Water Quality Best Management Practices Design Recommendations

For Kitsap County Public Works

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INTRODUCTION

This report covers the requirements for Task 1 – Literature Review and Technical Report. The contract specified that the Contractor (Gary Minton) conduct a thorough literature review of laboratory and field studies of water quality best management practice. The literature search will form the basis for recommendations in design criteria for the following BMP subject areas.

- Wet ponds
- Wetlands
- Swales
- Oil Water Separators
- Sand Filters
- Infiltration Treatment Layers
- Enhanced (metals) Treatment Device Selection
- Phosphorus Treatment Device Selection

Recommendations are provided for one or more design criterion for each of the above BMP subject areas. A discussion is presented for each criterion using a standard format consisting of the following sections.

- **Current criterion:** As proposed in the Department of Ecology manual (Ecology, 2005). In some cases this may differ from current Kitsap County criteria. However, the authors of the Ecology manual have generally attempted to keep the sizing of BMPs similar to that present in its previous manuals, despite the proposal to switch from the NRCS/TR55/SBUH (herein known as SBUH) hydrologic method to WWHM.
- **Origin of the current criterion:** The basis for the current criterion; where Ecology likely obtained the criterion.
- **Proposed criterion:** What is recommended for Kitsap County.
- **Rationale for proposed criterion:** Support for the proposed criterion, derived from the literature review.
- **Further considerations:** Additional aspects that bear on use of the proposed criterion.

Table 1 summarizes the criteria to consider changing, with corresponding Ecology criteria, proposed changes, and explanation.

TABLE 1 SUMMATION OF RECOMMENDED DESIGN CRITERIA AS RELATED TO ECOLOGY REQUIREMENTS

SYSTEM & CRITERION	ECOLOGY'S METHOD OR DESIGN CRITERIA	PROPOSED CHANGE	EXPLANATION
WET POND AND WETLAND			
Method to give basin volume	WWHM is used to determine the volume of a wet basin.	Replace with the USEPA method as currently used by King County.	Procedure in WWHM for wet basin volume is incorrect. USEPA method based on long-established engineering principles.
Basin volume itself	King County adjusts the volume of the wet basin by a factor of three.	Remove the adjustment.	Field data indicate adjustment is too conservative. Indirectly the WWHM method has a factor of about 2.3.
Wetland volume	Wetland has the same volume as a wet pond.	Wetland volume equal to 75% of the required wet pond volume.	There are benefits of using a wetland rather than pond: habitat, aesthetics, and possibly better performance. But for the same volume, wetlands require more space discouraging their use. Allow a smaller volume based on the argument that a shallow basin performs better with a lower hydraulic loading rate.
Forebay size	Forebay is specified as 33% of the total basin volume.	Reduce to 10%.	The purpose of a forebay is to trap sand and coarse silt in a relatively small area to ease cleaning. A large forebay defeats this purpose. There are no data supporting 33%.
Forebay design	Earthen forebay is specified by Ecology.	Allow manufactured vaults in lieu of earthen forebays.	Vaults use less space; likely easier to clean. Ecology specifies forebay be 33% of the basin volume, which inadvertently disallows manufactured vaults. Yet Ecology's has approved these vaults for pretreatment, the purpose of forebays.
Inlet/outlet	Should be submerged.	Baffling and inlet T.	Improve performance by avoiding short-circuiting
GRASS SWALE			
Width and length adjustments	Ecology specifies that the width and length obtained from WWHM be adjusted to provide a swale of about the same size as determined by the SBUH method.	Drop adjustments.	The adjustment is made to account for WWHM giving a much lower peak flow than the SBUH method, resulting in a narrower swale but of the same length as from SBUH. The peak estimated by WWHM should be accepted as substantially more correct than SBUH.
Basic design	A swale in which the water is treated as it flows through the grass.	Replace with a bioretention filter swale, known as "dry swale" on the east coast.	Field data indicates the grass swale does not meet the Basic Goal for TSS removal. The proposed design is essentially a narrow bioretention cell, either stepped or sloped. It is widely used in the eastern United States, known as the Dry Swale.

SYSTEM	ECOLOGY'S METHOD OR DESIGN CRITERIA	DESIGN IDEA	EXPLANATION
Design integration	None	Size using Manning's Equation grass swale but a residence time of 4.5 rather than 9 minutes.	This criterion decreases the length of the swale by 50%, compensating for the increase in cost of a bioretention swale in comparison to the current grass swale.
OIL WATER SEPARATORS			
Design temp	The design temperature is 0°C.	Use 5°C.	Use average ambient temperature for January.
Flow rate adjustment	Adjustment is made to design flow rate from WWHM.	Drop the adjustment factor.	Same consideration as presented with the grass swale.
SAND FILTER			
Media thickness	Sand media thickness of 18" for the rectangular basin filter and 12" for the lineal or perimeter filter.	Decrease media thickness to 12" (possibly 6") for filters cleaned by hand.	Most of the sediment settles on the top of the sand and within the first inch or two. So why use 18 inches?
Underdrain design for small filters	Underdrain consists of 8" layer of rock covering perforated pipe.	Simpler underdrain system of plastic channels wrapped in fabric.	For small filters a simpler and cheaper solution is flat "panel" plastic matrices of 1 to 2 inches in height through which the treated water exits. Saves vault height as well.
Pretreatment	Sizing pretreatment unit is not clear.	Use the USEPA method. Allow manufactured vaults.	Size the pretreatment unit using the USEPA method to achieve 50% TSS removal. Allow the use of manufactured vaults.
INFILTRATION BASIN			
Infiltration basin	Full treatment is required if the infiltration rate exceeds 2"/hour, requiring additional space and cost.	Place treatment layer using Ecology Mix in the infiltration basin, saving space and expense.	In some cases the engineer may find it cost-effective to place a layer of filter media on the surface of the infiltration basin, which meets the Ecology requirement for treatment.
ENHANCED (METALS) TREATMENT DEVICE SELECTION			
Menu	Menu is enlarged unit treatment operations, and combinations of two full sized treatment operations.	Replace the menu with bioretention filter cell and swale, wet pond, wetland, and certified products.	The original menu was derived in 1994 when there was minimal field performance data. Field data now available indicate a more effective and cost-effective menu is possible.
PHOSPHORUS TREATMENT DEVICE SELECTION			
Menu	Menu is enlarged unit treatment operations, and combinations of two full sized treatment operations.	Same as for Enhanced Menu with some design differences except wet ponds not allowed.	The original menu was derived in 1994 when there was minimal field performance data. Field data now available indicate a more effective and cost-effective menu is possible.

WET PONDS AND WETLANDS

CRITERION: *METHOD TO DETERMINE THE BASIN VOLUME*

The method that is currently proposed to size the volume of a wet basin using WWHM is not based on the correct engineering principles.

Current criterion: Ecology (2005) has two options: the volume of the 6-month/24-hour event from SBUH, or the volume from the Western Washington Hydrologic Model (WWHM). Within WWHM volume is determined by multiplying 24 hours times the flow rate at which if treated achieves the 91% requirement. A time of 24 hours presumably represents a residence time. In effect, if the runoff were to remain constant at the noted flow rate a residence time of 24 hours occurs theoretically. Hours converted to seconds times cubic feet per second, the units of flow rate, gives cubic feet.

Origin of the current criterion: Since Ecology's first manual (Ecology, 1992) we have been using the SBUH model to define the volume of wet basins. Simulations of a specified rainfall event give both a peak and runoff volume. Ecology (1992) specified that the volume of the wet basin be equal to the volume of runoff from what it called the 6-month/24-hour rainfall event, an event that occurs presumably twice per year. The Department of Ecology was not the originator of this specification. It was originally developed as a sizing criterion for an unpublished BMP manual that I prepared for the City of Seattle in 1988 (Minton, 1989). At that time I did a very simple analysis of the historic record of the rain gage at the SeaTac airport. I determined that the aggregate rainfall depth of all storms up to a depth of about 1.2 inches represented 90% of the total rainfall. This event turned out to occur about twice per year over the rainfall record; ergo, the 6-month event. Treating 90% of the stormwater seemed a reasonable criterion at the time. The storm depth of about 1.2 inches was inputted into the SBUH model to give simple sizing criterion in terms of cubic feet and cubic feet per second per development acre for basins and swales, respectively. A representative of the Department of Ecology was a member of the technical advisory group to the preparation of the Seattle manual who incorporated the method explicitly in Ecology's first manual (Ecology, 1992).

Performance data available in the late 1980s was very limited, but suggested that the volume generated by SBUH with the 6-month/24-hour event was reasonable to obtain a high performance with respect to TSS removal.

By happenstance multiplying the peak rate from WWHM by 24 hours gives a volume similar to that from SBUH. It is understood that this was Stan Cuiba's intent when he developed the specification for the WWHM model in 2002 (Brasher, pers. comm.). The concept of a 24-hour residence time in a basin was original to Ecology's 1992 manual, as perhaps an attempt to provide relevance to the use of 24-hour rainfall event as used in SBUH).[1]

Proposed criterion: Replace the Ecology method with the method developed by the USEPA (1986). King County currently uses the USEPA method. The method bases the volume of the wet basin on the volume of the mean annual rainfall runoff event, tying this relationship directly to performance.

[1] pg III-1-2 in Ecology(1992)

King County uses the following equation.

$V_b = (V_b/V_r \text{ ratio}) \times V_r$ **Equation 1**

V_b = volume of the basin
V_r = volume of the mean annual runoff event
V_b/V_r ratio = a factor representing the adjustment of the volume to achieve a high removal of TSS.

King County uses a V_b/V_r ratio of 3.

The volume of the runoff is calculated as follows:

$V_r = (0.9A_f + 0.25A_{tg} + 0.10A_{tf} + 0.01A_o) \times (S_m/12)$ **Equation 2**

A_f = area of impervious surface
A_{tg} = area of tilled soil covered by grass
A_{tf} = area of till soil covered by forest
A_o = area of outwash soil covered by grass or forest
S_m = mean storm depth

Equation 2 accounts for differences in infiltration/abstraction of a portion of the rainfall by soil type. For example, the equation in effect states that 10% of the rainfall falling on impervious surfaces does not runoff; 75% for till soil covered by grass. Equation 3 is a simpler as it ignores the nuances above. Given the simplistic assumptions of the USEPA method, described below, it is not unreasonable to use the simpler equation. There is a slight difference in the two equations. Equation 2 uses the rainfall depth of the average annual storm, which King County determined to be 0.4 or 0.5 inches depending on the location in the county, whereas Equation 3 uses the mean runoff depth, calculated to be 0.48 inches (Driscoll et al., 1989) in support of the USEPA method. There is therefore some difference between the two analyses inasmuch as the analysis by USEPA assumed an abstraction of 0.1 inches.

$\text{Volume} = AR_c(V_b/V_r)S_m$ **Equation 3**

A = drainage area
R_c = runoff coefficient
S_m = mean storm runoff depth
V_b/V_r ratio = ratio of the basin volume to the mean runoff event

Runoff coefficients as those used in the Rational Method could be used in Equation 3. As with Equation 2 some adjustment must be made to avoid double counting of abstraction.

Rationale for proposed criterion: The determination of a volume by either the SBUH or WWHM method is arbitrary with no relationship established as to performance. Using a residence time to define a basin volume is wrong and inconsistent with basic settling theory followed by wastewater and water treatment engineers for over a century (Metcalf and Eddy, 1991). Performance of a wet basin during periods of flow is directly a function of the hydraulic loading rate, not residence time.

Residence time is relevant to settling of particles in standing water, which in the case of stormwater treatment represents the time between storms. However, this residence time differs significantly both in concept and calculation than the 24 hours presumed in the WWHM method.

In contrast, the USEPA method is directly related to performance. The method incorporates a distribution of settling velocities of particles in stormwater and simple statistics related to the variations in storm depths, durations, and intervals for a given region like the Seattle area. The distribution of settling velocities used by the USEPA was derived from settling column tests conducted in the early 1980s as part of the USEPA Nationwide Urban Runoff Program (NURP). The selected distribution was intended to reasonably represent the "average" condition of particles (sediment) in stormwater.

The USEPA method explicitly incorporates sound engineering principles, using equations that have been well established for decades to represent settling of particles during each runoff event, based on the hydraulic loading rate, and between runoff events, based on the long-term residence of stormwater between storms. While the method is simplistic in its mathematical assumptions, settling velocities, and runoff statistics, the underlying engineering principles upon which it is based are valid, unlike the SBUH and WWHM methods.

Furthermore, the concept of treating effectively 91% of the stormwater has no relevance to systems with standing water. Consider the sump in a catch basin. Essentially all of the stormwater occurring over time goes through a catch basin, which with its sump is a small wet vault. Yet it does not meet the requirement of Basic Treatment, the sump being too small. The concept of 91% treated is relevant only to "fill-and-draw" basins namely sand filters, infiltration basins, bioretention, and extended detention. It is has no relevance to basins with standing water.

Further considerations: None

CRITERION: *BASIN VOLUME*

The USEPA method requires a decision regarding the V_b/V_r ratio as seen in Equations 1 and 3. King County decided to use a value of 3 in its 1994 manual. Performance data now available indicate that basins can be much smaller than currently specified yet meet the Ecology performance goal for Basic Treatment. Also, the data indicate that making the basin larger does not improve performance.

Current criterion: King County uses a V_b/V_r ratio of 3 to adjust the volume of the basin relative to the volume of the runoff of the mean annual event. The approximate V_b/V_r ratio resulting from the WWHM method is about 2.3.

Origin of the current criterion: At the time the USEPA method was under consideration by King County a V_b/V_r ratio of 3 appeared reasonable given the limited amount of performance data (Minton, 1994). Of greater relevance at the time was that the adjustment also gave a basin volume similar to that given by the SBUH method and therefore was consistent with the Ecology specification in effect at that time (Ecology, 1992).

