Green Infrastructure: Assessing the Benefits of Bioretention over Traditional Stormwater Management

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Abstract:-
Stormwater management is a key component of Green Infrastructure, which is based on ecosystem conservation, and low impact development practices (LID). One low impact development practice utilized along highways and road pavement is bioretention. Bioretention systems employ the natural elements of landform, soil and vegetation, to capture and remove harmful pollutants from stormwater runoff. Filtration, absorption, and evapotranspiration are the key mechanisms responsible for the removal of impurities from the soil. The infiltration time that happens before runoff reaches the stormwater outlet allows these functions to occur. This paper uses a System Optimization (SO) approach that incorporates a link performance function based on soil permeability rate, for a comparison between bioretention systems and conventional stormwater management systems. Further, the paper puts forth several comparisons between bioretention systems and conventional stormwater management systems, but contends that the delay time to allow runoff to permeate the soil is the most important one. The SO approach is used to predict runoff rate and flow volume on a stormwater management system. It shows that the rate of flow is increased but the volume of outflow is decreased when comparing the bioretention cell to the conventional storm drainage system.

Key words: Green Infrastructure, Bioretention, Infiltration, System Optimization

1. Introduction

Green Infrastructure is ecosystem conservation, through strategic planning and management of open space, landscape, and other natural land networks, which adds value and provides benefits to human populations. (1) The value added by these networks is that stormwater is naturally managed, the risk of flooding is reduced, pollution is captured, and water quality is improved. Critical elements of green infrastructure implementation include Low Impact Development (LID) practices, Stormwater Best Management Practices (BMP), conservation developments and green/grey interface. An area where green infrastructure components have been successfully implemented is in the development of green highways (2).

1. **Green Highways** utilize techniques to reduce the impact on the natural environment. The result is that highways become more aesthetically pleasing in cities and more a part of the natural environment in rural areas. Another benefit of green highways is that lower long-term or life-cycle costs is achieved through sustainable highway construction. Using bioretention systems to manage stormwater and reduce runoff volume is a viable technique for green highway design.

2. Research Scope

In this paper, the benefits of bioretention over traditional stormwater management will be discussed. A case study demonstrating how particular bioretention systems have been utilized by the Maryland Department of Transportation will also be presented. Finally, we will introduce a System Optimization (SO) approach to measure the rate of outflow for both a bioretention cell and a conventional system where runoff goes directly to pipe with no infiltration time. A numerical example showing the applicability of the SO approach will also be presented.

3 Bioretention Systems

Bioretention systems are storm water's best management practices that use filtration to treat storm water runoff. Using vegetation to remove pollution from runoff, bioretention cells often use upland terrestrial forest or meadow ecosystems as a model. Bioretention systems are designed to treat stormwater form impervious surfaces. Bioretention employs a simplistic, site integrated, terrestrial based design that ponds runoff for infiltration and uptake by vegetation. Runoff is captured and filtered through prepared soil medium. Once soil pore space capacity is exceeded, runoff will pool at the surface of the soil. Soil ponding will last for less then1/2 hour with the use of the recommended engineered soil and an under-drain system. Ponding will last longer if the system is dewatered by infiltration alone. Runoff can be directed into the system directly through swales, cutter collection systems or pipes. Runoff filters through vegetation and soil in the bioretention area is collected in an underground drainage system or allowed to filtrate into the ground. Unlike end of pipe systems, bioretention facilities can be distributed across a site resulting in smaller more manageable watersheds. This helps to control runoff close to the site where it is generated.

3.1 Performance

Bioretention removes stormwater pollutants through physical and biological processes including absorption, plant uptake, filtration, microbial activity, decomposition, and sedimentation. Absorption is the process where particulate pollutants attach themselves to soil and vegetation. Adequate contact time between the surface and pollutant removal must be provided in the system design for adequate absorption to occur. As runoff passes through the bioretention media infiltration occurs. Pollutant removal may decrease if the infiltration rate of the soil exceeds those specified in the bioretention cell design. Pollutant removal may include metals, phosphorus, and hydrocarbons. Pollutant uptake by plants also occurs through the biological process that occurs in the wetlands. Common particulates removed by plants include phosphorus, suspended solids, and particulate organic matter. Vegetation in most bioretention cells is modeled after properties of a terrestrial forest community. This includes an ecosystem dominated by mature trees, sub-canopy of under story trees, shrubs, and herbaceous plants. Plants are selected based on their tolerance to varying hydrologic or wetland conditions, and soil and ph requirements. The soil in the system contains a mixture of disintegrated material, humus, and mineral and biological complexes. Plant material growth is sustained by intake of nutrients from the solid. Woody plants lock up these nutrients for use during the seasons. Microbial activity within the soil contributes to the removal of nitrogen and organic matter. Nitrogen is removed by nitrifying and denitrifying bacteria. The decomposition of organic matter is accomplished through the work of aerobic bacteria, those that live only in the presence of oxygen. Therefore, if bioretention area is not adequately aerated a depletion of oxygen occurs, which is needed for microbial processes.

