Appendix C

Derivation of the Retrofit Pollution Removal Adjustor Curves

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7-C.1.0 INTRODUCTION

In early 2012, the Urban Stormwater Work Group of the USEPA Chesapeake Bay Program formed an expert panel to define pollutant removal rates for urban stormwater retrofit projects. The Panel started by noting the strong relationship between the runoff volume treated and the degree to which runoff reduction is achieved at individual BMPs. The primary source was a comprehensive analysis of runoff reduction and pollutant event mean concentration reduction data for a wide range of BMPs that are typically applied in retrofitting (CWP and CSN, 2008).

7-C.2.0 PROCESS

CSN (2011) developed a general table to determine nutrient removal rates for all classes of retrofits, and this approach was used as a starting point. The basic technical approach defines an "anchor" rate for composite stormwater treatment (ST) and runoff reduction (RR) practices for one inch of runoff treatment (see **Table 7-C.1** below). The RR practices included six different LID practices including bioretention, dry swales, infiltration, permeable pavement and green roofs/rain tanks.

The composite for ST practices included wet ponds, constructed wetlands, sand filters, and wet swales. Dry ponds and Dry ED pond were omitted from the ST category since they have such low removal rates that they are typically not targets of retrofitting. The annual mass nutrient removal rates associated with each practice presented in **Table 7-C.2** below was averaged for the composite practices, as shown in **Table 7-C.1**.

Table 7-C.1. Composite Approach to Derive Nutrient Mass Load Reductions for RR ad ST Practices [1, 2]

PRACTICE	TP Mass Reduction (%)	TN Mass Reduction (%)
Bioretention	73	77
Dry Swale	66	63
Infiltration	75	78
Permeable Pavers	70	70
Green Roof/Rain Tank	55	55
Average RR	**70**	**70**[2]
Wet Ponds	63	35
Constructed Wetlands	63	40
Filtering Practice	63	38
Wet Swale	30	30
Average ST	**55**	**35**

[1] Source: Table A-4, nutrient rates computed using the average mass reduction for both Design Level 1 and Level 2.

[2] This value was subsequently discounted by 18% to reflect the impact of nitrate migration from runoff reduction practices described later in this appendix.

The next step involved using a rainfall frequency spreadsheet analysis from Washington, D.C. to estimate how the anchor removal rate would change based on different levels of runoff capture by the composite practice. The percent of the annual rainfall that would be captured by a retrofit designed for a specific control depth was estimated by summing the precipitation for all of the

Table 7-C.2. Mass Nutrient Removal Rates for Stormwater Practices

Practice	Design Level[1]	TN Load Removal[4]	TP Load Removal[4]
Rooftop Disconnect [5]	*1*	*25 to 50*	*25 to 50*
	2 [6]	*50*	*50*
Filter Strips [5]	*1*	*25 to 50*	*25 to 50*
	2 [6]	*50 to 75*	*50 to 75*
Green Roof	*1*	*45*	*45*
	2	*60*	*60*
Rain Tanks & Cisterns [7]	*1*	*15 to 60*	*15 to 60*
	2	*45 to 90*	*45 to 90*
Permeable Pavers	*1*	*59*	*59*
	2	*81*	*81*
Infiltration Practices	*1*	*57*	*63*
	2	*92*	*93*
Bioretention Practices	*1*	*64*	*55*
	2	*90*	*90*
Dry Swales	*1*	*55*	*52*
	2	*74*	*76*
Wet Swales	*1*	*25*	*20*
	2	*35*	*40*
Filtering Practices	*1*	*30*	*60*
	2	*45*	*65*
Constructed Wetlands	*1*	*25*	*50*
	2	*55*	*75*
Wet Ponds [8]	*1*	*30 (20)*	*50 (45)*
	2	*40 (30)*	*75 (65)*
ED Ponds	*1*	*10*	*15*
	2	*24*	*31*

Notes

[1] See specific level 1 and 2 design requirements within each practice specification