Proposed criterion: Use a V_b/V_r ratio of 1 for residential and office-commercial developments. A ratio of 1.5 seems reasonable for retail commercial, commercial streets, arterials, and

highways, and industrial areas where influent TSS concentrations are generally higher. These ratios give reasonable assurance that the Ecology performance goal will be met.

Rationale for proposed criterion: Figure 1 is a plot of performance predicted by the USEPA method, showing the relationship between the relative size of a 5-foot deep wet pond and % removal. The method predicts that a wet pond achieves the Ecology performance goal of 80% TSS removal at a V_b/V_r ratio of 1.

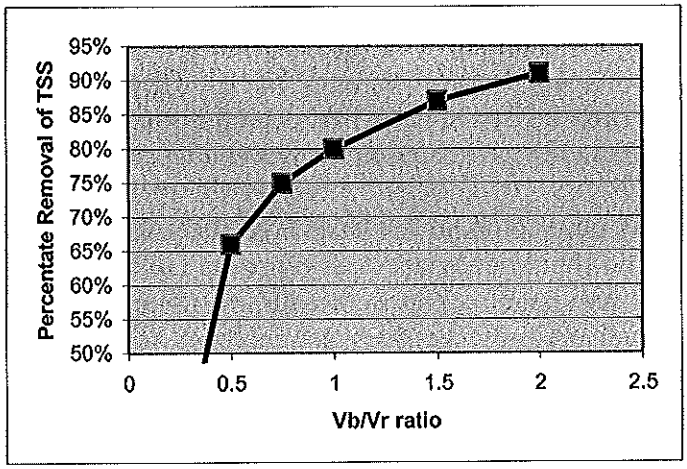


FIGURE 1 Simulations Of Performance With The USEPA Method for Seattle Region

The body of field data is as expected much greater than in 1994 when a coefficient of 3 was adopted by King County. Figure 2 is a plot of currently available performance data for wet ponds and wetlands. Each data point represents the results of one pond or wetland whose performance was evaluated. Note that the Y-axis is effluent concentration[2] rather than percent removal. Most of the data and information to calculate the V_b/V_r ratio of the facility[3] were obtained from the International BMP Data Base (as of early 2008) supplemented by several additional studies.

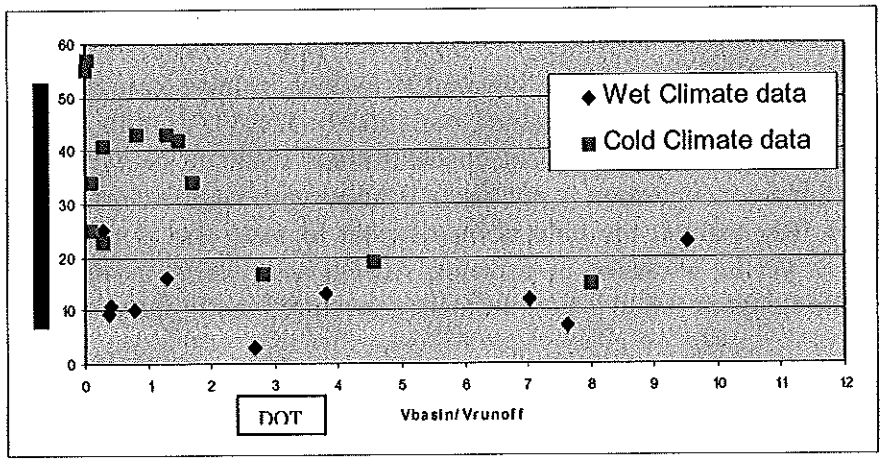


FIGURE 2 Field Data Relating Performance To Basin Volume

[2] It is more appropriate to compare median concentrations or geometric means. However, while all reports present means many do not provide medians or geometric means. Therefore means are used in the analysis.

[3] The values shown in Figure 2 are the actual ratios in effect during the monitoring period in each study, derived from information on inflow and discharge volumes.

In examining the available performance data it was found that wet ponds and wetlands located in cold climate regions do not perform as well as their counterparts in wet climate regions such as the Puget Sound area. Hence, a distinction is made in Figure 2 between the two climate regimes.[4] Performance may be poorer in cold climates (northern tier states and Ontario) differ for either of two reasons or both: higher influent concentrations of TSS with the use of deicing sand, and slower settling velocities due to colder, saline stormwater.

WSDOT has published performance data of two wet ponds and two wet vaults (WSDOT, 2007). The V_b/V_r ratios are unknown but would be in the range of 2 to 2.5 if sized according to Ecology criteria, and rainfall during the sample period was normal. The performances of these four systems were (average influent/effluent mg/L): 69, 4; 32, 2; 56, 5; and, 72, 10. These influent concentrations are very low for freeways, suggesting the stormwater first passed through grassed areas before reaching the basins. These four studies are represented as a block in Figure 2.

Figure 2 indicates that for wet climates the V_b/V_r ratio could be less than 1 yet meet the Ecology requirement for basic treatment; but what the ratio should be is not clear other than to state that a ratio greater than 1 does not appear to provide any benefit. The field data in Figure 2 are not consistent with Figure 1 in two respects. Actual performance does not increase as the basin increases in size as estimated with the USEPA method. It is believed this inconsistency is due to algae growth. Algae grow in the surface basins, generally from Spring through Fall, and exit in the effluent as a light complex of algae/bateria/clay (Marsalek, 1999). The USEPA method does not include this factor. The field data are also inconsistent with Figure 1 at the lower values of the V_b/V_r ratio. The USEPA method predicts a decline in performance. No decline is found with the smaller ponds and wetlands located in wet climates.

A possible consideration in the performance of small wet basins is influent concentrations. For example, a greater influent concentration may imply more clay-size material that does not settle well. Figure 2 is repeated below as Figure 3 with the mean influent concentration included for each study in which the TSS concentration was about 100 mg/L or less. Basins in cold climates are in black; those in wet climates in white. The three studies marked with a letter and underlined are of basins located in western Washington (Bellevue), one of which (A) is a pretreatment vault.

Figure 3 suggests low effluent concentrations may be related to low influent concentrations observed in the very small basins studied in wet climates, particularly at a V_b/V_r ratio less than 0.5. Stated differently, for small basins higher influent concentrations result in higher effluent concentrations. In contrast, influent concentration is not likely a factor with large basins, perhaps above a V_b/V_r ratio of 2 to 3. Regardless, the data is insufficient to state that concentration matters; but rather, it cannot as yet be excluded as a factor. Absent are data of basins in wet climates with V_b/V_r ratios in the range of 0.5 to 2 with influent concentrations in the range of 50 to 100 mg/L.

How do the TSS concentrations in Figure 2 compare to "typical" PNW data for residential and commercial developments. The City of Portland (Portland, 2006) recently reviewed its extensive data base, drawing these conclusions with respect to mean concentrations of TSS from different land uses: heavy residential, 60 mg/L; light residential, 60 mg/L; commercial, 79 mg/L; industrial, 134 mg/L; and streets and highways, 170 mg/L. These data are similar to a previous synthesis (Strecker, et al., 1997). A manufacturer conducting storm sampling at a shopping mall

[4] Only one of the basins in Figure 2 is located in a semi-arid area

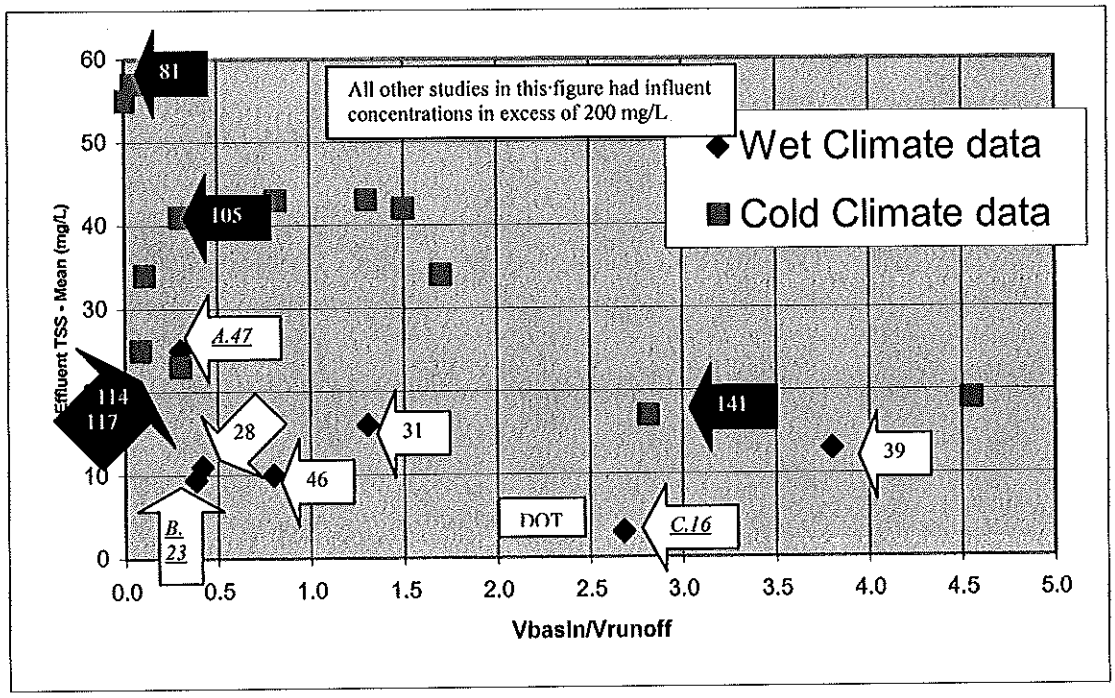


FIGURE 3 Possible Effect of Influent Concentration on Performance

in Vancouver found a mean of 85 mg/L over 22 storms, with two storms that exceeded 900 mg/L.[5] A study by the City of Seattle of a residential area found a mean concentration of 34 mg/L. The low influent concentrations in the lower left-hand corner of Figure 2 are therefore not too far from "typical."[6]

Another perspective is gained from the consideration of manufactured vaults, which have been approved for pretreatment by the Department of Ecology. They are purportedly capable of removing 50% of the incoming TSS and/or reducing the concentration to at least 50 mg/L.

These devices are very small with V_b/V_r ratios in the range of 0.05 to 0.1. It can be reasonably concluded based on the experience with the manufactured vaults that a V_b/V_r ratio of 2 to 3 is excessive to meet Basic Treatment as it represents 20 to 60-fold increase of the V_b/V_r ratio, just to increase performance from 50% to 80%. The performance of manufactured vaults is presented further in this memo when discussing their use as forebays for wet basins.

It could be reasoned that a decision on the V_b/V_r ratios should await studies of basins having ratios in the range of 0.5 to 1.5 and at influent concentrations of 50 to 100 mg/L. A reasonable consideration is whether this gap in the performance data should forestall a decision, or whether it is likely to be filled in the near term by pending studies[grm1]. However, basins of this size should not exist in Western Washington. Two-cell basins could be studied: the first cell representing the lower V_b/V_r ratio pond. Regardless, there is no assurance that the TSS concentrations will fall within the desired range. There are two studies in Figure 2 with V_b/V_r ratios in the range of

[5] The two extreme events were due to the washoff of tree buds in the Spring.

[6] Another factor is the equipment. The studies in wet climates at low ratios may have used older samplers that were not very effective at picking up sand. This is the case for pond C, which was commercial area. A low concentration of only 16 mg/L is difficult to believe.

about 0.8 to 1.5, with influent of 46 and 31 mg/L, respectively. While a bit low they are within a reasonable range of what is expected from residential and office-commercial parking lots.

Given the performance data and expected TSS concentrations a V_b/V_r ratio of 1 is reasonable for residential developments. This ratio is also reasonable for light commercial developments; namely employee parking lots at commercial offices and wholesale businesses. A ratio of 1.5 appears more appropriate for retail commercial, commercial streets, arterials, and highways, and industrial areas, given the generally higher TSS concentrations.

Further considerations: The impact of reducing the wet basin volume depends on the type of facility: treatment-only wet basin, or combined flood control/channel protection/treatment facility. For combined flood control/channel protection/treatment facility no reduction will likely occur because the detention volume usually defines the footprint area. If detention is not required, but only the treatment basin, the footprint reduction is in a range of 50 to 75%, increasing with larger basins. This range is based on five-foot water depth and 3:1 side slopes.

Reduction in the basin footprint reduces habitat for mosquitoes mentioned above (good), waterfowl (not good for the waterfowl but good for pollutant reduction, particularly phosphorus, nitrogen, and bacteria), and other birds (not good, impact of their presence likely minor), and furry creatures (same effect with waterfowl). The wet pool in a combined flood control/treatment basin may be simply a smaller wet pond as illustrated below situated within the larger flood control footprint.

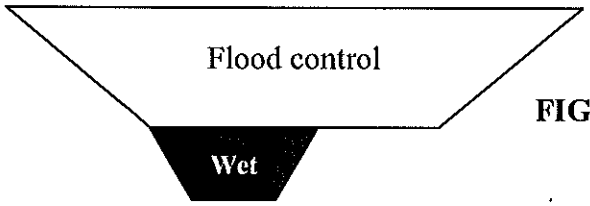


FIGURE 4 One combined Facility Configuration

Alternatively the wet pool can be a wetland covering the entire bottom of the combined facility. An outcome of reducing the wet pool volume may be more wetlands. This may raise concerns about mosquitoes as they appear in greater numbers in wetlands as compared to wet ponds (CDHS, 2002). The mosquito fish known commonly as gambusia cannot survive in our region requiring water temperatures above 40°F. However, the footprint of a wetland using the proposed criterion of 1 or 1.5 for the Vb/Vr ratio would be smaller than wet ponds sized to the WWHM method.

