Stream meander restoration

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STREAM MEANDER RESTORATION[1]

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ABSTRACT: Stream meander restoration designs currently used by many state and local government agencies are often based on empirical equations, such as those developed by Leopold and Wolman (1957; 1960). In order to assess the suitability of these equations and propose alternative strategies, 18 sites in Central Maryland were selected and data on channel planform, cross-sections, sediments, and spacing and sizing of the pools and riffles were collected and analyzed to characterize the channel type in the study area. A large bias was found comparing the meander parameters measured to those computed using the Leopold and Wolman equations for the streams in central Maryland. Based on these results, appropriate empirical equations for the study area that can assist in stream restoration designs were investigated. An additional approach that can assist in stream restoration consists of the application of a detailed stream reconnaissance to verify that the restoration project is consistent with the natural form and processes of the river.

(KEY TERMS: stream restoration; meanders; channel form; channel adjustments; stream reconnaissance.)

INTRODUCTION

During recent decades, many urban streams were straightened or lined for various purposes, such as flood control and drainage improvement. In many cases channel modifications and urbanization caused excessive erosion or sedimentation, and destroyed most of a stream's habitat value. Recently, increased emphasis and attention has been given to river management and restoration of modified or otherwise degraded streams (Gore, 1985; Brookes, 1988; Gardiner, 1991; Boon *et al.*, 1992). Stream recovery and restoration techniques generally include (Brookes, 1988): (a) construction of asymmetrical cross-sections; (b) techniques to induce the stream to develop point bars in desired locations (Nunnally, 1978; Keller, 1978); (c) two-stage channel designs (Keller and Brookes, 1984); (d) floodplain approaches (Palmer, 1976; Gardiner and Cole, 1992); (e) pools and riffles re-creation; and (f) sinuosity and meander restoration (Hasfurther, 1985; Brookes, 1987; Newbury, 1995). Stream restoration procedures currently used by many state and local government agencies are based on a stream restoration procedure developed by Rosgen (1993). The procedure uses a stream classification system to describe the morphological stream types (Rosgen 1994) and meander parameters determined from empirical equations developed by Leopold and Wolman (1957; 1960).

Meander restoration, consisting of the creation of meanders in desired reaches of a stream, is an increasingly common technique in stream restoration. The main objectives of such techniques are to dissipate excess stream energy; to stabilize the stream; to decrease transport capacity, thereby reducing the sediment supply downstream in the fluvial system; and to recover the habitat value of the stream. Although these are worthy objectives, it is difficult to define the appropriate planform geometry and meander size. Modifications of the planform geometry can induce undesirable morphological and ecological consequences and significant channel adjustments that, depending on energy conditions of the flow, can result in failure of the restoration design through either erosion or sedimentation. Brookes (1990) evaluated the success of different kinds of restoration projects in terms of unit stream power. He showed that, for high

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values of stream power, projects are likely to fail by erosion; for low stream power (less than 15 Wm^{-2}), failure is to be expected from excessive deposition. Most successful projects are associated with intermediate values of stream powers (median value of about 35 Wm^{-2}).

The planform geometry and meander size for restoration design are often obtained using empirical relationships developed for other regions. However, the application of such relationships is questionable for regions with differences in geology, climate, hydrology, soil types, and for streams with differences in channel type, sinuosity, bank material, vegetation, and processes of adjustment. Many restoration projects are designed for relatively small streams, while empirical relationships widely reported in the literature have been derived from investigations conducted on larger streams. For example, the equations developed by Leopold and Wolman (1957, 1960) were based on channel widths ranging from 0.5 to 1506 meters, with an average of 207 meters. Channel widths of streams for which restoration projects are typically designed range from a few meters to less than 20 meters. Identification of unstable streams as a consequence of disturbed basin conditions is crucial in meander restoration in order to assess the suitability of the project or to adopt alternative solutions consistent with forms and processes, and to promote the recovery of stream stability (Shields *et al.*, 1995). Empirical relationships concerning channel form parameters are usually based on data from rivers in dynamic equilibrium. They should be applied cautiously to predict a stable configuration in the case of unstable streams that have radically altered flow and sediment regimes in comparison with their undisturbed conditions.

This study has been performed in order to provide preliminary guidelines for stream restoration of central Maryland streams. Specific objectives include: (1) assessing the suitability of currently used meander restoration procedures and empirical equations; (2) obtaining empirical relationships specific to small suburban streams in the study area; and (3) providing suggestions for developing alternative strategies for stream restoration based on geomorphological reconnaissance.

STUDY AREA

The study area is located in the Piedmont Province, one of five distinct physiographic regions of Maryland, and includes the upper and middle portions of the Patuxent River, Patapsco River and Rock Creek basins (see Figure 1). Bedrock in this region is composed of hard, crystalline igneous and metamorphic rocks. Soils are mainly deep, well drained, sloping or moderately steep. The climate is temperate with warm summers and mild winters, with average temperatures of 25°C and 2°C, respectively. Mean annual precipitation is about 1100 mm, with average monthly rainfall ranging from about 60 to 100 mm. The lower courses of Patuxent and Patapsco rivers cross the Coastal Plain and flow into the Chesapeake Bay; Rock Creek flows into the Potomac River. Hydrologic data for the Little Patuxent River and Middle Patuxent River are summarized in Table 1.

