\hat{h}-h_{obs}$	S'_{obs}	S^
102.0	278	269#	0	1.0	2.9*
113.9	280	280	0	2.0	2.9*
134.7	300	300	0	7.1	2.9*
134.7	300	300	0	7.1	4.6*
136.5	303#	303#	0	16.3	4.6*
160.9	340	340	0	2.0	4.6*

$\underline{d}$, km	h_{obs}	$\hat{h}_{exp}$	$\hat{h}-h_{obs}$	$\hat{h}_{par}$	$\hat{h}-h_{obs}$	S'_{obs}	$S^\wedge_{exp}$	$S^\wedge_{par}$
136.5%	321$	322$	+ 1	324$	+ 3			
160.9	340	340*	0	340*	0	2.0	2.5	2.4
184.0	360	361	+ 1	361	+ 1	4.1	3.0	3.2
201.3	380	379	- 1	381	+ 1	4.1	3.5	3.8
215.6	400	396	- 4	401	+ 1	4.1	3.9	4.3
227.1	420	412	- 8	418	- 2	4.1	4.2	4.7
238.3	440	428	-12	436	- 4	5.1	4.6	5.1
251.0	460	448	-12	458	- 2	5.1	5.1	5.6
261.6	480	467	-13	478	- 2	6.1	5.5	5.9
270.9	500	484	-16	497	- 3	7.1	6.0	6.3
280.1	520	503	-17	516	- 4	6.1	6.4	6.6
292.3	540	530	-10	543	+ 3	6.1	7.0	7.0
300.8	560	550	-10	563	+ 3	8.1	7.5	7.3
307.6	580	567	-13	580	0	8.1	7.9	7.5
316.6	600	592	- 8	603	+ 2	9.1	8.5	7.9
323.6	620	612	- 8	621	+ 1	9.1	9.0	8.1
331.1	640	635	- 5	641	+ 1	10.2	9.6	8.4
algebraic sum			-135		- 1			

Equations ($\underline{d}$ in km, h in ft):

$102 \leq \underline{d} \leq 134.7$ km:

S' = 2.9, assumed to be constant.

$H = 169.9 + 0.966\,\underline{d}$

$134.7 < \underline{d} < 160.9$ km:

S' = 4.6, assumed to be constant

$H = 95.1 + 1.521\,\underline{d}$

$\underline{d} \geq 160.9$ km:

Exponential (n=62, r^2=0.74):

$S' = 0.7117\,e^{0.007845\underline{d}}$

$h = 29.77\,e^{0.007845\underline{d}} + 234.8$

Linear slope and parabolic elevation (n=62, r^2=0.89):

$S' = 0.0349\underline{d} - 3.199$

$h = 0.00573\underline{d}^2 - 1.0495\underline{d} + 360.6$

For the entire river between $160.9 \leq \underline{d} \leq 372.5$ km at Hampshire, WV:

$S' = 0.3333\,e^{0.01126\underline{d}}$ (n=74, r^2=0.82)

****

Explanatory notes:

obs, contour line crossing the river at indicated distances

exp, from exponential curve-fitting

par, from parabolic curve-fitting

S', 10^4S, where S is the actual slope value

* Assigned to assume this value
\# Known or predicted elevation at base of dam
$ Known or predicted elevation at top of dam
% This row of numbers refers to prediction from equations upstream from this point.

Appendix 1. Data on control points for measuring river distance between Fourteenth Street Bridge, Washington DC, and Keyser, WV

The control points given below are keyed to relevant parts of U.S. Geological Survey topographic quadrangle maps (scale 1:24,000) listed below (see Figure A1-1). The ordinals of the control points (CP) increase in the upstream direction, beginning just downstream from Fourteenth Street Bridge linking the District of Columbia with Arlington, Virginia. Distance in kilometers and fractions thereof. For every point, the latitude north and longitude west, based on the North American Datum of 1927, are given in that order (e.g. 390356 = 39°03'56"N) between square brackets [], as is the abbreviated name of the 7-1/2 minute topographic quadrangles published by the U.S. Geological Survey. Precision of measurement of points is 0.5 mm, corresponding to ground distance of 12 m which is consistent with recording the distance to a last digit of 10 m. Overall precision of location of points is 1 mm, which translates to 1 second of longitude and 3/4 second of latitude. Though the measurements were made on paper copies, no systematic error is introduced, provided paper shrinkage is uniform, because the dimensions of each copy was individually calibrated within a few hours of measuring. The estimated overall uncertainty of the latitude and longitude is ±2 seconds. Unless otherwise stated, all points are located within the main river channel.

Quadrangle abbreviations, in alphabetical order of abbreviations (all USGS 1:24,000 scale, 7-1/2 min. quadrangles).

1, Ax, Alexandria
2, Am, Artemas
3, Bg, Bellegrove
4, Bk, Buckeystown
5, BP, Big Pool
6, Cb, Cumberland
7, Cp, Cresaptown
8, CR, Cherry Run
9, Ct, Charlestown
10, EC, Evitts Creek
11, FC, Falls Church
12, GC, Great Cacapon
13, HF, Harpers Ferry
14, Hk, Hancock
15, Hv, Hedgesville
16, Ks, Keyser
17, Kv, Keedysville
18, Lb, Leesburg
19, Lc, Lonaconing
20, Ot, Oldtown
21, PC, Patterson Creek
22, PP, Paw Paw
23, PR, Point of Rocks
24, Pv, Poolesville
25, Rk, Rockville
26, Sn, Seneca
27, Sp, Shepherdstown
28, St, Sterling
29, Vn, Vienna
30, Wf, Waterford
31, Wp, Williamsport
32, Wt, Westernport
33, WW, Washington West

0. R0.00 Southeast edge of closed depression defined by 8-meter contour downstream from Fourteenth Street Bridge [385222; 770217; Ax]
1. R2.22 Memorial Bridge at drawbridge span mark [385314; 770322; WW]
2. R3.54 Off Harbor Place and Kennedy Center [385356; 770331; WW]
3. R4.62 Key Bridge (tidewater) [385407; 770413; WW]
4. R6.12 Above Three Sisters Island [385415; 770515; WW]
5. R7.78 Opposite Georgetown Reservoir [385447; 770609; WW]
6. R8.29 Just upstream from Canal Rd/Reservoir Rd corner [385502; 770616; WW]
7. R9.85 Just below Chain Bridge [385542; 770657; WW]
8. R10.36 Little Falls [385557; 770703; WW]

9. R11.73 Off head of narrow channel near High Island [385629; 770737; FF]
10. R12.53 Off south end of Snake Island [385654; 770747; FF]
11. R15.07 Off Cabin John Island at Cabin John Creek [385759; 770852; FF]
12. R16.51 Off Wade Island [385807; 770950; FF]
13. R17.93 Upstream side of Cabin John (I-495) bridge [385809; 771049; FF]
14. R18.51 Above I-495 bridge [385808; 771110; FF]
15. R20.23 Downstream of Turkey Island [385812; 771222; FF]
16. R20.71 Between Turkey Island and Vaso Island [385824; 771237; FF]
17. R21.96 Off Offutt Island [385823; 771327; FF]
18. R22.83 Below Sherwin Is., NE of point off Black Pond [385848; 771346; FF]
19. R23.09 Off Sherwin Island [385847; 771357; FF]
20. R23.39 Off Difficult Run [385840; 771404; FF]
21. R24.41 South end Mather Gorge [385858; 771441; FF]
22. R25.80 Off NW corner Rocky Island [385941; 771459; FF]

23. R26.11 Off SW corner Olmsted Island [385944; 771511; Vn]
24. R26.59 Along Seneca-Vienna quadrangle boundary [390000; 771511; Sn/Vn]

25. R27.10 South end Conn Island at dam [390015; 771505; Sn]

26. R27.84 North end Conn Island [390037; 771453; Rk]
27. R29.12 South end Bealls Island [390113; 771429; Rk]
28. R29.64 North end Bealls Island [390131; 771432; Rk]
29. R30.00 South end Gladys Island [390140; 771442; Rk]

30. R32.76 East end southern Sycamore Island off Watkins Island [390228; 771617; Sn]
31. R35.78 East end Katie Island [390317; 771804; Sn]
32. R37.58 East end Pond Island [390334; 771915; Sn]
33. R39.40 Off Lock 24 and Seneca Creek [390354; 772025; Sn]

34. R42.47 West end Sharpshin Island just upstream of Sugarland Run [390353; 772232; St]
35. R44.00 West end Tenfoot Island [390356; 772335; St] 36. R47.31 West tip of Van Deventer Island [390420; 772549; St]
37. R50.06 Quadrangle ninth tick mark above Van Deventer Island [390459; 772730; St]
38. R51.45 [390531; 772808; St]

39. R53.84 Pipeline alignment [390637; 772902; St]
40. R55.35 Leesburg quad boundary [390657; 773000; St/Lb]

41. R56.50 South tip of Harrison Island [390709; 773046; Lb]
42. R57.32 Waterford quad boundary [390730; 773105; Lb/Wf]

43. R58.54 Opposite Harrison Island in main channel [390809; 773101; Wf]
44. R60.08 South tip of tiny island above Harrison Island [390857; 773117; Wf]
45. R60.76 Near Whites Ferry [390920; 773116; Wf]
46. R63.56 Opposite Mason Island [391043; 773034; Wf]
47. R64.45 Poolesville quad boundary [391056; 773000; Wf/Pv]

48. R66.31 [391115; 772846; Pv]
49. R67.39 [391146; 772826; Pv]
50. R68.59 [391225; 772822; Pv]
51. R70.70 Frederick-Montgomery County line, confluence of Monocacy River [391307; 772723; Pv]
52. R71.56 [391342; 772730; Pv]
53. R74.86 Buckeystown quad boundary [391500; 772905; Pv/Bk]

54. R75.51 East tip of island [391512; 772928; Bk]
55. R76.30 Point of Rocks quad boundary [391516; 773000; Bk/PR]

56. R78.06 East tip of Heaters Island [391536; 773110; PR]
57. R80.85 East tip of Paton Island below Catoctin Creek (Virginia) [391626; 773247; PR]
58. R83.10 West tip of island with 216-ft BM [391726; 773338; PR]
59. R84.24 [391803; 773339; PR]
60. R8280 Confluence of Catoctin Creek (Maryland) [391825; 773354; PR]
61. R88.12 Below town of Brunswick [391812; 773602; PR]
62. R90.26 Harpers Ferry quad boundary [391823; 773730; PR/HF]

63. R92.05 Brunswick townline and Dutchman Creek [391842; 773841; HF]
64. R95.32 Washington-Frederick county line [391934; 774040; HF]
65. R96.32 West tip of small island below highway bridge [391918; 774138; HF]
66. R99.40 BM287 mark at top of Harpers Ferry peninsula, confluence with Shenandoah River [391923; 774346; HP]
67. R99.71 Above Harpers Ferry [391932; 774318; HP]
68. R100.94 Boundary against Charlestown quad [392001; 774500; HP/Ct]

69. R101.98 [392022; 774534; Ct]
70. R102.48 [392039; 774531; Ct]
71. R103.32 Boundary of Harpers Ferry quad [392051; 774500; Ct/HF]

72. R104.76 [392132; 774431; HF]
73. R105.20 [392146; 774431; HF]
74. R106.71 Northwest corner of 4-quad junction, Harpers Ferry- Charlestown-Shepherdstown-Keedysville [392230; 774500; HF/Ct/Sp/Kv]

75. R107.31 [392248; 774509; Sp]
76. R107.66 Keedysville quad boundary [392257; 774500; Sp/Kv]

77. R108.99 [392313; 774408; Kv]
78. R109.78 [392339; 774408; Kv]
79. R112.95 Shepherdstown quad boundary [392512; 774500; Kv/Sp]

80. R113.48 [392527; 774513; Sp]
81. R114.15 [392540; 774535; Sp]
82. R116.69 [392549; 774719; Sp]
83. R117.84 Below Route 34 bridge [392606; 774802; Sp]
84. R118.30 Above Route 34 bridge [392620; 774808; Sp]
85. R119.67 [392633; 774714; Sp]
86. R120.15 [392646; 774704; Sp]
87. R121.68 [392720; 774750; Sp]
88. R122.10 [392733; 774755; Sp]
89. R122.51 [392740; 774741; Sp]
90. R123.65 [392733; 774654; Sp]
91. R124.02 [392738; 774640; Sp]
92. R124.38 [392748; 774639; Sp]
93. R126.02 [392815; 774738; Sp]
94. R126.57 [392830; 774751; Sp]
95. R127.01 [392844; 774751; Sp]
96. R127.66 [392858; 774731; Sp]
97. R129.75 [392922; 774609; Sp]
98. R130.13 [392930; 774558; Sp]
99. R130.54 At Mondell [392043; 774555; Sp]
100. R131.32 [392959; 774619; Sp]
101. R132.33 [392958; 774701; Sp]
102. R132.86 On rapids [392946; 774717; Sp]
103. R133.42 [392930; 774730; Sp]
104. R134.56 West tip of Shepherd Island [392925; 774807; Sp]
105. R135.99 [392839; 774913; Sp]
106. R137.36 [392846; 775010; Sp]
107. R138.33 Boundary of Williamsport quad [393000; 775046; Sp/Wp]

108. R138.58 [393007; 775050; Wp]
109. R140.84 [393053; 774936; Wp]
110. R141.90 [393126; 774923; Wp]
111. R142.50 Near Cedar Grove [393144; 774930; Wp]
112. R143.27 [393157; 774957; Wp]

113. R143.74 [393156; 775016; Wp]
114. R144.24 [393144; 775029; Wp]
115. R145.35 [393108; 775034; Wp]
116. R145.68 [393101; 775045; Wp]
117. R147.00 [393052; 775140; Wp]
118. R147.39 Opequon Creek [393059; 775153; Wp]
119. R147.69 [393109; 775157; Wp]
120. R149.79 [393216; 775153; Wp]
121. R150.53 [393236; 775211; Wp]
122. R151.11 Boundary of Hedgesville quad [393247; 775230; Wp/Hv]

123. R152.21 [393307; 775309; Hv]
124. R152.91 [393328; 775316; Hv]
125. R153.56 [393341; 775255; Hv]
126. R154.18 Boundary of Williamsport quad [393347; 775230; Hv/Wp]

127. R157.18 [393351; 775025; Wp]
128. R157.83 East end of third tiny islet counting from west [393404; 775004; Wp]
129. R160.18 At northern of two powerline crossings [393518; 774946; Wp]

130. R161.84 North of the more northerly of two bridges at Williamsport, just above Conococheaque Creek [393611; 774956; Wp]
131. R162.39 [393623; 775014; Wp]
132. R162.86 [393627; 775031; Wp]
133. R164.80 [393636; 775152; Wp]
134. R165.88 Boundary of Hedgesville quad [393653; 775230; Wp/Hv]

