Introduction to Best Management Practices for Stormwater Management:

The Design and Maintenance of (Bio)Swales

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After reading this you should:

- Know the importance of minimizing the quantity of stormwater runoff and improving its quality
- Know soil and biological considerations involved in designing a bioswale
- Be able to create design guidelines
- Be able to perform routine maintenance on a bioswale

The original purpose of stormwater management was primarily the prevention of floods as a matter of public safety. Hence, methods were solely developed to capture and transport mass quantities of water away from the public as rapidly as possible. In the late 1970's however, scientific research began to reveal that stormwater might be a significant contributor to chemical pollutants entering the nation's waters. Consequently, traditional methods were called into question and new management strategies began to be developed with the aim to not only reduce the quantity of stormwater, but improve its quality as well. Furthermore, over time, the potential for the chemical and nutrient composition of stormwater to threaten public health and alter ecosystems expanded to recognize that beyond volume, the other physical properties of stormwater (flow rate and temperature) could be equally, if not more, damaging. Thus, the definition of stormwater was further broadened to include not only runoff from precipitation (wet-weather events), but also runoff from "dry weather" events, such as pavement washing and irrigation water.

Introduction

In order to adequately address this more comprehensive definition of stormwater, alternative management solutions began to be explored. Over time, these investigations resulted in the idea of source control and the development of what are known today as Best Management Practices (BMPs).

> "*Best Management Practices utilize a variety of different control measures, which aim to reduce pollution problems, conserve natural water resources, and also enhance the amenity value of watercourse in the urban environment" (Ole, 2005).*

BMPs can be discussed in three aspects: non-structural practices; structural practices; and/or overall watershed/site-level designs. Nonstructural practices include a combination of educational efforts and ordinances, such as educating citizens about the benefits of landscaping with drought-resistant native species and municipal restrictions on irrigation water. The success of such practices depends on community receptiveness to behavioral changes and the resources allotted towards continual monitoring and enforcement of implemented programs. Structural BMPs utilize hydrologic, biological, physical and chemical principles/properties to maximize interception, infiltration, filtration[1], and evaporation, thus reducing the quantity and improving the quality of stormwater runoff.

Designing for large-scale sustainable urban drainage in developing countries can be a daunting task for the following reasons:

- a lack of data regarding the existing drainage network (its hydraulic capacity)
- difficulty predicting future growth patterns,
- illegal connections
- political cohesion (funding and support)
- technical and environmental educational gaps

With this in mind, micro-scale solutions offer great promise. In fact, "prevention or mitigation of runoff problems at the source is regarded as a key principle" for both developing and developed countries alike (Ole & Parkinson, 105). That said, three conventional "conveyance" methods that have found their way to the developing world are drainage channels, covered drains, and culverts (Mihelcic et al., 2009). Working under the same constraints and requirements, structural BMP design could replace technologies in the form of: filter strips or swales, filter drains and permeable surfaces, infiltration devices, and basins and ponds. The figures below represent such a situation in which a conventional concrete culvert (1) could be replaced by a bioswale (2).

Figure 1 – Conventional drainage channel, Tampa FL, (Putnam, 2010)

Figure 2 – Bioswale, Minneapolis, MN (Putnam, 2010)

[1] Infiltration is the seepage of water into the ground whereas filtration refers to the removal of pollutants, nutrients, and sediments as the water infiltrates through the substrate.

While both conventional and BMP technology may offer the short-term benefits, Table 1 shows that BMPs will offer medium and long-term benefits as well.

Benefits of Establishing BMP	
Short-term	Flood protection Environmental health protection Erosion and sediment control
Medium-term	Pollution prevention, control, and mitigation Water conservation Preservation of natural hydrology
Long-term	Amenity Protection of natural habitats Resource conservation

Table 1- "Objectives of Stormwater Management Strategies" (Ole and Patterson, 2006, pg 37)

The focus of this technical brief will be on (bio)swales[2], which are highly appropriate for the low-density developments and/or areas with small populations that are commonly found in many areas of the developing world. In addition, swales work best in areas with soils that have good infiltration capacity and low ground-water tables. In contrast, they are not well suited for areas with flat grades, steep topography, and/or poorly-drained soils.

Substrate

To begin, one of the key factors in determining the expected performance of a bioswale is the composition of its substrate. While bioswales are flexible to a wide variety of substrate compositions, it is essential that whatever mixture of soil, sand, gravel, rock, and organic materials present, that the substrate remain non-compacted. This is for the sake of infiltration, as well as for proper development of the beneficial plants and microorganisms necessary for effective filtration. The USEPA recommends a minimum infiltration rate of ½ inch per hour (1999). In regards to filtration objectives, some soil properties to consider are outlined in Tables 2 and 3 below.