[2] Annual runoff reduction rate (%) as defined in CWP and CSN (2008)

[3] Change in nutrient event mean concentration in and out of practice, as defined in CWP and CSN (2008)

[4] Load removed is the product of annual runoff reduction rate and change in nutrient EMC

[5] Lower rate is for HSG soils C and D, Higher rate is for HSG soils A and B

[6] Level 2 design involves soil compost amendments, may be higher if combined with secondary runoff reduction practices

[7] Range in RR depends on whether harvested rainwater is used for indoor, outdoor or discharged to secondary runoff reduction practice. Actual results will be based on spreadsheet

[8] lower nutrient removal parentheses apply to ponds in coastal plain terrain

storms less than the control depth, plus the product of the number of storm events greater than the control depth multiplied by the control depth. This sum was then divided by the sum of the total precipitation. A visual representation of this may be helpful and can be seen as follows:

$$\% \, Annual \, Rainfall = \frac{(SUM \, P_{<CD} + \, CD(in) * (\# \, of \, Storms \, P_{>CD}))}{Sum \, of \, Total \, Precipitation \, (inches)}$$

Where:

$P_{<CD}$ = Precipitation of Storms less than Control Depth (inches)
$P_{>CD}$ = Precipitation of Storms greater than Control Depth (inches)
CD = Control Depth (inches): the depth of rainfall controlled by the practice

Once the percent annual rainfall has been determined for a specific control depth, we can use this along with the anchor pollutant removal rates to determine the pollutant removal values associated with a specific control depth. For example:

$$Pollutant \, Removal_{\, CD} = \frac{(Pollutant \, Removal \, Value_{AR} * \% \, Annual \, Rainfall_{CD})}{\% \, Annual \, Rainfall_{AR}}$$

Where:

Pollutant Removal Value $_{AR}$ = The anchor rates for N, P or TSS and ST or RR practices per 1.0” of Control Depth (~88% Annual Rainfall)

Phosphorus		**Nitrogen**		**Sediment**	
ST	RR	ST	RR	ST	RR
55%	70%	35%	60%	70%	75%

% Annual Rainfall $_{CD}$ = The % Annual Rainfall for a specific Control Depth as determined by the previous equation

% Annual Rainfall $_{AR}$ = This will always be 88%

The same basic approach was used to define maximum mass nutrient reduction rates for storms above the anchor rate, up to the 2.5 inch storm event. In general, no BMP performance monitoring data is available in the literature to evaluate removal for runoff treatment depths beyond 1.5 inches, so this conservative approach was used for the extrapolation. The Panel had limited confidence in removal rates in the 1.5 to 2.5 inch range, although it was not overly concerned with this limitation, since few of any retrofits are sized to capture that much runoff. A spreadsheet that defines how the anchor rates and bypass adjustments were derived can be obtained from the Chesapeake Stormwater Network (CSN).

The tabular data was converted into a series of curves to make it easier for users to define a rate for the unique combination of runoff capture volume and degree of runoff reduction. This was done by fitting a log-normal curve to the tabular data points, which came within a few percentage points of the tabular values for a wide range of runoff capture depths and removal rates.

A 0.05 inch runoff capture volume was established as the cut-off point for getting any retrofit removal rate, since this roughly corresponds to the depth of initial abstraction that occurs on impervious surface. It should be noted that retrofits in this small size range will require very frequent maintenance to maintain their performance over time.

The Panel concluded that the generalized retrofit removal adjustor curves were a suitable tool for estimating the aggregate pollutant load reductions associated with hundreds or even thousands of future retrofit projects at the scale of the Bay watershed and the context of the Chesapeake Bay Watershed Model.

7-C.2.1 Notes on the Standard Retrofit Equation

The specific retrofit storage volume achieved at an individual site is usually "discovered" and is measured or estimated by an engineer based on site constraints. The retrofit storage volume (usually reported in acre-feet) needs to be converted into the appropriate unit on the X-axis of the curves (i.e., depth of runoff captured by retrofit per impervious acre).