Poor hydraulic efficiency is insufficiently recognized as a major factor in wet basin performance: that is, avoiding direct movement of incoming stormwater to the outlet (short circuiting) and water remaining stagnant in corners during storms (dead zones). Improvement in the hydraulic efficiency is paramount if the volume of the wet basin is decreased, particularly wet ponds. Implied in some of our design criteria is hydraulic efficiency: These criteria include (Ecology, 2005) length/width ratios (3:1 or 4:1) and dividing the basin into two cells.[7]

The one-cell configuration with extensive fringe vegetation in Figure 5 is to be avoided. Short-circuiting through the open water area occurs due to the vegetation along the basin sides. Extensive areas of fringe vegetation occur in small wet ponds with safety benches, but large wetlands as well where a large percentage of the basin is allocated to shallow water depths Figure 6 is a graph from Jenkins and Greenway (2005) who evaluated the effect of the fringe

[7] Ecology specifies the wet pool be divided into two cells separated by a baffle or berm with the first cell with 25 to 35 % of the total wet pool volume. Not clear if this is the forebay or in addition to the forebay, which results in three cells.

vegetation, area covered and density, on hydraulic efficiency using two-dimensional model simulations. The parameter λp represents the area/density of fringe vegetation, with 1 being none and 0.30 being extensive. Figure 6 shows that the hydraulic efficiency, and in turn removal efficiency, can be reduced by as much as 75%. They have shown that the effect is particularly pronounced when the vegetation exceeds an aggregate of 50% of the wet basin along the length of the pond; that is, all 50% could be along each side ranging to 25% on each side.

FIGURE 5 Fringe Vegetation

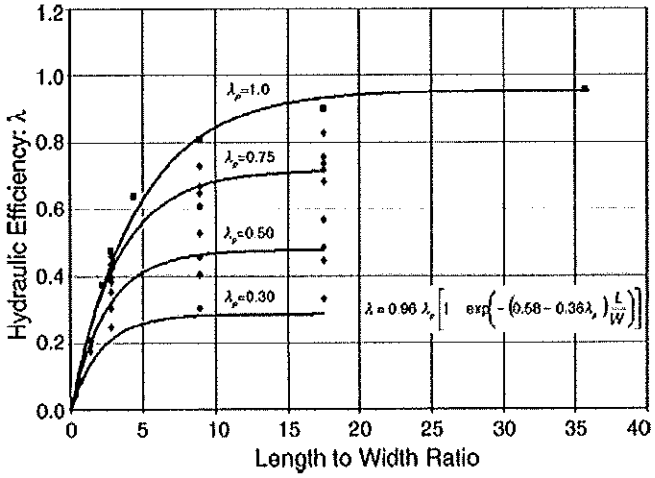


FIGURE 6 Effect of Fringe Vegetation on Hydraulic Efficiency

Division into two cells as prescribed by Ecology does not help if extensive fringe vegetation occurs in both cells. Deep water/open areas can be present in a wetland but must be randomly spaced rather than as one large area in Figure 5. Alternatively, the wet basin is a fully open wet pond with little fringe vegetation. This may difficult to achieve with small ponds having 3:1 side slopes. It is probably better to have a wetland fully covered with vegetation. However, it has not yet been established that a mature wetland is hydraulically more efficient than a wet pond. Studies to-date whether field or modeling was of evenly spaced plants. Over time differing plant densities likely develop resulting in differing resistances to flow, and in turn dead zones and preferential flow paths. The modeling of Jenkins and Greenway (2005) cited previously assumed even density of vegetation.

King County has found porous dikes commonly clog (Billica and Booth, 1996), probably due to sediment washed off during the construction of the development. A better design may be as shown in Figure 7, called a hummock or banded wetland. The dikes are not porous. The top is about 1 foot below the surface, with wetland vegetation, a necessity to promote hydraulic efficiency. The configuration is more hydraulically efficient than a single-cell basin (Jenkins and Greenway, 2005).

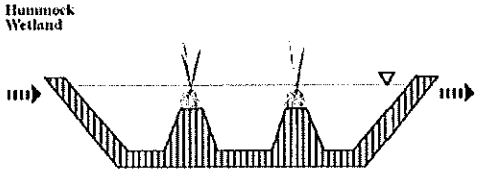


FIGURE 7 Hummock Wetland

The current length/width specification of 4:1 (for one cell pond) seems sufficient particularly if recommendations made later in this report regarding inlet and outlet design are followed. Walker (1998) studied several L/W ratios for open, unvegetated basins up to 8:1 at flow volumes at differing fractions of the basin volume, finding little additional benefit beyond 2:1. A graph of his results is shown in Figure 8. Figure 6 suggests 15:1 for open water basins, differing from Walker (1998). However, Walker (1998) evaluated the effect at different storm volume sizes, which found as expected the smaller the storm volume relative to basin volume, the less relevant the L/W ratio.

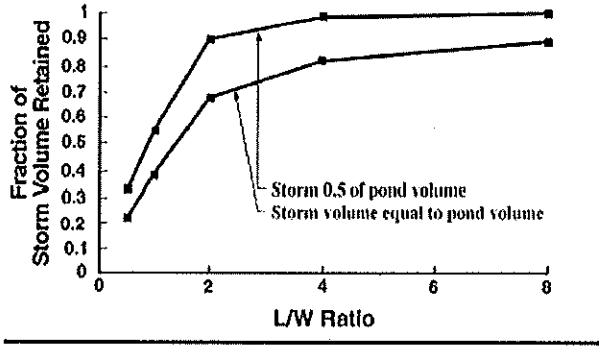


FIGURE 8 Relationship between L/W and fraction of stormater retained (hydraulic efficiency)

CRITERION: *WETLAND VOLUME*

There are benefits of using a wetland rather than pond: aesthetics, habitat, and likely better pollutant removal: not only TSS and attached pollutants but also dissolved pollutants with the greater soil surface area. However, there is the space penalty. A wetland of the same volume requires more space than a wet pond. A wetland with an average depth of two feet requires about twice the area of a wet pond with an average depth of five feet, both with 3:1 side slopes.

Current criterion: Wetland has the same volume as a wet pond

Origin of the current criterion: Long standing criterion from earliest state manuals in the eastern United States.

Proposed criterion: Specify the wetland volume as 75% of the wet pond volume.

Rationale for proposed criterion: Engineers have long established both in theory and practice that sedimentation is more effective with a shallower basin of the same volume due to a lower hydraulic loading rate.[8] The facilities in Figure 2 are of both wet ponds and wetlands. Which is a pond and which is a wetland is not clear due to incompleteness of reports and differing definitions of what constitutes a pond or wetland.

The USEPA method can be used to simulate the difference in volumes between a wet pond and wetland to give generally the same performance with respect to TSS removal. Using the method I determined that a wetland with an average depth of two feet gives the same performance as a wet pond with an average depth of five feet if the volume of the wetland is about 60[grm2]% of the volume of the wet pond. Results are presented in Table 2.

[8] Hydraulic loading rate is the proper design criterion, not residence time nor volume per se (Hazen, 1904).

TABLE 2

INPUTS				RESULTS		
SET	DESIGN Vb/Vr	WATER DEPTH	HYDRAULIC EFFICIENCY ADJUSTMENT	EFFICIENCY % REMOVAL		
				DYNAMIC	QUIESCENT	TOTAL
Pond	1	5	0.67	*68*	*13*	*81*
Wetland	0.6	2	0.67	*72*	*9*	*81*

Further considerations: A reduction in the wetland volume to 75% of a wet pond does not entirely offset the increased area by a shallower basin. As noted above a wetland with an average depth of two feet requires about twice the area of a wet pond with an average depth of five feet, both with 3:1 side slopes. A reduction of the volume of the wetland to 75% of the wet pond still requires more space, on the order of a 75% rather than 100% increase. An added benefit is less mosquito habitat than if the wetland were not reduced in size.

CRITERION: *FOREBAY VOLUME*

The purpose of a forebay is to trap sand and large silts in a relatively small area for ease of removal.

Current criterion: Specified as 33% of the basin volume.[9]

Origin of the current criterion: Unknown.

Proposed criterion: Reduce to 20% if the basin is sized according to the USEPA method using a V_b/V_r ratio of 1 or 1.5. Reduce to 10% if the WWHM method is used.

Rationale for proposed criterion: A forebay that is excessively large defeats its intended purpose, which is to reduce cleaning costs. It is generally believed that about 50% of the sediment in stormwater from most sites (absent deicing) is sand. The generally accepted performance goal or expectation for pretreatment is 50% according to the Department of Ecology, a reasonable performance. Hence, if the removal of sand is targeted the goal can be reached with a modest forebay. As sand settles quickly a relatively small forebay should suffice. Given our mild storms however sand may be less than the commonly stated 50%. A manufacturer testing its device at a shopping mall in Vancouver found that the incoming stormwater sediment was only about 10% sand. However, it should be noted that the original view of 50% came from an old study in Bellevue (Pitt and Bissonette, 1984).

Forebay sizing differs across the United States. State manuals that specify a sizing criterion use one of three similar types of criteria.

1. Based on a percentage of the basin volume like Ecology (2005) ranging from 10 to 33% depending on the manual (8 manuals).

[9] Ecology (2005) specifies the wet pool be divided into two cells separated by a baffle or berm with the first cell with 25 to 35 % of the total wet pool volume. If this is the forebay the criterion is inconsistent with the statement elsewhere in the manual that the forebay should be 33% of the volume.

2. A volume equal to 0.1 inches of runoff per impervious acre, which is equivalent to about 10% of the total volume of the basin (3 manuals).
3. Based on a percentage of the basin surface area ranging from 10 to 50% depending on the manual (4 manuals), which amounts to a somewhat higher volume percentage given that the forebay is commonly deeper than the main body of the wet basin.

None of the above criterion appears to be based on studies of forebay performance or calculations as to what is needed to effectively capture sand. Studies of forebay performance do not appear to exist. The relative consistency above occurs simply because manual authors borrow from other manuals. Regardless, the Ecology criterion results in the largest forebay. Those manuals that specify an area as high as 50% do so within a range whose minimum is less than Ecology's specification of 33%. Of the above 15 manuals reviewed,[10] ten specify 10% or a range with 10% as the minimum, whether of area or of volume. It seems reasonable to make a distinct specification rather than a range.

Figure 1 suggests that a V_b/V_r ratio of about 0.4 is needed to obtain 50% TSS removal. This amounts to about 725 ft^3 per acre of impervious surface. However, the settling velocity distribution used in the USEPA method assumes only about 20% of sediment in stormwater has a settling velocity like sand. Using the more common figure of 50%, a ratio of 0.2 seems reasonable, which becomes about 363 ft^3 per acre of impervious surface. Adopting this factor would result in a forebay that is 20% of the total basin volume if the basin has a V_b/V_r ratio 1.

Additional evidence that supports a smaller forebay is the approval of manufactured vaults by Ecology as pretreatment devices. The expectation of Ecology is 50% removal or 50 mg/L when the influent concentration is less than 100 mg/L (Ecology, 2008). These devices purportedly meet Ecology's goal with a V_b/V_r ratio in the range of only 0.03 to 0.05. This is considerable less than the current Ecology specification for the forebay, which gives by happenstance a V_b/V_r ratio on the order of 0.75.

A V_b/V_r ratio of only 0.03 to 0.05 is considerably lower than what is proposed for an earthen forebay: 0.2. However, an earthen forebay is not as hydraulically efficient as a manufactured vault as the latter contain sophisticated baffling. Two studies (Walker, 1998; Jenkins and Greenway, 2005) have shown that a forebay with a length to width rate of 0.3 to 0.5[11] has a hydraulic efficiency of only about 20%, reduced to as low as 10% by fringe vegetation (Jenkins and Greenway, 2005). Hence, an earthen structure as the forebay ought to be larger than a manufactured vault serving the same function. Ergo, a V_b/V_r ratio of 0.2 seems reasonable, which amounts to 20% of the total volume if the total basin is based on a V_b/V_r ratio of 1. How to improve the hydraulic efficiency of an earthen forebay is presented further later in this report.

Further considerations: It should be noted the specification by Ecology (2005) for the forebay of an oil water separator is 20 ft^2 per 10,000 ft of drainage area. Assuming a water depth of five feet gives a V_b/V_r ratio of about 0.25. There does not seem to be any reason why the size of the forebays in wet basins and oil water separators should differ.

[10] Two of the 15 manuals reviewed were city manuals, Denver and Portland, as their states do not have a state manual. The Portland specification is 10% of the basin surface area.
[11] To fit logically into a pond or wetland the width of the forebay becomes considerably greater than its length.

CRITERION: *MANUFACTURED VAULTS AS FOREBAYS*

The Ecology manual specifies a volume for forebays of ponds and wetlands that is substantially larger than the volume of manufactured vaults (commonly called hydrodynamic separators), despite presumably having the same objective; the removal of about 50% of the TSS. This inadvertently and presumably disallows the use of manufactured vaults as forebays. Yet Ecology has approved manufactured vaults as pretreatment operations, which is the purpose of forebays. Manufactured vaults use considerably less space than currently specified by Ecology (2005). They are also likely easier to maintain.

Current criterion: Specified as 33% of the basin volume.

Origin of the current criterion: NA

Proposed criterion: Allow use of manufactured vaults. However, base sizing on a peak hydraulic loading rate of 10 GPM/ft^2, rather than the manufacturers' model selection chart.

