Technical Note #115 from Watershed Protection Techniques 3(3): 729-734

Dynamics of Urban Stream Channel Enlargement

It is widely accepted that urbanization can alter the geometry and stability of stream channels. Both anecdotal evidence and field research support the notion that the larger and more frequent discharges that accompany watershed development cause downstream channels to enlarge, whether by widening, downcutting, or a combination of both. Channel enlargement severely degrades the quality of instream habitat structure and sharply increases the annual sediment yield from the watershed. These two factors, in turn, are thought to be responsible for the sharp drop in aquatic diversity frequently observed in urban streams (EPA, 1997).

Despite the large body of research available, many questions about the channel enlargement process in urban streams remain to be answered. For example, exactly how much will a channel enlarge, and how many years will it take to do so? Can the degree of enlargement be predicted by watershed indicators, such as impervious cover, age of development, geology or stream gradient? Finally, what stormwater management strategies can engineers use to mitigate the amount of future channel enlargement?

In this article, we review past research on channel enlargement processes in urban streams and explore how long it takes streams to reach a "new" equilibrium once watershed development is completed. These concepts are illustrated with some recent and historical geomorphological data drawn from Watts Branch, an urban stream in the Maryland Piedmont that has been the subject of considerable development and study for more than 40 years.

Evidence of the Impacts of Watershed Development on Channel Enlargement

The first evidence that stream channels enlarge in response to watershed development can be found in the high bank erosion rates measured for urban streams. In a recent study, bank erosion accounted for an estimated two-thirds of the measured instream sediment load of an urban stream in California (Trimble, 1997). In contrast, most geomorphologists have found that bank erosion in rural streams comprises only 5% and 20% of the annual sediment budget (Walling and Woodward, 1995; Collins *et al.*, 1997). Evidently, channel enlargement can begin at a relatively low level of watershed development, as indicated by the amount of impervious cover. One study estimated that channel erosion rates were three to six times higher in a moderately urbanized watershed (14% impervious cover) than in a comparable rural one, with less than 2% impervious cover (Neller, 1998).

Further evidence that stream channels enlarge in response to watershed development lies in research studies that have tracked the change in the cross-sectional area of stream channels over time. The simplest way to quantify these changes is to define an "enlargement ratio," which represents the ratio of a stream's current cross-sectional area to its pre-development cross-sectional area (or, in some cases, a cross-section from an adjacent undeveloped stream of equivalent watershed area). The concept of the channel enlargement ratio can be easily grasped by examining past and current stream cross sections in Watts Branch (Figure 1).

Watts Branch was first studied by Luna Leopold and others in the early 1950s, when development first began to spread across what was a predominately rural watershed (less than 3% impervious cover). Since then, the watershed has been gradually, but continuously,

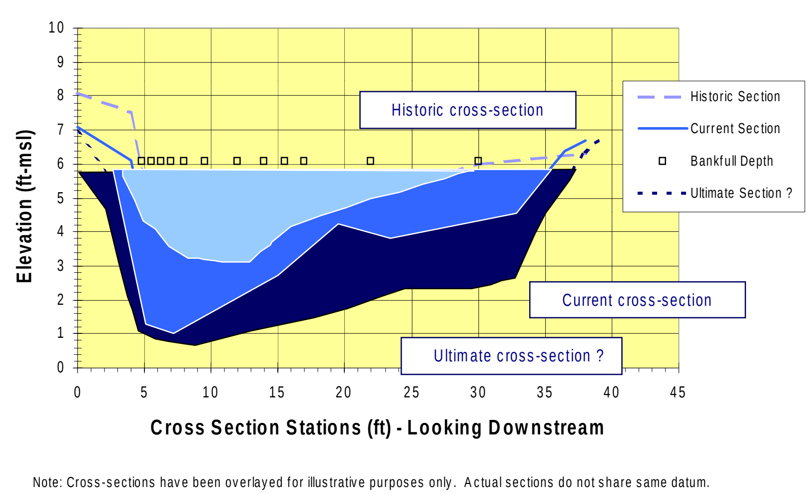

Figure 1: Change in a Stream Cross-Section of Watts Branch Over Time

converted to suburban development, with current impervious cover at about 30%. Some indication of the land use conversion can be gleaned from Figure 2, which shows aerial photographs of the watershed taken in 1968 and 1997. Based on current zoning and development trends, the watershed is expected to be fully built out by the year 2005, and has a projected impervious cover of 36%. How has the stream channel changed over time in response to this watershed development?