Streams and valleys of the Piedmont region generally have higher gradients and sediment supply than Coastal Plain streams. The present floodplains of many Piedmont streams are quite narrow or discontinuous, with common interaction between channel and valley side slopes. In the Coastal Plain, sedimentation processes prevail, with large floodplains and typical meandering forms. The stratigraphy and sedimentology of Maryland Piedmont floodplains show three distinct units corresponding to different periods of land use (Jacobson and Coleman, 1986): (1) relatively thin overbank and lateral accretion sediments deposited in presettlement time (prior to about 1730); (2) thicker overbank and lateral accretion deposits accumulated in the agricultural period (about 1730 to 1930); and (3) thick lateral accretion deposits corresponding to very recent time.

During the last several decades a rapid land use change from agricultural to urban occurred in large portions of the study area. A large increase in sediment yield occurred during construction activities in the first years of intense urbanization, followed by a reduction in sediment production after a portion of the source areas had been paved (Wolman, 1967).

DATA COLLECTION

An initial stream reconnaissance was conducted at each of a number of sites in the fluvial system in order to identify dominant processes and characteristic channel forms, to assess the general stability conditions of the streams, and select sites for data collection. Geomorphological stream reconnaissance includes a range of methodologies and field techniques for a wide ranging analysis of a fluvial system and can be applied at various levels of detail, depending on the objectives and scope of the study (Simon *et al.*, 1989; Thorne and Easton, 1994; Simon and Downs, 1995). For stream restoration projects, an initial qualitative assessment of the whole fluvial system is desirable in order to identify dominant channel processes, adjustments, instabilities, and crucial sites

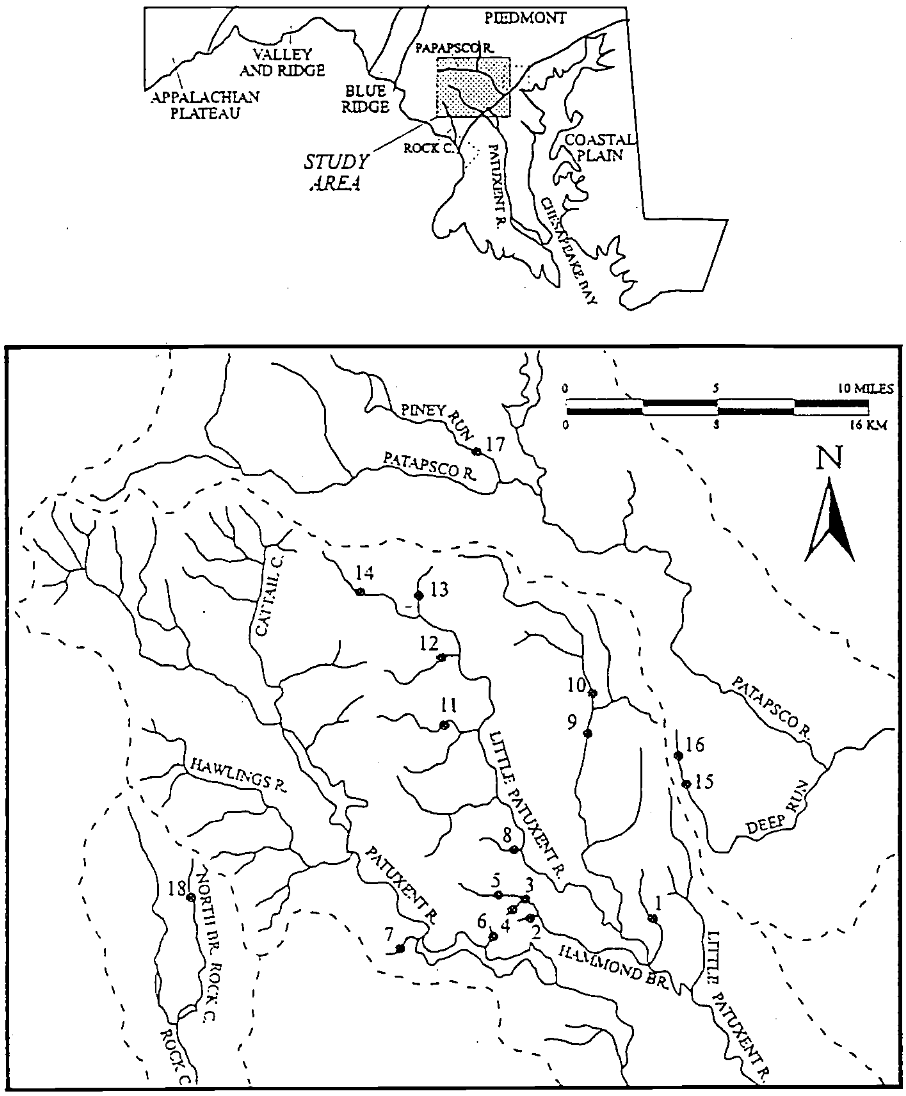


Figure 1. Study Area Location and Selected Stream Sites.

TABLE 1. Hydrologic Data for Gaged Streams in the Study Area.

River	Average Monthly Flow (m^3/s)	Maximum Monthly Flow (m^3/s)	Minimum Monthly Flow (m^3/s)
Middle Patuxent at Clarksville	1.36	2.46	0.65
Little Patuxent at Guilford	1.22	2.66	0.65
Little Patuxent at Savage	3.00	4.30	1.81

or reaches, followed by a more detailed investigation of the reaches selected for restoration designs to obtain details and specific information for stream management and restoration (Thorne and Easton, 1994). In this study, observations made during the initial stream reconnaissance included planform configuration, altimetric relation between floodplain and channel bed, presence and types of bars, presence and spacing of pools and riffles, bank erosion and widening processes, riparian vegetation, and bed and bank sediment characteristics.