135. R166.86 [393659; 775310; Hv]
136. R167.19 [393649; 775317; Hv]
137. R168.39 [393614; 775254; Hv]
138. R168.98 [393556; 775300; Hv]
139. R169.44 [393552; 775319; Hv]
140. R172.49 Below dam #5 [393619; 775521; Hv]
141. R173.79 At Lock #46 [393650; 775545; Hv]
142. R174.47 [393710; 775609; Hv]
143. R175.14 [393708; 775637; Hv]
144. R175.61 [393655; 775647; Hv]
145. R175.92 [393648; 775648; Hv]
146. R176.60 North end of islet [393635; 775616; Hv]
147. R178.92 [393520; 775623; Hv]
148. R179.55 [393505; 775640; Hv]
149. R180.12 [393517; 775700; Hv]
150. R181.13 [393550; 775705; Hv]
151. R182.14 [393622; 775704; Hv]
152. R182.88 [393633; 775731; Hv]
153. R183.92 [393623; 775812; Hv]

154. R184.84 [393600; 775837; Hv]
155. R186.84 Boundary of Big Pool quad [393604; 780000; Hv/BP]

156. R187.61 [393609; 780032; BP]
157. R190.50 Boundary of Cherry Run quad [393730; 780134; BP/CR]

158. R192.01 [393810; 780209; CR]
159. R193.33 [393836; 780251; CR]
160. R194.51 West tip of island off Licking Creek [393909; 780318; CR]
161. R195.20 Southeast tip of big island [393923; 780340; CR]
162. R197.21 [394011; 780437; CR]
163. R198.43 Norwest tip of island off Millstone (Moffet Station) [394027; 780527; CR]
164. R199.80 [394053; 780612; CR]
165. R210.78 Boundary of Hancock quad [394120; 780730; CR/Hk]

166. R203.53 [394127; 780840; Hk]
167. R205.07 [394138; 780942; Hk]
168. R206.50 [394149; 781040; Hk]
169. R207.30 West edge of Route 522 bridge [394141; 781112; Hk]
170. R208.73 Near BM 455 [394103; 781147; Hk]
171. R209.71 [394037; 781212; Hk]
172. R210.72 [394037; 781253; Hk]
173. R211.90 [394035; 781342; Hk]
174. R212.54 [394022; 781402; Hk]
175. R212.96 [394009; 781359; Hk]
176. R214.07 [393942; 781328; Hk]
177. R214.86 [393922; 781348; Hk]
178. R215.66 Sir Johns Run [393910; 781418; Hk]
179. R217.06 Boundary of Bellegrove quad, north edge of island [393839; 781500; Hk/Bg]

180. R217.54 West tip of island [393829; 781515; Bg]
181. R218.94 [393751; 781547; Bg]
182. R219.59 Boundary of Great Cacapon quad [393730; 781550; Bg/GC]

183. R220.08 [393714; 781552; GC]
184. R220.36 [393710; 781602; GC]
185. R222.13 West tip of islet [393720; 781725; GC]
186. R222.77 Boundary of Bellegrove quad [393730; 781737; GC/Bg]

187. R224.59 [393754; 781848; Bg]
188. R225.64 [393806; 781929; Bg]
189. R227.48 [393823; 782045; Bg]
190. R228.12 [393827; 782111; Bg]
191. R228.49 [393827; 782126; Bg]
192. R228.85 [393818; 782137; Bg]
193. R229.20 At start of Turkey Foot Bend [393807; 782134; Bg]

194. R229.88 [393750; 782116; Bg]
195. R230.29 [393737; 782120; Bg]
196. R230.78 [393734; 782140; Bg]
197. R231.50 [393746; 782206; Bg]
198. R232.10 Boundary of Artemas quad [393751; 782230; Bg/Am]

199. R232.77 [393744; 782257; Am]
200. R233.23 Boundary of Paw Paw quad and Fifteen Mile Creek [393730; 782302; Am/PP]

201. R233.59 [393719; 782302; PP]
202. R234.74 Boundary of Great Cacapon quad [393651; 782230; PP/GC]

203. R235.12 [393639; 782224; GC]
204. R235.36 Boundary of Paw Paw quad [393633; 782230; GC/PP]

205. R235.65 [393632; 782242; PP]
206. R236.52 [393641; 782316; PP]
207. R237.44 At railroad bridge [393700; 782346; PP]
208. R240.06 [393729; 782528; PP]
209. R240.58 [393725; 782549; PP]
210. R241.15 [393711; 782603; PP]
211. R241.74 [393653; 782557; PP]
212. R243.78 West tip of bar [393600; 782504; PP]
213. R245.50 Off Randolph tunnel [3935311; 782403; PP]
214. R246.26 [393511; 782344; PP]
215. R246.90 [393454; 782357; PP]
216. R247.66 [393443; 782426; PP]
217. R248.67 [393452; 782505; PP]
218. R249.56 [393512; 782532; PP]
219. R250.90 [393528; 782625; PP]
220. R251.46 [393530; 782648; PP]
221. R252.52 [393515; 782730; PP]
222. R253.48 [393444; 782731; PP]
223. R254.08 Southeast tip of islet [393428; 782720; PP]
224. R254.94 Northwest tip of big island [393407; 782655; PP]
225. R256.23 Southeast tip of same big island [393343; 782612; PP]
226. R257.10 Downstream of Graham Tunnel Bridge [393332; 782537; PP]
227. R258.42 [393258; 782505; PP]
228. R258.87 Off Little Steer Run [393244; 782514; PP]
229. R259.27 [393244; 782531; PP]
230. R260.34 [393306; 782548; PP]
231. R260.71 Above second Graham Tunnel Bridge [393314; 782612; PP]
232. R261.13 [393303; 782623; PP]
233. R261.93 [393241; 782607; PP]
234. R262.46 [393223; 782610; PP]
235. R262.70 [393221; 782618; PP]

236. R263.90 [393252; 782648; PP]
237. R264.48 Upstream of Kesier Tunnel [393303; 782707; PP]
238. R265.17 [393305; 782737; PP]
239. R265.42 [393300; 782745; PP]
240. R265.81 [393248; 782744; PP]
241. R266.17 Railroad bridge by BM 548 [393240; 782733; PP]
242. R266.88 [393236; 782703; PP]
243. R267.09 [393230; 782658; PP]
244. R267.45 [393219; 782702; PP]
245. R268.23 Near Paw Paw tunnel entrance and gauging station [393218; 782733; PP]
246. R268.68 [393208; 782749; PP]
247. R269.08 Mouth of Purslane Run [393155; 782748; PP]
248. R269.56 [393140; 782741; PP]
249. R270.18 North tip of islet [393120; 782746; PP]
250. R270.86 [393103; 782803; PP]
251. R271.26 [393058; 782819; PP]
252. R272.34 [393112; 782901; PP]
253. R273.01 West tip of island [393108; 782928; PP]
254. R273.78 Boundary of Oldtown quad [393110; 783000; PP/Ot]

255. R274.22 [393111; 783019; Ot]
256. R275.47 [393128; 783105; Ot]
257. R276.38 [393130; 783143; Ot]
258. R276.81 [393124; 783200; Ot]
259. R277.17 [393125; 783215; Ot]
260. R278.32 [393117; 783302; Ot]
261. R279.26 [393117; 783340; Ot]
262. R279.74 [393112; 783401; Ot]
263. R281.08 [393139; 783445; Ot]
264. R281.85 At confluence of North and South Branches of Potomac River [393143; 783516; Ot]
265. R282.38 [393154; 783631; Ot]
266. R282.86 [393209; 783624; Ot]
267. R283.10 [393214; 783631; Ot]
268. R283.63 East tip of islet at Seven Springs Run [393209; 783651; Ot]
269. R284.25 East tip of islet [393156; 783611; Ot]
270. R284.51 West tip of larger island next west [393201; 783620; Ot]
271. R284.72 East tip of large island [393208; 783624; Ot]
272. R285.37 West tip of island below bridge from Oldtown to Green Springs [393216; 783649; Ot]
273. R286.37 Boundary of Patterson Creek quad [393223; 783730; Ot/PC]

274. R286.88 [393222; 783751; PC]
275. R287.35 West tip of island [393214; 783808; PC]
276. R288.76 East tip of island at mouth of Kern Hollow [393208; 783907; PC]
277. R289.42 West tip of same island [393210; 783934; PC]
278. R289.88 [393214; 783952; PC]

279. R290.42 [393226; 784009; PC]
280. R291.02 East tip of very large island [393226; 784032; PC]
281. R292.82 West tip of same island [393302; 784130; PC]
282. R293.37 [393316; 784145; PC]
283. R293.66 [393316; 784157; PC]
284. R294.11 East tip of large island [393321; 784214; PC]
285. R294.71 [393331; 784236; PC]
286. R-26521 [393345; 784247; PC]
287. R295.88 [393350; 784315; PC]
288. R296.21 By BM574, Patterson Creek [393350; 784329; PC]
289. R297.08 [393415; 784342; PC]
290. R297.53 [393428; 784413; PC]
291. R298.90 [393511; 784400; PC]
292. R299.20 Railroad bridge [393512; 784413; PC]
293. R299.56 [393509; 784427; PC]
294. R299.77 [393503; 784431; PC]
295. R299.98 [393457; 784435; PC]
296. R300.25 [393450; 784438; PC]
297. R300.57 [393447; 784451; PC]
298. R300.83 Boundary of Cresaptown quad [393451; 784500; PC/Cp]

299. R301.02 [393456; 784507; Cp]
300. R301.47 [393452; 784524; Cp]
301. R302.21 Southeast tip of large island [393508; 784548; Cp]
302. R302.88 Northwest tip of same island [393525; 784605; Cp]
303. R303.48 Southeast tip of islet [393543; 784613; Cp]
304. R303.91 [393551; 784627; Cp]
305. R304.51 North tip of islet [393611; 784625; Cp]
306. R304.83 Northeast tip of large island [393620; 784619; Cp]
307. R305.26 [393629; 784606; Cp]
308. R305.88 [393635; 784542; Cp]
309. R306.75 Northwest tip of islet [393635; 784506; Cp]
310. R306.96 Southeast tip of islet [393629; 784501; Cp]
311. R307.18 Boundary of Patterson Creek quad [393621; 784500; Cp/PC]

312. R307.44 [393618; 784450; PC]
313. R307.99 West tip of island [393631; 784435; PC]
314. R308.33 East tip of same island [393633; 784421; PC]
315. R309.12 [393651; 784359; PC]
316. R309.70 North tip of islet [393710; 784403; PC]
317. R310.12 [393721; 784413; PC]
318. R310.68 Boundary of Evitts Creek quad [393730; 784433; PC/EC]

319. R311.20 [393737; 784452; EC]
320. R311.39 Boundary of Cumberland quad [393736; 784500; EC/Cb]

321. R311.73 Boundary of Cresapton quad [393730; 784512; Cb/Cp]

322. R312.85 [393709; 784549; Cp]
323. R313.12 East tip of large island [393712; 784559; Cp]
324. R313.65 West tip of same island [393717; 784621; Cp]
325. R314.01 Southeast tip of curved island [393719; 784636; Cp]
326. R314.37 Boundary of Cumberland quad [393730; 784638; Cp/Cb]

327. R314.61 North tip of small island [393738; 784637; Cb]
328. R314.99 [393749; 784629; Cb]
329. R315.95 At dotted line (trail) crossing [393817; 784611; Cb]
330. R316.55 County and State boundary crossing and 600-ft contour crossing [393835; 784559; Cb]
331. R317.08 At confluence of Wills Creek [393851; 784555; Cb]
332. R317.28 [393856; 784600; Cb]
333. R317.50 [393849; 784609; Cb]
334. R318.03 [393846; 784632; Cb]
335. R318.22 [393843; 784638; Cb]
336. R319.23 [393813; 784656; Cb]
337. R320.07 [393818; 784730; Cb]
338. R320.38 Above rapids [393817; 784742; Cb]
339. R320.47 [393815; 784746; Cb]
340. R320.80 [393806; 784750; Cb]
341. R321.47 [393745; 784755; Cb]
342. R321.70 [393744; 784805; Cb]
343. R321.84 [393741; 784808; Cb]
344. R322.18 Boundary of Cresaptown quad [393730; 784806; Cb/Cp]

345. R323.26 North tip of island [393657; 784750; Cp]
346. R323.64 At 620-ft contour crossing [393645; 784746; Cp]
347. R324.16 [393628; 784745; Cp]
348. R324.33 [393623; 784747; Cp]
349. R324.52 [393619; 784752; Cp]
350. R324.76 [393619; 784802; Cp]
351. R324.97 [393625; 784807; Cp]
352. R325.38 [393627; 784823; Cp]
353. R325.66 [393629; 784834; Cp]
354. R326.51 Dam crossing [393903; 784844; Cp]
355. R326.80 [393553; 784845; Cp]
356. R327.52 [393539; 784908; Cp]
357. R327.78 Near Seymour [393530; 784906; Cp]
358. R327.97 [393525; 784910; Cp]
359. R328.48 [393525; 784932; Cp]
360. R328.84 North tip of island [393515; 784938; Cp]
361. R330.04 [393436; 784936; Cp]
362. R330.33 West tip of island at railroad crossing [393434; 784924; Cp]

363. R330.69 Southeast tip of island [393427; 784912; Cp]
364. R331.30 Southeast tip of next island [393412; 784855; Cp]
365. R331.71 Railroad crossing [393359; 784851; Cp]
366. R332.28 East tip of island [393343; 784903; Cp]
367. R332.80 West tip of same island [393341; 784925; Cp]
368. R333.22 [393348; 784940; Cp]
369. R333.43 [393353; 784944; Cp]
370. R334.32 [393402; 785019; Cp]
371. R334.50 By gaging station in Pinto [393400; 785026; Cp]
372. R335.01 East tip of islet [393347; 785038; Cp]
373. R335.41 Bridge crossing [393344; 785055; Cp]
374. R335.89 [393334; 785108; Cp]
375. R336.04 [393330; 785106;Cp]
376. R336.55 At confluence with small stream [393313; 785108; Cp]
377. R336.79 [393305; 785109; Cp]
378. R338.19 [393229; 785143; Cp]
379. R338.35 [393228; 785151; Cp]
380. R339.01 [393221; 785216; Cp]
381. R339.23 North tip of point (bar?) [393214; 785219; Cp]
382. R339.59 North tip of islet [393203; 785214; Cp]
383. R339.88 South tip of same islet [393153; 785213; Cp]
384. R340.84 Boundary of Lonaconing quad [393125; 785230; Cp/Lc]

385. R341.27 [393117; 785245; Lc]
386. R341.99 Above Ashcabin Run confluence [393123; 785314; Lc]
387. R342.33 [393132; 785323; Lc]
388. R342.66 [393128; 785336; Lc]
389. R342.90 [393121; 785338; Lc]
390. R343.36 [393107; 785331; Lc]
391. R343.86 [393051; 785334; Lc]
392. R344.06 [393046; 785339; Lc]
393. R344.87 [393046; 785413; Lc]
394. R345.08 [393043; 785421; Lc]
395. R345.29 At crossing of 700 ft contour [393036; 785420; Lc]
396. R345.89 [393016; 785417; Lc]
397. R346.43 Boundary of Keyser quad [393000; 785425; Lc/Ks]

