Urban Stream Restoration Best Management Practice
Definition and Nutrient and Sediment Reduction Efficiencies
For use in calibration of the Chesapeake Bay Program's Phase 5.0 Watershed Model

Tom Simpson and Sarah Weammert at the University of Maryland (UMD) contracted with Andy Baldwin at the UMD to conduct a literature review and his findings follow. He stated that he is not comfortable recommending changes because of insufficient data but feels the TP reduction value is too high. Using Andy's report and our best professional judgment, UMD project staff recommends the following efficiencies:

TN	0.02 lb/ft removed
TP	0.0025 lb/ft removed
TSS	2.00 lb/ft removed

These efficiencies are conservative yet within

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Recommendations for Formal Approval by the Nutrient Subcommittee's Tributary Strategy and Urban Stormwater Workgroups

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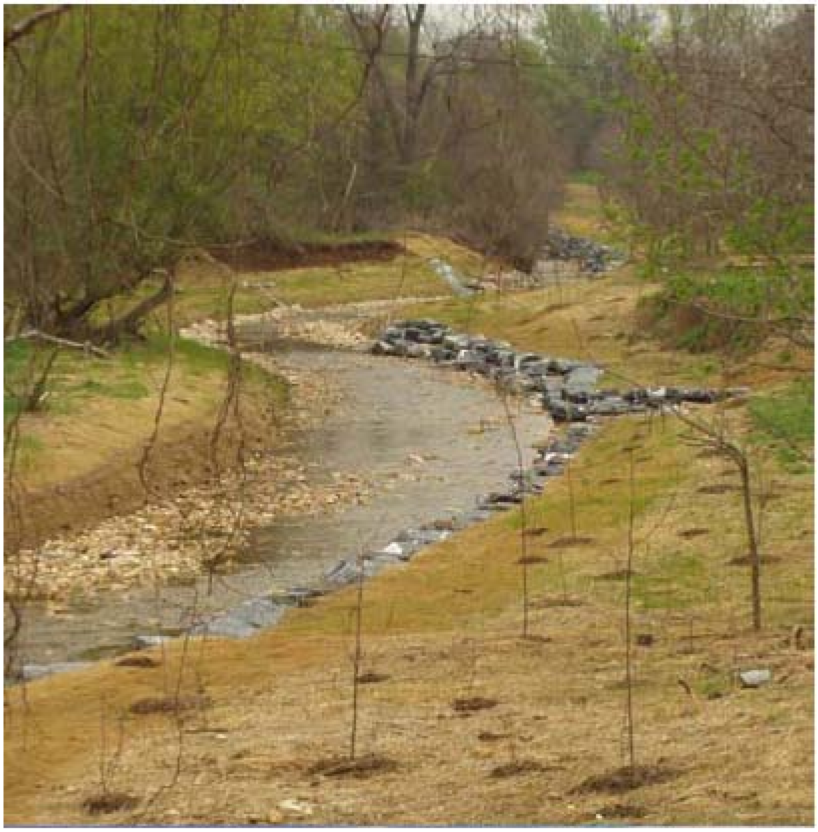
Introduction

This document summarizes the recommended definition and nutrient and sediment reduction efficiencies for the Urban Stream Restoration Best Management Practice for review and final approval by the Tributary Strategy Workgroup and Urban Stormwater Workgroup. Included in these recommendations is a full accounting of the Chesapeake Bay Program's discussions on this BMP and how these recommendations were developed, including data, literature, data analysis results, and discussions of how various issues were addressed.

Photograph of BMP



Stream restoration projects can include creating meanders, stabilizing banks, and reforesting riparian buffer zones. Source: http://www.palmerlab.umd.edu/stream_restoration_webpage.htm.

Rock cross vane installed in Paint Branch adjacent to University of Maryland in College Park. This structure directs erosive waters away from banks and controls grade (Virginia Department of Conservation and Restoration 2004). Photograph by A.H. Baldwin.