In 1953, Leopold measured a cross-sectional area of 30.4 square feet for the stream channel reach. By 1999, the same stream channel had enlarged in size to about 70.3 square feet in area, according to Brown and Claytor (2000). Assuming that the 1953 cross-section approximates pre-development conditions, the current enlargement ratio for this stream reach is calculated to be about 2.3. It is interesting to note that this enlargement occurred despite the fact nearly half of the watershed development was built with two-year peak discharge controls. Further, recent rapid channel assessments by Brown and Claytor (2000) indicate that the stream channel has not yet finished the enlargement process, and is ultimately predicted to have an enlargement ratio of 4.4.

Can Channel Enlargement be Predicted on the Basis of Impervious Cover?

Other researchers have also noted the tendency of urban stream channels to enlarge in response to relatively low levels of watershed development (Allen and Narramore, 1985; Krug and Goddard, 1986; Murphey and Grissinger, 1985; Neller, 1989; Booth, 1990 and May *et al.*, 1997). Some researchers have demonstrated a direct relationship between channel enlargement and urban land use in the watershed area. For example, Morisawa and LaFlure (1979) investigated 11 small watersheds near Pittsburgh, PA and Binghamton, NY and found a strong relationship between the watershed urbanization (defined as the fraction of the watershed area that had more than 5% impervious cover) and channel enlargement (Figure 3).

Hammer (1977), working in northern Virginia streams, also found that watershed development had a general influence on channel enlargement, with the greatest factors being impervious cover, the presence of storm sewers and the age of development (see Table 1).

While past research indicates that stream channels do enlarge in response to watershed development, it is not always clear precisely how much enlargement can be expected for a given level of impervious cover, nor what form the new channel will take. For example, Neller (1988) investigated 14 urban streams in South Wales, Australia and discovered that while urban stream channels were 3.8 times larger than comparable rural streams, the amount of impervious cover in a watershed could not precisely predict the degree of enlargement. The lack of a precise relationship was attributed to highly localized factors, such as stream gradient, riparian disturbance and historical channel alteration. Murphey and Grissinger (1985) have observed severe channel enlargement in some rural watersheds with virtually no impervious cover that was caused by channelization, grazing or other human disturbances.

The variability in stream channel enlargement ratios was evident in the Watts Branch watershed. Figure 4 shows current and forecasted channel enlargement in 1999 for 10 stream reaches that had watershed impervi-