Characteristic	Associated Performance Benefits
Anion (negative charge) Exchange Capacity	-removal of positively charged metals such as Copper (Cu), Cadmium (Cd), Iron (Fe), Manganese (Mg), Aluminum (Al), and Mercury (Hg) -the recommended cation exchange capacity (CEC) is **greater than 15 meq/100g** of soil (alkaline) *most soils are naturally negatively charged, see Table 4
Cation (positive charge) Exchange Capacity	-removal of turbidity
pH	-removal of heavy metals and nutrients, **6.5-8.5** -interdependent with CEC which can be expected to increase by 50% if pH is raised from 4 to 6.5 and 100% if raised from 4 to 8.

[2] The words bioswale and swale are often used interchangeably. However, it could be said that, depending on context, the use of the word bioswale captures incorporation of the benefits of filtration, while swale alone does not necessarily imply more than enhancing infiltration.

Electrical Conductivity	-affects biota's ability to process pollutants and nutrients, **.04 meq/L or less** is ideal
Anoxic (little to no oxygen)	-removal of nitrogen and metals
Organic content	-establishment of a healthy biological colony such that insoluble pollutants/nutrients can be transformed to forms

Table 2 – Relationship between performance in improving water quality and soil characteristics

Substrate		**Meq/100g**
Sand		1-5
Fine Sandy Loam		5-10
Loam		5-15
Clay	Kaolinite	3-15
	Loam	15-30
	Illite	15-40
	Montmorillonite	80-100
Organic Matter		200-400

Table 3 – Ranges of milliequivalents per 100 grams of various soil types

Biology –microorganisms and vegetation

As mentioned in Table 3, the establishment of a healthy population of microorganisms is critical when it comes to pollution removal; microbes are the primary mechanism for the stabilization, removal, and conversion of organic carbon and nutrients required for vegetative growth and overall filter performance (Oregon DEQ, 2003). The addition of a carbon source during construction of the bioswale will help to accomplish this goal.

With regards to vegetation, a mix of three vegetation types (shown in Table 4) should be considered.

	Zone	**Species Description**
Bottom	Hydric	Tolerant of standing/fluctuating water level
Side slopes	Mesic	Erosion control, intermediate water availability
Top	Xeric	Tolerant of drier conditions

Table 4 - Appropriate mix of vegetation

The general aim when selecting vegetation is to achieve a dense cover aboveground with a fibrous and extensive root system underground. In this regard, grass species are well suited for bioswales. In particular, when compared to perennial grasses that grow into sod or as bunches, annual grasses, which grow quickly and in a dense manner, are good initial (establishment) candidates.

Ultimately however, the proper selection of vegetation will depend on climate, expected pollutants, expected flow volume, velocity of incoming water, and the seasons the vegetation should be active (rainy season). Native species are likely to be the most adaptable and appropriate to any given situation and, whenever possible, should be selected. In the selection of vegetation, utilizing local knowledge and resources is likely to be very beneficial to the performance of the swale. As a final note, it is important to note that even if growth rate is a concern, do NOT add fertilizers and herbicides as these are some of the very pollutants a bioswale seeks to minimize.

Design

There are two principal types of bioswales, fully vegetated and open channel, which exhibit one of three typical shapes: U, V, or trapezoidal. In terms of pollutant removal, studies have shown trapezoidal, fully-vegetated, swales (Figure 3) to be the most effective. However, as previously mentioned, swale design will ultimately be dictated by available space, average loading, and climate.

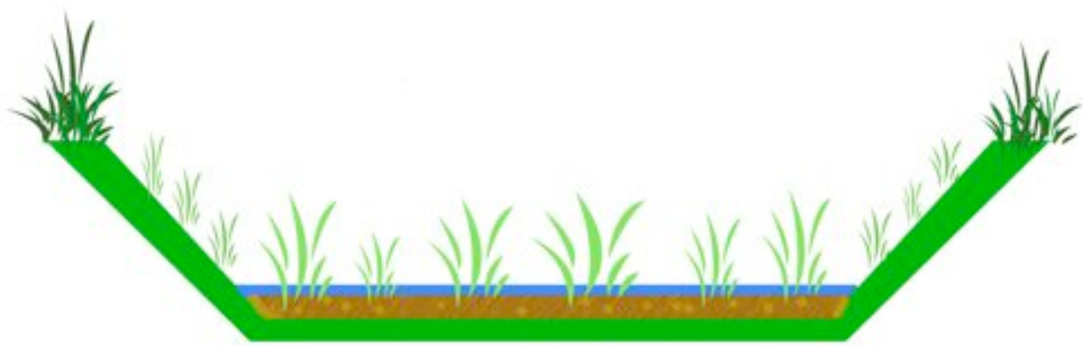

Figure 3 - Basic schematic of the frontal view of trapezoidal, fully-vegetated, swale (Putnam, 2010)