Description/Definition

The objectives of projects to restore aquatic and terrestrial ecosystems are to improve the ecological or socioeconomic values and functions of systems that have been degraded or destroyed, either by human activities or natural processes. The Society for Ecological Restoration defines ecological restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.” (SER 2002). Ecosystem and socioeconomic functions and values that may be desired outcomes of restoration projects include habitat for plants and animals (biological diversity), nutrient cycling, water and air quality improvement, aesthetics, and recreational opportunities. (Mitsch and Gosselink 2000; SER 2002). Stream and river restoration projects most commonly seek to manage or improve water quality, riparian zones, habitat for aquatic organisms, ease of fish passage, and bank stabilization (Bernhardt et al. 2005).

The importance of streams and rivers in removing or transforming nutrients from surface water has been increasingly recognized (e.g., Ensign and Doyle 2006). While considerable information exists on the nutrient processing capacity of naturally-occurring streams, comparatively little information exists on this capacity in degraded urban streams or in restored streams (Bernhardt and Palmer 2007). Factors affecting the uptake can be classified as either biochemical or geomorphic (Ensign and Doyle 2006). Biochemical factors include uptake by bacteria, fungi, and algae, while geomorphic configurations of the stream channel control hydrologic variable such as residence time and transient storage and interaction of water with stream biota responsible for nutrient processing. Because streams and rivers are flowing-water systems, the processes of nutrient uptake into benthic biota, temporary retention, and then remineralization as water flows downstream have been termed “nutrient spiraling” (Ensign and Doyle 2006). The primary soluble and bioavailable forms of nitrogen dissolved in surface waters are nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+). Dissolved organic forms can also be abundant on some systems. Particulate organic nitrogen also occurs in the form of plant and animal detritus. These organic forms are converted to ammonium and nitrate in the stream via the microbially-mediated processes of ammonification and nitrification (Mitsch and Gosselink 2000). Phosphorus removal in streams is controlled by a range of biologically-mediated and abiotic factors, including assimilation into biota, water pH and temperature, sorption and desorption from sediments, redox potential, stream discharge, and phosphorus concentration (Triska et al. 2006). Phosphorus occurs in its soluble and bioavailable form phosphate (PO_4^{3-}) in the water column of streams, but as for nitrogen, organic phosphorus also occurs in detritus and metabolic waste products.

Streams are capable of removing high levels of suspended sediments, but excessive sedimentation destroys stream habitat and alters other ecosystem functions by changing stream geomorphology, bed texture, and biogeochemistry. Therefore, designing stream restorations as a BMP for sediment removal is not advised.

The practice of stream restoration has become a major industry, and utitilizes a number of approaches to reconnect streams and floodplains, modify flow patterns and velocities, improve recreation and aesthetics, and reshape stream channels (Bernhardt et al. 2005). The guidelines and approaches for stream restoration are well-established, and include the following approaches and BMPs (Virginia Department of Conservation and Recreation 2004):

Bank Protection

Cedar Tree Revetments
Rootwad Revetments
Stacked Stone
Boulder Revetments
Rock Toe Revetment
Live Crib Wall
Interlocking Concrete Jacks

Bank Stabilization
Natural Fiber Rolls
Live Soil Lifts
Natural Fiber Matting
Live Fascines
Brush Mattresses
Live Stakes
Branch Layering

Grade Control Structures
Rock Cross Vanes
Rock W-Weirs
Rock Vortex Weirs
Step Pools
Log Drops and V Log Drops

Flow Deflection/Concentration
Rock Vanes
J-Hook Vanes
Wing Deflectors
Log Vanes
Cut-Off Sills

Additionally, stream restoration if often enhance if riparian zones bordering the stream are also restored or enhanced, as shown in the photograph above.