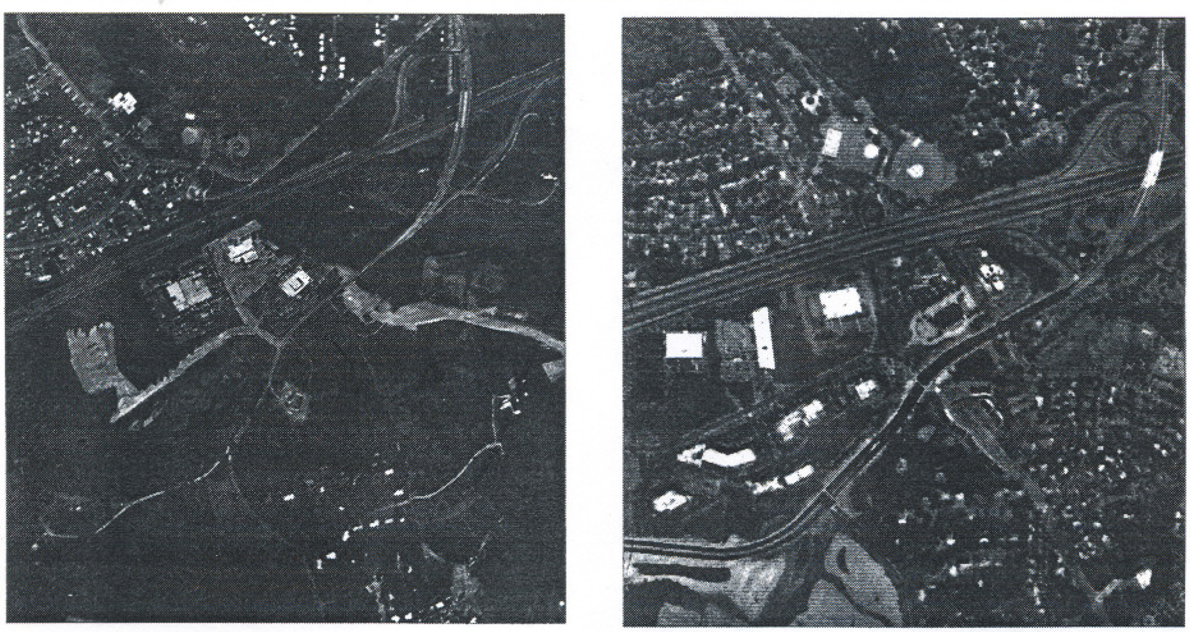

Figure 2: Aerial photos of Watts Branch in 1968 (left) and 1997 (right)

ous cover ranging from 26% to 50%. No clear trend between impervious cover and channel enlargement is evident within this relatively narrow range of impervious cover. While impervious cover influences channel enlargement, it cannot always predict how much will occur. Localized factors, such as stream gradient, age of development, and channel constrictions were thought to play a role in explaining the variance in Watts Branch. For example, if the geology or soils of the streambed and bank materials are highly resistant to erosion, channel enlargement tends to occur at a slower rate. In addition, stream gradient has a strong influence on the rate of enlargement and the new channel form. All other factors being the same, a steep gradient stream tends to enlarge faster than one with a gentle gradient. Finally, artificial constrictions in the stream, such as a bridge or culvert, can dramatically alter cross-sections from reach to reach.

Booth (1990) describes two forms of channel enlargement: *expansion* and *incision*. Channel *expansion* tends to occurs gradually, and results in increases in channel width and depth, roughly in proportion to the increase in peak flows. *Incision*, on the other hand, is when the stream cuts deeper into its bed, and the increase in channel area can be out of proportion with increases in stream discharge. Booth concludes that the difference between these two modes of erosion can be largely predicted based on the materials in the bed and bank of the stream, as well as the gradient. Similarly, Allen and Narramore (1985) found channel enlargement ratios for urban streams in Texas were 12% and 67% greater for streams with chalk bed materials than those with shale beds.

How Long Does it Take for Channel Enlargement to Occur?

Watershed managers often ask how long it takes an urban stream channel to reach its ultimate size. The answer appears to be many decades, but can depend on local stream characteristics. To begin with, watershed development does not happen overnight. Development tends to be a gradual but continuous process that

Table 1: Effects of Different Land Cover Types on Channel Enlargement in a One Square Mile Watershed (Hammer, 1977)

Land Use	Enlargement Ratio
Cultivated Land	1.29
Woodlands	0.75
Golf Course	2.54
Houses on Sewered Streets[1]	2.19
Sewered Streets[1]	5.95
Other Impervious Area[1,2]	6.79
Pervious Urban Areas[1]	1.08
Open Land	0.9

Notes:

1: *Impervious areas only include areas greater than four years old. Impervious area less than four years old is included with pervious urban areas.*

2: *Other Impervious Areas includes commercial areas, and other impervious cover not associated with sewed streets or houses.*