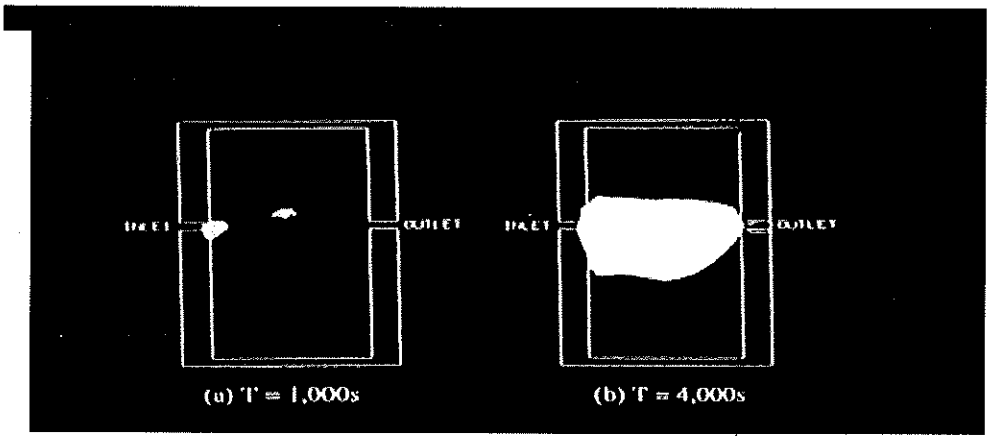
Rationale for proposed criterion: According to Ecology (2008) a reasonable performance goal for pretreatment is on the order of 50% of sediment greater than 50 microns, at influent concentrations exceeding 100 mg/L, and 50 mg/l when the influent concentration is below 100 mg/L with respect to this goal. Ecology has certified the performance claims of several precast vaults: AquaSwirl, BaySeparator (conditional only), CDS, Downstream Defender, Stormceptor, and Vortechs. These devices should therefore be allowed in lieu of forbays.

With a V_b/V_r ratio of 1 and forebay at 20% of the basin volume as recommended previously, the forebay volume is about 100 to 200 ft^3 per acre of residential development.[12] In contrast, the volume of the manufactured vaults, depending on the particular product, is on the order of 25 ft^3 per acre of residential development, with a V_b/V_r ratio of only about 0.03 to 0.05. The diameter of the vault would be on the order of about 5 to 10 feet for a 10-acre development depending on the product under current Ecology sizing criteria.[13,14]

It has already been noted that a manufactured vault more substantially efficient hydraulically than an earthen forebay. Figure 9 below shows with dye the short-circuiting occurs in a basin shape likely for forebays (Walker, 1998). The picture on the left is at 1,000 seconds into the dye study, and 4,000 seconds (1.3 hours) on the right. In contrast manufactured vaults have internal elements, one purpose of which is to avoid short-circuiting. Because of the internal design manufactured vaults are likely less susceptible to resuspension and short-circuiting than earthen forebays, and provide good energy dissipation.

[12] If WWHM is used the volume of the forebay would be about 300 to 450 ft^3 per acre of residential development.
[13] Criteria established through the TAPE process.
[14] Given our modest peak flows a residential development must be on the order of about 10 acres before the engineer moves to the second model on the selection charts of most manufacturers; perhaps 5 acres for commercial developments. Hence, a 1-acre commercial development would have the same size vault as a 5-acre development where only one product is being considered.

FIGURE 9



Why specify a standard hydraulic loading rate, such 10 GPM/ft2, rather than select models based on the individual design criteria of each manufacturer?[15] Although Ecology has certified many vaults only two have undergone extensive field tests. Most of their testing was conducted prior to adoption of the first TAPE protocol in 2002. Certification of the other vaults was based on controlled tests in a hydraulic laboratory with sediment-laden potable water. Fortuitously a few field tests have occurred in western Washington but show variable results or are inconclusive due to low influent concentrations. Relevant data are provided in Table 3. This suggests caution in the use of manufactured vaults as forebays (pretreatment in general). Background information is provided in this regard with a final recommendation on vault selection.

TABLE 3 RESULTS OF WESTERN WASHINGTON FIELD STUDIES

Site	Acres	# of storms	TSS Range (mean) Influent	Effluent	Comments
Stormceptor (Clark County, 2000; Taylor Associates, 2005, Stormceptor, Inc)					
#1 Gas station	1	4	16 – 240	5 – 18	One storm with influent of 240. Other three storms 16 to 40 mg/L. Likely oversized
#2 Parking lot	0.8	8	19 – 47 (33)	19 – 38 (27)	Likely oversized. Little accumulated sediment.
#3 Shop	1.1	6	36 – 226	16 – 210	One storm with effluent of 210. Rest were from 16 to 48 mg/L. Likely oversized
Vortechs[a] (Taylor Associates, 2002, Taylor Associates, 2005)					
#4 SR405	28	11	30 – 580 (140)	24 – 440 (102)	Likely oversized originally.[b]
#5 Residential	25	16	13 – 154 (34)	14 – 210 (29)	Possibly oversized. Poor removal appears an artifact. See text.
Downstream Defender[a] (Taylor Associates, 2005)					
#6 Residential /Commercial/ I5 freeway	208	18	24 – 201 (75)	38 – 218 (75)	Likely undersized. Poor removal appears an artifact. See text.

a. Since the above installations Ecology has required manufacturer reduce the rated capacities of their models.
b. Removal efficiency appears about 30%, but is only 20% when based on flow weighting of individual storms.

[15] Ecology has set design criteria for each product: AquaSwirl, 24 GPM/ft2; Vortechs, 35 GPM/ft2; Downstream Defender, 40 to 70 GPM/ft2 depending on model; Stormceptor, 10 GPM/ft2

Two products with extensive field tests are Stormceptor, and Vortechs, appearing in Table 3. The one study noted for the Downstream Defender appears to be its only field test.

Field data for Stormceptor are available from eight locations; a total of about 50 storm events. Taking all sampled storms into consideration influent concentrations ranged from 8 to 1058 mg/L with an average of 193 mg/L. The effluent concentration ranged from 5 to 507 mg/L with an average of 86 mg/L. Overall removal averaged 53%. Four sites were located where winter sand was likely or known to be used: Minnesota, Wisconsin, Edmonton, and Boston. Denver was the eighth site, resulting in some storms with high influent concentrations.

Vortechs has been field tested at seven locations, two in western Washington (Table 2). The rest were sites where it appears winter sanding occurred with concentrations up to 5,000 mg/L. At one site high TSS concentrations (exceeding 1000 mg/L) were observed throughout the summer and fall. However, effluent concentrations remained low during summer and fall storms, averaging 22 mg/L indicating very good performance. Statistics from the sites in western Washington are presented in Table 3.

The drainage areas of the sites in Table 3 for the Stormceptor were small, indicating the substantial likelihood that the models selected were "oversized" for the site. This is also likely true for the Vortechs and Downstream Defender models selected at that time, based upon approximate peak flow calculations that I have done from information provided in those studies. However, since these units were installed Ecology has through the TAPE certification process required these two manufacturers to significantly reduce the rated flow capacities of their models. As a consequence the models selected appear to have flow capacities that are near their newly required rated capacities. In contrast, the Stormceptor was not required to modify its design flow capacities. Hence, the model used at the sites indicated are likely still "oversized." This therefore raises the question of why the Stormceptor appeared to perform rather poorly at two of the their sites. A possible answer for the parking lot is the very low influent concentrations. Note that the influent concentratons relatively low when compare to the supposed concentrations that are to be found as discussed on page 9.

Three studies (#3, Stormceptor; #5 Vortechs; #6, Downstream Defender) showed no removal when comparing influent and effluent concentrations. However, comparing influent and effluent concentrations can be misleading. A discrepancy can occur due to the inconsistent ability of automatic samplers to pick up sand from the influent, understating the influent concentration. In studies #5 and #6 significant amounts of sediment were found in the bottom of each facility, contradicting the conclusion that there was no removal based on the influent and effluent samples. The Vortechs device for example, accumulated about 5,400 pounds of sediment, suggesting an average influent concentration considerably above 100 mg/L. The one exception appears to be the Stormceptor. There was about three inches of sediment in the bottom of the facility when the testing began and four inches at the end. The sediment depth fluctuated between two and four inches during the test period suggesting loss of sediment in some storms. As noted previously the apparent poor efficiency and washout is atypical with other studies of this vault.

Regarding lab tests, few of the manufacturers followed the TAPE or TARP protocol. The TAPE protocol specifies the use of Sil-Co-Sil 106. TARP has its own special size distribution similar to Sil-Co-Sil 106. Most manufacturers used mixes that were essentially 100% sand. In approving

various vault products Ecology also specified the design hydraulic loading rate in GPM/ft^2: Vortechs, 35; AquaSwirl, 24; Stormceptor, 10; and Downstream Defender, 40 to 76, differing with the model. Of these four products only Stormceptor followed the protocol. It also has the lowest HLR, and has been field tested extensively. Although their field tests have been somewhat inconsistent, as noted previously, a specified design HLR of 10 is reasonable.

The result of the proposed criterion is to increase the sizes of all other vaults, given that the HLR used by Stormceptor is the lowest of the certified products. Table 4 can guide the engineer in selecting a model. It can be expanded to include all product sizes currently allowed in Washington. The engineer selects the model with the nearest capacity equal to or greater than the calculated design flow. The Vb/Vr ratio would be on the order of 0.01 with large developments, increasing to about 0.05 for small developments given the effect of minimum model size with each vendor.

TABLE 4 Sizing Of Small Manufactured Vaults For Forebays[a]

VAULT DIAMETER	SPECIFIED TREATMENT CAPACITY[b] GPM	CFS
4	125	0.30
6	285	0.60
8	500	1.10
10	785	1.75

a. Based on a HLR of 10 GPM/ft2 at the design peak flow
b. Each model will have a much greater hydraulic capacity, identified by the manufacturer

Perhaps manufacturers currently allowed by Ecology to use a higher HLR will object to the criterion. The County response would be "you did not conduct laboratory tests using the appropriate sediment, Sil-Co-Sil 106 or equivalent, nor have you conducted sufficient field tests to give us confidence the pretreatment goal is obtained with your product based on your design HLR value. Should you produce such information we will reconsider."

Further considerations: A concern regarding small vaults is frequent cleaning. Earthen forebays are not typically cleaned annually given their size. However, an increasing number of studies suggest forebays should be cleaned annually, either to remove decaying vegetation that enters with the stormwater, and/or to remove sediments whose metal content may exceed sediment quality criteria. Decaying vegetation has been found to release pollutants to a degree that their concentration rises in the effluent (O'Connor and Rossi, 2009). The sediment quality criteria relate to toxic effects on biota. The overall cost of cleaning a small vault once per year is likely less than cleaning a large forebay every five years.

CRITERION: *INLET AND OUTLET DESIGN*

Inlet and outlet design is important regardless of basin size, that is the Vb/Vr ratio, but becomes increasingly important with smaller ratios. Hence, it is considered separately. The suggestions presented herein also may significantly affect cost.

Current criterion: The inlet to the wet pond shall be submerged with the inlet pipe invert a minimum of two feet from the pond bottom. The pond outlet pipe shall be back-sloped or have a turn-down elbow, and extend 1 foot below the WQ design water surface.

Origin of the current criterion: Unknown. The intent is to minimize resuspension at the inlet and to retain flotables and surface oil with respect to the outlet.

Proposed criterion: Inlet baffle and/or T splitter at end of inlet. Deeper minimum depths.

Rationale for proposed criterion: The most common configuration of our wet basins is O-4 in Figure 10. Yet of the six basins O-4 was found to have the lowest hydraulic efficiency (Mangelson and Watters, 1972). The ranking of the configurations from best to worst is I-5>M-3>O-5>O-1>O-3>O-4.

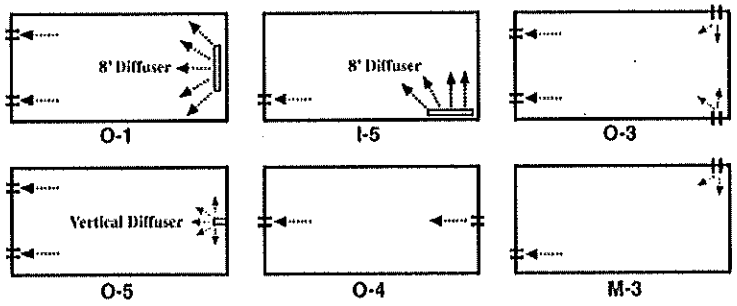


FIGURE 10 Effect Of Inlet And Outlet Configuration On Hydraulic Efficiency

In addition to I-5 and M-3 in Figure 10 as the better configurations, multiple inlets across the width of the basin with a single outlet (multiple outlets was not studied) was found to give the best hydraulic efficiency (Persson, et al., 1999).

With forebays and two-cell basins we might expect better hydraulic conditions than O-4 in Figure 10. However, as noted previously two modeling studies (Walker, 1998; Jenkins and Greenway, 2005) have shown that a forebay with a length to width rate of 0.3 to 0.5[16] has a hydraulic efficiency of only about 20%, which is further reduced to as low as 10% with significant fringe vegetation (Jenkins and Greenway, 2005). See Figures 5, 6, and 9. A lateral dike as in Figure 11 might suffice, with an inlet having either a baffle immediately in front, a few feet, or a T-splitter. These concepts are shown below in Figure 11.