When designing a bioswale several things to consider beyond substrate and biota include: storm design event; flow velocity, excess runoff considerations; cross-section selection; swale slope, width, length and depth; level spreader use; check damns, and construction season" (Oregon DEQ, 2003).

Bioswales are typically designed to withstand a two-year (minimum) to ten-year 24-hour storm event. In the U.S., the 24-hour design storm is defined "as the amount of runoff that must be treated before being released into a conveyance storm drain network or receiving water" (EPA, 1999). In the developing world however, there may or may not be an established storm drain network. Thus, the importance of minimizing runoff at the micro-scale becomes ever more important. Design storms are typically reported as depths, but the rainfall intensity is also required in order to appropriately size a swale. The volume of runoff a particular bioswale will treat is a function of how much rain falls on the ground over a given period of time, how much evaporation takes place, and the rate of infiltration. More information on hydrology and drainage can be found in Chapter 10 of *Field Guide to Environmental Engineering for Development Workers* (Mihelcic et al., 2009).

There is currently no consensus on any specific guidelines for sizing swales. In the United States, regulation regarding setbacks and water quality vary between and within states, resulting in a variety of rules and regulations for minimums/maximums (Table 5). In the developing world, it is likely that such restrictions and regulations will not exist.

Source	Bottom Width	Depth	Side slope	Longitudinal Slope	Retention Time (min)
City of Salem, MA. (2005)	1 – 4 m	1 – 4 m (**2.5**)	**20**-25%	1 – 6 (**3**)%	5-10
Oregon Department of Environmental Quality (2003)	2 – 8	6" deeper than maximum flow depth	4:1	**1** – 6%	>5
City of Eugene, Oregon. (2008)	2-8	4-12"	<10%	**0.5-6%**	>9

Table 5 – Variation in design guidelines where **bold** numbers indicate the preferred (optimal) side of any ranges given.

Regardless, some general parameters are summarized in the following:

- **Surface area** of the swale should be 1% of the area that drains to the swale. The University of Florida recommends they drain areas less than ten acres with slopes no greater than 5% (2008). Recall that the area that drains to the swale will be all the flow encompassed within the topographic highpoints that surround it. If space constraints limit the necessary length the bioswale needs to be to achieve a sufficient surface area, the swale should be combined with another pollution control BMP such as a retention pond.
- **Longitudinal slope** determines the velocity of flow. Keeping the slope as minimal as possible will limit the degree of erosion as well as increase pollutant removal by increasing the flow's residence time within the swale. However, if the slope is <1%, standing water could result. If the longitudinal slope is between 2-6%, check damns may need to be constructed in order to maximize retention time within swale by decreasing flow velocities and promoting particulate settling. Slope can be measured using an abney level.
- **Check dams** can be made of stone, boards, or concrete weirs. The frequency of their placement should be governed by both longitudinal slope and channel geometry (reported values of 12-50 foot increments). They should be located such that the upstream limit of ponding from one check dam is just below the downstream edge of the adjacent check dam. Complete infiltration of water within the swale should be achieved no more than a day after the end of the storm. In addition, an opening should be constructed at the base of each dam for low flow periods.
- **Velocity** is calculated for two storm sizes: water quality design storm and the peak flow design storm. "Velocity should be less than or equal to one-and-a-half feet per second for the water quality design storm, and below five feet per second ... for the peak flow design storm" (Oregon DEQ, 2003). If the average discharge exceeds three feet per second, erosion control fabric or geotextiles may be needed to achieve added resistance.
- **Residence time** – If the flow entering the bioswale is evenly distributed along its length, then the residence time must be calculated from the midpoint to the discharge point (half the total length). If flow enters at one point near the entrance, it is a good idea to install a flow spreader (riprap).