398. R346.94 [392946; 785437; Ks]
399. R347.19 [392942; 785446; Ks]
400. R347.45 [392935; 785453; Ks]

401. R348.26 [392911; 785502; Ks]
402. R349.07 At railroad bridge [392914; 785536; Ks]
403. R349.86 East tip of island [392909; 785608; Ks]
404. R350.70 [392851; 785634; Ks]
405. R351.21 Below narrows [392835; 785630; Ks]

406. R351.45 Under cliffs [392830; 785623; Ks]
407. R351.59 Under cliffs [392827; 785622; Ks]
408. R351.74 At crossing of 740 ft contour [392823; 785626; Ks]
409. R352.64 [392803; 785648; Ks]
410. R353.25 Downstream from BM775 [392751; 785711; Ks]
411. R353.63 West tip of small islet [392750; 785728; Ks]
412. R353.90 [392744; 785735; Ks]
413. R354.35 On quad ninth crossbar [392729; 785731; Ks]
414. R354.78 Under cliffs [392719; 785720; Ks]
415. R354.89 [392717; 785717; Ks]
416. R355.13 [392711; 785724; Ks]
417. R355.50 Just below railroad bridge at BM794 [392707; 785738; Ks]
418. R355.62 BM794 [392703; 785739; Ks]
419. R356.03 South tip of small islet [392654; 785728; Ks]
420. R356.20 [392649; 785724; Ks]
421. R356.78 [392630; 785722; Ks]
422. R356.92 [392626; 785726; Ks]
423. R357.50 [392622; 785749; Ks]
424. R357.65 At 780 ft contour crossing; Limestone Run and New Creek [392619; 785755; Ks]
425. R358.07 [392628; 785808; Ks]
426. R358.35 Below Route 220 bridge in Keyser [392637; 785821; Ks]
427. R358.71 [392641; 785824; Ks]
428. R359.10 At 800 ft contour crossing [392651; 785836; Ks]
429. R359.46 Near BM831 [392659; 785847; Ks]
430. R360.10 [392707; 785912; Ks]
431. R360.41 [392709; 785924; Ks]
432. R360.96 [392718; 785945; Ks]
433. R361.06 [392719; 785949; Ks]
434. R361.24 [392723; 785945; Ks]
435. R361.38 Boundary of Westernport quad, 7 mm below 27'30" tick [392725; 790000; Ks/Wt]

436. R361.86 [392734; 790017; Wt]
437. R362.34 [392739; 790036; Wt]
438. R362.46 [392743; 790037; Wt]
439. R362.82 Northwest tip of island [392751; 790049; Wt]
440. R363.34 [392802; 790104; Wt]
441. R363.47 [392804; 790109; Wt]
442. R363.83 [392759; 790122; Wt]
443. R364.42 [392754; 790146; Wt]
444. R364.75 [392759; 790159; Wt]
445. R364.94 [392803; 790204; Wt]
446. R365.35 [392815; 790210; Wt]
447. R365.56 [392822; 790209; Wt]
448. R365.90 [392833; 790212; Wt]
449. R366.05 Southeast tip of island [392837; 790215; Wt]
450. R366.41 Northwest tip of next island [392843; 790228; Wt]

451. R366.70 Southeast tip of next, long island [392846; 790239; Wt]
452. R366.98 Northwest tip of same island [392855; 790243; Wt]
453. R367.26 At railroad bridge, Westernport to Piedmont [392901; 790251; Wt]
454. R367.55 [392859; 790303; Wt]
455. R367.67 [392857; 790308; Wt]
456. R367.86 [392852; 790312; Wt]
457. R368.00 North tip of island [392848; 790314; Wt]
458. R368.27 South edge of highway bridge, near BM995 [392840; 790315; Wt]
459. R368.99 [392816; 790321; Wt]
460. R369.13 [392814; 790325; Wt]
461. R369.44 Near BM965 [392818; 790337; Wt]
462. R370.40 [392846; 790355; Wt]
463. R370.64 Confluence of Savage River [392849; 790404; Wt]
464. R370.86 [392843; 790408; Wt]
465. R371.06 South edge of railroad bridge [392837; 790406; Wt]
466. R371.30 [392829; 790408; Wt]
467. R371.50 [392827; 790415; Wt]
468. R371.88 West tip of island [392825; 790431; Wt]
469. R372.64 Confluence of Piney Swamp Run, above hamlet of Hampshire [392817; 790500; Wt]
470. R373.14 [392819; 790521; Wt]

Appendix 2. Numerical manipulations on the river profile data, between Dam no. 3 and Wills Creek

The profile of the Potomac River (Figure 2) and the derived plot of river gradient (Figure 3) merit a closer examination than that given in the main text. The gradients, it will be recalled, were derived from data recorded on U.S. Geological Survey 7-1/2minute topographic quadrangle maps. Distances are those along the actual thalweg, and elevations are those at water surface, assumed consistent from one quadrangle sheet to the next, interpolated between successive contour crossings (C.I.=20 ft). Gradients were obtained by using the river levels at the ends of 3-km compartments of the river water-surface profile. This method introduces reading errors and a saw-tooth pattern to the values. However, errors in successive compartments should be self-compensating because they are constrained by the contour line crossings at known river distances and may be expected to be largely removed by the procedure of curve-fitting.

Simple equations to fit the data were sought. An equation either could be fitted to the gradient, integrated to obtain the profile, or could be fitted to the profile, differentiated to obtain the gradient. Gradient data are fitted because integration is a fairly forgiving process but differentiation magnifies small errors.

Examination of the gradient plot (Figure 3) shows that no single equation would fit the entire set. Apart from the large spikes within the the gorge section below Great Falls, discontinuities appear at the boundary between the Piedmont and the Culpeper Basin, and at the boundary between the Blue Ridge province and the Valley and Ridge province. Both discontinuities reflect the upstream passage of the river from resistant metamorphic and igneous bedrocks to much less resistant sedimentary rocks. These discontinuities form nickpoints in the profile; the reaches separated by nickpoints are treated separately. Within the Valley and Ridge province, only the 215 km of river between its eastern boundary near Harpers Ferry (Dam no. 3) and the confluence of Wills Creek at Cumberland are examined, for reasons that will become clear.

Even within this restricted reach the gradient plot contains a pair of large spikes between river distances 138 and 132 km. The spikes are caused in part by Dam no. 4 at 136.5 km. The 320-ft contour line is shown to pass across the top of the dam on the U.S. Geological Survey 7-1/2 minute Shepherdstown quadrangle map. The top is actually at 321 ft and the height of the dam is 18 ft (Ranger Monte Crooks, C&O Canal National Historical Park, oral communication, December, 1996; I verified the height by direct observations. Davies, 1971, gave the height as 20 ft), so the water level at the base is about 303 ft. The 300-ft contour is crossed at 134.7 km and the 280 ft contour is crossed at 114 km.

Therefore, the profile and gradient data are fitted in three segments: above 160.9 km, where the 340 ft contour crosses the river (this is 16 km upstream from Lock no. 41, the first lock upstream from the "Big Slackwater" created by Dam no. 4, and thus well free of the influence of ponding of water at the dam; see Hahn, 1992, p. 135 ff), between 160.9 km and Dam no. 4 at 136.5 km, and between the dam and the boundary of the Valley and Ridge province at 102 km. Lacking detailed data, the two latter segments are assigned constant gradients defined by the contour-line crossings. Their equations are given in Table A2-1.

An increase of gradient below Dam no. 4 seems reasonable because dams that support the operation of the C&O Canal are generally located at the head of steep reaches in order to feed the locks. The steeper channel in this reach might reflect incomplete migration of the nickpoint at Harpers Ferry between the Valley and Ridge province and the Blue Ridge province.

For the main section of the river above river distance 160.9 km, Table A2-1 summarizes both the "observed" and "reconstructed" gradients against the river distances which are midpoints within successive 3-km compartments (S_{obs}; in the table the gradients are 10^4 the actual values). The gradient data are fitted by least-squares procedure to both exponential and linear equations. As indicated above, a simple interpolated linear equation is used downstream of river distance 160.9 km (Figure 7). The equation for linear slope has a higher value of r^2 (0.89) compared to the exponential equation (0.74). By itself this difference is not definitive, but the integrated elevation equations, pegged to the 340 ft elevation at 160.9 km, show a vastly better result using the quadratic equation integrated from the linear gradient equation. In the main diagram of Figure 6, only those data points found in gradient compartments showing crossing of contour lines are plotted. The inset on an expanded scale contains all the gradient values used for the least-squares fitting.

Figure 7 gives the integrated elevation. Here again, the reaches upstream and downstream from 160.9 km are separately handled. The quality of the quadratic fit may be compared with that of the exponential fit through a plot of the residuals. The quadratic fit continues to do well in an upstream direction all the way to Pinto, even though above Cumberland the river changes its character from one flowing athwart the regional structure to one largely along it. Above Pinto, the deviation becomes large and disastrously so above Keyser. This interval between Pinto and Keyser coincides with the reach of the river where it tracks the boundary between the Valley and Ridge province and the Allegheny Plateau. North Branch above Pinto behaves differently in the hydraulic sense than below.

Note that between the South Branch and Cacapon River (river distances 220-280 km), the residuals are consistently negative whereas both upstream and downstream of this reach they are consistently positive. I have made no effort to ascertain whether this reflects the hydraulics of the river, or is a fluke.

To summarize: surprisingly, a simple, 1-parameter equation gives a good fit to the elevation of the river over a large distance. This fit is not affected by the bedrock. For the linear slope equation, the average gradient from river distance d=160.9 km to Wills Creek is 0.05%. From river distance 160.9 km (near Williamsport) to Oldtown, where South Branch comes in, the average slope is 0.045%; between Oldtown and Wills Creek, it is 0.07%. The gradients are not affected by the entrenched meander clusters or the bedrock geology; nor do they appear to be affected by large tributaries (i.e., volume of flow) with the possible exception of Conococheague Creek, below whose confluence the gradient steepens; unfortunately the effect of Dam no. 4 cannot be unequivocally removed to establish this point for certain.

Because

omega = rho.g.D.uS (Bagnold, 1966) and

Q = DuW

where omega is the unit stream power (in newtons/m/s or watts/m^2), rho is the specific gravity of the medium, g is the gravitational acceleration (rho.g is the specific weight of the medium), D is the average depth of the river and W is its width, Q is the flux, u is the current speed, and S is the slope, we can write

S = omega.W/rho.g.Q

where S may be given by its functional relation to distance, as given above. Q/W is the flux divided by the channel width, and may be considered as unit flux. Thus, the unit stream power normalized by the unit flux, scaled by the physical constant rho.g, is a simple function of the river distance along this stretch of the Potomac River.

Appendix 3. Data used for least-squares fitting of paleo-Potomac channels.

(A) Elevation and location data on boulder beds, trimmed spurs, and entrenched meanders and entrenched confluences of tributaries to the Potomac River in the Blue Ridge, Culpeper Basin, and Piedmont provinces.

Point	River distance, km	Elevation above sealevel, ft	Comments (CP, control points; s, strath level; t, tributary)
1	25.0	200	s. Boulder bed at Glade Hill
2	37.5	230	t. Hanging ravines in trimmed spur section across Piedmont-Mesozoic basin boundary
3	39.0	250	t. Seneca Creek
4	42.0	250	t. Sugarland Run
5	45.8	245	s. Quartzite boulder at McPherson Circle
6	48.3	250	t. Broad Run
7	52.5	245	t. Two determinations for
8	52.5	250	Goose Creek
9	71.5	290	t. Two determinations for
10	71.5	300	Monocacy River
11	80.5	300	t. Two determinations for
12	80.5	310	Catoctin Creek (Virginia)
13	85.0	290	t. Three determinations for
14	85.0	310	Catoctin Creek (Maryland); 310
15	85.0	340	level is abandoned meander bend
16	88.5	300	t. Two determinations for
17	88.5	360	Quarter Branch
18	92.0	350	t. Two determinations for
19	92.0	370	Dutchman Creek
20	96.0	340	t. Israel Creek
21	98.0	380	t. Pinney Run

22	99.0	350	t. Shenandoah River
23	99.0	410	s. Valley near Snyders Hill, projected
24	101.5	380	t. Elks Run

Least-squares regression equation:

$H = 142.78 + 2.206 \underline{d}$ ($r^2 = 0.93$, $n=24$)

With H in feet and $\underline{d}$ in km. As 2.206/3281 = 0.00067, the dimensionless slope is 0.07%.

(B) Elevation and location data on entrenched meanders and entrenched confluences of tributaries to the Potomac River in the Valley and Ridge province.

Point	River distance, km	Elevation above sealevel, ft	Comments (CP, control points; m, meander; t, tributary)
1	105	400	t. Nameless stream from east between CP 72 and 73
2	107.5	390	m. Terrace near CP 76
3	109	390	t. Nameles stream from east at CP 77
4	112.5	390	t. Antietam Creek near CP 79
5	115.5	400	t. Nameless stream from south followed by Trough Road between CP 81 and 82
6	118	440	m. Terrace near CP 86
7	123	460	m. Terrace near CP 88
8	124.5	460	m. Terrace near CP 91
9	127	440	m. Terrace near CP 95
10	131	460	m. Interfluve at Terrapin Neck near CP 97
11	132	420	t. Marsh Run between CP 100 and 101
12	145	460	m. Interfluve at Whitings Neck near CP 112
13	147.5	420	t. Two determinations for
14	147.5	440	Opequon Creek near CP 118
15	153.5	540	m. Interfluve occupied by Falling Waters Road near CP 124
16	161.5	460	t. Interfluve of Conococheague Creek, projected
17	169.5	460	m. Interfluve at Millers Bend near CP 138

18	171	380	t. Two determinations for
19	171	400	Little Conococheague Creek near CP 140
20	175.5	460	m. Interfluve just above Dam no. 5 near CP 141
21	179.5	480	m. Interfluve, The Neck, near CP 148
22	182.5	520	m. Interfluve on south side of river near CP 152
23	186	420	t. Two determinations for Back
24	186	440	Creek between CP 154 and 155
25	191	400	t. Two determinations for
26	191	450	Cherry Run at CP 157
27	194	440	t. Two determinations for
28	194	500	Licking Creek near CP 160
29	198	440	t. Two determinations for
30	198	510	Sleepy Creek near CP 163
31	205	460	t. Tonoloway Creek near CP 167
32	206.5	500	t. Dry Run between CP 167 and 168
33	215	500	t. Sir John Creek at CP 178
34	215.5	500	t. Nameless stream occupied by Seavolt Road (Hahn, 1993, p. 174) above CP 178
35	221.5	500	t. Two determinations for
36	221.5	530	Cacapon River near CP 185
37	222.5	660	m. Interfluve on Cacapon just above confluence
38	226.5	540	t. Sideling Hill Creek between CP 188 and 189
39	233	500	t. Fifteen Mile Creek at CP 200
40	235	500	t. Rockwell Run at CP 203
41	235.5	530	m. Meander cutoff near Little Orleans

42	236.5	560	m. Base of trimmed spur near Doe Gully within meander loop at CP 206
43	243	600	t. Nickpoint in Devils Alley between CP 211 and 212
44	246.5	580	m. Base of trimmed spur along Kasecamp Road within meander loop near CP 214
45	250	620	t. Nickpoint in Roby Hollow between CP 218 and 219
46	254	600	m. Terrace near Cherry Orchard Cemetery at CP 224
47	255	650	t. Nickpoint in Tunnel Hollow
48	257	600	t. Nickpoint in Sprigs Hollow
49	263	600	t. Big Run near CP 235
50	265	610	m. Interfluve at Bevan Bend near CP 242
51	269	650	t. Purslane Run at CP 247
52	272	650	t. Nameless stream in Reckley Flat above CP 252
53	273	640	t. Little Cacapon River at CP 253
54	276	600	t. Brights Hollow at Okonoko between CP 256 and 257
55	277.5	560	m. Interfluve at mouth of Town Creek between CP 259 and 260
56	277.5	610	t. Town Creek at CP 259
57	282	650	t. South Branch of Potomac River at Oldtown, abandoned interfluve at CP 264
58	284.5	600	t. Seven Springs Run at CP 271
59	285	560	t. Green Springs Run at CP 272
60	293	660	t. Dans Run at CP 281

61	296	590	t. Patterson Creek at CP 288
62	306	680	m. Large interfluve northwest of community of North Branch north of CP 298
63	311	650	t. Evitts Creek at CP 318
64	317	650	t. Wills Creek in Cumberland at CP 331
65	318.5	660	m. Terrace between CP 335 and 336
66	331.5	700	m. Terrace near CP 365

Least-squares regression equation:

$H = 246.21 + 1.306\ \underline{d}$ ($r^2 = 0.89$, $n=66$)

With H in feet and d in km. As 1.306/3281 = 0.000398, the dimensionless slope of the line is 0.04%.