The basic rationale is that the Rainfall Frequency Analysis method used to derive the adjustor curve (above and below the anchor points) is based on the assumption that the runoff delivered to a practice is generated from a unit impervious acre. By contrast, the retrofit storage volume available at each retrofit is unique, based on the upstream land cover, soils and the drainage area. Consequently, the retrofit storage volume must be adjusted to get a standard depth of runoff treatment per unit impervious cover to get the correct depth to use on the x-axis of the retrofit adjustor curves.

This is done by using standard retrofit equation which multiplies the retrofit storage volume by 12 to get acre-inches, and then is divided by the impervious acres to get the desired unit for the retrofit adjustor curves. Numerically, the standard retrofit equation is:

$$= \frac{(RS\ )(12)}{IA}$$

The removal rates determined from the retrofit removal adjustor curves are applied to the entire drainage area of the retrofit, and not just its impervious acres. Also, the retrofit reporting unit is the entire treated area, regardless of whether it is pervious or impervious.

7-C.2.2 Notes on the Derivation of Sediment Removal Rates

The original retrofit removal rate adjustor table (CSN, 2011) did not include estimates for sediment removal. They were derived in January of 2012 after a detailed analysis of BMP sediment removal rates drawn from the following sources – Brown and Schueler, (1997), Winer (2000), Baldwin et al, (2003), CWP (2007), Simpson and Weammert, (2009), and ISBD (2011a). Collectively, these BMP performance research reviews analyzed more than 200 individual urban BMP performance studies conducted both within and outside of the Chesapeake Bay watershed. The following general conclusions were drawn from the analysis.

Sediment removal by both traditional BMPs and LID practices was consistently higher and less variable than nutrient removal. This is attributed to the particulate nature of sediment which makes it easier to achieve reductions through settling, trapping, filtering and other physical mechanisms.

The analysis began with an examination of existing CBP-approved rates (see **Table 7-C.3**). Two important trends were noted. First, TSS removal always exceeded TP and TN rates for every category of urban BMP. Second, nearly all the rates were within a fairly narrow range of 60 to 90%.

Table 7-C.3. Approved CBP BMP Efficiency Rates for Retrofit Analysis [1, 2, 3]

URBAN BMP		**TOTAL NITROGEN**	**TOTAL PHOSPHORUS**	**TSS**
		MASS LOAD REDUCTION (%)		
Wet Ponds and Constructed Wetlands		20	45	60
Dry Detention Ponds		5	10	10
Dry Extended Detention Ponds		20	20	60
Infiltration		80 (85)[4]	85	95
Filtering Practices (Sand Filters)		40	60	80
Bioretention	C & D w/UD	25	45	55
	A & B w/ UD	70	75	80
	A & B w/o UD	80	85	90
Permeable Pavement	C & D w/UD	10 (20)	20	55
	A & B w/ UD	45 (50)	50	70
	A & B w/o UD	75 (80)	80	85
Grass Channels	C & D w/o UD	10	10	50
	A & B w/o UD	45	45	70
Bioswale	aka dry swale	70	75	80

[1] In many cases, removal rates have been discounted from published rates to account for poor design, maintenance and age, and apply to generally practices built prior to 2008

[2] Current Practices are designed to more stringent design and volumetric criteria, and may achieve higher rates –see Table A-4

[3] Some practices, such as forest conservation, impervious cover reduction, tree planting are modeled as a land use change. Urban stream restoration is modeled based on a reduction per linear foot of qualifying stream restoration project

[4] Numbers in parentheses reflect design variation with a stone sump to improve long term infiltration rates

The same composite BMP method was employed using the CBP-approved rates to define sediment removal rates for RR and ST practices. The ST practice category included wet ponds, constructed wetlands and sand filters, which collectively had a TSS removal rate of 70%. The RR category included all design variations of bioretention, permeable pavement, infiltration and bio-swales in **Table 7-C.3**, and had a slightly higher composite TSS removal rate of 75%.