Efficiency

The removal efficiencies for urban stream restoration BMPs used in the Chesapeake Bay watershed model are currently 0.02 lbs/ft, 0.0035 lbs/ft, and 2.55 lbs/ft for nitrogen (N), phosphorus (P), and sediment, respectively. These units correspond to load reduction per linear foot of stream, and therefore do not take into account the width of the stream. To evaluate the validity of these numbers, a review of peer-review and gray literature was conducted. No research reports were found that expressed nutrient removal or reduction on a linear foot basis. Therefore, it was not possible to use literature to directly evaluate the currently used removal efficiencies. However, nutrient uptake values were summarized and used to qualitatively evaluate the currently used values

Literature Review and Data Analysis Methods

Gray literature such as reports, web sites, and other information not subjected to the peer-review process was obtained through material already in hand, contacts with the Center for Watershed protection, references listed in refereed and gray literature already in hand, and web searches. Literature in peer-reviewed journals was identified using electronic databases such as ISI Web of Science. Literature was reviewed to find nutrient uptake rate data, generally for NO_3^-, NH_4^+, and PO_4^{3-}. No literature was found for uptake or removal of Total Nitrogen, Total Phosphorus, or suspended solids (e.g., Total Suspended Solids, TSS).

Data on commonly used metrics of nutrient uptake rate were tabulated (see Appendix). The uptake values for the various studies were classified according to one of four types of stream types: Urban Restored (UR), Urban Enhanced (UE), Urban Non-restored (UN), and Non-Urban or Forested (NUF). Because few studies on restored sites were found, the urban restored and urban enhanced sites were combined for analysis. Summary statistics were calculated for each type of stream to allow comparisons between sites (mean, standard deviation, range, and N). Because a large literature exists on nutrient processing for non-restored streams, a comprehensive literature review of these systems was not performed. Instead, a few studies that themselves reviewed many studies or evaluated many different sites were included so that the non-restored systems would be well-represented.

Results of Literature Review

Only three studies were found that quantitatively measured nutrient uptake in restored streams (see Appendix). These studies each reported uptake values for different stream types or reaches, asometimes resulting in more than three values for the various nutrient uptake metrics (Tables 1, 2, and 3).

Nitrate. Comparisons of nitrate uptake parameters between urban restored or enhance (UR/UE), urban non-restored (UR), and non-urban or forested (NUF) streams suggest that restored urban streams have higher rates of nutrient uptake than non-restored urban streams. The uptake rate constant k and the uptake velocity V are both at least an order of magnitude higher for restored than for non-restored urban streams (Table 1), although this result should be interpreted with caution because of the low numbers of sites studied. Potential net nitrification rates were lower for UR/UE than for UN streams, which is desirable if the goal is to keep nitrate levels low by reducing the conversion of ammonium to nitrate (e.g., by immobilizing ammonium in the floodplain; Groffman et al. 2005). The non-urban or forested stream had similar uptake velocity to the restored urban stream, but a shorter uptake length, S, meaning that the average distance a nutrient molecule travels downstream before being taken up is shorter.

Taken together, the limited data available suggest that the relative rate of net nitrate removal in different stream types is: NUF > UR/UE > UN.

Ammonium. Ammonium uptake appears to be higher in restored than in non-restored urban streams, given higher average values of the uptake rate constant k and the areal uptake rate U (Table 2). However, uptake velocity V is lower in restored or enhanced streams than urban non-restored streams. This result at first appears contradictory to the previous suggestion that restoration may improve immobilization of ammonium in the floodplain. However, the non-urban or forested streams had an average uptake velocity an order of magnitude higher than the

UN streams, suggesting that the restored streams studied are not immobilizing ammonium at a velocity comparable to less disturbed streams.

Taken together, the limited data available suggest that the relative rate of net ammonium removal in different stream types is: NUF > UR/UE > UN.

Phosphate. The restored stream was more effective in taking up phosphate than the non-restored urban streams, as reflected in higher uptake rate constant k and shorter uptake distance U (Table 3). Uptake velocity of the restored and non-restored urban streams was similar. The non-urban or forested streams are more effective than the urban streams based on higher uptake velocity and shorter uptake distance.

Taken together, the limited data available suggest that the relative rate of net phosphate removal in different stream types is: NUF > UR/UE > UN.