(C) Data on high-level straths, not regressed. Data from interfluves of the meander loops of Cluster 7 downstream from Paw Paw unless otherwise specified.

Point	River distance, km	Elevation above sealevel, ft	Location (CP, control points)
1	~18	~450	Projected location of Miocene-Pliocene overlap at Tyson's Corner
2	234	750	CP202; Little Orleans loop
3	240	750	CP208; Beanpatch Hollow loop
4	246	770	CP215; Green Ridge loop
5	248	820	CP217; Green Ridge loop
6	250	820	CP219; Green Ridge loop
7	253	840	CP221; Jerome loop
8	253	750	CP221; Jerome loop
9	255	780	CP224; Jerome loop
10	260	900	CP231; Tunnel Hollow loop
11	270	834	CP249; between Reckley Flats and Pursalane Run (benchmark)
12	279	860	CP263; junction with South Branch

Appendix 4. Recovering information on strath levels of Cluster 7 between Paw Paw and Little Orleans.

Cluster 7 contains five meander loops. With amplitude and wave length of about 5 km, these loops are the largest on the Potomac River. From downstream to upstream, these loops are hereby designated the Little Orleans, Beanpatch Hollow, Green Ridge, Jerome, and Tunnel Hollow loops (Figure 8). Adjacent loops, of course, have reverse polarity.

As mentioned in the main text, the interfluves for Cluster 7 are found 300-400 ft above the modern river, whereas the "normal" interfluves are about 150 ft above water level within this reach of the river. The high interfluves now form deeply dissected but flattop hills. The large amplitudes and wave lengths could be a record of considerably greater paleo-discharge caused by either larger watershed area or by wetter climate (the "static entrenchment" model; see Leopold, Wolman and Miller, 1964). Alternatively, one could envision that the amplitudes were enlarged by erosion into the concave bank at the same time that the thalweg was lowered. This "slipslope" model predicts slipslopes in the interfluve area that incline progressively toward the bend of the loop.

I tested the two models in the following way. A longitudinal profile is constructed for each interfluve area, each beginning at the modern river and ending where it intersects the line connecting the prows of the two adjacent loops that define the meander belt (Figure 8). The profile is divided into 300-meter (1000-ft) segments, and the maximum hilltop elevations between the two limbs of the meander are scanned normal to the profile for each successive segment, i.e., across the entire interfluve (note that for this reason the precise location of the profile is not important). If there is no "hilltop", i.e. closed contour, within a strip, then the highest *shoulder elevation* is recorded and so noted. The width of the segment is chosen so as to be consonant with the scale of the landform; hilltops are used because the working assumption is that they are remnants of one or more straths. My expectation was that slipslopes (dominance of shoulder elevations monotonically inclined toward the modern river) and straths (dominated by "hilltops" of similar elevations from one segment to another) are distinguishable.

Figure 9A shows the results; the polarities are reversed for alternate loops so the river begins at the same point along the horizontal axis which gives the numerical sequence of the strips. Figure 9B shows the same results normalized so that the profiles share a common river elevation.

This pair of figures shows several interesting features. First, there is a strong concentration of an elevation of about 750 ft over wide reaches of all strips, best seen in Figure 9B (suggesting, though not proving, that the modern rate of river level decrease, 10-ft per meander loop, was perhaps a fair representation of the ancient situation). Second, there is a weaker concentration of hilltop elevations (excluding shoulders of hills) at about 850 ft; this elevation is absent only for the shortest Little Orleans profile. Again, this level lacks indication of a riverward slipslope. Jerome and Beanpatch Hollow profiles seem to favour the 850-ft level within the parts of the profiles away from the meander prow, whereas the other three profiles do not seem to record this level. Third, significant excursions from these normative elevations do exist. The Little Orleans profile has a deep sag midway along the profile at about 560 ft (actual saddle elevation of this sag is 550 ft; this sag is used by the Western Maryland Railroad track) that is clearly a abandoned meander cutoff when the channel was at that level (it belongs, in fact, to the dataset for the strath fitted by the least-squares equation of the main text). For some reason, this channel did not survive subsequent downcutting. Another deviation from the main strath levels is the 1010-ft hilltop along the Tunnel Hollow profile; it is flanked by 850-ft hilltops and suggest a former island in the interfluve.

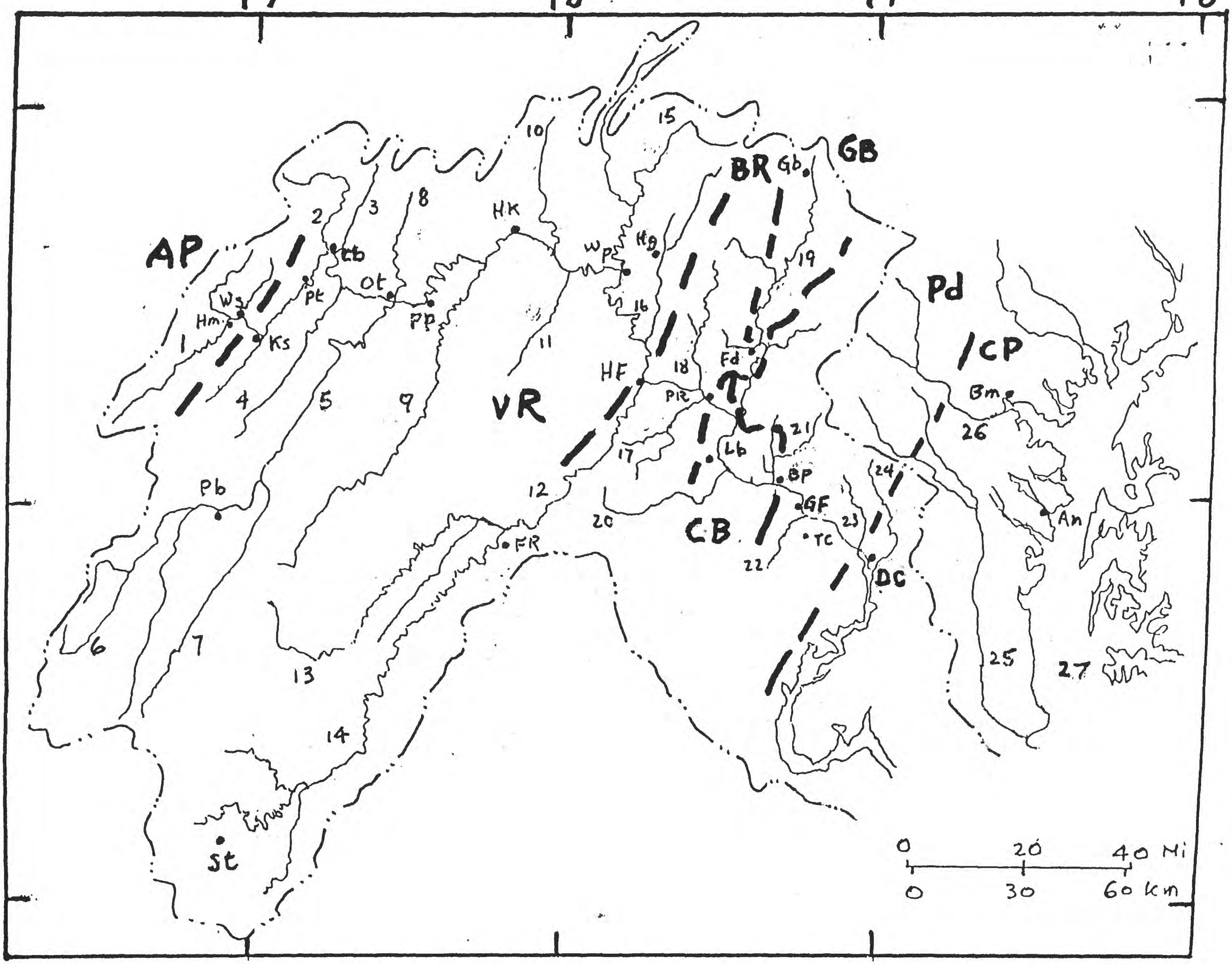
Other rises and dips on the profiles simply record the locations of dissecting ravines. For example, on the Jerome profile one readily identifies the crossings with Sprigs Hollow, Station Hollow, and Hales Hollow cutting into an "upland" surface at about 850 ft. On the Tunnel Hollow profile, the depressions of Tunnel Hollow and one used by the Kesler Tunnel are readily identified. The Tunnel Hollow profile, showing more rises and falls, is somewhat suspect because this loop merges upstream with the younger, smaller, and lower loops of Cluster 8, and so its topography might have been complicated by that development.

The profiles suggest that the adjustment of the channel to downcutting was considerably more complex than a simple model of formation of slipslopes with concomitant increase of the amplitude of the meander. On the whole, the interfluves seem to record two distinct levels. I hypothesize that both levels represent entrenchment within then-active floodplain areas which became more restricted in extent with downcutting. Here and there, the channel split, leaving islands of abandoned straths; one of these channels would further deepen and stay active.

Tributaries to the meandering Potomac River during the intermediate channel levels are locally preserved. Both Roby Hollow and Devil's Alley of the Green Ridge loop are peculiarly narrow and deep ravines that turn abruptly into the modern channel, and show nickpoints at about 600-ft level (Appendix 3B, points 43, 45) which agrees with the interfluve at Bevan Bend (*ibid*, point 50) upstream and with the meander cutoff at Little Orleans (*ibid*, point 41). A concordant nickpoint can be located in the narrow Tunnel Hollow (*ibid*, point 47), but modification by the construction of the Paw Paw Tunnel of the C&O Canal makes map interpretation risky even though the hollow was a natural feature (and was called Athey's Hollow; Hahn, 1992, p. 195).

We can bound the extent of increase of the meander amplitude between the formation of the 750-ft interfluve level and the modern river. Any inclination of the profile that might demonstrate a slipslope is confined to a width of about 500 m for four of the profiles; the Beanpatch Hollow profile might contain a slipslope as wide as 800 m. These are respectively 10% and 20% of the amplitude of the meander. Add to this limit the existence of abandoned cutoff channels and paleo-hills, as well as the problem of a mechanism for entrenchment that would affect the entire reach of the river simultaneously without regional tilting, the data seem to support the view that the amplitude as well as the wave length of the meanders of Cluster 7 by and large preserve their original configuration despite the subsequent events attending the river entrenchment.