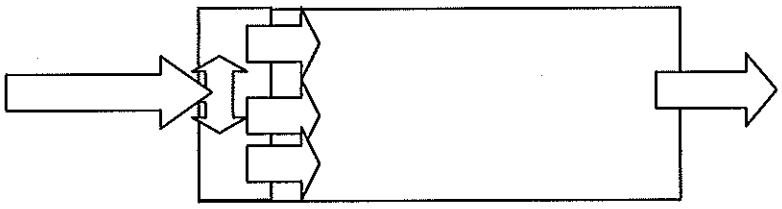


FIGURE 11 Possible Inlet Configuration With A Small Forebay – Plan View

The two important studies cited previously, Walker (1998) and Jenkins and Greenway (2005), did not consider either the impact of thermal stratification or density differences between the incoming stormwater and water in the basin, also due to differences in temperatures. Either can result in short circuiting. With thermal stratification the surface entry of stormwater passes

[16] To fit logically into a pond or wetland the width of the forebay becomes considerably greater than its length.

through the pond in the lighter water layer on the surface of the pond, not mixing with the bottom stagnant layer, as illustrated below in Figure 12. Efficiency decreases correspondingly. The issue is relevant for late summer storms. A dye and hydraulic study of a large wet pond in northeast Seattle suggests that stratification occurs in western Washington and with a water depth of only three to five feet (Minton, et al., 2005).

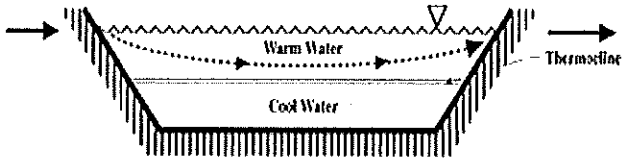


FIGURE 12 Effect Of Thermal Stratification On Incoming Stormwater

Thermal stratification results in zero dissolved oxygen in the bottom, altering several important pollutant removal processes related to nitrogen, phosphorus, and bacteria removal. Pollutants previously removed under aerobic conditions may desorb during anaerobic conditions, particularly phosphorus and perhaps metals.

These considerations have a bearing on the most appropriate vertical location of the inlet and outlet. Should locations be surface, bottom, or midpoint? We don't know due to insufficient field tests. Stormwater entering at the bottom could possibly break up the thermal stratification, with the full pond functioning rather than just the upper layer during each storm. But this could result in the discharge of pollutants that may have dissolved into the bottom water due to anaerobic conditions prior to the storm. Dislodging of the thermal condition by a storm is temporary, lasting but a day or two before the thermal condition reestablishes. Hence with bottom entry each incoming summer storm could push out desorbed pollutants.

It has been the view for many years that a steady incoming base flow is the appropriate approach to avoid anaerobic conditions along the bottom. However, it has never been established how much base flow is needed. Moreover we now have field data indicating that base flows cause desorption of pollutants (Minton, 2005).

Absent any additional forthcoming information it seems most appropriate for the incoming stormwater to enter at the bottom. This will assure the full volume of the pond is used during each storm for treatment and short-circuiting is minimized.

The vertical point of entry is irrelevant for wetlands with their shallowness unless the pipe enters a deep pool like a forebay. The options presented above would apply.

The entrance to the outlet should be subsurface. Ecology (2005) specifies a minimum of 12 inches beneath the normal water surface. However, for wet ponds it should be lower, due of the reduction of the water level during the summer. It should be placed at or near the bottom to minimize thermal stratification. A bottom exit minimizes the potential for outlet clogging.

Further considerations: A potential disadvantage of bottom entry is resuspension. This could occur in the forebay. As an earthen forebay is commonly deeper than the main part of the basin, the entry point into the forebay could be at the same elevation is the main area of the basin. This leaves some vertical distance between the inlet and the bottom of the forebay. The issue can be

avoided by the use of a manufactured vault, discussed previously in this report. The benefits of bottom entry on thermal stratification are likely offset by multi-cell designs.

A study of various configurations determined that the configurations below were to be avoided (Persson, et al., 1999)

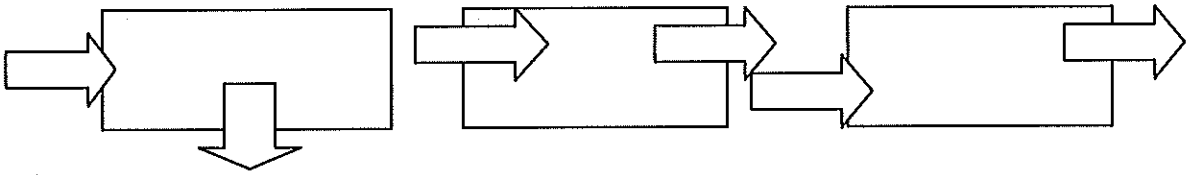


FIGURE 13 Two Inlet/Outlet Configurations To Avoid – Plan View

GRASS SWALES

CRITERION: *ECOLOGY ADJUSTMENTS OF WIDTH AND LENGTH*

Current criterion: Swale width is increased by the factor 2.5 in Equation 4. Length is increased by a factor presented in the two figures below. The verbiage below the equation is from the Ecology manual.

$$b \approx \frac{2.5Qn}{1.49y^{1.67}s^{0.5}} - Zy$$

Equation 4

For a trapezoid, select a side slope Z of at least 3. Compute b and then top width T, where T = b + 2yZ. *(Note: Adjustment factor of 2.5 accounts for the differential between Water Quality design flow rate and the SBUH design flow. This equation is used to estimate an initial cross-sectional area. It does not affect the overall biofiltration swale size.)*

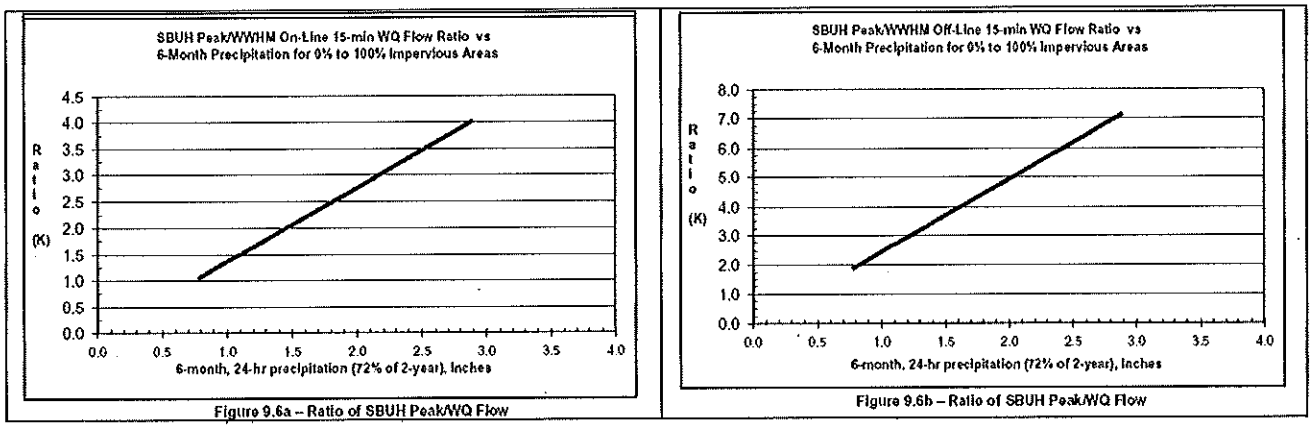


FIGURE 14 Ecology Adjustment Ratios

Increasing the width by 2.5 however results in a decrease in the length of the swale. This is because the length of the swale is a function of the forward velocity of the stormwater down the swale. Increasing the width with the adjustment factor decreases this velocity, correspondingly decreasing the swale length. Consequently, swale length is increased by applying the adjustment factors in Figure 14. In effect, the velocity is adjusted upwards, which in turn increases the length back to that found with the peak flow from SBUH.

Origin of the current criterion: As stated in the verbiage beneath Equation 4 the adjustment is made to account for WWHM giving a much lower peak flow than the SBUH method. The intent is to have a swale that is about the same size as from using SBUH. Ecology is concerned that reducing the swale area would compromise performance (Ed O'Brien, pers. comm.), particularly given that it is the general perception that existing grass swales may not meet the current performance goal specified by Ecology (2005), particularly with regard to meeting the requirement of 20 mg/L in the effluent when the influent concentration is less than 100 mg/L.

Proposed criterion: Drop swale size adjustments.

Rationale for proposed criterion: WWHM provides a peak flow that is substantially less than SBUH. The peak flow from WWHM should be trusted as the most accurate simulation available.

There is a fallacy in believing the width has a direct relationship to performance. It does not. The width is established to achieve the goal of treating "effectively" 91% of the stormwater runoff over time. Thus, if WWHM gives the most accurate design flow, it should set the width of the swale. On paper, this width will achieve the 91% goal. It is length that is relevant to performance, not width.

Further considerations: There is a more appropriate way of assuring the proper width. This recommendation also corrects an omission in Ecology (2005). The manual specifies a design flow depth: two inches if mowed frequently and four inches of mowed infrequently. Missing is a specification for the grass height. The depth of water at the design depth must be below the top of the grass. To avoid grass laying down the depth should be at least no more than 50% of the grass height but more likely 33%. It is meaningless to specify a water depth without the companion criterion of grass height. Absent the criterion the grass could be cut much too short.

It is recommended that the maximum water depth at design flow be set to three inches for all swales with the companion specification of grass height set at six inches regardless of whether the grass is mowed frequently or infrequently, and irrespective of the type of development.

It is best to accept the results of WWHM as the best estimate of the design peak flow, set both the water and grass height conservatively as proposed in this discussion, and calculate the length correctly using the nine minute residence time.

Ecology (2005) specifies a minimum width of two feet. It requires about 1½ acres of impervious surface before the calculated width exceeds the minimum width when adjusted with the factor of 2.5. Hence, for small sites the Ecology factor of 2.5 does not affect swale width but results in a length longer than currently required.[17] If the adjustment factor of 2.5 is not used as proposed in this report it takes about fives acres before the minimum width is exceeded. But the length is shortened due to using the actual rather than adjusted flow rate. It is possible that the minimum length of 100 feet will "kick in" for small sites.

CRITERION: *DRY SWALE DESIGN*

Elsewhere in the United States, but particularly in eastern states, the Grass Swale has been replaced with a BMP called the Dry Swale. The intent is to provide better treatment than the grass swale, based on the view that the grass swale does not meet the commonly used performance goal of 80% TSS removal. The grass swale is generally used only on the west coast as a BMP meeting the common performance goal for TSS. It is only used elsewhere if it is combined with some other treatment BMP such as a wet pond.

The design of the dry swale differs significantly from the grass swale. The dry swale is a filter, illustrated in Figure 15. The stormwater moves downward through filter media to an underdrain collection pipe. The native soil is excavated and replaced with a specified mix of filter media. The pipe is commonly included because the dry swale is generally used in soils with inadequate infiltration rates. A better name for the dry swale would be a bioretention filter swale, inasmuch as its design is the same as a flat bioretention cell or basin, except that it is long and narrow rather than generally rectangular in shape. The dry swale may be sloped like the grass swale, or it may consist of a series of narrow flat cells stepped down to reflect the slope of the site. Dry (bioretention) swale size is based on volume like the common rectangular bioretention cell, sand filter, wet pond or wetland.

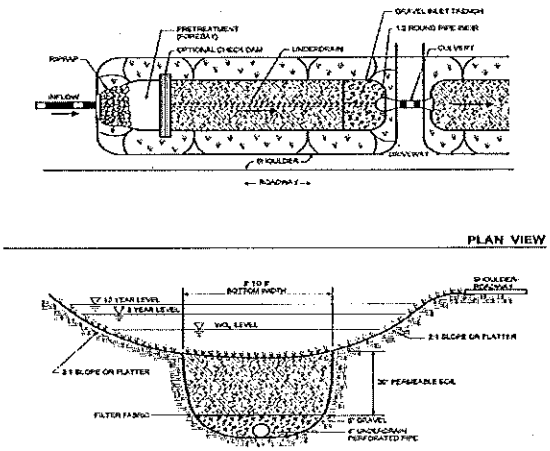


FIGURE 15 Basic Design of the East Coast Dry Swale

Current criterion: For grass swales the treatment concept is to have stormwater flow through a grassed area with the treated water passing out at the bottom of the swale. The high resistance to flow of the grass reduces the velocity of the stormwater, allowing the sediment with attached pollutants settle to the bottom of the swale. The gently sloped swale is essentially a shallow settling basin.

[17] This is because the width remains as it was before the WWHM adjustment but the forward velocity and therefore length is increased according to Figure14.

Origin of the current criterion: The current grass swale concept originated in Washington. The first design publication established the use of Manning's Equation to size the swale width (Horner, 1988). The length was set at a standard 200 feet. A subsequent report (Khan, et al., 1992) proposed that the swale length be based on a residence time somewhere between 4.5 and nine minutes based on field studies of a 200-foot swale.

Proposed criterion: Use the Dry Swale in lieu of the grass swale, but [grm3]call it a Bioretention Filter Swale.

Rationale for proposed criterion: The first consideration is whether the grass swale as currently designed meets the Ecology performance goal for Basic Treatment, which is an average removal of 80% TSS at influent concentrations between 100 and 200[18] mg/L, and an effluent concentration of 20 mg/L or less for influent concentrations below 100 mg/L.

Two graphs are presented. The graph on the left is a plot of data available prior to 2002[19] when Ecology first established the above performance goal and grass swales were accepted as meeting this goal.[20] The data are of individual storms from three studies (Goldberg, 1993; Khan, 1992; King County, 1995).[21] The graph on the right includes data collected since 2002 by the City of Portland (two swales)(e.g. Portland, 2002) and Caltrans (six grass swales)(Caltrans, 2004) all designed to the Ecology (2002) method.