Following the initial stream reconnaissance, morphological, hydraulic and sedimentary data were collected for a series of selected meander sites. Criteria for meander site selections included: (a) at least one well defined meander in the stream reach; (b) absence of direct disturbances by human interference or structures; and (c) minimum control or constraint by bedrock in the channel or by valley walls. The data collected at each site included bed material samples and measurements of the morphological characteristics of the channel in selected meandering reaches. Meander wavelength, amplitude, radius of curvature, bend length, and belt width were measured for each selected meander from a topographic field survey (see Table 2), according to the definitions given by Leopold and Wolman (1960) and Williams (1986) (see Figure 2). In these small streams it was difficult to identify reaches with several consecutive well defined meanders. Therefore the topographic survey usually included a single meander or, for three sites, two meanders. In these latter cases, average values of the parameters were used.

TABLE 2. Meander Parameters of the Study Streams (see Figure 2 for parameter definition). λ = wavelength; *Rc* = radius of curvature; *Am* = amplitude; *Lb* = bend length; *B* = belt width; *SI* = sinuosity index.

Site	*λ (m)*	*Rc (m)*	*Am (m)*	*Lb (m)*	*B (m)*	*Si*
1	53.5	11.6	17.4	32.6	25.6	1.19
2	15.2	7.7	3.1	8.2	7.1	1.10
3	28.4	7.6	6.6	16.0	16.0	1.13
4	10.3	3.5	5.7	8.3	10.8	1.48
5	23.2	4.9	11.5	17.9	21.2	1.64
6	30.3	7.2	15.8	24.8	22.1	1.57
7	42.9	8.0	15.9	27.3	23.5	1.28
8	63.2	15.8	26.3	44.4	37.9	1.36
9	43.0	13.6	15.6	28.4	24.3	1.46
10	80.0	20.3	33.9	58.3	62.9	1.46
11	31.1	7.2	22.2	29.5	30.0	1.55
12	30.1	5.1	31.0	37.1	37.3	2.20
13	23.9	4.2	14.5	20.2	23.3	1.64
14	28.4	8.0	7.5	17.2	15.0	1.21
15	21.2	5.7	12.0	17.8	18.0	1.49
16	32.6	6.5	17.4	25.9	25.0	1.64
17	69.2	15.1	31.8	50.1	47.2	1.39
18	15.3	2.0	5.0	10.0	8.5	1.30

Pool and riffle sequences represent an important feature of river channels and need to be considered in designs for channel restoration. For each selected reach, pools and riffles were identified during the field investigation based on changes in bed-material size, bed topography and flow velocity (at low flow stage). Once the limits of each riffle and pool were established based on these evidences, riffle length and pool length were measured along the thalweg. Mean values of riffle length and pool length for the reach were used (see Table 3). Riffle-to-riffle and pool-to-pool spacing were measured as the average of the distances along the thalweg between the mid-points of each riffle-pool pair. Riffle-pool spacing of the reach was assumed as the average of riffle-to-riffle and pool-to-pool spacing (Table 3). Reaches with poorly defined characteristics were not included in the measurements. Pool and riffle sediments were collected in shallow water (during low flow stage) by bulk samples, and the median diameters were obtained by standard sieve analysis (Table 3).

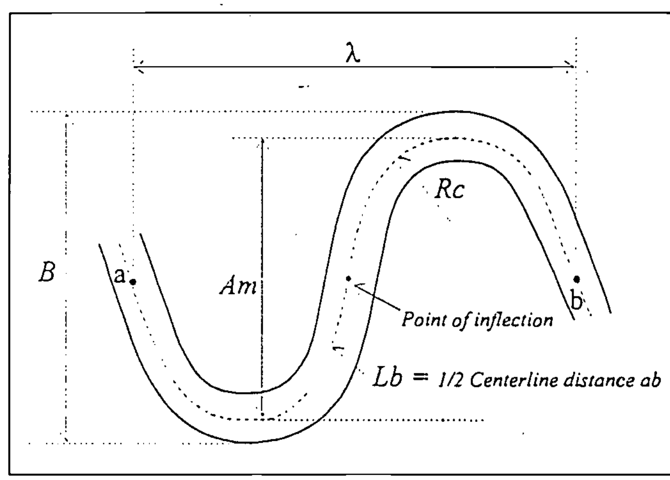


Figure 2. Sketch of Idealized Meander (Leopold & Wolman, 1960, modified).

For each site, stream bed and low water surface gradients were measured and two cross-sections, one in a riffle and one in a pool, representative of the general channel shape and size, were selected and surveyed in detail from the topographical field survey. Bankfull elevations for these two cross sections were identified in the field as the elevation of the active floodplain (Wolman and Leopold, 1957), coinciding with the top of the lower channel bank. That is the stage above which discharge begins to flow over the floodplain. Identification of the bankfull as the elevation of the active floodplain required particular care because, in case of degraded streams, the previous floodplain can become a terrace after the bed lowering. At most sites, the presently building floodplain is slightly below the large valley floor that is actually a terrace as a result of minor degradation occurred during the last decades (Jacobson and Coleman, 1986). Other field evidence of bankfull elevation, such as limit of perennial vegetation and grain size changes, often resulted in markedly different values and therefore was not adopted. Identification of bankfull was carried out in many points of the entire reach surveyed and a bankfull elevation profile was obtained as suggested by Dunne and Leopold (1978) to avoid inconsistent measurements using only two cross sections.