Recommended Removal Efficiencies for Model

As mentioned previously, the removal efficiencies for urban stream restoration BMPs used in the Chesapeake Bay watershed model are currently 0.02 lbs/ft, 0.0035 lbs/ft, and 2.55 lbs/ft for nitrogen (N), phosphorus (P), and sediment, respectively. The units these values are expressed in do not allow direct comparison with the nutrient uptake metrics presented in Tables 1-3. To provide a means of evaluating the currently-used values, average areal uptake values (U) from Tables 1-3 were converted first to English units and expressed on an annual basis (Table 4). Then, the removal rates were expressed as removal per linear foot of stream length for streams of three different widths (Table 5). Finally, the removal rates for the ion forms reported in the literature (NO_3^-, NH_4^+, and PO_4^{3-}) were expressed rates of removal of nitrogen occurring in nitrate form (nitrate-nitrogen, NO3-N), nitrogen occurring in ammonium form (ammonium-nitrogen, NH4-N), and phosphorus occurring in phosphate form (phosphate-phosphorus, PO4-P) (Table 5). It is these values that should be compared with the values currently used in the Chesapeake Bay model.

A limitation of using the aerial removal rate metric (U) is that data are available only for non-urban or forested (NUF) streams for $NO_3^-$and PO_4^{3-} (Tables 1 and 3). Data on NH_4^+ are available for urban restored or enhanced (UR/UE) and urban non-restored (UN) streams as well as NUF streams. Assuming that the net rate of nutrient removal is highest in NUF streams, lowest in UN streams, and intermediate in UR/UE streams (as suggested by the data summarized in Tables 1-3) will help in evaluating the current values in the Bay Model.

An additional limitation of the current data is that removal of forms of nitrogen and phosphorus other than those reported in the literature is likely occurring (e.g. particulate or dissolved organic forms). The extent to which total N or total P is changing cannot be determined from the available literature.

Nutrient removal efficiencies. For nitrogen, the value of 0.02 lb/ft currently used in the Bay model is lower than that reported for NO3-N in non-urban or forested streams (of 3-30 ft width). While the removal rate for NO3-N is likely lower in urban restored streams than in non-urban streams, the degree to which it is lower cannot be determined based on the available data. However, the 0.02 lb/ft value is in the range of reported values for NH4-N in urban restored or enhanced streams of 3-30 ft width. Based on these results, **changes to the current value of 0.02 lb/ft for N removal cannot be justified at this time.**

The currently used value for phosphorus of 0.0035 lb/ft may be too high. Removal of PO4-P ranged from 0.0014-0.0144 lb/ft/yr in non-urban or forested streams of 3-30 ft width. Removal of PO4-P is presumably lower in restored urban streams, suggesting that the values currently used in the Bay model are appropriate only for larger streams. It is possible that phosphorus sorbed to soil particles or in particulate organic matter may be removed by sedimentation, but this pathway is likely to be small in streams that do not receiving excessive sediment in eroded soil. These results suggest that **while the available data suggest that the current phosphorus removal value of 0.0035 lb/ft is too high, there are insufficient data to recommend a specific lower value**

As noted previously, no studies were found that examined sediment removal in restored or non-restored streams. Therefore, available data do not support any changes to the currently-used value. However, it is the opinion of the author that restored streams cannot sustainably accrete 2.55 lb/ft of sediment indefinitely without experiencing detrimental hydrologic, biogeochemical, or habitat changes.

Factors affecting BMP performance. The impacts of watershed urbanization on stream hydrology, water quality, geomorphology, biological diversity, and ecosystem processes have been well-documented (e.g., Walsh et al. 2005). Many of these changes are associated with increases in the area of watershed coverage by impervious surfaces and more efficient conveyance of surface runoff into stream channels (Schueler 1994). Therefore streams that are restored in urbanized watersheds may regain some of the characteristics of degraded urban streams if changes in the hydrology of the watershed are not also made, for example by implementation of BMPs for stormwater retention. Additionally, additional development or other land use changes in the watershed may damage restored streams and reduce their capacity for nutrient processing.