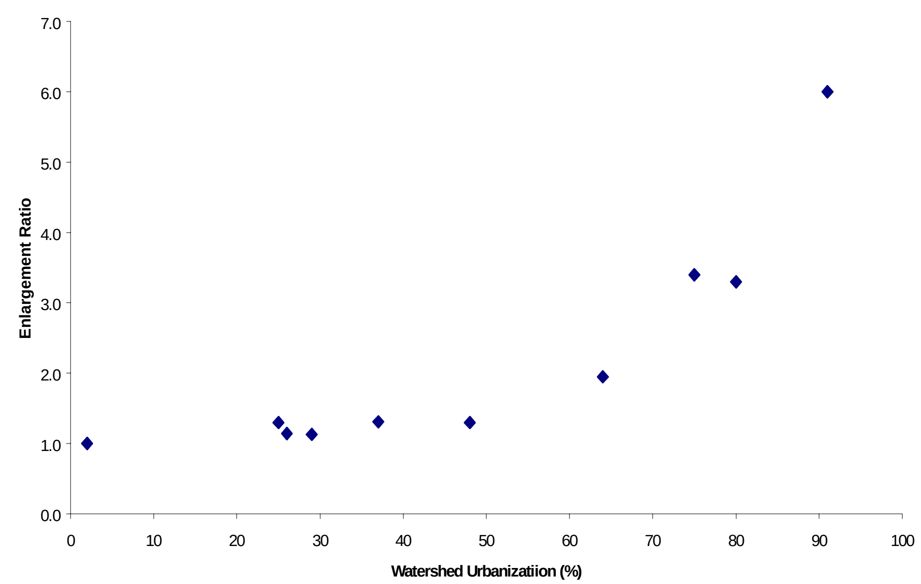

Figure 3: Influence of Urbanization Channel Enlargement in New York and Pennsylvania (Morisawa and LaFlure, 1979)

extends over several decades. Consequently, many urbanizing watersheds have yet to reach their ultimate hydrologic condition, let alone their ultimate channel enlargement. Thus, the urban stream channel cross-section we measure now has probably not reached its ultimate size. This is an important fact to keep in mind when interpreting stream geometry data, since current cross-sections may only represent one snapshot in time.

Most past research has acknowledged that time plays a considerable role in the process of channel enlargement. For example, early researchers noted that watershed development less than five years old had little immediate effect on channel enlargement. They observed a "lag time" between when development is first constructed and when streams fully enlarge (Hammer, 1977). Until recently, however, there has been little research to define how long it actually takes for an urban stream channel to reach a new equilibrium, or whether such an equilibrium can ever be achieved.

Craig MacRae and his colleagues have focused on this issue, and have recently developed techniques to predict an "ultimate" enlargement ratio for urban streams. This ratio represents the ultimate enlargement that is projected to occur, given the current level of watershed development, rather than the current degree of channel enlargement measured now.

These effects have resulted in the development of a curve fitting technique used to forecast ultimate channel enlargement for relatively erodible alluvial streams (MacRae and DeAndrea, 1999). Based on these techniques, it is estimated that it may take 50 to 75 years for channel enlargement to be completed once watershed development starts. This analytical method assumes that the enlargement process is predictable, and that an urban stream will ultimately reach a new equilibrium in response to its altered hydrology.