From the surveyed cross-sections, width, depth, area, hydraulic radius and width to depth ratio were measured for the bankfull stage. Cross-section parameters are given in Table 4. The parameters represent an average value of the pool and riffle cross-sections. Bankfull discharge was calculated using Manning's equation, in which the roughness coefficient n was estimated in the field and from photographs. In order to define the main hydraulic characteristics for the bankfull stage, total stream power, unit stream power, and boundary shear stress were also computed. Total stream power is defined as $\Omega = \gamma QS$, where γ is the specific weight of the water, Q the discharge, S the gradient.

Unit stream power ω (or stream power per unit of streambed area) is defined as the ratio between total stream power Ω, and channel width W:

$$\omega = \frac{\Omega}{W} = \frac{\gamma QS}{W} \tag{1}$$

Boundary shear stress is defined as $\tau = \gamma RS$, where R is the hydraulic radius. Values of total stream power, unit stream power, and boundary shear stress for the studied streams are and given in Table 4.

TABLE 3. Riffles and Pools Geometry and Sediment Size for Selected Stream Reaches. *RL* = riffle length; *PL* = pool length; *SP* = riffle-pool spacing; *D50R* = median diameter of riffle; *D50P* = median diameter of pool.

Site	*RL (m)*	*PL (m)*	*SP (m)*	*D50R (mm)*	*D50P (mm)*
1	19.2	20.1	38.0	10.5	1.6
2	5.7	4.6	10.7	11.5	1.8
3	5.5	4.7	11.2	14.3	1.3
5	10.9	11.8	25.3	16.5	0.8
7	12.3	12.9	24.9	21.7	1.9
8	11.0	6.2	18.6	14.2	0.4
11	6.1	7.3	13.3	14.6	1.7
12	7.5	11.4	19.5	11.1	0.4
14	10.6	9.2	19.3	14.0	3.1
15	6.9	5.4	12.8	12.1	9.7
16	7.9	10.7	16.2	6.9	1.4
17	25.9	32.6	56.8	10.4	2
18	4.8	5.0	7.4	17.2	18.5

TABLE 4. Bankfull Cross-Section Morphological Parameters and Hydraulic Parameters. *W* = width; *D* = depth; *W/D* = width to depth ratio; *A* = area; *R* = hydraulic radius; *S* = channel gradient; *n* = Manning's coefficient; *Q* = discharge; Ω = total stream power; ω = unit stream power; τ = boundary shear stress.

Site	*W (m)*	*D (m)*	*W/D*	*A* (m^2)	*R (m)*	*S*	*n*	*Q* (m^3/S)	Ω (Wm^{-1})	ω (Wm^{-2})	τ (kPa)
1	11.7	1.1	10.6	5.9	0.5	0.0069	0.033	8.9	600.1	51.1	0.032
2	3.9	1.1	3.5	2.5	0.5	0.0200	0.045	5.1	1006.6	258.8	0.103
3	8.9	1.4	6.4	6.6	0.7	0.0081	0.042	10.9	864.3	97.6	0.054
4	3.0	0.3	10.0	0.8	0.3	0.0143	0.045	0.8	113.2	37.4	0.037
5	5.8	1.0	5.8	3.5	0.6	0.0045	0.040	4.3	188.5	40.9	0.028
6	7.8	0.9	8.7	3.3	0.4	0.0132	0.033	5.98	774.5	99.5	0.050
7	7.0	1.2	5.8	5.4	0.7	0.0123	0.033	13.8	1670.2	239.7	0.081
8	8.2	1.1	7.5	6.0	0.7	0.0086	0.030	14.3	1208.9	148.1	0.057
9	9.0	1.4	6.4	8.9	0.0	0.0009	0.041	5.8	49.2	5.4	0.007
10	14.4	2.0	7.2	19.7	1.2	0.0015	0.041	21.2	304.2	21.1	0.018
11	5.5	1.2	4.6	4.8	0.7	0.0030	0.038	5.4	160.1	28.9	0.021
12	7.8	1.1	7.1	4.4	0.5	0.0040	0.033	5.3	206.9	26.4	0.020
13	6.8	1.0	6.8	3.3	0.4	0.0152	0.033	7.2	1070.7	156.7	0.066
14	8.4	1.4	6.0	5.4	0.6	0.0027	0.032	6.0	158.6	18.8	0.015
15	7.4	1.3	5.7	5.8	0.7	0.0192	0.040	15.7	2965.4	403.2	0.132
16	5.4	1.2	4.5	4.4	0.7	0.0100	0.038	8.8	859.8	158.8	0.066
17	14.5	1.4	10.4	13.1	0.9	0.0038	0.031	23.3	868.6	60.0	0.032
18	3.9	0.6	6.5	1.2	0.3	0.0044	0.045	0.7	31.3	8.1	0.012

CHANNEL PROPERTIES

The stream morphology is the ultimate result of all the physical processes taking place at basin scale, and it is primarily affected by the water discharges and sediment supply. Both discharge and sediment transport rate are not constant and vary through time as a result of variations in natural factors or by human impact.

In the Maryland Piedmont area, significant variations in hydrology and sediment yield occurred during the last centuries as a result of changes in land use. Jacobson and Coleman (1986) made an estimation of relative changes in sediment supply and flood discharge over the time period from 1730 to the present, and Wolman (1967) showed the variations in the values of sediment yield through time after 1780 as result of land use changes.