Construction

Once the bioswale is sized, the following basic materials: shovels, media, compost, rakes (especially if seeding), vegetation, gravel, rocks (large and small) will need to be gathered. Preparation of the soil should include tilling in additives such as grit in the form of sand and gravel, and usually compost in a 1:3 ratio with existing soil. Do not underestimate the degree of compaction that may have occurred during construction of the swales as, depending on soil type and moisture content, compaction can extend to a depth of thirty inches. If velocity guidelines described above are not met, soil should be overlain with some type of erosion control material. In the developing world, the geotextile nettings and reinforcement mats available in the developed world may not exist. In low-velocity situations, natural mulches can be used to keep soil, seeds, and young plants in place to the best degree possible. Erosion control blankets and netting can also be made from jute (Asia), coconut fibers (Tropics), and straw.

Performance

The two primary goals of bioswales are to reduce the flow and improve the quality of stormwater. Accordingly, the effectiveness of a swale is dependent on its ability to facilitate infiltration, sedimentation (flocculation), biological conversion/consumption, and support a healthy rate of vegetative uptake. These mechanisms are primarily dependent on the soil and vegetation present in the swale as well as retention time. It may require at least two years to effectively establish the healthy microbial community and rich/productive bioswale vegetation necessary for optimum performance.

In general, bioswales are particularly effective for removing suspended solids and oil and grease. The reduction of heavy metals is fairly good (20-60%), with accumulation generally occurring within the top two inches (clayey/loamy) to four inches (sandy) of soil. The removal efficiency's for a particular swale (relatively typical size) are summarized in Table 6. To date, no studies have found the degree of accumulation to be at toxic levels. Note that as far as potable water is a concern, bioswales have not proved to be capable of pathogen removal.

Pollutant	Obtainable Removal (%)
Total Suspended Solid (TSS)	83-92
Turbidity	65
Lead	67
Copper	46
Total Phosphorus	29-80
Aluminum	63
Total Zinc	63
Dissolved Zinc	30
Oil/Grease	75
Nitrate-N	39-89

Table 6 - Removal rates for a swale designed as such: 200' long, >2.5 minute residence time, runoff velocity 1.5 ft/sec, water depth 1-4", and grass height >6" (Oregon DEQ, 2003).

Maintenance and Lifetime

Regular removal of trash, debris, dead vegetation, and accumulated sediments may be required depending on the type of stormwater the bioswale receives. In order to prevent woody species from taking over the bioswale, vegetation may need to be trimmed every couple of years. Depending on the source of water, vegetative clippings may contain hazardous toxins. Thus, erring on the side of caution, these clippings should be disposed of accordingly; away from sources of drinking water, crops, and play areas. If properly maintained in this way, bioswales can last indefinitely.

Cost

The cost to create a bioswale in the U.S. can vary depending on context from roughly $16 to $30 per linear meter ($4.90-$9.00 per linear foot) (EPA, 1999). However, in the developing world, necessary materials will likely be locally available and inexpensive if not free. Thus, cost of implementation will mostly be a function of labor.

Final Considerations on Filtration

A document published by the EPA on bioswales in 1999 highlighted that it was still unclear whether "pollutant removal rates decline with age, what effect slope had on the filtration capacity of vegetation, the benefits of check dams, and the degree to which design factors can enhance the effectiveness of pollutant removal."

Accordingly, many universities began to investigate these questions. In the Department of Civil and Environmental Engineering at the University of Maryland, numerous research studies on bioretention cells, both small and large-scale, have repeatedly quantified volume reduction and pollutant removal for suspended solids, nutrients, hydrocarbons, and heavy metals. These studies seek to create models for optimum design based on the specificity of the site and the target problems/pollutants at hand. These studies range from tested variations of different media types and media layering patterns to pretreatment options and vegetation selection. Analysis of studies done from 1999-2009 point to several conclusions:

- Phosphorus and nitrogen which tend to exhibit poor removal (in past BMP studies) have the potential to be managed by increasing the growth and harvesting of vegetation
- Bioretention cells/rain gardens should be constructed such that the more porous media (ex. sand) is on top of the more impervious media (ex. clay)
- The simple addition of mulch works well for the removal of heavy metals; and the ability of bioswales to eliminate/reduce bacteria and thermal pollution needs further investigation.

Further Reading

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Disclaimer

This document was prepared for one of the following two classes at the University of South Florida (Tampa): CGN6933 "Sustainable Development Engineering: Water, Sanitation, Indoor Air, Health" and PHC6301 "Water Pollution and Treatment". Please contact the instructor, James R. Mihelcic (Department of Civil & Environmental Engineering) for further information (jm41@eng.usf.edu. (learn more about our mission and development education and research programs at: www.cee.usf.edu/peacecorps).

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