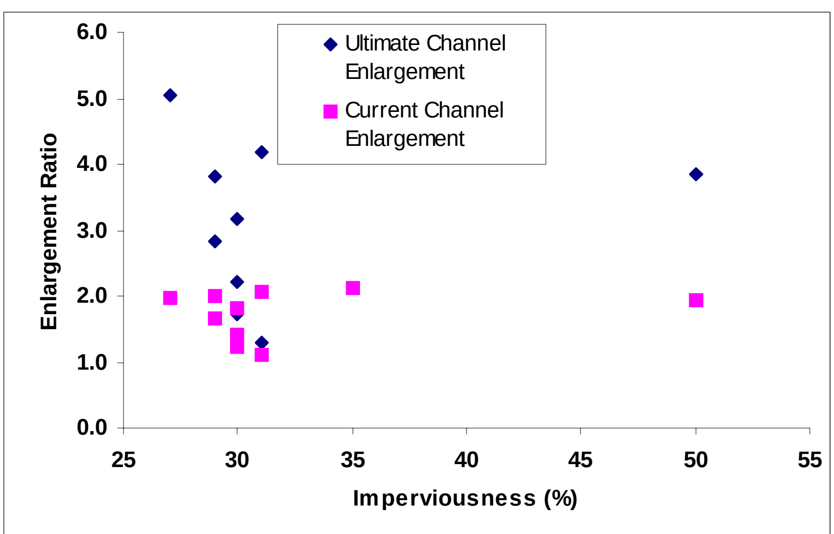

Figure 4: Current and Forecasted Channel Enlargement in 1999 for 10 Stream Reaches With Impervious Cover Ranging From 26% to 50%

The MacRae and DeAndrea method utilizes historical and current data on stream cross sections and land use. Historic cross-sections are obtained from many sources including prior geomorphological research, engineering surveys or flood plain modeling. Current and historic impervious cover are derived from low altitude aerial photographs taken at different intervals through the urbanization process (e.g., Figure 2). Using a basic hydraulic model, these data are used to characterize the pre-development and current channel cross-sections, and predict the ultimate channel cross-sections. An ultimate enlargement curve for 60 channel reaches of alluvial streams in Texas, Maryland and Vermont is presented in Figure 5. A regression line shows the "best fit" through the data which provides watershed managers a rough sense of how much channel enlargement can be expected for different levels of impervious cover. It should be noted that this general curve does not apply to stream channels with a rock bed or rock banks.

Can We Prevent Channel Enlargement?

Past efforts to control channel erosion through stormwater management have been largely unsuccessful. The root of this failure appears to be a misinterpretation of past geomorphological research. Engineers reasoned that if natural channels are largely formed by "bankfull" storm events that occur on average once every one or two years (Leopold *et al.*, 1964), then stormwater ponds should detain the post development peak discharge for the two-year storm to its pre-development level (i.e., two year storm control). There are two problems with this approach. First, while the magnitude of the peak discharge may not change from pre- to post-development with two-year control, the duration of erosive flows sharply increases. Second, the bankfull event shifts to rainfall events smaller than the two-year return frequency. Consequently, the total energy available to transport bed materials can actually increase when two-year peak discharge control is used.

The choice of two-year storm control neglects this increased frequency of bankfull and sub bankfull flows in urban watersheds. For example, Leopold (1994) observed that the average number of bankfull flow events in Watts Branch increased from two to seven times per year between 1958 and 1987, and is expected to increase slightly in the coming years due to more recent watershed development. Regrettably, two-year peak discharge control cannot reduce the frequency or duration of these channel-forming and channel enlarging events.

Engineers have several options that can guard against future channel enlargement. The first option is to design ponds to detain a greater range of storm events, considering the characteristics of bed and bank materials at a downstream control section (MacRae, 1991). The objective is to minimize the alteration in the transverse distribution of erosion potential about a channel parameter, over the range of available flows, such that the channel is just able to move the dominant particle size of the bed load. The drawback of this method is that requires complex field assessments and sophisticated modeling to determine the hydraulic stress and erosion potential of bank materials at each development site.

A second and more simple option is to establish a single channel protection criterion for all development sites that detain smaller runoff events that can cause channel enlargement. A notable example is Maryland, which recently adopted a requirement that dispenses with two-year peak discharge control and replaces it with 24-hour detention of the one-year storm (MDE, 2000). For most parts of the state, a three-inch storm must be detained for 24 hours, which also results in at least six hours of detention of smaller storms (one to two inches). The basic premise of this approach is that runoff will be stored and released from a pond in such a gradual manner that critical erosive velocities will seldom be exceeded in downstream channels, over a wide range and frequency of channel-forming events. The required storage volume needed for 24-hour detention of the one-year storm is not trivial; it is roughly comparable to the storage volume for 10-year peak discharge control. More stream research is needed to determine how well this criterion can prevent the channel enlargement process.