After the European settlement around 1730, the Maryland Piedmont basins changed from largely forested to cropping, farming and poor land use practices, resulting in a progressive increase in both flood discharges and sediment supply. Sediment yield reached a maximum around the end of the 19th century and the beginning of the 20th century. With the change from agricultural to very recent conditions, sediment yield decreased because of the agricultural decline during the 1930s. The abandoned farmland was replaced by woods, shrubs, and grazing, contributing to a reduced volume of sediment supplied to the fluvial system. Although flood discharges also decreased, the reduction in sediment yield was proportionally much greater, inducing a higher transport capacity of the streams. As a result, streams during the last decades are reworking the floodplain sediments deposited during the previous phase of high sediment supply.

Wolman (1967) and Wolman and Schick (1967) furthermore emphasized the effects of urbanization on sediment yield, that increased from estimated values ranging from 80 to 200 t/km^2/yr for prevalently farmed basins to estimated values ranging from several hundreds to 55,000 t/km^2/yr from construction areas. After a short period of very high values, sediment yield decreased very fast to the previous values after the construction phase.

Changes in flood discharges and sediment yield through time have had a significant influence on stream processes and channel form. Jacobson and Coleman (1986) report a flood plain development model, based on stratigraphic records, showing a progressive channel deepening and widening during the agricultural period (about 1730 to 1930) and very recent period (mid-1900s to present). During the last period, the increased transport capacity of the streams caused in many cases a minor degradation.

During recent decades, urbanization has induced further alterations in sediment yield and hydrologic regime of a basin. During the construction phase, the imposition of large quantities of sediments produced significant increases in channel bar deposition, bank erosion, and channel avulsion in many streams (Wolman and Schick, 1967). Leopold (1973) showed an increase in the mean depth of several cross sections of Watts Branch, Maryland, mainly as a result of overbank deposition following the first years of intense urbanization.

After the construction phase, an increase in both peak discharges and total volume of runoff for a given rainfall event results from reduction of vegetation in urbanized areas, increase of impermeable surfaces, and construction of storm sewers and channelized stream segments (Hammer 1972). Channel widening, as a natural response to more frequent and greater peak discharges, is indicated as the dominant channel adjustment due to urbanization during the post-construction phase (Hammer, 1972; Gregory and Park, 1976; Fox, 1976; Arnold *et al.,* 1982). In most locations within the Patuxent River basin, Gupta and Fox (1974) and Fox (1976) report a significant channel widening occurred during high-magnitude floods in 1971 and 1972, increasing in the downstream direction in the fluvial system and ranging from 0 to 6 m, depending on the drainage area of the streams.

The present planform and cross-section properties of the streams in the Maryland Piedmont are therefore affected by the variations in sediment supply and discharges that occurred during the last centuries, and by the resultant channel adjustments in the fluvial system. Although many streams have been subjected to widening and minor degradation during the last decades, at present changes are probably occurring at slow rates, and most of the streams appear to be dynamically stable or recovered, with minor amounts of widening and actively migrating across the floodplain through the building of point bars and erosion on the opposite banks.

Morphologic, hydraulic, and sediment properties data have been used to characterize channel types in the study area in terms of general planform properties, cross-sectional geometry, flow characteristics, spacing and size of the pools and riffles, and size of the bed material.

Planform properties of meandering rivers and different classifications of meander forms are defined and described by several authors (Leopold and Wolman, 1957; Brice, 1964, 1984; Langbein and Leopold, 1966; Hey, 1976). According to most of these authors, the basic properties of a meandering river or the meandering reach of a river are the repetitive symmetry of a sequence of arcs and a strong interdependence of the meanders geometric properties (Brice, 1964).

Streams in the study area exhibit planform properties that are significantly different from meandering rivers described in the literature, presenting an irregular planimetric form with sporadic reaches of irregular meanders, according to the classification of Kellerhals *et al.* (1976), alternated with sinuous or almost straight reaches. The planform of many streams is controlled by bedrock and valley walls. The sizes of well developed meanders are summarized in Table 2. Sinuosities of the selected reaches were measured from the field survey and therefore relative to developed meanders. Sinuosities at six sites are less than 1.3, at eleven sites range from 1.3 to 1.7, and one site (12) is 2.2. These values represent local sinuosities that are higher than the mean sinuosities of the reaches. Quantitative measurements of the sinuosity from topographic maps are somewhat inaccurate for this size stream, but most of the streams in the area appear to have relatively low sinuosities. Dominant factors controlling the degree of sinuosity appear to be bedrock control (narrow floodplains) and the riparian vegetation; the influence of bank vegetation is particularly pronounced.

The streams in the selected reaches are characterized by medium or high bed gradients, ranging from 0.0009 to 0.02. Unit streampower at bankfull stage is relatively high, as it commonly exceeds 35 Wm^{-2}. Bankfull widths vary from 3 m to 14.5 m; the shapes of the cross sections are expressed in terms of the width to depth ratio, ranging from 3.5 and 10.6.

Pools and riffles are common in streams with bed material including gravel fractions. Riffle sediments usually consist of gravel with median diameters (D_{50}) ranging from 6.9 to 21.7 mm and are coarser than adjacent pools (except for the site 18), that are primarily composed of sand and occasionally fine gravel, with D_{50} ranging from 0.4 to 18.5 mm.

The banks of the study streams are typically cohesive, predominantly made of silt and sand and their height ranges from 0.5 to 2 m. Dominant bank erosion processes and mechanisms of failure include: (a) fluvial entrainment at the basal area, particularly on the outer banks of meanders and bends due to high boundary shear stress; (b) downcutting and oversteepening of the bank causing cantilever failure of the upper levels; and (c) planar failure in cohesive banks. Vegetation plays an important role in bank stability; the occurrence of trees, at least for relatively small streams, appears to have a dominant control on channel migration and meander development (Beeson and Doyle, 1995).