Zen Figure 1



79
78
77
76
40
39
38
AP
VR
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GB
CB
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CP
HK
Wp
Hg
Gb
Ot
Pp
Cb
Pt
Ws
Hm
Ks
Pb
HF
PR
Fd
Lb
BP
GF
TC
DC
FR
Bm
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1
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3
4
5
6
7
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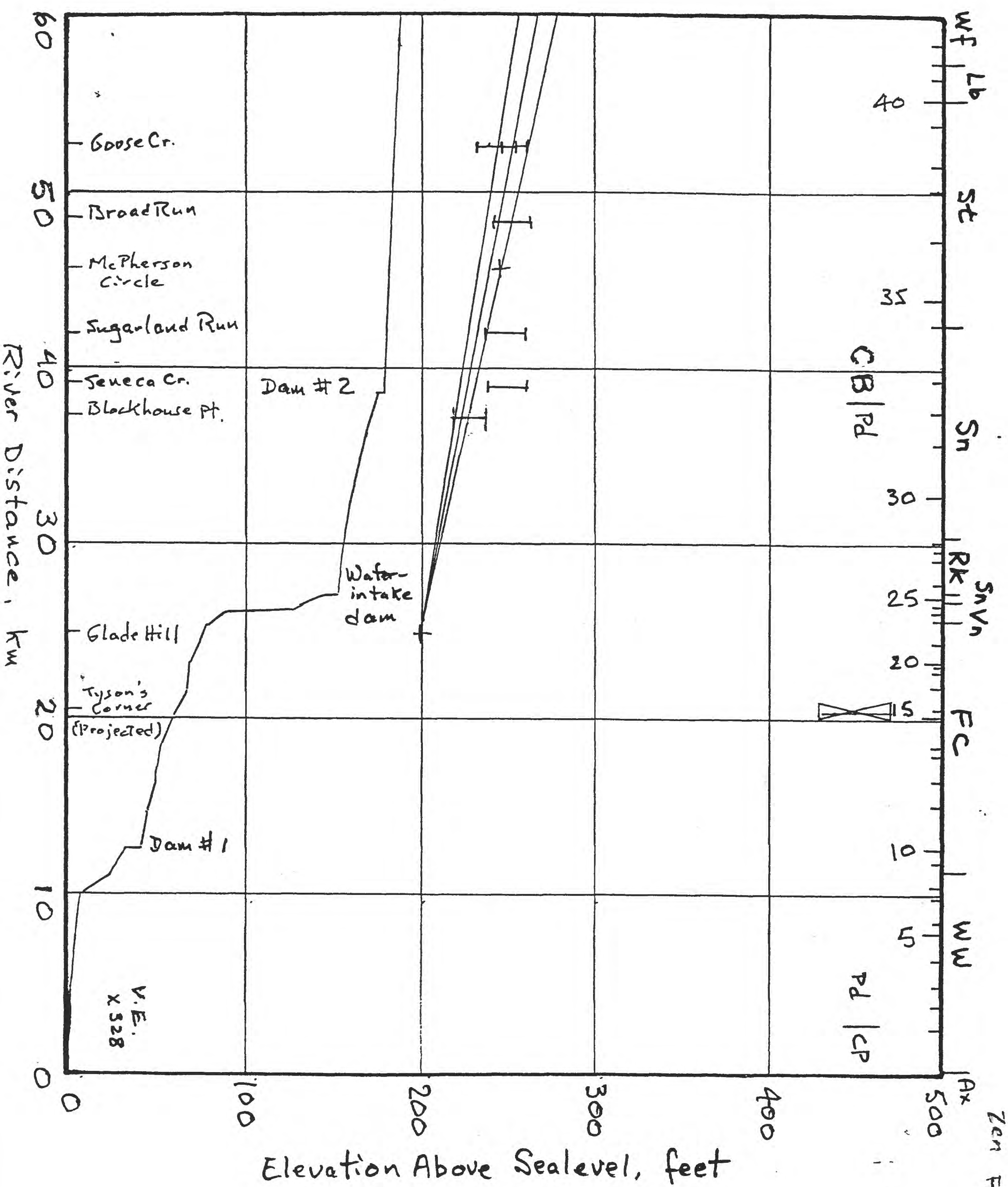
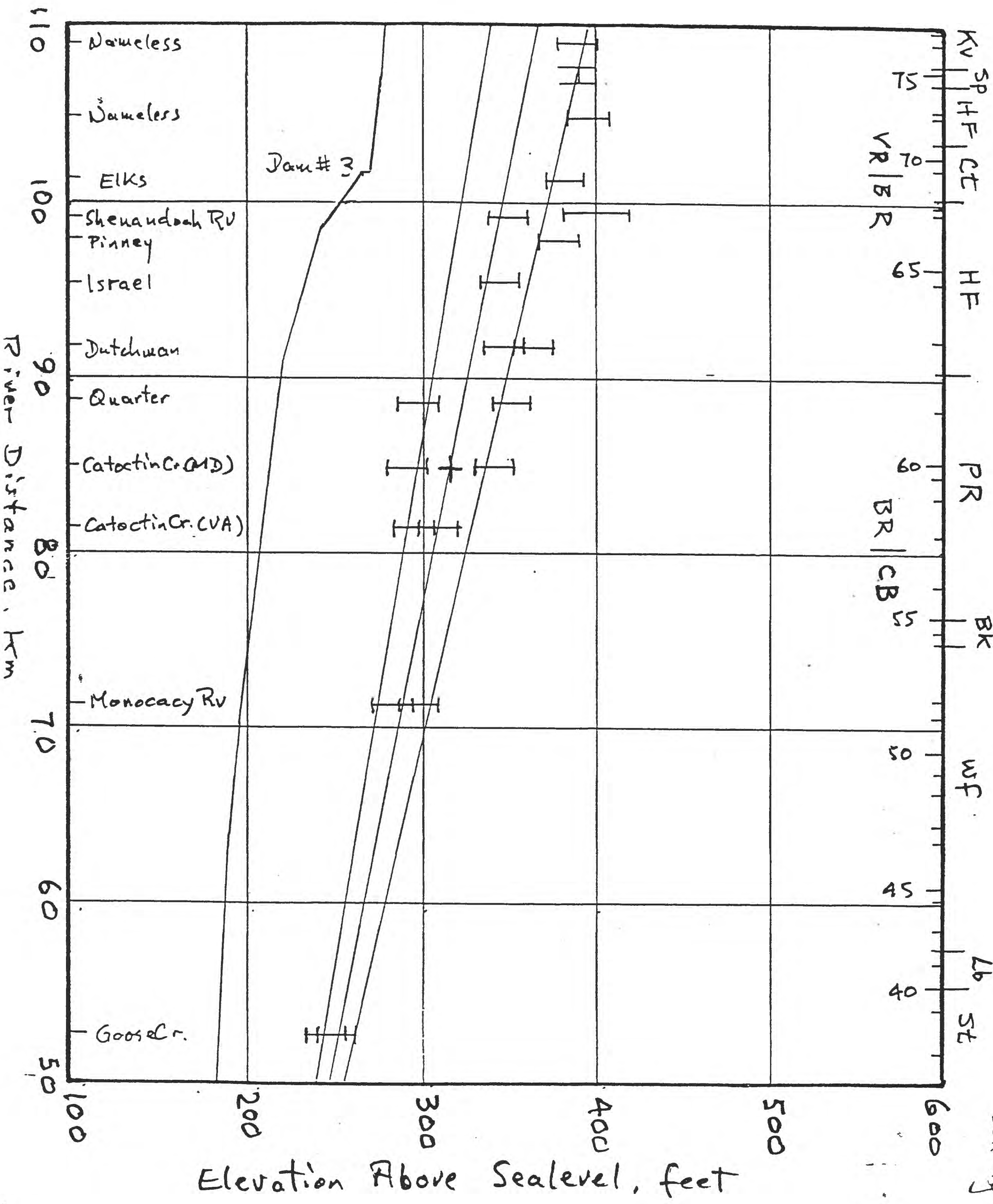
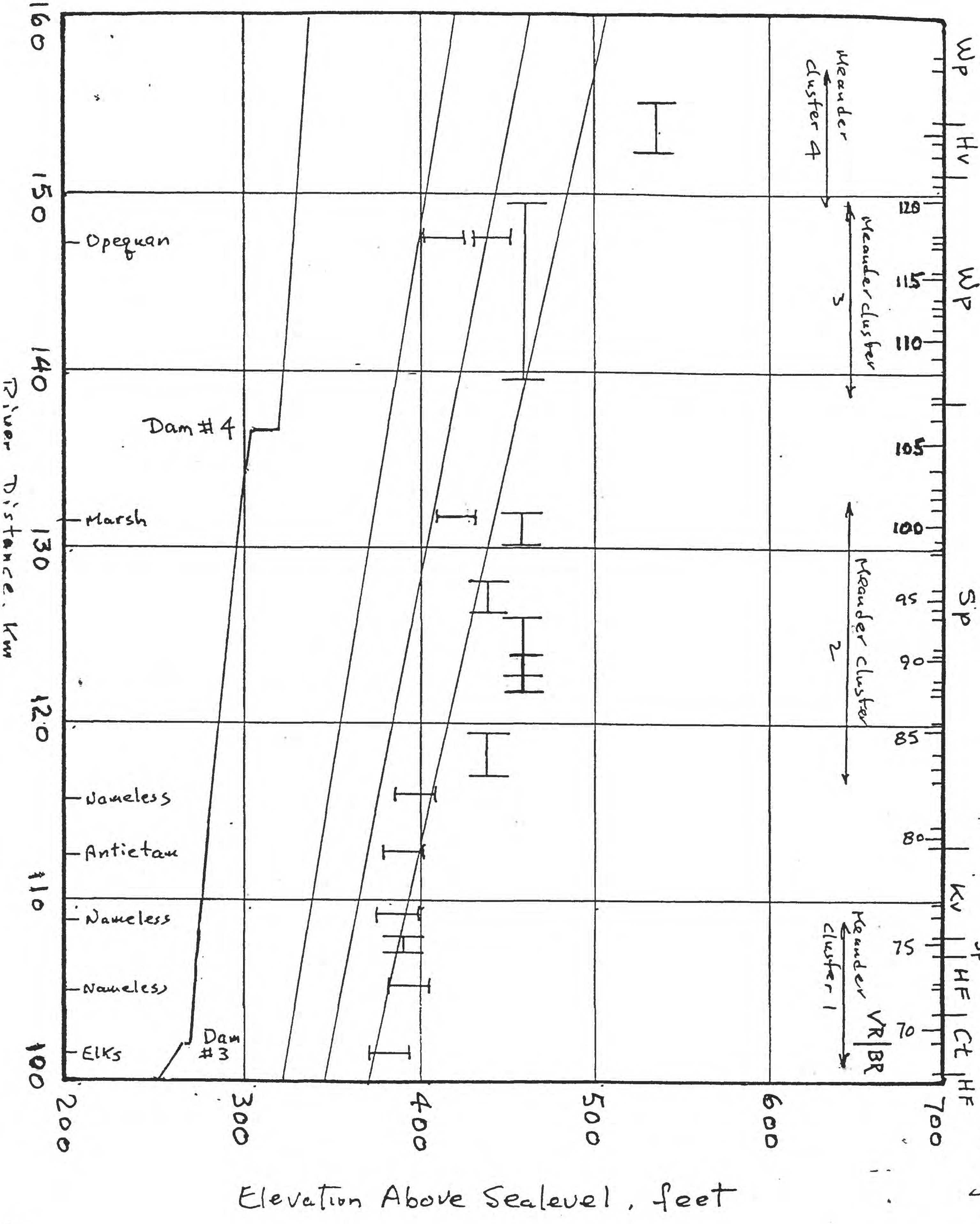
22
23
24
25
26
27
0
20
40 Mi
0
30
60 km



River Distance, km
Elevation Above Sealevel, feet
0
100
200
300
400
500
10
20
30
40
50
60
Goose Cr.
Broad Run
McPherson Circle
Sugarland Run
Seneca Cr.
Blockhouse Pt.
Dam #2
Water-intake dam
Glade Hill
Tyson's Corner (Projected)
Dam #1
V.E. x 328
Wf
Lb
St
CB | Pd
Sn
Rk
SnVn
FC
WW
Pd | CP
Ax
5
10
15
20
25
30
35
40

Zen Fig 2 (A)


Nameless
Nameless
Elks
Dam # 3
Shenandoah Rv
Pinney
Israel
Dutchman
Quarter
Catoctin Cr. (MD)
Catoctin Cr. (VA)
Monocacy Rv
Goose Cr.
River Distance, km
110
100
90
80
70
60
50
100
200
300
400
500
600
Elevation Above Sealevel, feet
75
70
65
60
55
50
45
40
Kv
SP
HF
Ct
VR
B
R
HF
PR
BR
CB
BK
Wf
Lb
St
Zen Fig 2 (B)

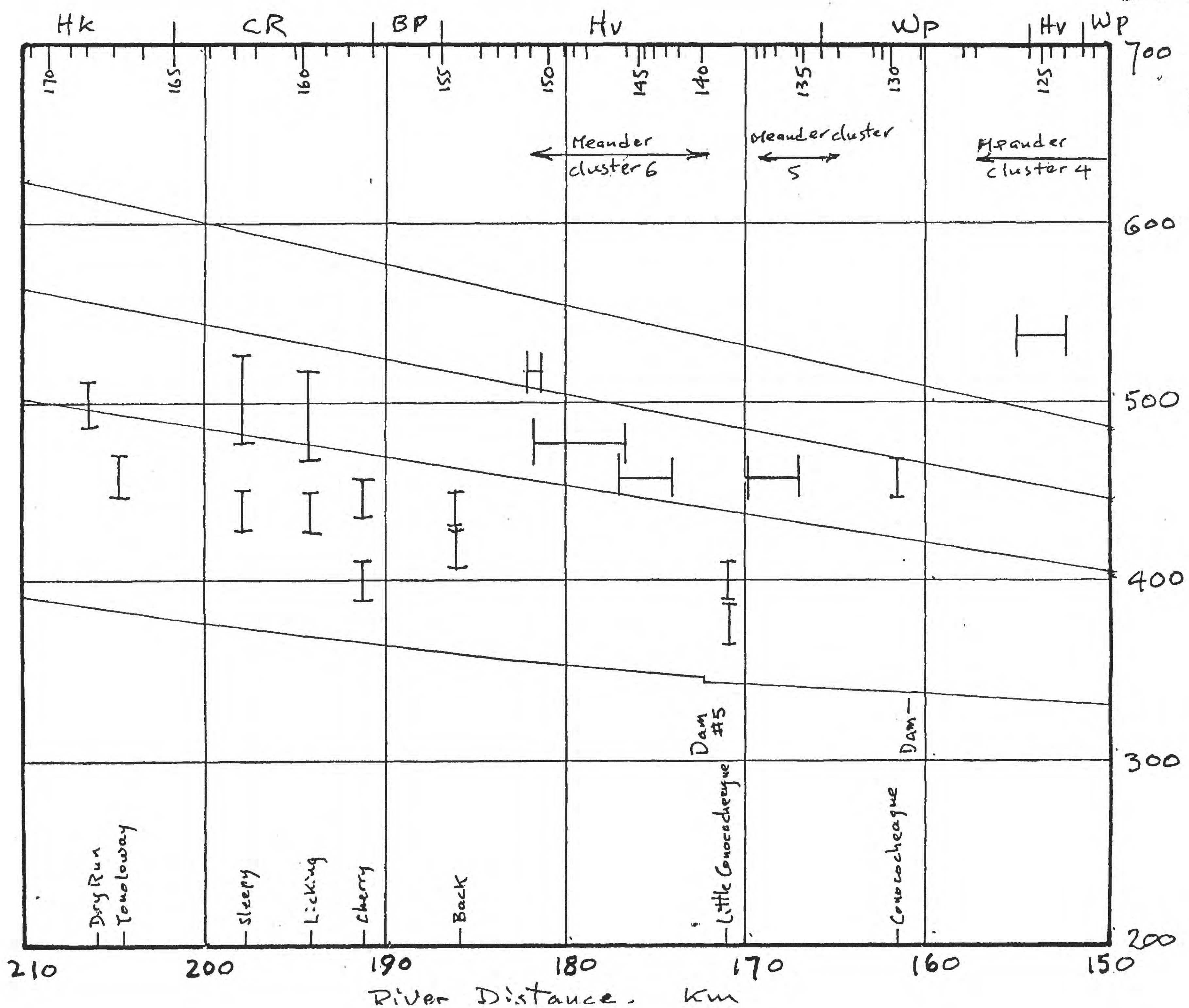


River Distance, km
160
150
140
130
120
110
100
Opequan
Marsh
Nameless
Antietam
Nameless
Nameless
Elks
Dam #4
Dam #3
Meander cluster 4
Meander cluster 3
Meander cluster 2
Meander cluster 1
120
115
110
105
100
95
90
85
80
75
70
Wp
Hv
Wp
Sp
Kv
Sp
HF
VR
BR
Ct
HF
200
300
400
500
600
700
Elevation Above Sealevel, feet

Zen Fig 2 (C)