Implications of Channel Enlargement for Watershed Managers

While it is not always easy to predict the absolute degree of channel enlargement caused by watershed development, it is clear that enlargement will occur in the absence of sophisticated stormwater controls. What other implication does channel enlargement have for the watershed manager? First, the notion that channels can enlarge by as much as a factor of 10 is yet another convincing argument to establish wide stream buffers in communities. The existence of a buffer puts some distance between the landowner and the growing stream, and helps to reduce future complaints about bank erosion and backyard flooding that are an inevitable consequence of watershed development. Second, channel enlargement has great implications for urban stream restoration practitioners, who need to base their designs on future enlargement rather than just current stream cross-section. Designers that fail to appreciate this difference are likely to see many of their practices wash out, undercut or otherwise fail as the channel increases in size. It also underscores the need to install upstream stormwater retrofits to arrest the channel enlargement process at downstream urban stream restoration projects.

Third, engineers need to plan for ultimate channel enlargement when locating infrastructure in or around a stream, whether they are a planning a culvert, sewer, bridge or pipeline. This planning is not only needed to protect infrastructure from damage, but also to prevent the infrastructure from becoming a barrier to fish migration in the future. Lastly, stormwater managers need to develop and assess stormwater design criteria that

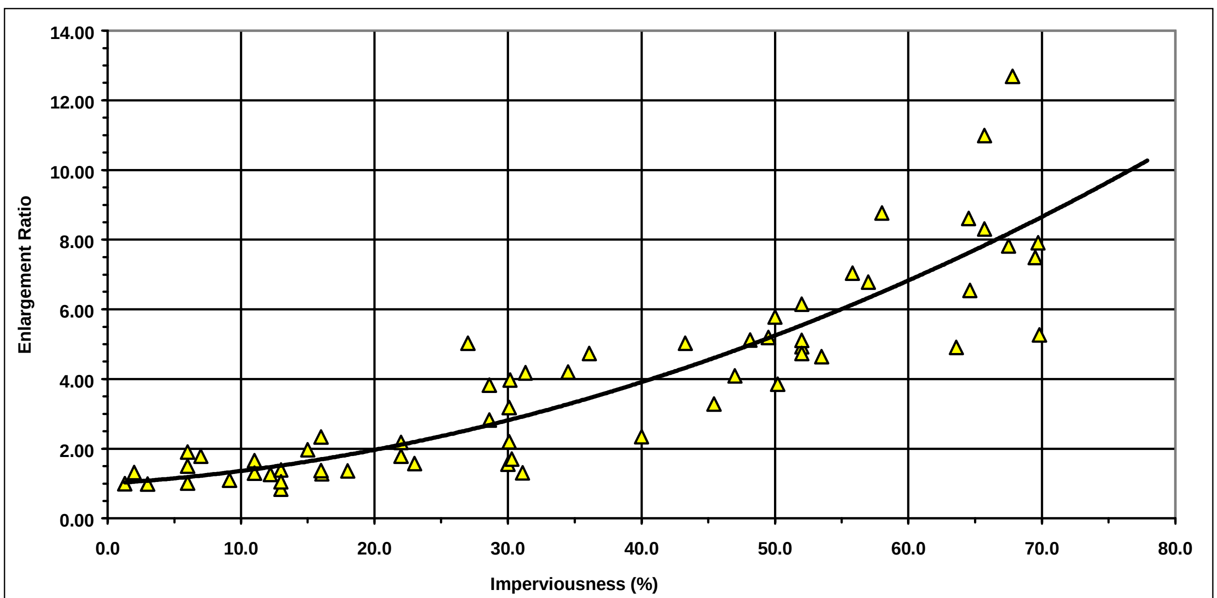

Figure 5: "Ultimate" Channel Enlargement as a Function of Impervious Cover in Alluvial Streams in Maryland, Vermont and Texas (MacRae and DeAndrea, 1999; and Brown and Claytor, 2000)

directly address the channel enlargement problem. Until these channel protection criteria are more widely adopted, stormwater managers will have great difficulty in maintaining downstream habitat and aquatic diversity. ***-DSC***

References

Allen, P. and R. Narramore. 1985. "Bedrock Controls on Stream Channel Enlargement With Urbanization, North Central Texas." *Water Resources Bulletin*. 21(6): 1037-1048.