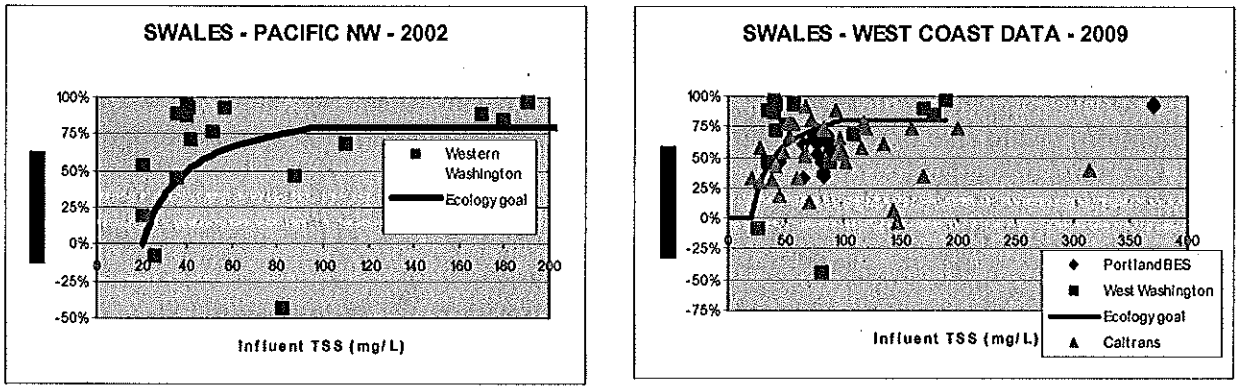


FIGURE 16 Swale Data on TSS Removal

Comparing the two graphs in Figure 16 establishes that swales do not reliably meet the Ecology goal. We should note that two of the swales originally studied, represented in Figure 16, were very long: 375 feet (King County, 1995) and 570 feet (SPU). It is not unreasonable to conclude that the more recent studies are a better indicator of swale performance.

Comparing the two graphs in Figure 16 establishes that swales do not reliably meet the Ecology goal. We should note that two of the swales originally studied, represented in Figure 16, were

[18] Presumably Ecology expects a higher efficiency at influent concentrations above 200 mg/L. Sites where the average influent concentration is above 200 mg/L is not likely to occur in western Washington except possibly industrial sites with substantial outdoor activity, or possibly unpaved areas.

[19] There were no field studies between 1999 and 2002.

[20] Grass swales were actually accepted in the 1992 manual prior to the establishment of performance goals , based on Horner (1988) with no data, Kahn (1992), and possibly pre-published data of Goldberg (1993).

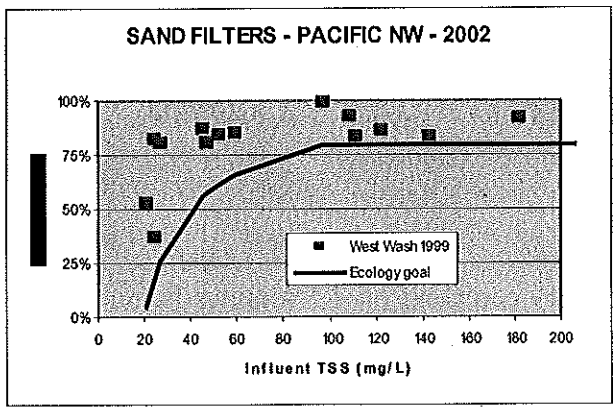
[21] Only storms with influent TSS >20 mg/L and <200 mg/L are shown

very long: 375 feet (King County, 1995) and 570 feet (SPU). It is not unreasonable to conclude that the more recent studies are a better indicator of swale performance.

It could be argued that the desired performance could be achieved by increasing the detention time above 9 minutes. However, there is no evidence that this will result in further treatment. Like with basins as shown in Figure 3, increasing the size of the system does not guarantee improvement. In the study by Khan et al. (1992), performance was evaluated at 100 feet (4.5 minutes) and 200 feet (9 minutes). Khan et al. (1992) concluded that there was in fact no statistical difference between the performance at 4.5 and 9 minutes. Hence, it is not apparent that increasing the length with a residence time of, for example, 20 minutes will result in a higher quality of effluent.

Before leaving the topic of performance lets look at performance data for sand filters: data prior to 2002 and total to-date. We do this to make certain that there was not something peculiar about the studies in Portland and California that resulted in lesser performance of their swales. We see in Figure 17 that the sand filters evaluated by the City of Portland and Caltrans performed as well as found in the earlier studies, giving us some confidence that our conclusion regarding the inadequate performance of swales is valid.

Further considerations: We can expect that the bioretention filter swale is more expensive than the grass swale. The media specification should be the same as for the standard bioretention filter. Like a standard bioretention cell or basin the swale is sized by volume not flow rate. WWHM can be used for sizing. There are some savings from having dropped the Ecology width and length adjustments.



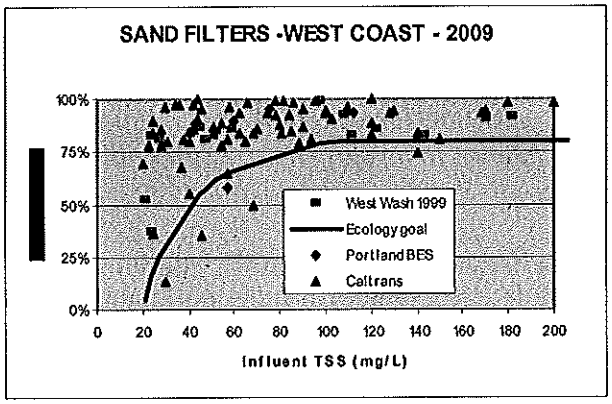


FIGURE 17 Sand Filter Data on TSS Removal

CRITERION: *HYBRID DESIGN*

As noted above the bioretention filter swale (aka dry swale) is sized as a volume device, similarly to an infiltration basin or sand filter. It's size is similar but likely larger than the grass swale. A means of reducing the size while still meeting Ecology performance goals is to integrate design concepts from both the grass swale and the bioretention filter swale. What is proposed is to retain the filtration concept of the bioretention filter swale but size using Manning's Equation like the grass swale. The swale would be sloped like a grass swale. Given the improved treatment through the filter, we can reduce the size of the system yet still meet the Basic Performance Goal.

Current criterion: NA

Origin of the current criterion: NA

Proposed criterion: Size using Manning's Equation as with the grass swale but use a residence time of 4.5 rather than 9 minutes.

Rationale for proposed criterion: With the proposed design most stormwater passes down through the filter media, providing much more effective removal of TSS than if were to pass downward through the swale as with the grass swale. At high flow rates and large storms a portion of the stormwater reaches the surface outlet at the end of the swale like the grass swale. If a retention time of nine minutes is used the performance will exceed Ecology performance goal for TSS. It is therefore justifiable to reduce the size of our swale.

Cutting the residence time in half to 4.5 minutes is supported by the conclusion in the report of the study from which we established the approach of determining swale length by residence time, the 1990 study of a swale in Mountlake Terrace (Khan, 1992). In the study performance was evaluated at the mid-point and end of the swale, corresponding to 4.5 and 9 minutes. The conclusion of the report was as follows:

> *"it (the data) is suggested that a residence time of 9 minutes is sufficient to assure good pollutant removals. A minimum hydraulic residence time cannot be given with certainty, although it can be said that with residence times of about 4.5 minutes, deterioration in performance is likely, especially during larger storms."*

The report also said:

> *"The performance of the ...100 and 200 feet, 4.5 and 9 minutes residence time could be shown to be statistically different only for zinc and iron removals."*

The first statement suggests caution regarding 4.5 minutes, but the second statement suggests time is irrelevant with most pollutants. The cautionary comment on 4.5 minutes is not without basis as only six storms were sampled at each length. Nonetheless, even if a modest reduction in performance occurs with a shorter swale, it will still meet the Ecology goal for TSS. ? It can be reasonably assumed that stormwater treated by a standard grass swale gives a TSS concentration in the effluent of 40 mg/L. A bioretention filter gives an effluent of 10 mg/L. To achieve an average discharge of 30 mg/L requires about 70% of the stormwater to pass down through the filter.

Further considerations: This criterion decreases the length of the swale by 50%, compensating if not fully offsetting the increase in cost of including filter media and underdrain pipe. We also have savings from having dropped the Ecology adjustment factors.

The new design concept likely reduces the potential for channelization and erosion, and enhances infiltration. We can refine the determination of length with the use WWHM, to achieve the estimated filter goal outlined above of 70%.

OIL WATER SEPARATORS

CRITERION: *DESIGN TEMPERATURE*

Current criterion: The design temperature is 0°C

Origin of the current criterion: Unknown

Proposed criterion: Use 5°C.

Rationale for proposed criterion: At 0°Cs the water is frozen. The average ambient temperature for January, the coldest month of the year, seems reasonably conservative which is about 5°C.

Further considerations: None

CRITERION: *ECOLOGY ADJUSTMENT OF DESIGN FLOW*

Current criterion: As with the grass swale Ecology (2005) adjusts the flow rate determined from WWHM using Figure 14 previously introduced.

Origin of the current criterion: The intent of Ecology (2005) appears to be to keep oil water separators the same size as generated with SBUH, as with grass swales.

Proposed criterion: Drop the adjustment.

Rationale for proposed criterion: Same rationale as previously given for grass swales.

Further considerations: Our current design criteria are conservative; a peak flow that seldom occurs; ignoring that droplets coalesce as they rise increasing the rise rate that most of the oil is attached to sediment that settles to the bottom; that 99% of the droplets must be removed to meet the performance goal. The last point is illustrated with Figure 18. Ecology (2005) specifies a design oil droplet size of 60 microns. Figure 18 shows that at this size about 99% by volume of the oil is removed. Unfortunately there are no useful performance data from oil water separators.

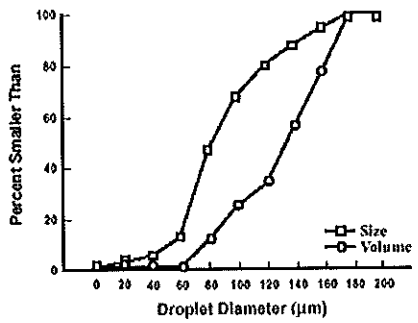


FIGURE 18 Only Known Data On Size Distribution of Oil-Droplets In Stormwater (Minton, 2005)

SAND FILTERS

CRITERION: *FILTER THICKNESS*

It has long been known in the treatment of potable water with sand filters that most of the incoming sediment is removed on top and within the first few inches of the sand.

Current criterion: Sand media thickness of 18 inches for the rectangular basin filter and 12 inches for the lineal or perimeter filter.

Origin of the current criterion: The City of Austin was the first to use sand filters. As they based their design criterion on potable water filters they first specified 36 inches for the thickness of the sand. Within a few years it occurred to them that 36 inches was substantially more than necessary and that they could reduce the area of the filter by about 25% if they reduced the sand thickness by 50%. The choice of 18 inches was arbitrary. The criterion of 36 inches was simply cut by half, without the benefit of performance data.

Proposed criterion: Decrease media thickness to six inches for sand filters that are cleaned by hand, not with heavy equipment. The filter surface would be covered with a fabric.

Rationale for proposed criterion: Laboratory column studies have shown essentially all removal on top and within the first two inches of the sand (Clark, 1996). Another laboratory study found no difference in TSS removal between 6 and 12 inches of sand (Amini, 1996). Table 5 has data from Caltrans (2004). The study included one 12-inch and five18-inch filters. The effluent from the 12-inch had higher TSS but so did the influent, which may or may not account for the difference.[22] Regardless, the effluent TSS concentration for the 12-inch filter is only 12 mg/L, which is less than the Ecology goal of 20 mg/L.

TABLE 5 PERFORMANCE DATA - TSS MEDIANS (mg/L)

STUDY	INFLUENT	EFFLUENT
18-inch filters	69	6
12- inch filter	90	12

Further considerations: Ecology (2005) specifies 18 inches for the sand filter basin but only 12 inches for the lineal or perimeter filter. Hence, with respect to performance there is no reason not to allow 12 inches with standard rectangular basins. However, consideration must be given to the weight of equipment cleaning the surface of the filter. A thickness of 6 inches is sufficient if the surface is cleaned by hand. This would be the procedure for small sand filters placed subsurface in vaults for small commercial developments like fast food restaurants, convenience stores, and gas stations. An acre of commercial development requires a filter area of about 700 ft^2 in western Washington, or about 200 ft^2 for ¼ acre.

[22] Analysis of the data indicated the difference in effluent TSS between the two filter thickness was not statistically significant.

The design criteria could therefore be as follows:

- The thickness of subsurface filters is 6 inches, cleaned by hand
- The thickness of surface filters less than 5,000(?) ft^2 can be 12 inches, cleaned by hand or small, light weight rubber tired loaders or a Bobcat.[23]
- The thickness of large surface filters, greater than 5,000 (?) ft^2 must be 18 inches, on the assumption that heavier equipment will be used for cleaning.

For larger filters requiring cleaning by heavy equipment the media thickness remains at 18 inches to protect the underdrain system. However, engineers could allow 12 inches if the underdrain system is designed to handle the loading, including a reasonable safety factor.

It may be desirable to place a fabric at the entrance end of the filter or a porous plastic shield to provide energy dissapation.

CRITERION: *UNDERDRAIN DESIGN*

The objective is to reduce costs.

Current criterion: The underdrain consists of eight inches of rock covering perforated underdrain pipe.

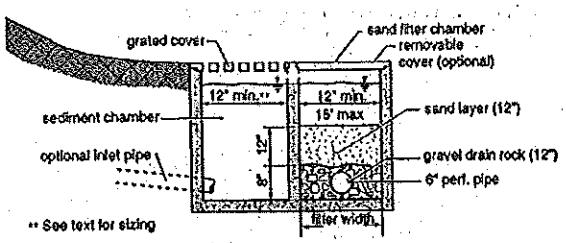


FIGURE 19 Current Design

Origin of the current criterion: Water treatment filters.

Proposed criterion: A system of shallow flat plastic channels is proposed, wrapped in fabric. An example is shown in Figure 20.

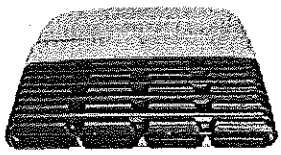


FIGURE 20 Example Of A Thin Underdrain

Rationale for proposed criterion: Save costs.