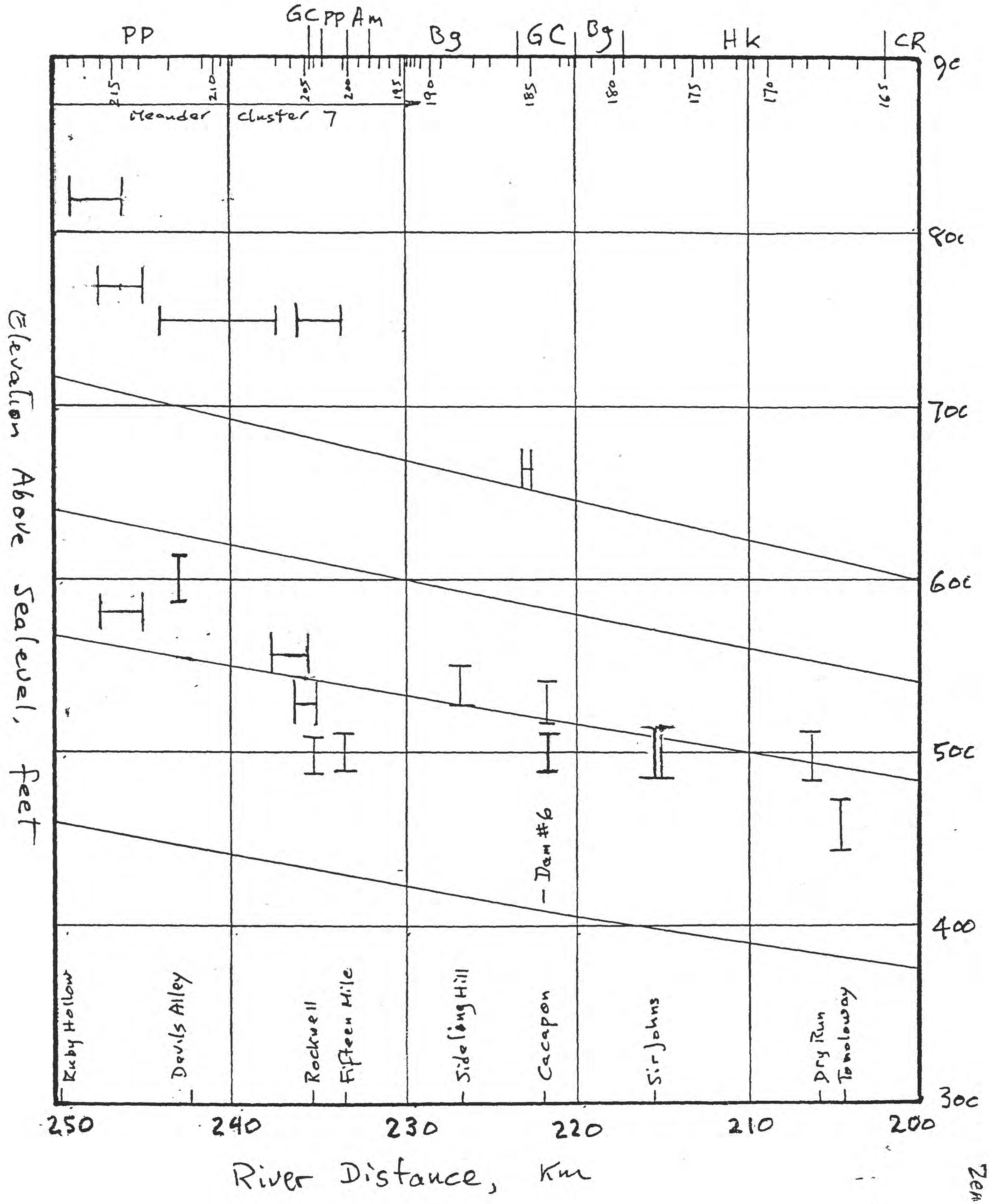
4

Zen Fig 2 (D)



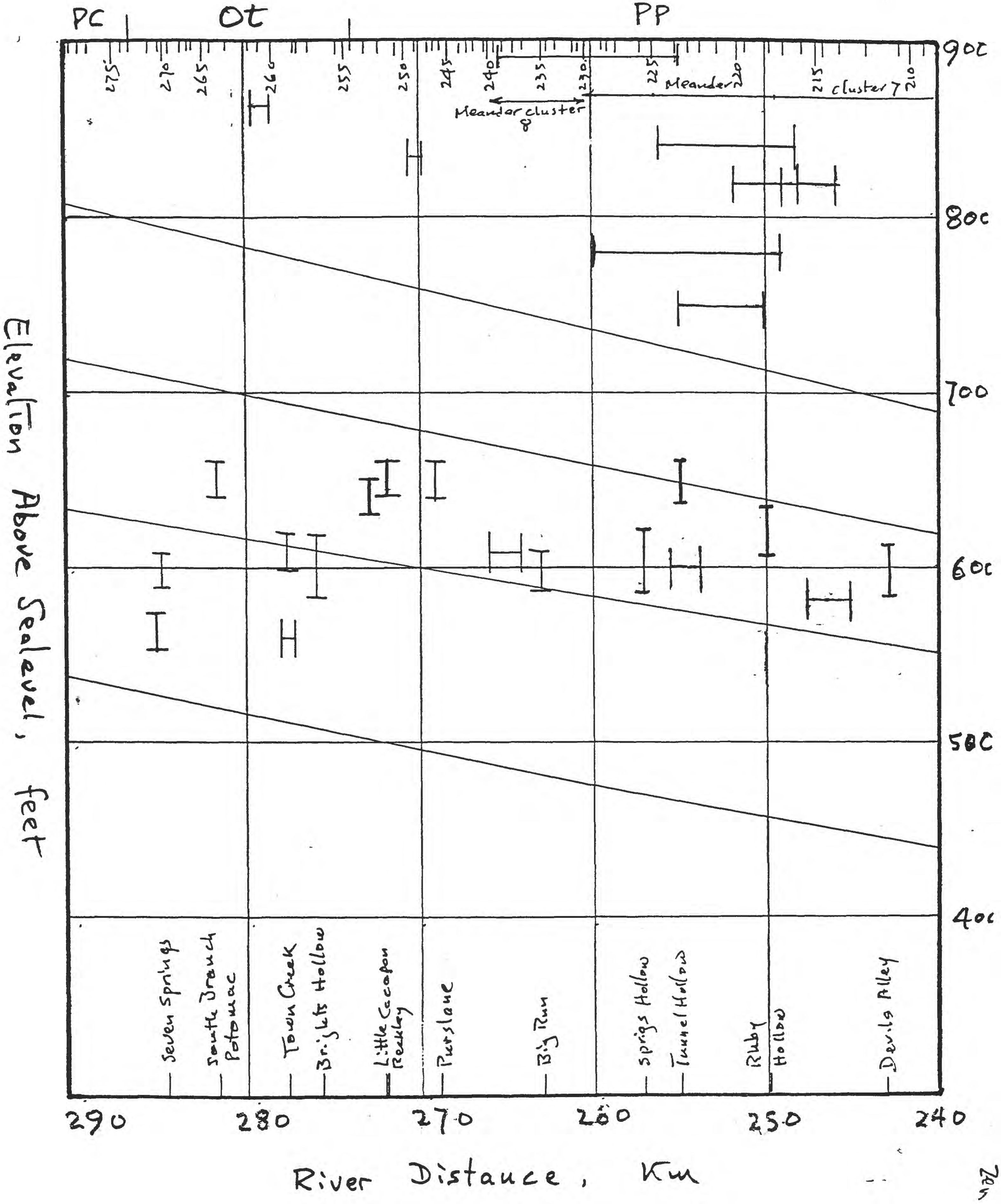
Hk
CR
BP
Hv
Wp
Hv
Wp
170
165
160
155
150
145
140
135
130
125
700
600
500
400
300
200
Meander cluster 6
Meander cluster 5
Meander cluster 4
Dam #5
Dam
Dry Run
Tonoloway
Sleepy
Licking
Cherry
Back
Little Conococheague
Conococheague
210
200
190
180
170
160
150
River Distance, Km

5

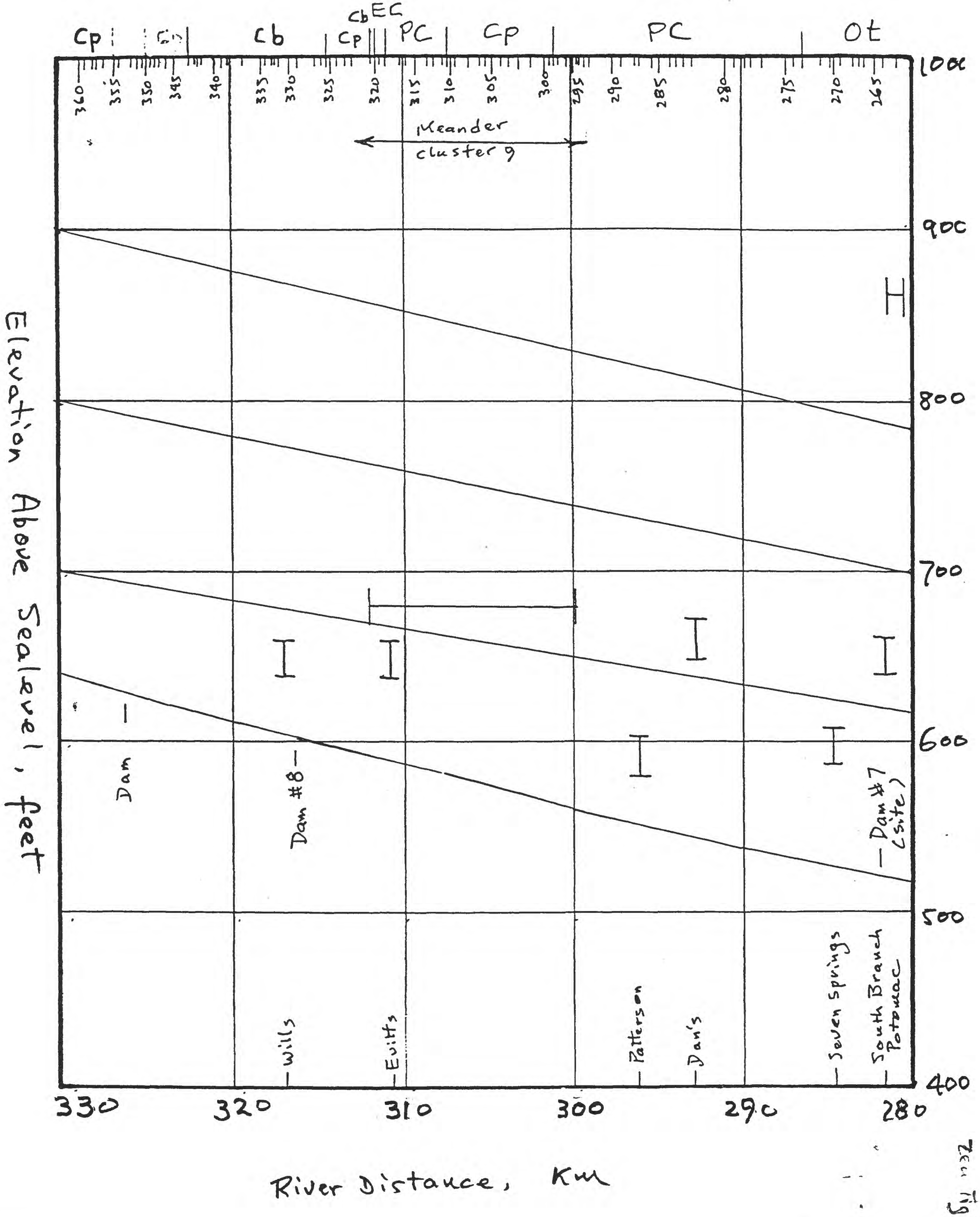

PP
GC PP Am
Bg
GC
Bg
Hk
CR
215
210
205
200
195
190
185
180
175
170
165
Meander cluster 7
Elevation Above Sealevel, feet
900
800
700
600
500
400
300
Dam #6
Ruby Hollow
Devils Alley
Rockwell
Fifteen Mile
Sideling Hill
Cacapon
Sir Johns
Dry Run
Tonoloway
250
240
230
220
210
200
River Distance, Km

Zeh Fig 2(B)

6

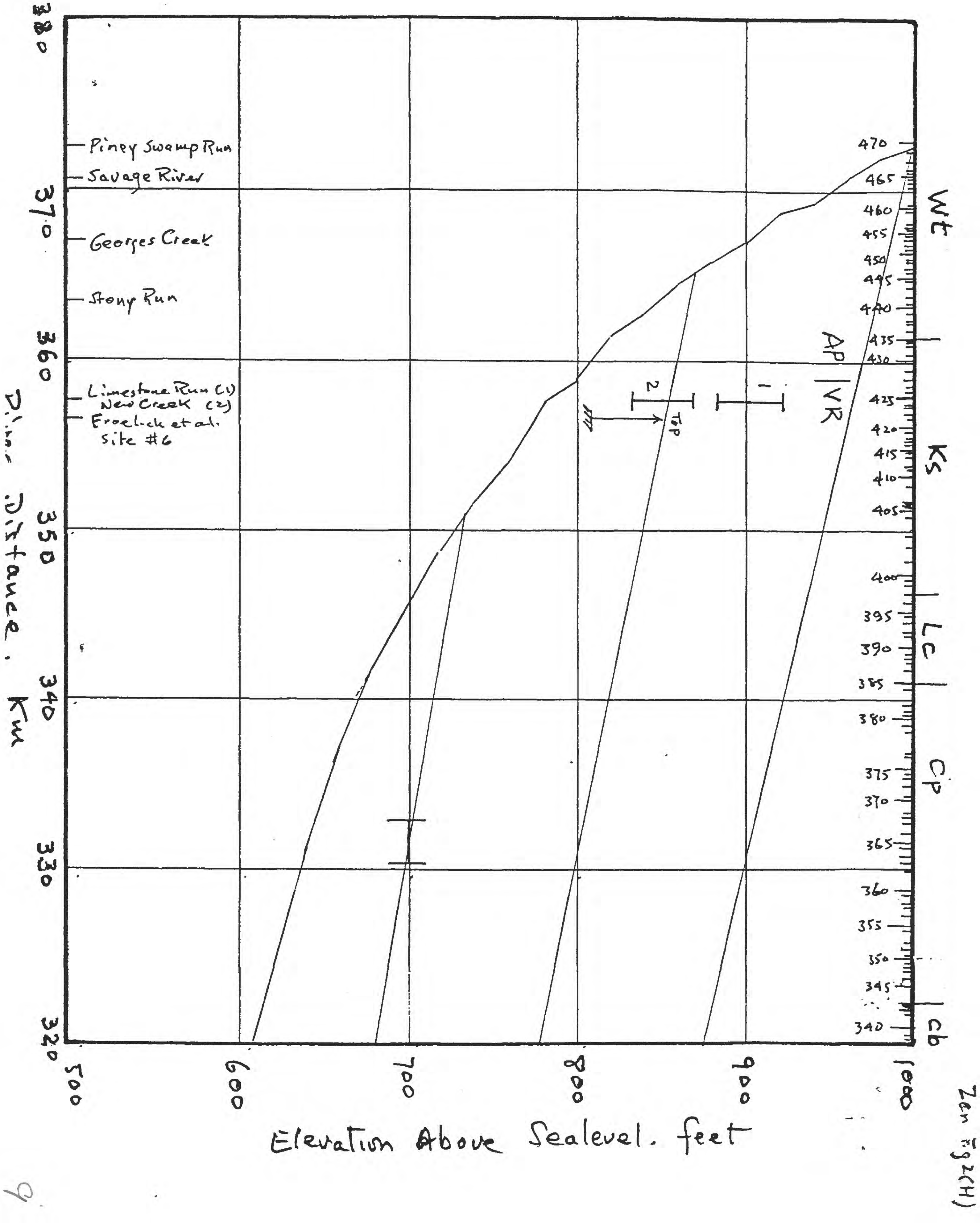

PC
Ot
PP
275
270
265
260
255
250
245
240
235
230
225
220
215
210
Meander cluster 8
Meander cluster 7
900
800
700
600
500
400
Elevation Above Sealevel, feet
Seven Springs
South Branch Potomac
Town Creek
Brights Hollow
Little Cacapon Rockley
Purslane
Big Run
Sprigs Hollow
Tunnel Hollow
Ruby Hollow
Devils Alley
290
280
270
260
250
240
River Distance, Km