Other BMP performance reviews have also noted that TSS removal rates exceed TP or TN removal rates for all individual studies of traditional urban BMPs (up to 1.0 inch of runoff treated, Winer, 2000 and CWP, 2007).

The sediment removal rate for traditional BMPs is ultimately limited by particle size considerations. Studies have shown that there is an irreducible concentration associated with the outflow from traditional BMPs (Winer, 2000 and NRC, 2008) around 15 to 20 mg/l which reflects the limits of settling for the most fine-grained particles. In practical terms, this sets an upper limit on maximum sediment removal around 70 to 80% for the range of monitored BMPs (i.e., sized to capture 0.5 to 1.5 inches of runoff).

Additional analysis was done to examine whether sediment removal rates for LID practices (i.e., runoff reduction practices) would achieve high rates of runoff reduction. Recent sediment mass removal rates were reviewed for bioretention, permeable pavers, green roofs, rain tanks, rooftop disconnection and bioswales (Simpson and Weammert, 2009, ISBD, 2011a, and a re-analysis of individual studies contained in CWP and CSN, 2008). The following general conclusions about LID sediment removal rates were drawn from the analysis:

- Most LID practices had lower TSS loadings than traditional BMPs, primarily because there was no major up-gradient sediment source area (e.g., green roofs, rain tanks, permeable pavers, rooftop disconnection) or a small contributing drainage area (bioretention, bio-swales).

- In general, LID practices had a slightly lower outflow sediment concentration than their traditional BMP counterparts (around 10 mg/l-- ISBD, 2011a).

- The ability of LID practices to change the event mean concentration of sediment as it passed through a practice differed among the major classes of LID practices. For example, nearly a dozen studies showed that bioretention and bioswales could achieve significant reduction in sediment concentrations. On the other hand, permeable pavers and green roofs generally produced low or negative changes in sediment concentrations through the practice. This finding was not deemed to be that important given how low the sediment inflow concentrations were.

Based on these conclusions, the Panel took a conservative approach and did not assign higher sediment removal rates for LID practices that achieved a high rate of runoff reduction, at least for facilities designed to capture less than an inch or more of runoff.

Beyond that point, the Panel did assign a modest increase in sediment removal rate for LID practices under the assumption that the combination of high runoff capture and reduction would work to reduce or prevent accelerated downstream channel erosion. The Panel notes that the extra sediment removal rate for this range of LID practices is an untested hypothesis that merits further research.

7-C.2.3 Notes on Revising the TN Adjustor Curve to Reflect Base flow Nitrate Movement in Urban Watersheds

The adjustor curves are used to define a removal rate that applies to both the pervious and impervious areas in the contributing drainage areas for the stormwater treatment practices. The removal rates properly apply to surface runoff and some portion of the interflow delivered to the stream, but may not properly apply to groundwater export of nitrate-nitrogen from the urban landscape. The "missing" nitrate may be nitrate that exits a runoff reduction via infiltration into soil, or slow release through an under drain (e.g., bioretention).

Once stormwater runoff is diverted to groundwater, the overall load is reduced by using the ground as a filtering medium, but not eliminated. Therefore, the WTWG concluded that the original TN adjustor curves developed by the expert panel may over-estimate TN removal rates, and should be discounted to reflect the movement of untreated nitrate from runoff reduction BMPs. This discounting is not needed for TKN, TP or TSS as these pollutants are not mobile in urban groundwater.

The USWG concurred with this approach and developed the following procedure to derive a new TN adjustor curve to account for groundwater nitrate migration from runoff reduction practices. The basic approach is documented in Schueler (2012a and 2012b).

This discount factor is fairly straight forward to calculate and is simply based on the ratio of nitrate in relation to total nitrogen found in urban stormwater runoff. Stormwater runoff event mean concentration data from the National Stormwater Quality Database (Pitt et al, 2004) was analyzed for more than 3000 storm events, and the nitrate-to-TN fraction was consistently around 0.3. This sets an upper boundary on the fraction of the inflow nitrate concentration to the BMP which could be lost to groundwater or under drains at about 30%.