Statement of Conservatism

The level of uncertainty surrounding the reported results is affected by, at a minimum, the number of studies available for a given parameter, the methods used to determine nutrient processing rates (e.g. number of replicates, analytical methods), and watershed characteristics. Given the numerous variables that may influence the performance of individual restored streams for nutrient processing, any single numerical uptake metric will not apply to all situations. Because only a few studies were found, the reported studies do not incorporate a range of BMP designs of different ages across a wide geographic area. Therefore, there is considerable uncertainty in predicting the performance of actual BMPs across the Chesapeake Bay watershed. Using a confidence scale of low, medium-low, medium, medium-high, and high, I would rate the degree of confidence in the recommended values as low.

Future Research Needs

Clearly there is very little information available on nutrient processing in restored urban streams, and apparently no information concerning sediment removal (although sediment removal is not a desired function of most stream restoration projects, as mentioned previously). More research is necessary that measures nutrient processing rates across a range of different restored streams in watersheds of varying levels of urbanization. Furthermore, researchers should be encouraged to consistently measure the same suite of parameters (e.g., k, V_f, S_w, and U) to improve comparability between studies and sites. Efforts should be made to quantify all dominant forms of nitrogen and phosphorus so that total nutrient processing can be evaluated. In the future, when the data is available, efficiencies should be assigned based on stream width.

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Table 1. Summary statistics of nitrate-related nutrient uptake metrics* from studies on nutrient removal in streams. The specific experiments used in calculating summary statistics are identified in the Appendix using these classes: UR = Urban Restored, UE = Urban Enhanced, UN = Urban Non-restored, NUF = Non-Urban or Forested.

Type	Statistic	Potential net nitrification (mg N/kg/day)	Nitrification ($gN/m^2/day$)	k (/m)	V_f (mm/s)	S_w (m)	U ($ug NO_3/m^2/s$)
Restored or enhanced (UR, UE)	mean	0.21		0.0016	0.021	617	
	SD	0.19					
	min	0.02		0.0016	0.021	617	
	max	0.40		0.0016	0.021	617	
	N	3	0	1	1	1	0
Urban non-restored (UN)	mean	0.62		0.000085	0.0013		
	SD	0.58		0.000049	0.0012		
	min	0.17		0.000050	0.0005		
	max	1.40		0.000120	0.0022		
	N	4	0	2	2	0	0
Non-urban or forested (NUF)	mean		0.022		0.0233	236	14.61
	SD		0.031				34.24
	min		0.002		0.0233	236	0.09
	max		0.109		0.0233	236	84.48
	N	0	11	0	1	1	6

* nutrient uptake metrics (Meyer et al 2005; Ensign and Doyle 2006):
k(/m) = first-order uptake rate constant = fraction of uptake per unit distance
V_f (mm/s) = uptake velocity, or mass transfer velocity = velocity of nutrient molecules through the water column toward the bottom (i.e., benthos)
U ($ug/m^2/s$) = uptake rate = areal rate of uptake of a nutrient into the benthos
S_w (m) = Uptake length = average distance traveled by a nutrient molecule before being taken up

Table 2. Summary statistics of ammonium uptake metrics* from studies on nutrient removal in streams. The specific experiments used in calculating summary statistics are identified in the Appendix using these classes: UR = Urban Restored, UE = Urban Enhanced, UN = Urban Non-restored, NUF = Non-Urban or Forested.

Type	Statistic	k (/m)	V_f (mm/s)	S_w (m)	U (ug $NH_4/m^2/s$)
Restored or enhanced (UR, UE)	mean	0.0027	0.018		0.88
	SD	0.0009	0.008		0.35
	min	0.0018	0.013		0.56
	max	0.0039	0.030		1.35
	N	4	4	0	4
Urban non-restored (UN)	mean	0.0016	0.045		0.49
	SD	0.0009	0.047		0.27
	min	0.0006	0.005		0.27
	max	0.0027	0.133		0.83
	N	4	8	0	4
Non-urban or forested (NUF)	mean		0.194	185	1.22
	SD		0.158	388	1.29
	min		0.034	14	0.29
	max		0.687	1350	3.81
	N	0	14	12	7