BIAS ASSOCIATED WITH MEANDER PARAMETER RELATIONSHIPS

The Leopold and Wolman equations for meander characteristics are often used in channel restoration design (Rosgen, 1994) and are given by (Leopold and Wolman, 1960):

$$\gamma = 10.95\, W^{1.01} \tag{2}$$

$$A = 4.48\, W^{1.02} \tag{3}$$

and

$$R_c = 2.59\, W^{1.01} \tag{4}$$

where γ = meander wavelength (m), W = bankfull channel width (m), A = amplitude (m), and R_c = radius of curvature (m).

The appropriateness of using these equations for channel restoration design depends on the similarity between the planform and hydraulic geometry of the streams used in developing the regression equations and the streams in the region where the design will be implemented. If the stream planforms and geometries are outside of the range of data, the equations may not be applicable. In addition, if the streams have undergone different geomorphic processes, then the equations also may not be applicable. For the 18 streams in this study, Rinaldi and Johnson (1996) showed that a bias exists between meander parameters predicted from Equations (1), (2), and (3) and the observed values. The equations consistently overpredicted by as much as five times the observed values.

The large bias that exists in using the Leopold and Wolman meander equations for the streams in central Maryland brings into question the use of these equations to predict appropriate meander characteristics for stream restoration designs. Restoring meanders to a stream in this particular region using the Leopold and Wolman equations would yield a stream with very large regular meanders, uncharacteristic of any other stream in the area.

The reason for the large bias in each of the meander equations is due to differences in geological, climatic, hydrologic and hydraulic conditions in the streams analyzed and the physical processes resulting from those differences. In particular, Maryland Piedmont streams exhibit a lack of regular and well defined meanders. A comparison of the range of data used by Leopold and Wolman in calibrating their equations with the data from this study was made by Rinaldi and Johnson (1996). They showed that the average values of the data used to calibrate Equations (1), (2), and (3) are two orders of magnitude larger than the data used in this study. The sinuosity of the 49 Leopold and Wolman streams were predominantly greater than 1.2, thus yielding meanders with relatively large meander characteristics. The Leopold and Wolman data included only six streams in the size range of the streams from this study; however, with one exception, they were all streams in Wyoming. Therefore, the data of Leopold and Wolman appear to be from a different population than the data of this study.

For small eastern streams, bank vegetation plays an extremely important role in limiting the meandering and sinuosity of the stream and, therefore, the magnitude of the meander parameters. The effect of vegetation on channel sinuosity is variable, depending on geologic, pedologic, physiographic, climatic, hydrologic conditions of the basin as well as the sizes of the rivers. However, it appears to be more pronounced on smaller alluvial channels, where vegetation seems to play a dominant role in controlling sinuosity (Ebisemiju, 1994).

Another reason for the large bias may be associated with the channel adjustments induced by intense land use changes. The increased channel width due to widening resulting from urbanization is an important factor in comparing the measured values of the meander parameters with the values computed from the Leopold and Wolman equations. The Leopold and Wolman equations are based on streams that had not been altered by urbanization.

The combined effects of the lack of regular, well defined meanders, bank vegetation, stream size, and channel adjustments due to variations in land use appear to be the primary causes for the large biases in the Leopold and Wolman equations.

ALTERNATIVE STRATEGIES FOR MEANDER RESTORATION

Regional Empirical Relationships

Given the biases inherent in using Leopold and Wolman equations for small streams in the Maryland Piedmont, the next step is to derive a set of appropriate equations that can assist in stream restoration designs, although other uncertainties can arise when in applying different empirical equations. Among these new uncertainties are included those due to the fact that the streams may not be in equilibrium with changing flow conditions and therefore are changing their channel form with time. In the study case, some uncertainties can be attributed to this reason, although at present the streams seems to be dynamically stable. In other words, they seem to have recovered after that urbanization caused most of the channel changes during the previous decades.

Despite the various uncertainties, a new set of regional empirical equations, expressing the interrelations among the morphological parameters representing the present channel form, is considered more appropriate than equations existing in literature on the assistance of stream restoration design. Every possible combination among the available variables (meander parameters, cross-section parameters, riffle-pool geometry, sediment size) has been analyzed. The correlations showing low R^2 were eliminated, and the main relationships that could be useful in defining meanders and riffle-pool geometry were selected (Table 5 and Figure 3). No statistically acceptable relationships were found for sediment size and channel slope. Although the number of observations is limited and the values of R^2 are relatively low, the correlations obtained can be useful as preliminary equations for stream restoration in the region.

Relationships between cross-sectional parameters (channel width and area) and meander parameters (Equations 1 and 2 in Table 5) are typically power functions, while linear regressions between meander parameters (Equations 3 and 4) result in the higher values of R^2. Although Leopold and Wolman (1960) originally proposed a power function between meander wavelength and radius of curvature, the equations representing interrelations between meander features included in Williams (1986) are typically linear. The channel width and riffle-pool spacing relationship is given by Keller and Melhorn (1978) as a power function. However, in the case of the Maryland data, the value of R^2 for linear regression is significantly greater in comparison to the power function. The ranges over which the equations apply are indicated in Table 5 for each equation. The equations provided in Table 5 are intended to be applied for preliminary planning of streams in the study area only.