The next step is to account for any nitrate loss within the BMP due the combination of either plant uptake and storage and/or any de-nitrification within the BMP. Most runoff reduction practices employ vegetation to promote ET and nutrient uptake, whereas the de-nitrification process is variable in both space and time.

Over 70 performance studies have measured nitrate removal within runoff reduction BMPs. A summary of the national research is shown in **Table 7-C.4** below. Clearly, there is a great deal of variability in nitrate reductions ranging from nearly 100% to negative 100% (the negative removal occurs when organic forms of nitrogen are mineralized/nitrified into nitrate within the BMP).

Some well studied runoff reduction practices, such as bioretention and bioswales, have a median nitrate removal ranging from 25 to 45%, presumably due to plant uptake. Initial results for green roofs indicate moderate nitrate reduction as well. Non-vegetative practices, such as permeable pavers and a few infiltration practices, show zero or even negative nitrate removal capability (see **Table 7-C.4**). Submerged gravel wetlands that create an aerobic/anaerobic boundary that promotes denitrification appear capable of almost complete nitrate reduction.

Therefore, it is recommended that maximum nitrate removal within runoff BMPs be assumed to be no more than 40%. Although this value may seem generous, it should be noted that some additional nitrate reduction occurs as the nitrate moves down-gradient through soils on the way to the stream. Under this conservative approach, no additional nitrate reduction is assumed after it exits the BMP and migrates into groundwater.

Given the nitrate inflow concentrations, the potential groundwater/under drain nitrate loss would be (0.3)(0.60) = 0.18, or a discount factor of 0.82

The discount factor is then applied to the anchor rates used to derive a new TN adjustor curve. The anchor rate for RR practices would be adjusted downward from the current 70% to 57%, and the existing runoff frequency spectrum equation would be used to develop a new, lower curve for TN removal. An example of the how this discount influences the existing TN adjustor curve is shown in **Figure 7-C.1** below.

It is also noted that no nitrate loss parameter needs to be defined for stormwater treatment (ST) practices, since inlet and outlet monitoring of these larger facilities already takes this into account (and is a major reason why the ST curve is so much lower than the RR curve).

The de-nitrification process can be enhanced through certain design features (inverted under drain elbows, IWS, enhanced media). Several good research reviews indicate that these design features show promise in enhancing nitrate removal (Kim et al, 2003, NCSU, 2009, Weiss et al, 2010), these features are not currently required in Bay state stormwater manuals. Should future research confirm that these features can reliably increase nitrate removal through denitrification and/or plant uptake, it is recommended that a future expert panel revisit the existing nitrogen adjustor curve.

Table 7-C.4 Nitrate Removal by Runoff Reduction Practices [1]

Practice	Median Removal Rate	No. of Sites	Range	Source
Bioretention [2]	43%	9	0 to 75	CWP, 2007
Bioretention [2]	44%	1	NA	UNH, 2009
Bioretention [2]	24%	10	NA	ISBD, 2010
Bioswales	39%	14	-25 to 98	CWP, 2007
Bioswales	7%	18	NA	ISBD, 2010
Infiltration [3]	0	5	-100 to 100	CWP,2007
Permeable Pavers	-50% [4]	6	NA	IBSD, 2010
Permeable Pavers	0	4		Collins, 2007
Green Roof [5]	Positive	4	NA	Long et al 2006
Gravel Wetland	98%	1	NA	UNH, 2009

Notes:

[1] As measured by change of event mean concentration (EMC) entering device and final exfiltrated EMC, and involves either or plant uptake or denitrification

[2] For "conventional" runoff reduction practices only, i.e., no specific design features or media enhancements to boost nitrate removal

[3] Category includes several permeable paver sites

[4] A negative removal rate occurs when organic forms of nitrogen are nitrified to produce additional nitrate which is