Studies have shown that properly designed and constructed bioretention cells can achieve efficient removal of heavy metals (3). Copper (Cu), Zinc (Zn) and lead (Pb) reductions of greater than 80% percent (see, Table 1) with only a small variation in results have occurred. Lead and Zinc have had removal effectiveness as high as 90% to 99%. The mulch layer is credited with having the most effect on this uptake, nearly all the metal removal occurring with the top few inches of bioretention. Phosphorus removal increases linearly with depth, reaching a maximum of approximately 80% by 2-3 feet depth. Seventy to eighty percent reduction in ammonia is achieved in the lower levels of sample cells. Nitrogen removal also depends on depth.

Table 1 Pollutants and their Removal Rates due to Bioretention

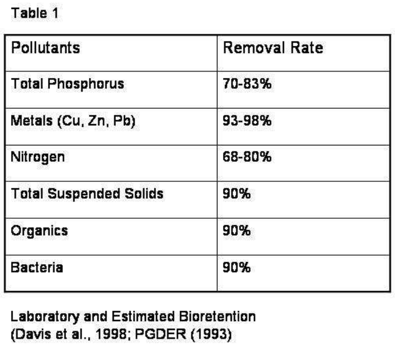

Table 1

Pollutants	Removal Rate
Total Phosphorus	70-83%
Metals (Cu, Zn, Pb)	93-98%
Nitrogen	68-80%
Total Suspended Solids	90%
Organics	90%
Bacteria	90%

Laboratory and Estimated Bioretention
(Davis et al., 1998; PGDER (1993)

3.2 Benefits of Bioretention Systems

Bioretention systems demonstrate a multitude of benefits, most importantly, the protection of ecosystem integrity. Important benefits to elements of the ecosystem protected by bioretention include:

1. Non point pollutant treatment
2. Resource conservation
3. Habitat creation
4. Nutrient cycles
5. Soil chemistry
6. Horticulture
7. Landscape architecture
8. Ecology

One primary objective of bioretention systems is to minimize post development runoff by mimicking predevelopment hydrology. Bioretention cells can reduce overall site runoff volume and help predevelopment peak discharge rate and timing through infiltration and temporarily storing runoff. Use of an under drain makes the system act more like a filter that dischargers water to a storm drain system than that as an infiltration device. The ponding capability of the cell reduces volume load on the storm drain system, reduces the peak discharge rates and results in increased ground water recharge. An additional hydrological benefit is the reduction of thermal pollution. Heated runoff from impervious surfaces is filtered through the bioretention facility and cooled. One study observed a drop in temperature of 12 degrees centigrade between influent and affluent water.

3.3 Design of Bioretention Systems

The bioretention cells should be sized to capture the pavement design storm runoff (see, Figure 1). In areas where the native soil permeability is less than 0.5/hr. an under drain should be provided. The cell should be designed to drain completely in 72 hours. Water should not be allowed to pond for more than 4 days. The ponded area should have a maximum depth of 6 inches, and the planting soil should have a minimum depth of 4 feet. The minimum depth of a bioretention cell should be 15 -25 feet. The length should be minimum 40 feet and at least twice the width. Approximately one tree or shrub per 50 feet squared of bioretention should be included in the bioretention landscape (4). The land within the area needs a gentle slope for overland flow and adequate storage. The bioretention should not be established until the watershed to which it contributes is stabilized. The major components (Figure 2) of a bioretention cell are as follows:

1. Pretreatment

An upstream pretreatment area may be needed for roads and parking lots where large volumes of debris or suspended material will be conveyed by stormwater. This may include:

   a. A grass or buffer strip to filter particles and reduce runoff.
   b. Oil and grease separators.
   c. Stilling basins.

2. Ponding area
3. A ponding area provides surface storage for stormwater runoff. It must have a maximum ponding depth and a limited duration of ponding.
4. Groundcover
5. An organic ground cover layer provides a medium for biological growth and carbon source for biological activities at the air/soil interface.
6. Planting Soil
7. A thick layer of soil located below ground cover layer supported by underlying insitu or foundation soils will provide for a deep root planting growth. The soil must have a high infiltration rate to absorb nutrients and pollutants and provide additional storage capacity for stormwater. Soil with 2.5 to 10% clay content and 1.5 to 3 percent organic content is preferred.
8. Insitu soil
9. Insitu soil provides foundation for planting soils and drains the infiltrated stormwater from the bioretention cell. If the cell drains poorly, the bioretention system will fail unless another means of drainage, like an under- drain, is established. Percolation test should be performed to demonstrate that insitu soil process at 12.7 mm/h infiltration capacity.
10. Plant material
11. Plant material acts to use nutrients, and removes water from the soil through evapotranspiration. Plant material should be tolerant of urban conditions, low maintenance, have aesthetic appeal, and be adaptable to runoff inundation. Vegetation should prosper when flooded to a depth of 0.15m (0.5ft.) or more frequent intervals.