The main specifications and recommendations for stream restoration in the study area based on the field data and observations are synthesized as follows:

- In the study area, the ranges for meander wavelengths are 2.9 to 7.7 times the channel widths, significantly lower than the 11 widths usually suggested for meander restoration.
- The ranges for the pool/riffle spacing are 1.2 to 4.3 times the channel widths, lower than the 5 to 7 widths usually suggested for stream restoration.
- Regular meanders should be avoided, based on field observations, as well as regular riffle/pool spacing.

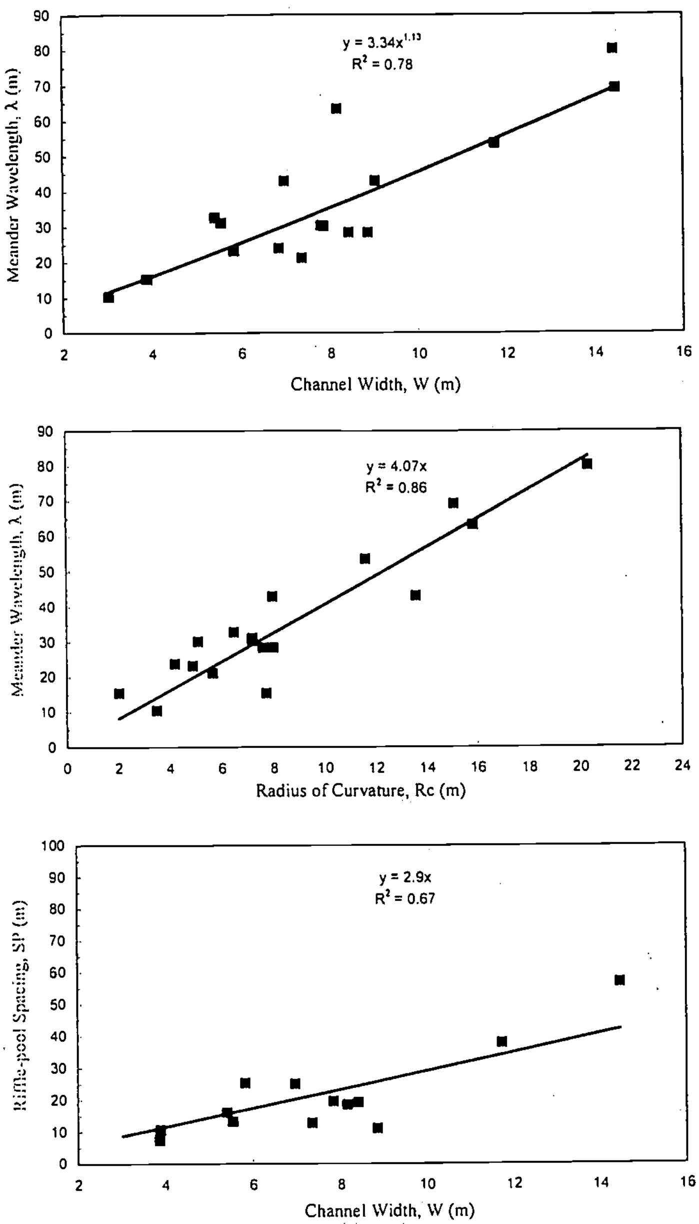


Figure 3. Regression Equations for Maryland Streams.

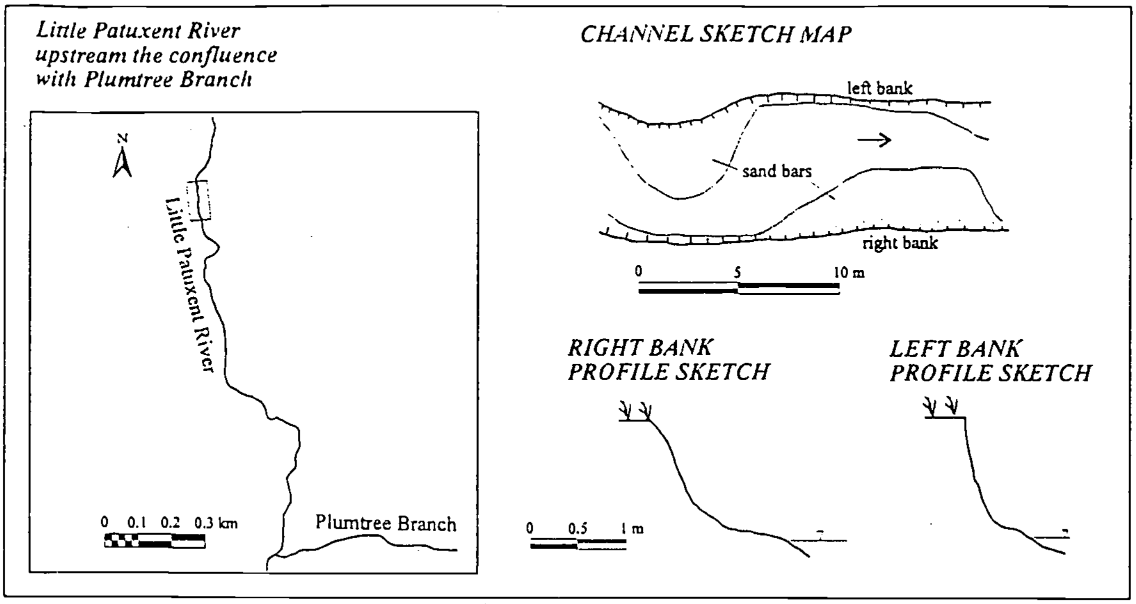
Detailed Stream Reconnaissance

During the planning stages of any stream restoration project, it is critical to conduct a detailed stream reconnaissance on that reach, and possibly on the larger fluvial system, prior to developing the restoration design. Information collected during the reconnaissance is necessary to verify that the restoration project is consistent with the natural form and processes of the river or nearby streams. Thorne and Easton (1994) developed a specific reconnaissance data collection form to collect geomorphological data and observations during a field visit. The detailed field forms are used to describe all aspects of various processes occurring at the banks and bed.