* nutrient uptake metrics (Meyer et al 2005; Ensign and Doyle 2006):
k(/m) = first-order uptake rate constant = fraction of uptake per unit distance
V_f (mm/s) = uptake velocity, or mass transfer velocity = velocity of nutrient molecules through the water column toward the bottom (i.e., benthos)
U (ug/m^2/s) = uptake rate = areal rate of uptake of a nutrient into the benthos
S_w (m) = Uptake length = average distance traveled by a nutrient molecule before being taken up

Table 3. Summary statistics of phosphate uptake metrics* from studies on nutrient removal in streams. The specific experiments used in calculating summary statistics are identified in the Appendix using these classes: UR = Urban Restored, UE = Urban Enhanced, UN = Urban Non-restored, NUF = Non-Urban or Forested.

Type	Statistic	k (/m)	V_f (mm/s)	S_w (m)	U (ug $PO_4/m^2/s$)
Restored or enhanced	mean	0.0026	0.04	380	
(UR, UE)	SD				
	min	0.0026	0.04	380	
	max	0.0026	0.04	380	
	N	1	1	1	0
Urban non-restored	mean	0.00133	0.062	944	
(UN)	SD	0.00085	0.045	602	
	min	0.00073	0.026	518	
	max	0.00193	0.138	1370	
	N	2	6	2	0
Non-urban or forested	mean		0.120	96	0.23
(NUF)	SD		0.079		
	min		0.037	96	0.23
	max		0.194	96	0.23
	N	0	3	1	1

* nutrient uptake metrics (Meyer et al 2005; Ensign and Doyle 2006):
k(/m) = first-order uptake rate constant = fraction of uptake per unit distance
V_f (mm/s) = uptake velocity, or mass transfer velocity = velocity of nutrient molecules through the water column toward the bottom (i.e., benthos)
U (ug/m_2/s) = uptake rate = areal rate of uptake of a nutrient into the benthos
S_w (m)= Uptake length = average distance traveled by a nutrient molecule before being taken up

Table 4. Average areal uptake rates (U) from Tables 1-3 converted into English units and expressed on an annual basis.

Parameter	Restored or enhanced	Urban non-restored	Non-urban or forested
U (ug NO3/m^2/s)			14.61
U (lb NO3/ft^2/yr)			0.0943
U (ug NH4/m^2/s)	0.88	0.49	1.22
U (lb NH4/ft^2/yr)	0.0057	0.0032	0.0078
U (ug PO4/m^2/s)			0.23
U (lb PO4/ft^2/yr)			0.0015

Table 5. Average areal nutrient uptake rate (from Tables 1-4) expressed as removal in lbs/linear ft for different stream widths (3, 10, and 30 ft). Uptake rates are expressed both as ion concentration (NO_3^-, NH_4^+, PO_4^{3-}) and as the concentration of nitrogen or phosphorus occurring as nitrate, ammonium, or phosphate (NO3-N, NH4-N, PO4-P). The current values for Total Nitrogen or Total Phosphorus currently used in the Chesapeake Bay model are included for comparison.

		Areal Uptake Rate U ($lb/ft^2/yr$)			
Parameter	Stream Width (ft)	Restored or enhanced	Urban non-restored	Non-urban or forested	Current Chesapeake Bay Model (lb/linear ft)
Nitrate (NO_3^-)	3			0.28	
	10			0.94	
	30			2.83	
Nitrate-nitrogen (NO3-N)	3			0.064	0.02
	10			0.213	0.02
	30			0.639	0.02
Ammonium (NH_4^+)	3	0.017	0.009	0.024	
	10	0.057	0.032	0.078	
	30	0.170	0.095	0.235	
Ammonia-nitrogen (NH4-N)	3	0.013	0.007	0.018	0.02
	10	0.044	0.025	0.061	0.02
	30	0.132	0.074	0.183	0.02
Phosphate (PO_4^{3-})	3			0.0044	
	10			0.0147	
	30			0.0442	
Phosphate-phosphorus (PO4-P)	3			0.0014	0.0035
	10			0.0048	0.0035
	30			0.0144	0.0035