Further considerations: The criterion for the underdrain pipes is 6-inch pipes on 15-foot centers. This gives about two square inches of underdrain per foot of filter width. The above plastic has a depth of two inches giving a capacity of 24 inches per foot of width. A one-inch depth is adequate. A linear filter two foot wide with a 6-inch pipe gives about 14 square inches per foot of width. The above underdrain gives 24 square inches of drainage area.

[23] The City of Austin , Texas maintains about 800 sand filters. They are cleaned with small, rubber tire loaders or a Bobcat. Most of their filtesr are 18 inches. A few are 12 inches. It is not recommended that this equipment be used on sand filters that are only 6 inches (Grube, pers. comm.)

CRITERION: *PRETREATMENT VOLUME*

Sizing of the pretreatment unit is not clear.

Current criterion: Ecology manual speaks to presettling but makes no specification on sizing. By inference the engineer would follow the criteria for a presettling basin on page 6-2 in Volume 5. This specification is 30% of the total volume of runoff from the 6-month, 24-hour storm event, or presumably 30% of the WWHM volume calculated for a wet basin.

Origin of the current criterion: Unknown

Proposed criterion: Use a Vb/Vr of 0.2 . Allow the use of manufactured vaults.

Rationale for proposed criterion: To be consistent with the design of forebays in wet ponds and constructed wetlands.

Further considerations: Ecology (2005) specifies a L/W ratio of 3:1, which does not work well for a forebay in sand filters. This restriction would be dropped. However, the inlet would have a baffle or T element (Figure 11) at the end of the inlet as proposed for wet basins. There would be an external baffle designed so as to retain floatables.

INFILTRATION BASINS

CRITERION: *TREATMENT LAYER*

Full treatment is required if the infiltration rate exceeds 2 inches/hour, requiring additional space and cost. By this is meant the stormwater must be treated with standard systems like a lined wet pond, sand filter, or grass swale before the stormwater enters the infiltration basin.

In some cases the engineer may find it cost-effective to place a layer of filter media on the surface of the infiltration basin meeting the Ecology requirement for treatment.

Current criterion: Full treatment with systems like a lined wet pond or grass swale.

Origin of the current criterion: Ecology's concern about groundwater pollution has been documented with stormwater infiltrated into glacial outwash soils (Minton, 2005).

Proposed criterion: Place a layer of engineered media on the bottom of the infiltration basin or trench. Either of two mixes would be used: standard bioretention mix, and the Ecology Mix developed by the Washington Department of Transportation. The media thickness is a minimum of 30 inches, but consistent with whatever is used for bioretention filter systems.

Rationale for proposed criterion: Presumably the concept is allowed. The intent is to make it explicit. The Ecology manual contains a system called bioinfiltration, effectively a grass covered infiltration surface. The system is commonly used in Spokane and Spokane County. With respect to infiltration basins the Western Washington manual states "Engineered soils may be used to meet the design criteria in this chapter and the performance goals in Chapters 3 and 4 of Volume V." It is not clear if this applies to excessively well-drained soils.

With respect to the above systems Ecology (2005) specifies the organic content and CEC for bioinfiltration. However, Ecology has approved the Ecology Mix, and the composition of bioretention mixes is well established. Both meet the organic content/CEC specifications. It is simpler to specify the standard mixes rather than specify organic concent and CEC.

With bioinfiltration Ecology limits the infiltration rate to 1 inch/hour. However, the LID guidance manual says 1 to 3 inches/hour. The Ecology Mix has an infiltration rate of 14 inches/hour. Restrictions of 1 to 3 inches/hour should be removed. The Ecology Embankment system in which WSDOT uses its Ecology Mix has a minimum thickness of 12 inches. However, the treatment layer should have the same thickness as bioretention filters, which is at least 30 inches.

Further considerations: The Eastern Washington manual oddly allows the bioinfiltration system in which the depth and characteristics of the treatment media are specified. Yet, in the section on infiltration basins the use of a treatment layer must be approved.

ENHANCED (METALS) TREATMENT DEVICE SELECTION

According to Ecology (2005) Enhanced Treatment is required for sites discharging directly or indirectly to fish-bearing streams and lakes from industrial sites, commercial sites, multi-family sites, and high AADT roads (see Ecology, 2005). A fundamental difficulty with developing an appropriate menu is Ecology's vague definition of enhanced removal: a system that does better than Basic Treatment. However, the range in capability of basic treatment BMPs is very broad: 0% (wet vaults), wet ponds/wetlands (50%+), and filter strips (95% based on loading).

CRITERION: *MENU*

The menu of options in the Ecology manual was developed in 1993 at a time when there was minimal field performance data. In 2009 much more is known of the performance of relevant treatment systems. Information now suggests a more effective and cost-effective menu of options can be identified.

Current criterion: The Ecology (2005) menu consists of enlarged or amended unit treatment operations, and combinations of two full sized treatment operations. These are:

1. Infiltration with appropriate pretreatment in moderately-drained soils
2. Infiltration preceded by basic treatment for excessively well-drained soils
3. Large sand filter: About 50% larger than standard filter[24]
4. Sand filter amended for dissolved metals removal
5. Constructed wetland
6. Compost-amended filter strip
7. Bioretention/rain garden
8. Ecology Embankment
9. Two-facility treatment trains as in Table 6

[24] Ecology requires treating 95% rather than 91% of the stormwater runoff over time, which results in the filter area increasing by about 50%

TABLE 6 Ecology Two-Facility Systems

Table 3.2 – Treatment Trains for Dissolved Metals Removal	
First Basic Treatment Facility	Second Treatment Facility
Biofiltration Swale	Basic Sand Filter or Sand Filter Vault or Media Filter(1)
Filter Strip	Linear Sand Filter with no pre-settling cell needed
Linear Sand Filter	Filter Strip
Basic Wetpond	Basic Sand Filter or Sand Filter Vault or Media Filter(1)
Wetvault	Basic Sand Filter or Sand Filter Vault or Media Filter(1)
Basic Combined Detention/Wetpool	Basic Sand Filter or Sand Filter Vault or Media Filter(1)
Basic Sand Filter or Sand Filter Vault with a presettling cell if the filter isn't preceded by a detention facility	Media Filter(1)
Footnote: (1) The media must be of a nature that has the capability to remove dissolved metals effectively based on at least limited data. Ecology includes Stormfilter's ™ leaf compost and zeolite media in this category.	

Origin of the current criterion: The menus were developed by Louise Kulzer then with King County and myself in 1993 in support of the update of the surface water design manual for King County, which occurred in 1994.

Proposed criterion: Replace the menu with these treatment systems:

1. Infiltration with appropriate pretreatment in moderately-drained soils
2. Infiltration preceded by *enhanced treatm*ent for excessively well-drained soils
3. Sand filter amended for dissolved metals removal with pretreatment
4. Bioretention filter cell
5. Rain garden
6. *Bioretention filter swale*
7. Filter strip (*not compost amended*)
8. Ecology Embankment
9. *Wet pond*
10. Constructed wetland
11. Manufactured systems certified to remove dissolved metals

Additions or differences from the current menu are indicated in italics. Where excessive well-drained soils occur (outwash) the stormwater is treated to remove dissolved metals. Wet ponds are allowed. All of the systems are of standard size: no enlargements. There would be no enlargement of the sand filter. The sand filter is not allowed because it is not effective at removing dissolved metals.[25] The double-box menu is dropped.

Rationale for proposed criterion:

Modification to infiltration: Ecology (2005) expects treatment prior to discharge into excessively well-drained soils. Their concern is with stormwater receiving inadequate treatment before

[25] Both the City of Portland and Caltrans have observed significant removal of dissolved copper and zinc. However, as the mechanism(s) of this removal has not been determined it is not prudent to rely on these data. Logically, sand should not remove dissolved metals. The likely mechanism is sorption on organic matter that has accumulated on the surface of the filter. But confirmation is needed.

reaching the groundwater due to outwash soils being very low in organic matter, a primary remover of dissolved metals (Adolfson, 1991). However, Basic Treatment, as Ecology now prescribes for treatment, will not necessarily result in the removal of dissolved metals. It depends on the system that is selected. More protective is to state specifically that dissolved metals are to be removed with Enhanced Treatment. There is been considerable documentation that if left untreated metals in stormwater reach the groundwater when discharged to outwash soils. This can include an 18-inch treatment layer using standard bioretention mix.

Deletion of large sand filter: Increasing the volume requirement from 91% to 95% increases the removal of dissolved metals by only 4% on an annual loading basis. This hardly seems cost-effective. Furthermore it does not reduce the effluent concentration. Rather, it simply reduces the frequency of bypass events. While this is laudable it has not been justified as constituting MEP.

Deletion of compost-amended filter strip: A study by WSDOT (Herrera, 2007) comparing the performance of un-amended with amended strips indicates that compost amendment adds little to performance. Two composted amended strips were evaluated. One reduced the dissolved copper concentration, and one did not, doing no better than the un-amended strip. The compost leached dissolved copper at about 20 ug/L, four times the concentration in the highway runoff. It is believed this is the normal condition (Batts, pers. comm.)[26] and has been observed in one other WSDOT study (Younge, 2000). A summarization (Lenth and Batts, 2007) showed the amended strips performed only modestly better. Total loading reduction for copper increased from about 96% to 98% with compost amendment. Total zinc removal was 98% without compost. The compost appears to improve infiltration, but there is no certainty that this will occur at all sites. Regardless, the modest increase in loading reduction and the questionable practice of using something that leaches copper calls into question the worth of the added cost. There also appears to be issues with dissolved phosphorus as well.

Addition of bioretention filter swale: as this design is essentially that of a bioretention filter with a standard shape, generally rectangular or of a irregular circle, there is no reason not to allow its use in the shape of a swale.

Addition of wet pond: Why Ecology does not allow the use of a wet pond is not clear. Perhaps it is the perception that it is plants that remove dissolved metals via their growth and metabolic needs. Hence, a wet pond having little vegetation is unlikely to remove dissolved metals. However, metabolic use is minor for plants (Minton, 2005). Most removal is by sorption to organic matter or ferric oxide coatings on sediments (e.g. clay) in the basin soils. Plant roots may play an important role. Dissolved zinc and copper sorb to iron oxide coatings (plaques) that coat the roots of plants. It is therefore likely wetlands do better than wet ponds given the larger bottom surface area and rooted plants. But there is no evidence to support this likely outcome. Shown below are two graphics showing the relationship between effluent concentrations and the unit volume of the wet ponds and wetlands (WERF, 2005). The numbers in the boxes next to each data point are the mean influent concentrations.

[26] This appears to be the normal condition of compost made from yard green wastes, possibly containing street sweepings (Batt, pers. comm.) and may call into question the advisability of using compost in rain gardens and bioretention systems unless tighter control on compost production is implemented.

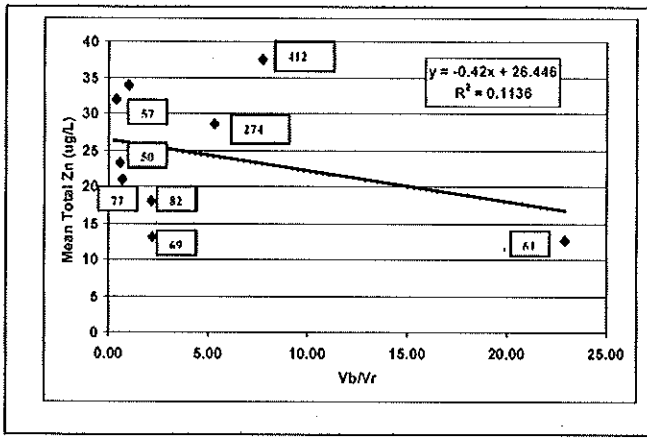


FIGURE 21 Basin Size and Zinc

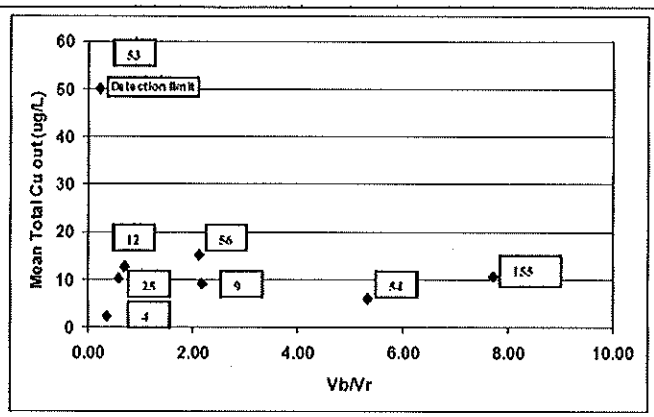


FIGURE 22 Basin Size and Copper

Regarding copper: Figure 22 shows with some basins the influent concentrations were very low, resulting in essentially no removal. It appears that 10 ug/L is the lowest possible effluent concentration where the influent concentration exceeds this value, and that the unit volume of the basin is irrelevant to achieve this concentration.

According to Figure 21 zinc may achieve lower effluent concentrations, at least more reliably, with a large unit volume. But basing a general conclusion on one data point, and for a very, very large basin (V_b/V_r ratio above 20) seems imprudent. Regardless, a total zinc concentration less than 50 ug/L is satisfactory. The receiving water standard for zinc[27] is in the range of 30 to 50 ug/L as dissolved zinc. Assuming 50% of the zinc in the effluent is dissolved a total concentration of 60 to 100 ug/L is acceptable. Therefore, using a normal size wet pond or wetland with V_b/V_r ratios previously proposed in this report is reasonable.