7



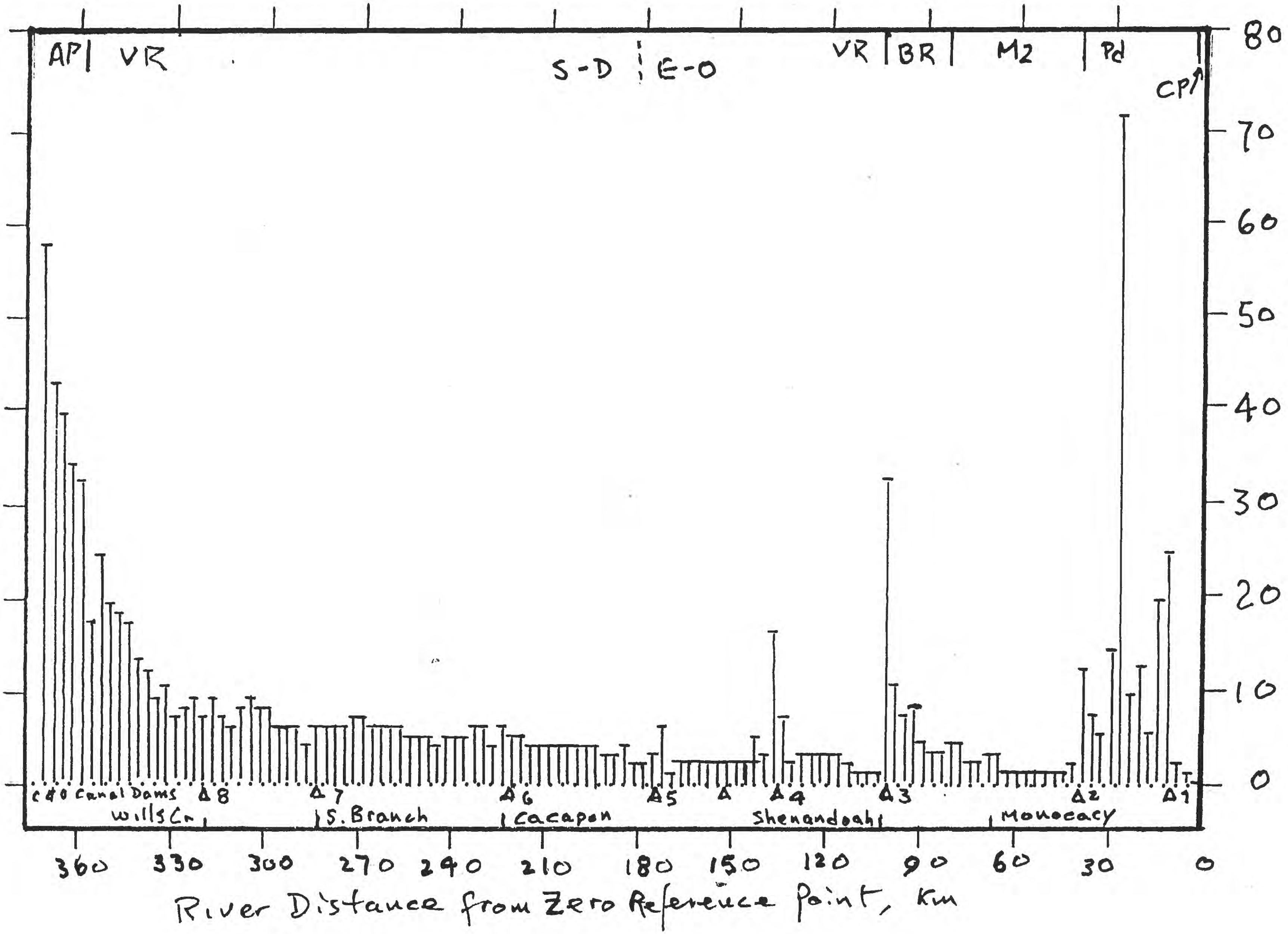
Cp
Cb
Cp
CbEC
PC
Cp
PC
Ot
360
355
350
345
340
335
330
325
320
315
310
305
300
295
290
285
280
275
270
265
1000
900
800
700
600
500
400
Meander cluster 9
Dam
Dam #8
Dam #7 (site)
Wills
Evitts
Patterson
Dan's
Seven Springs
South Branch Potomac
330
320
310
300
290
280
Elevation Above Sealevel, feet
River Distance, Km

Rev. Fig 2(b)



Piney Swamp Run
Savage River
Georges Creek
Stony Run
Limestone Run (1)
New Creek (2)
Froelich et al. Site #6
River Distance. Km
380
370
360
350
340
330
320
500
600
700
800
900
1000
Elevation Above Sealevel. feet
AP
VR
TOP
1
2
Wt
Ks
LC
CP
Cb
470
465
460
455
450
445
440
435
430
425
420
415
410
405
400
395
390
385
380
375
370
365
360
355
350
345
340
Zen Fig 2(H)

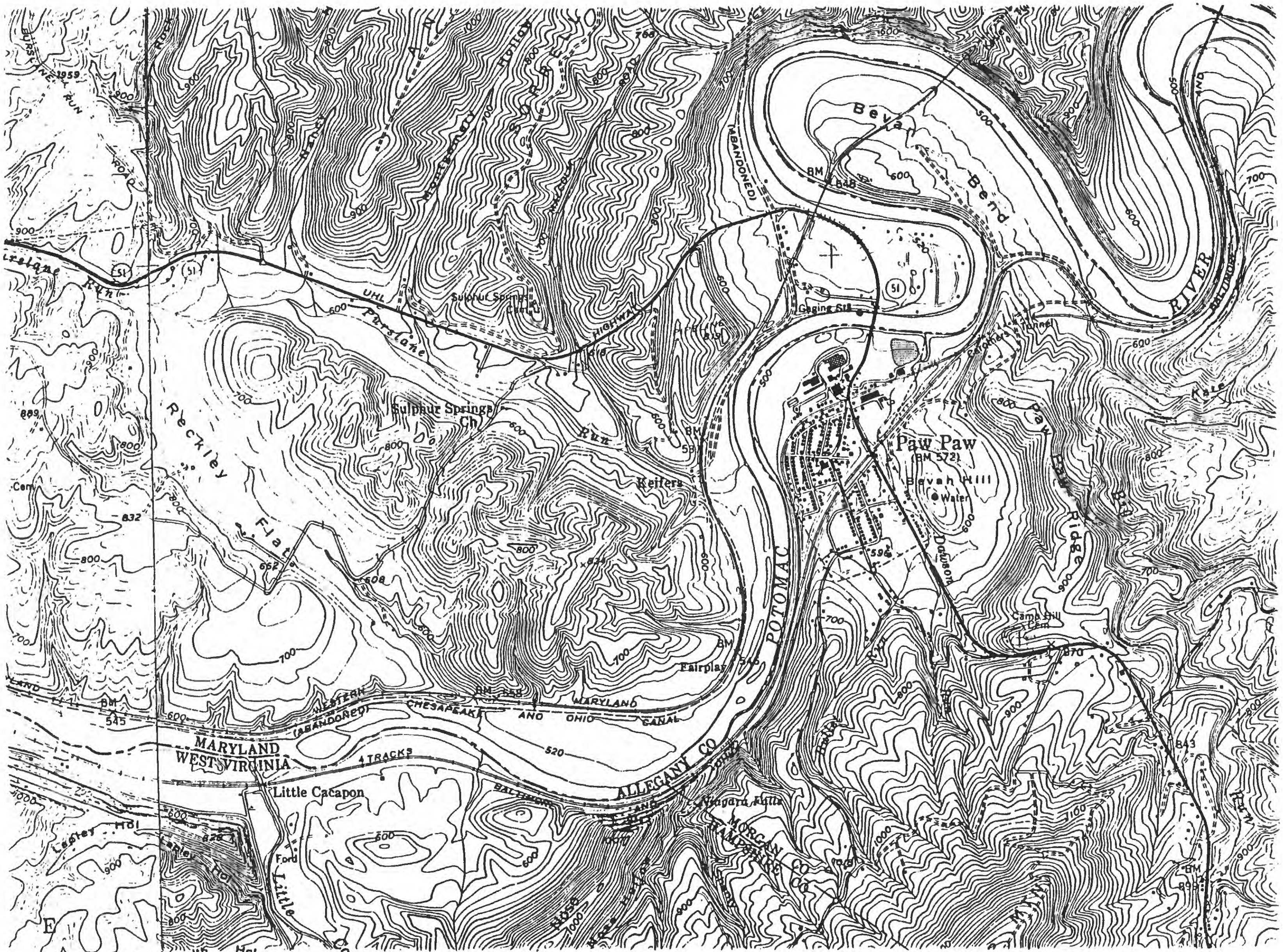
2+4 Fig 3



AP
VR
S-D
E-O
VR
BR
M2
Pd
CP
C&O Canal Dams
Wills Cr.
S. Branch
Cacapon
Shenandoah
Monocacy
Δ8
Δ7
Δ6
Δ5
Δ
Δ4
Δ3
Δ2
Δ1
0
10
20
30
40
50
60
70
80
Ri'ver slope, value x 10^4
360
330
300
270
240
210
180
150
120
90
60
30
0
River Distance from Zero Reference Point, km

10

Zen Fig 4



39° 32' 30"

78° 30' 00"

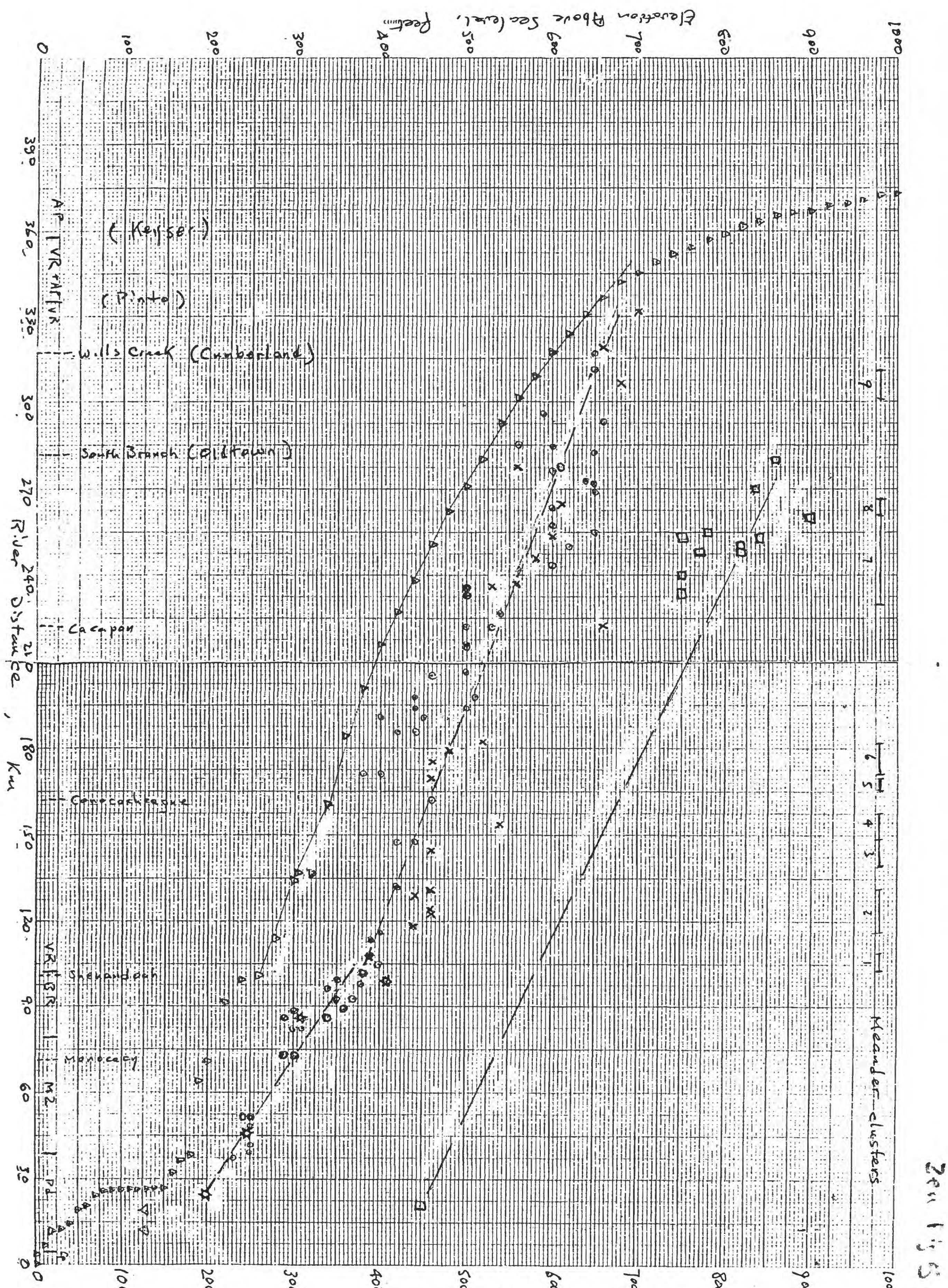
78° 27' 30"