[5] Test column study

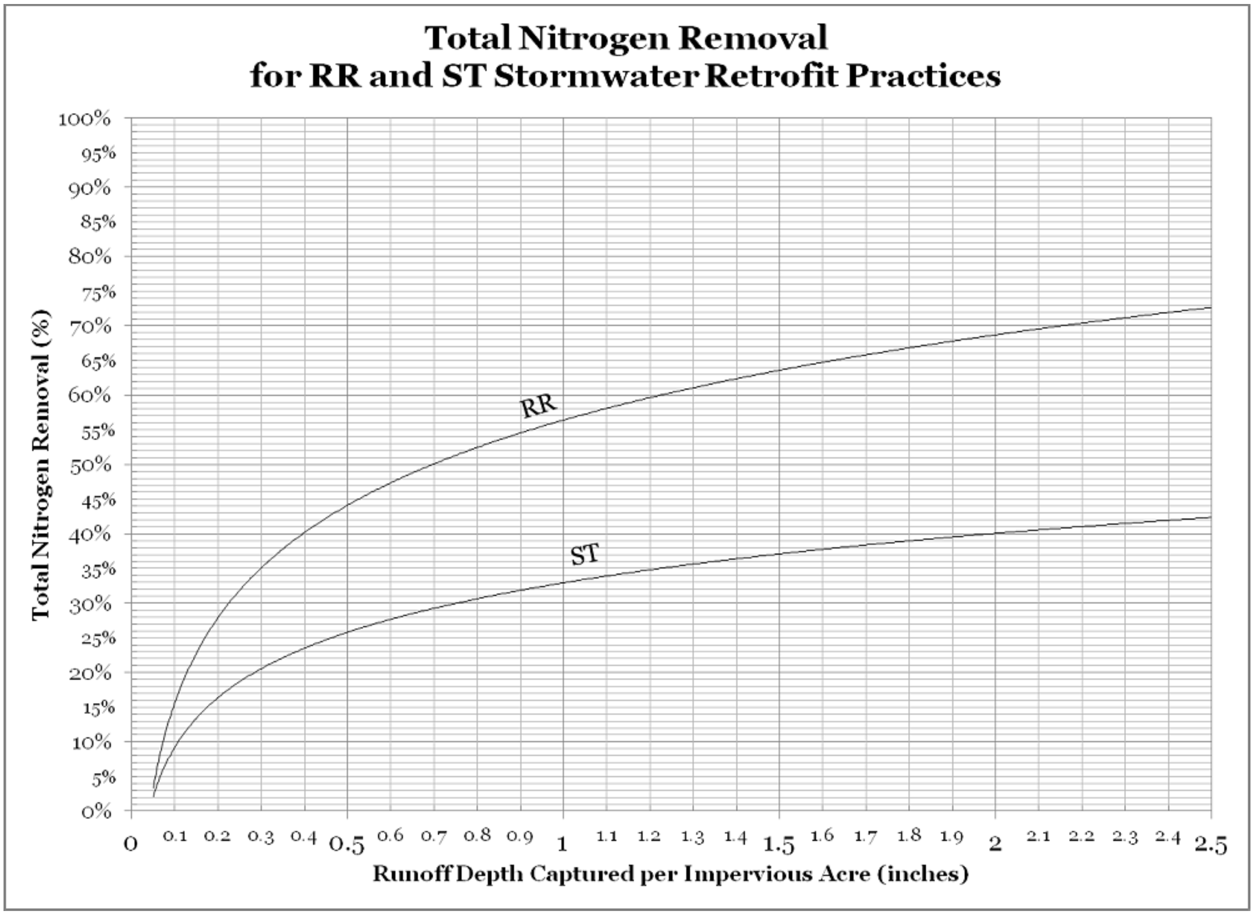

Figure 7-C.1. Revised TN Adjustor Curve

Text would be added to memos that acknowledge the “escaped nitrate" issue up gradient and down gradient of the BMP that might not be effectively captured by the BMP, but indicate that this should be resolved in the next version of CBWM.

7-C.3.0 REFERENCES

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