Booth, D. 1990. "Stream Channel Incision Following Drainage Basin Urbanization." *Water Resources Bulletin*. 26(3): 407-417.

Brown, E. and R. Claytor. 2000. *Draft Watershed Assessment Study for Watts Branch.* Watts Branch Watershed Plan. City of Rockville, MD. Center for Watershed Protection. Ellicott City, MD.

Collins, A, D. Walling, and G. Leeks. 1997. "Source Type Ascription for Fluvial Suspended Sediment Based on a Quantitative Composite Fingerprinting Technique." *Catena* 29:1-27

Hammer, T. 1977. "Stream Channel Enlargement Due to Urbanization." *Water Resources Research*. 8(6): 1530-1540.

Krug, W. and G. Goddard. 1986. "Effects of Urbanization on Streamflow, Sediment loads, and Channel Morphology in Pleasant Branch Basin Near Middleton, Wisconsin." *USGS Water Resources Investigations Report 85-4068.*

Leopold, L. 1994. *A View of the River.* Harvard University Press. Cambridge, MA. 298 pp.

Leopold, L., M. Wolman, and J. Miller. 1964. *Fluvial Processes in Geomorphology*. W. H. Freeman and Company. San Francisco, CA. 522 pp.

MacRae, C. 1991. *A Procedure for the Planning of Storage Facilities for Control of Erosion Potential in Urban Creeks.* Ph.D. Thesis. Department of Civil Engineering. University of Ottawa.

MacRae, C. and M. DeAndrea. 1999. *Assessing the Impact of Urbanization on Channel Morphology*. 2nd International Conference on Natural Channel Systems. Niagra Falls, Ontario. 1999.

Maryland Department of the Environment (MDE). 2000. *Maryland Stormwater Design Manual.* Volume One. Baltimore, MD.

May, C., R. Horner, J. Karr, B. Mar and E. Welch. 1997. "Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion." *Watershed Protection Techniques* 2(4):483-492.

McCuen, R. and G. Moglen. 1988. "Muilticriterion Stormwater Management Methods." *Journal of Water Resources Planning and Management*. 114(4): 414-431.

Morisawa, M. and E. LaFlure. 1979. "Hydraulic Geometry, Stream Channel Equilibrium and Urbanization." *Adjustments of the Fluvial System*. 10th Geomorphology Symposium. Binghampton, NY. pp. 333-350.

Murphey, J. and E. Grissinger. 1985. "Channel Cross-Section Changes in Mississippi's Goodwin Creek." *Journal of Soil and Water Conservation*. 46(1): 148-153.

Neller, R. 1988. "A Comparison of Channel Erosion in Small Urban and Rural Catchments, Armidale, New South Wales." *Earth Surface Processes and Landforms*. 13(1): 1-7

Neller, R. 1989. "Induced Channel Enlargement in Small Urban Catchments, Armidale, New South Wales." *Environmental Geology and Water Sciences*. 14(3): 167-171

Trimble, S. 1997. "Contribution of Stream Channel Erosion to Sediment Yield From an Urbanizing Watershed." *Science*. 278: 1442-1444.

U.S. EPA. 1997. *Urbanization and Streams: Studies of Hydrologic Impacts*. Office of Water. Washington, D.C. 841-R-97-009.

Walling, D. and J.Woodward. 1995. "Tracing Sources of Suspended Sediment in River Basins: A Case Study of the River Culm, Devon, UK." *Marine and Freshwater Research.* 46: 324-336.