1 ½ 0 1 MILE

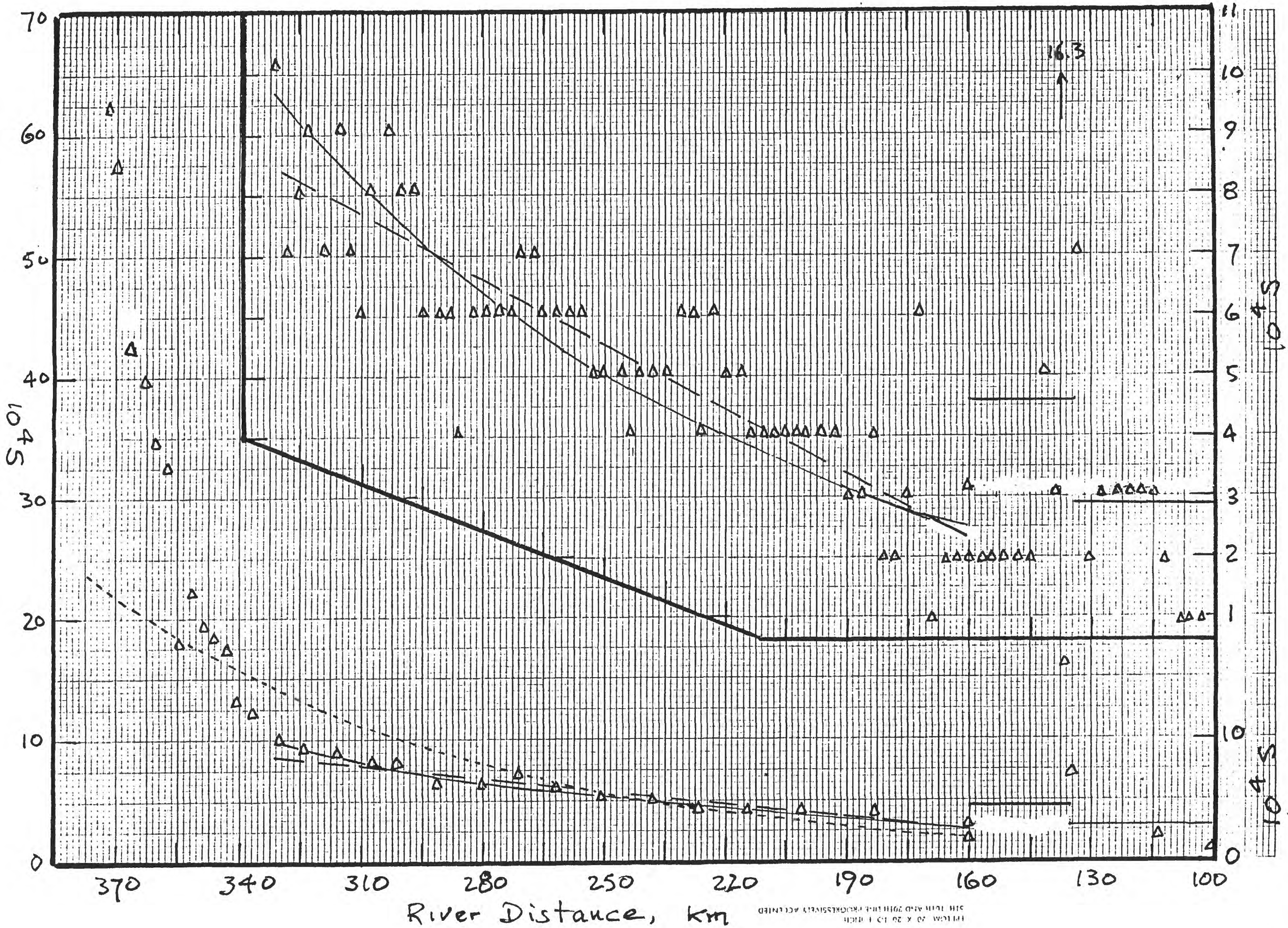
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

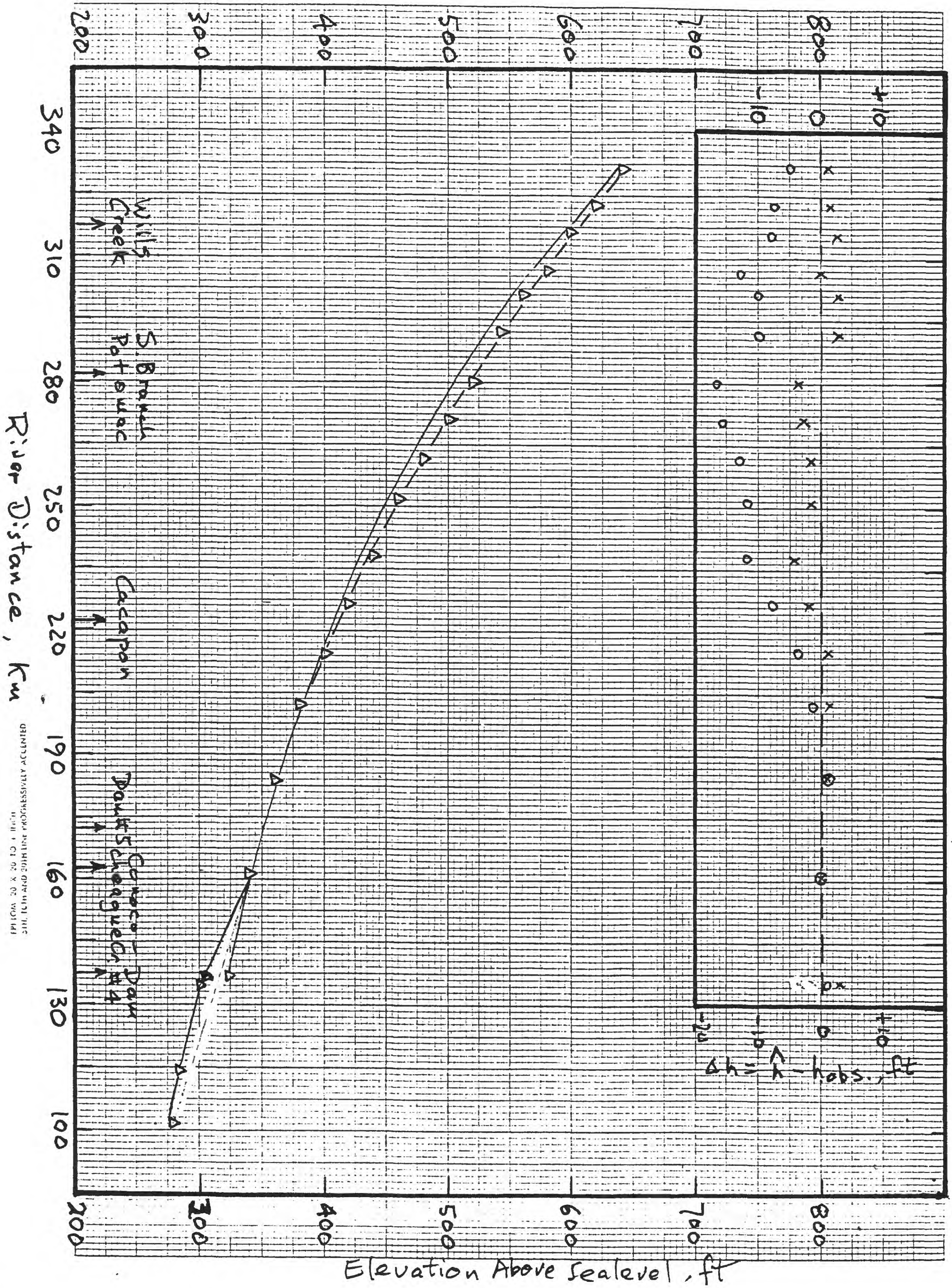
1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929


Elevation Above Sea level, feet
River Distance, Km
Elevation Above sea level, feet
(Keyser)
(Pinto)
Wills Creek (Cumberland)
South Branch (Oldtown)
Cacapon
Conococheague
Shenandoah
Monocacy
Meander clusters

Zcu T.S 6





Elevation Above Sealevel, ft
200
300
400
500
600
700
800
River Distance, Km
340
310
280
250
220
190
160
130
100
Wills Creek
S. Branch Potomac
Cacapon
Paw Paw
Conoco Dam
Hancock
Williamsport
Dam #5
Sharpsburg
Dam #4
Δh = ĥ − hobs., ft
−10
0
+10
−20

204 Fig 7

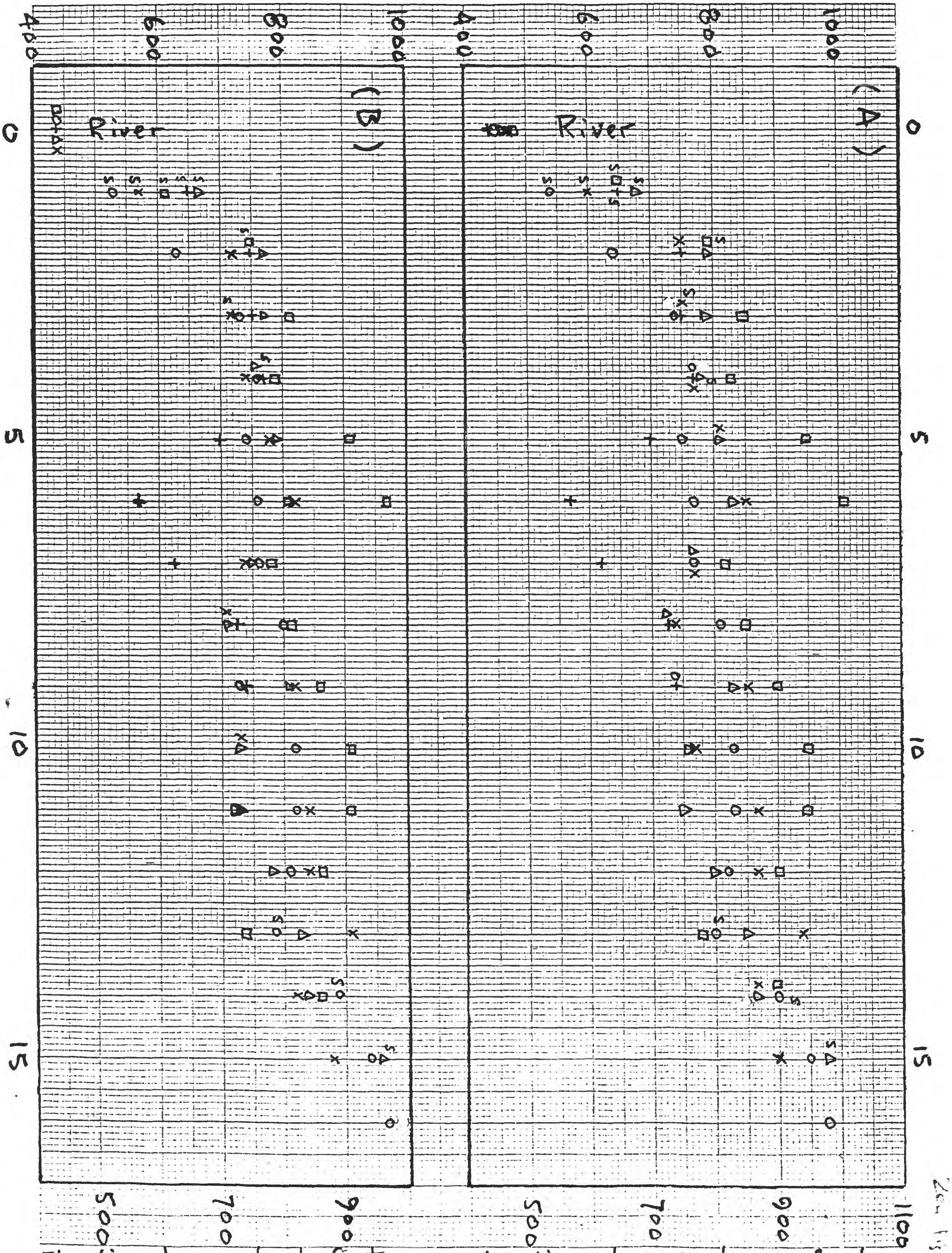
Zen Fig 8 5

39° 37'30"

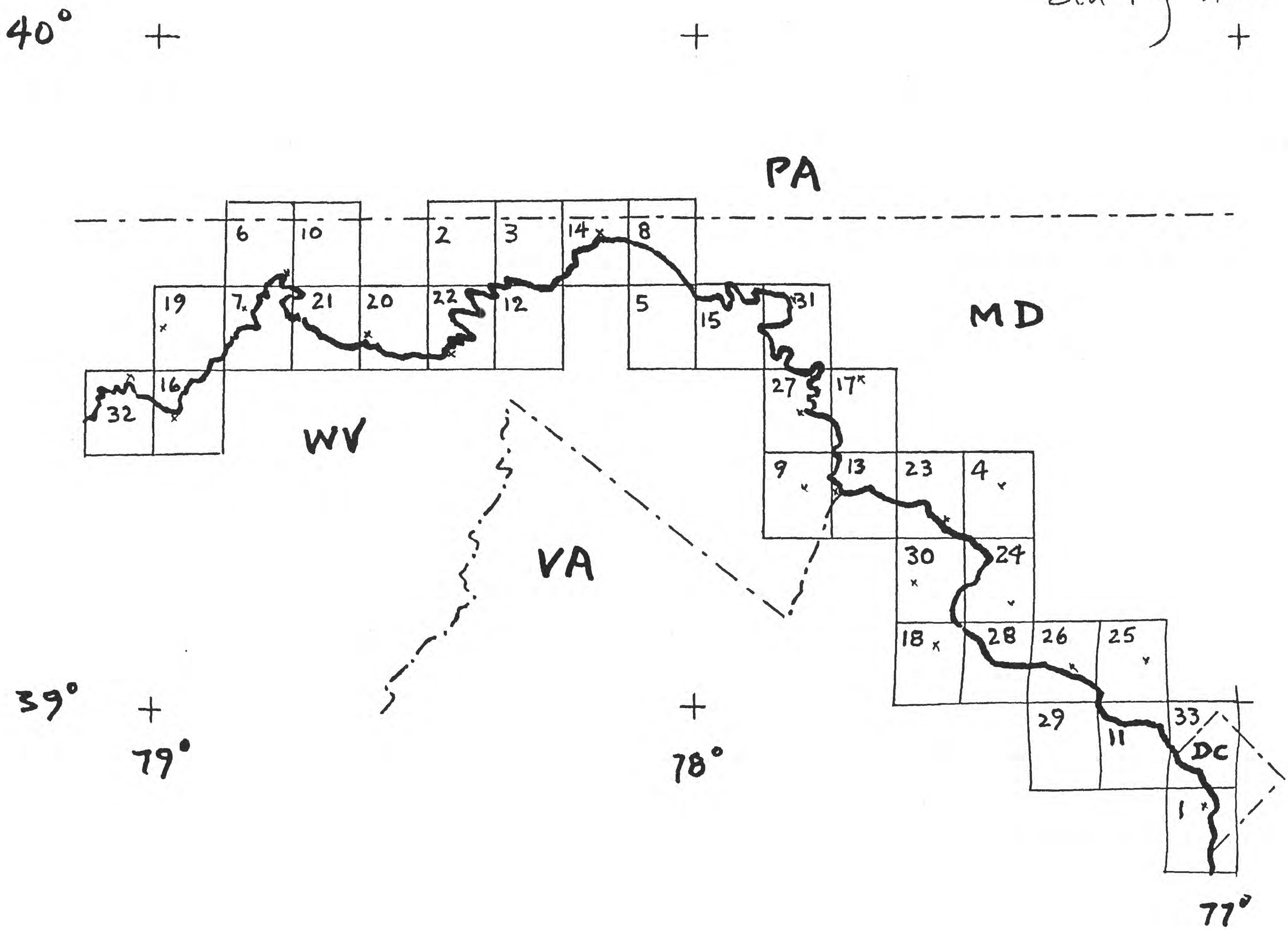
39° 35'00"

39° 32'30"

78°27'|30"   78°25'|00"   78°22'|30"


(B)
River
(A)
River
400
600
800
1000
0
5
10
15
500
700
900
1100
Elevation above sealevel, feet
Elevation above sealevel, feet

Zen Fig A1-1


40°
PA
MD
WV
VA
DC
39°
79°
78°
77°
6
10
2
3
14
8
19
7
21
20
22
12
5
15
31
32
16
27
17
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23
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18
28
26
25
29
11
33
1