Examples of detailed stream reconnaissance were carried out on streams in the study area. Figure 4 shows the main elements and observations collected during a detailed stream reconnaissance. In this example, based on the stream reconnaissance, bank erosion appears to be the most important problem within the reach. Dominant processes are fluvial entrainment at the basal area, planar failure and cantilever on the upper portion of the bank. Bank failure appears to be a very important source of sediment, producing high quantities of fine material, facilitating accretion and construction of bars. Bank erosion on both the banks is also evident, causing a significant widening of the reach. Based on the stream reconnaissance, meander creation in that site appears to be a possible way to dissipate energy and to reduce erosion and sediment supply. Alternatively, control of bank erosion through stabilization efforts and maintenance of channel width could be used to prevent additional widening and to reduce the supply of fine sediments.

TABLE 5. Preliminary Equations for Maryland Streams. (λ = meander wavelength; W = channel width; Rc = radius of curvature; A = cross-section area; Am = meander amplitude; Lb = bend length; SP = riffle-pool spacing.

Equation Number	Equation	R^2	Standard Error	Applicable Range
(1)	$\lambda = 3.34\ W^{1.13}$	0.78	9.92	$3 \leq W \leq 4.5$ m
(2)	$Rc = 2.79\ A^{0.64}$	0.72	2.45	$0.8 \leq A \leq 19.7\ m^2$
(3)	$\lambda = 4.07\ Rc$	0.86	1.82	$2 \leq Rc \leq 20.3$ m
(4)	$Lb = 1.34\ \lambda$	0.88	4.98	$10.3 \leq \lambda \leq 80$ m
(5)	$Am = 0.62\ Lb$	0.91	2.87	$8.2 \leq Lb \leq 58.3$ m
(6)	$SP = 2.9\ W$	0.67	7.39	$3 \leq W \leq 14.5$ m



CHANNEL DESCRIPTION

Planform
Sinuous with irregular meanders

Dimensions
Ave. Bankfull Width: 8.2 m
Ave. Bankfull Depth: 1.3 m
Ave. Water Width: 3.8 m
Ave. Water Depth: 0.7 m
Reach Slope: 0.0009
Flow Type: uniform / tranquil
Bed Controls: none
Width Controls: none

Bed Sediment Description
Bed Material: sand
Bed Armour: none
Bed Forms: ripples
Bars: frequent
Bar Types: alternate and point bars

RIGHT BANK SURVEY

Bank Characteristics
Type: cohesive
Bank Materials: sand / silt
Ave. Bank Height: 1.35 m
Ave. Bank Slope: 30°
Protection Status: unprotected
Tension Cracks: occasional

Bank-Face Vegetation
Vegetation Type: grass and flora
Density: sparse / clumps

Bank Erosion Processes
Erosion Location: opposite a bar
Present Status: eroding; dormant
Processes: parallel flow / sheet erosion

Bank Mass Movements
Failure Location: behind a bar
Present Status: unstable; dormant
Failure Blocks: recent
Failure Mode: slab type block
Failure Distribution: whole bank

LEFT BANK SURVEY

Bank Characteristics
Type: cohesive
Bank Materials: sand / silt
Ave. Bank Height: 1.2 m
Ave. Bank Slope: 60°
Protection Status: unprotected
Tension Cracks: frequent

Bank-Face Vegetation
Vegetation Type: grass and flora
Density: sparse / clumps

Bank Erosion Processes
Erosion Location: opposite a bar
Present Status: eroding; active
Processes: impinging flow, piping, sheet erosion

Bank Mass Movements
Failure Location: opposite a bar
Present Status: unstable; dormant
Failure Blocks: recent
Failure Mode: slab type, cantilever
Failure Distribution: whole bank

Figure 4. Example of Detailed Stream Reconnaissance: Main Observations Extracted by the Field Reconnaissance Sheet.

CONCLUSIONS

This study has pointed out the inappropriateness of using simple published regression equations in the design of meander restorations if the streams of the area show significant differences in channel morphology, sinuosity, and fluvial processes and adjustments compared to the rivers used to develop the equations.

Three main reasons for the large bias in using Leopold and Wolman equations for central Maryland streams have been identified as: (1) differences in morphological channel types; (2) control of vegetation on planform and sinuosity; and (3) channel adjustments due to intense land use changes. The study suggests that the following issues should be assessed through a field reconnaissance and analytical study to determine the appropriateness of using published regression equations for meander restoration design. First, the meander characteristics of the stream or streams to be restored as well as other stream properties, such as bankfull channel width, should be within the range of the data used to develop the regression equations. If the local streams are outside this range, the regression equations should be applied very cautiously. Second, regional differences in geology, climate, and soil types should be assessed. These differences can result in very different hydrologic and hydraulic conditions. Third, variations in fluvial processes and the history of those processes should be considered. Changes in stream morphology caused by a single hydrologic event or by land use changes can result in significant differences in the magnitude of the meander characteristics.

In case the published regression equations are inappropriate, it is possible to develop empirical relationships specifically for the study area. Detailed stream reconnaissance, based on the observation and interpretation of the forms and processes of the channel, is also suggested to verify whether the restoration project is consistent with the natural form and processes of the stream.

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