Deletion of two-facility treatment trains: There remain too few studies in which the incremental performance of each BMP (unit operation) in a treatment train (system) has been evaluated. The only apparent study of a wetland following a wet pond found no increase in copper or zinc removal (TRCA, 2002).

Five of the schemes in Table 4 involved a sand filter. It has been noted in Footnote 22 that while sand filters, despite the supposed inert nature of sand, remove dissolved metals, but as yet by unknown mechanisms. A wet vault does not so there is no reason to put it in front of a sand filter, given that a sand filter has a pretreatment unit anyway.

There is no basis to believe that putting a second full size treatment operation as in Table 4 will provide any better treatment than the single systems listed in the proposed menu. The menu in Table 4 was developed for the removal of total zinc not either total or dissolved metals; to provide what was perceived to be (but no evidence in 1993 to support) improved reliability of performance: "better two boxes than one." The menu developed in 1993 was only for "streams of regional significance:" i.e. streams in King County with significant salmon runs: Hence, the interest in an "insurance" policy. Furthermore, it makes no sense to put together combinations of treatment systems not known to remove or to reliably remove dissolved metals: e.g. a vault followed by a sand filter; or sand filter followed by a filter strip.

Further considerations: None.

[27] At the likely hardness values of 25 to 50 mg/L of streams during storms

PHOSPHORUS TREATMENT DEVICE SELECTION

According to Ecology (2005) the Phosphorus Treatment Menu applies to projects within watersheds that have been determined by local governments, the Department of Ecology, or the USEPA to be sensitive to phosphorus and that are being managed to control phosphorus inputs from stormwater. This menu applies to stormwater conveyed to the lake by surface flow as well as to stormwater infiltrated within one-quarter mile of the lake in soils that do not meet the soil suitability criteria in Chapter 3 of Volume III of Ecology (2005). The requirement is 50% removal of Total Phosphorus. However, it is soluble or dissolved phosphorus that is the primary driver of excessive algal growth. The menu should therefore focus on treatment systems capable of removing dissolved phosphorus.

CRITERION: *MENU*

The menu of options in the Current Ecology manual was developed in 1993. In 2009 much more is known regarding the performance of relevant treatment systems. Information now suggests a more effective and cost-effective menu of options can be identified.

Current criterion: Menu is enlarged unit treatment operations, and combinations of two full sized treatment operations. These are:

1. Infiltration with appropriate pretreatment
2. Infiltration preceded by basic treatment
3. Large sand filter: About 50% larger than standard filter[28]
4. Sand filter amended for phosphorus removal
5. Large wet pond: 50% larger than standard pond
6. Media filter[29] targeted for phosphorus removal
7. Two-facility treatment trains

TABLE 7 Ecology Two-Facility Systems

Table 3.1 – Treatment Trains for Phosphorus Removal	
First Basic Treatment Facility	Second Treatment Facility
Biofiltration Swale	Basic Sand Filter or Sand Filter Vault
Filter Strip	Linear Sand Filter (no presettling needed)
Linear Sand Filter	Filter Strip
Basic Wetpond	Basic Sand Filter or Sand Filter Vault
Wetvault	Basic Sand Filter or Sand Filter Vault
Stormwater Treatment Wetland	Basic Sand Filter or Sand Filter Vault
Basic Combined Detention and Wetpool	Basic Sand Filter or Sand Filter Vault

Origin of the current criterion: The menus were develop by Louise Kulzer then with King County and myself in 1993 in support of the update of the surface water design manual for King County which occurred in 1994.

Proposed criterion:

[28] Ecology requires treating 95% rather than 91% of the stormwater runoff over time, which results in the filter area increasing by about 50%

[29] Ecology is referring to manufactured filters.

1. Infiltration with appropriate pretreatment in moderately-drained soils
2. Infiltration preceded by *dissolved phosphorus removal* for excessively well-drained soils
3. Sand filter *with amendment for dissolved phosphorus*
4. Bioretention filter cell *with amendment for dissolved phosphorus*
5. Rain garden *with amendment for dissolved phosphorus*
6. *Bioretention filter swale with amendment for dissolved phosphorus*
7. Ecology Embankment
8. Constructed wetland
9. Manufactured filters certified to remove phosphorus

Additions or differences from the current menu are indicated in italics. The sand filter is not in the proposed Kitsap County menu as sand does not remove dissolved phosphorus. The double-box menu is dropped. Where excessive well-drained soils occur (outwash) the stormwater is treated to remove dissolved phosphorus. Wet ponds are allowed. All of the systems are of standard size: no enlargements. There would be no enlargement of the sand filter.

Rationale for proposed criterion: The original menu was derived at a time when there was minimal field performance data. Field data now available indicates a more cost-effective menu is possible.

Use of amendment in sand filters, infiltration basins of excessively well-drained soils, and bioretention systems including rain gardens. The Ecology goal for phosphorus removal is 50% of Total Phosphorus: particulate plus dissolved. However, it is the dissolved that is drives excessive algae growth in lakes. Consequently, the proposed menu for Kitsap County consists only of treatment systems that reliably remove dissolved phosphorus.

Sand found in western Washington is incapable of removing dissolved phosphorus. The bioretention system has been found inconsistent in the removal of phosphorus, achieving relatively low removal efficiencies of less than 25%, apparently due to the leaching of phosphorus in the soil. Without due care it is possible for bioretention systems including rain gardens to increase the level of dissolved phosphorus in the stormwater (Li, 2007; Smith, 2007) even though overall removal is positive. While these systems generally meet the goal of the Department of Ecology of 50% removal of total phosphorus they are ineffective or at best only modestly effective at removing dissolved phosphorus.

An amendment such as activated alumina or activated iron, or steel wool can be combined with sand or soil to remove dissolved phosphorus. Applications are with the sand filter, bioretention cell (and rain garden or swale), and as a treatment layer in an infiltration basin.

Steel wool removed about 50% of the dissolved phosphorus when mixed at 5% of volume (Shapiro, 1999). Bellingham (Bellingham, 2006[grm4]) has conducted some experiments with a mix of sand ($2/3^{rds}$)/activated alumina ($1/3^{rd}$), achieving about 50% removal. The Ecology Mix developed by the Washington Department of Transportation removes dissolved phosphorus and has been approved by the Department of Ecology as meeting the department's 50% TP removal goal. However, the mix has not been evaluated with respect to the removal of dissolved phosphorus. Furthermore, none of these studies has evaluated how long the media will continue to perform at the desired level of efficiency.

The volume of the amendment is determined with the following equation:

$$V_m = \frac{62.4 Q M_c (C_o - C)}{q_a}$$ **Equation 5**

Where:

V_m = volume of the amendment in pounds
Q = annual runoff flow in cubic feet per year
M_c = maintenance cycle in years
C_o = influent dissolved phosphorus concentration in mg/L
C = effluent dissolved phosphorus concentration in mg/L
q_a = operating capacity of the amendment in mg/kg

The greatest uncertainty lies with the assumed influent concentration for dissolved phosphorus. A synthesis of data collected by about a dozen communities in the Willamette Valley (Portland to Eugene) found the following average concentrations by land use: residential, 0.020 mg/L; commercial, 0.03 mg/L; and industrial, 0.06 mg/L (Strecker, 1997). A study by the City of Bellevue of a residential development found an average concentration of about 0.03 mg/L (Shapiro, 1999). An earlier study found 0.06 mg/L (Pitt and Bissonette, 1984). A range of 0.03 to 0.06 mg/L seems common. The following assumptions might be used: influent concentration of 0.050 mg/L; desired effluent concentration of 0.025 mg/L;[30] and a maintenance cycle of 10 years. Equation 5 becomes:

$$V_m = \frac{15.6 M_c (C_o - C)}{q_a}$$ **Equation 6**

Equation 6 gives the number of pounds of amendment that must be added into the media mix to provide the needed performance and capacity under the assumptions used. The determination of the size of the filter (sand, bioretention, etc) is determined separately. Several vendors provide activated alumina or activated iron and should be able to provide the capacity of their media[grm5]. However, the engineer must ask the vendor what is the capacity at an influent concentration of 0.05 mg/L. This is the operating capacity, which differs from the maximum saturation capacity[grm6] (Minton, 2005).

Modification to infiltration: Ecology (2005) expects treatment prior to discharge into excessively well-drained soils. Their concern is with stormwater receiving inadequate treatment before reaching the groundwater due to outwash soils being very low in organic matter, a primary remover of dissolved metals. However, Basic Treatment, as Ecology now prescribes for treatment, will not necessarily result in the removal of dissolved phosphorus. It depends on the system that is selected. More protective is to state specifically that dissolved phosphorus is to be removed. There is considerable documentation that phosphorus in stormwater will reach the groundwater when discharged to outwash soils.

Deletion of large sand filter: Increasing the sand filter by 50% so as to capture 4% more stormwater (91% to 95%) hardly seems cost-effective. Furthermore it does not reduce the effluent concentration. Rather, it simply reduces the frequency of bypass events. While this is laudable, it has not been justified as constituting MEP. Also, the standard size sand filter is not kept in the menu as sand does not removed dissolved phosphorus.

[30] These are very low concentrations. However, the City of Bellingham has been able to reduce the dissolved phosphorus concentration from about 0.050 mg/L to about 0.025 mg/L with the mix noted above.

Bioretention swale: as this design is essentially that of a bioretention filter with a standard shape, generally rectangular or of a irregular circle, there is no reason not to allow its use in the shape of a swale. Comments are provided above regarding the unreliability of bioretention to remove phosphorus, in particular dissolved. Therefore, the mix used in the bioretention swale would include an amendment as described above.

Dropping of enlarged wet pond and addition of constructed wetland: Increasing the size of the standard wet pond as defined by Ecology is likely to do little to improve the long-term removal of dissolved phosphorus. Shown in Figure 23 are data of total phosphorus in the effluent versus the size of the wet basin (WERF, 2005). The numbers in the boxes next to each data point or cluster of data points are the mean influent concentrations.

Figure 23 shows that the effluent concentration does not decrease with larger basins. The basin with a relatively high concentration had influent with abnormal concentrations in both storms and groundwater inflow, believed due to contamination from the fertilization of residential lawns in the drainage.

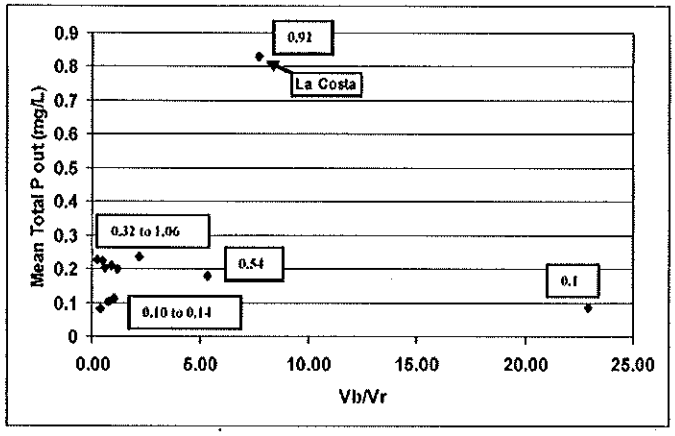


FIGURE 23 Basin Size And Effluent Phosphorus Concentration

Although Figure 23 indicates effective removal of phosphorus by wet ponds and constructed wetlands, there is doubt regarding their ability to continue to remove dissolved phosphorus over the long-term (Kadlec and McNight, 1996). The only long-term study found that a wet pond/wetland system removed about 72% of the total phosphorus during the first year but was not removing any phosphorus after ten years (Oberts, 1999). It is believed that within a few years of construction the chemical capacity of the soil is saturated. As for the plants, they use relatively little of the phosphorus in the stormwater as the amount in the influent commonly exceeds their metabolic requirements, except in the first few years when the infilling of plants occurs. Eventually, plant growth is balanced by plant death in which dissolved phosphorus removed is balanced by dissolved phosphorus released. Furthermore, when wetland plants become dormant each fall they release phosphorus in their tissues. The state of Maine, who has a phosphorus reduction performance goal of 60%, does not allow the use of constructed wetlands.

It is possible to keep the wetland functioning by cropping the foliage each year in the late summer. However, this is an onerous task, not likely to be done. Furthermore, about 50% of the phosphorus taken in by the plants is present in their roots, which are not removed with harvesting.

However, wetland ecologists have determined that a small portion of the plant matter does not decay when the plant dies, being very resistant to bacterial degradation in the bottom soil. As a consequence, some phosphorus is permanently retained in the bottom of the wetland. It is not released into the overlying water and lost in the stormwater flows exiting the wetland. Wetland ecologists have determined that natural wetlands are able to sequester about 0.5 to 1 gram of phosphorus per square meter of wetland surface area (Minton, 2005). Hence, the wetland can be sized based on its surface area such that the loading of phosphorus from the incoming stormwater does not exceed a loading rate of 4.5 to 9 pounds acre of wetland per year. Equation 7 is used to determine the area of the wetland.

$$A = \frac{0.3Q\,C_o}{L_p} \qquad \textbf{Equation 7}$$

Where:

- A = surface area of the wetland in square feet
- The factor 0.3 represents the combined ratio of unit conversion factors (28.3 liters/ft3; 10.76 ft2/m2 and 1000 mg/gm)
- C_o = influent dissolved phosphorus concentration in mg/L
- L_p = design loading of 0.5 gm/m2/year

Deletion of two-facility treatment trains: Sand filters and wet vaults do not remove dissolved phosphorus. Swales and strips are unreliable given the likely use of fertilizers and can export phosphorus (Caltrans, 2004). This eliminates all the combinations in Table 5. The only apparent study of a wetland following a wet pond found that the wetland increased the removal of total phosphorus by 13% from 76% to 89% (TRCA, 2002). However, it is likely that this can be achieved as well with one large wetland sized by the procedure introduced above.

Further considerations: None

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