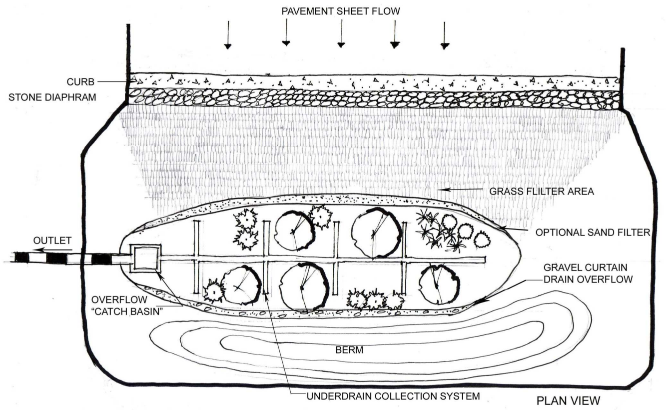

FIGURE 1 SCHEMATIC OF A BIORENTENTION CELL (MDE, 2000)

Figure 1.

Inlet and outlet controls

Inlet and outlet controls depend on whether a bioretention cell is online or off-line. An on-line facility does not have a bypass that diverts excess stormwater around the bioretention facility once it becomes full. Therefore, the inlets and outlets must be designed to ensure that the runoff rated does not damage the bioretention system. Rip rapped inlets and outlets can provide protection from erosion. Possible outlets for online areas include drop inlets or overflow weirs that feed downstream swales or pipe systems.

Offline bioretention requires smaller inlets then online facilities because inlets are designed to convey runoff from the time of runoff of the site. Without passing through the bioretention cell, all of the runoff must be diverted around the cell and downstream to subsequent swales or pipe systems. This diversion can be achieved by creating a ponding area in the bioretention cell which causes backwater conditions and a resulting shift in discharge direction.

Inlets to a bioretention system must be sized to keep entrance velocities in excess of 0.15m/sec. (0.5ft. /sec.) to help prevent clogging the inlet area.

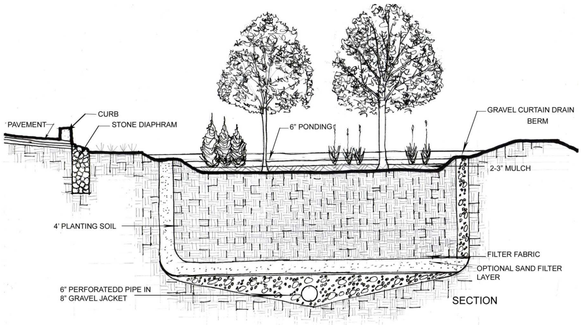

FIGURE 2 SCHEMATIC OF A BIORENTENTION FACILITY

Figure 2

3.4 Maintenance of Bioretention Systems

Inspection, repair or replacement of the bioretention area's components, is required for good maintenance. If plants were appropriately selected fertilizer, pesticide, water and overall maintenance requirements should be reduced. Through plant growth, root growth, organic decomposition, and the development of a natural soil horizon the facility's life span will be lengthened and reduce the need for extensive maintenance.

3.5 Costs

Construction costs estimates for bioretention systems are slightly greater than those that are required for landscaping of a new development. Commercial, industrial and institutional site costs can range from $10.00 to $40.00 per square foot, based on the need for control structures, curbing, storm drains and under drains. Retrofitting a site typically costs more than building a new cell, averaging $6,500 per bioretention area, due to demolition of existing concrete, asphalt, existing structures, and the replacement of fill material with planting soil (5). Bioretention reduces development costs by combining the design and construction cost of landscaping and stormwater management.

3.5 Comparisons with traditional end of pipe systems

The limitations of traditional end of pipe stormwater management controls such as ponds, wetlands in protecting water resources have been proven. While efficient in treating stormwater and reducing peak flows, they increase volume and temperature of runoff resulting in undesirable impacts on local streams and adequate life. Bioretention systems avoid some of the flow volume temperature related impacts of pond on receiving waters. Runoff flow is naturally infiltrated into the soil. This reduces the need for treatment, and eliminates the need for underground or site consuming detention facilities. Traditional end of pipe controls often take up value land. Space consumed for these facilities can be used for open space, landscaping, or other development. **B**ioretention is effective in reducing and delaying peak flows. Although bioretention cells may overflow, most runoff infiltrates into the ground or released back into the atmosphere through evapotranspiration. Installations of under drains help the infiltrated water to recharge groundwater and augment base flows in local streams. They help eliminate downstream flooding and prevent stream erosion caused by post development changes to flow patterns.

Compared to conventional systems, bioretention systems are easier to construct, and require less infrastructure and maintenance (6). The use of bioretention can decrease the cost required for constructing stormwater conveyance systems at a site.

4. Case Study

Maryland has been a National leader in stormwater management over the last two decades. The State has been motivated to protect its streams that discharge to the waters of the Chesapeake Bay, the Atlantic Coastal Bays, and the waters of the Ohio River in Garret County, Maryland (7). In an effort to increase onsite recharge and runoff reduction volumes the Maryland Department of Transportation is implementing several bioretention systems alongside highways, in medians and parking lots. Three of these are shown in Figs. 3, 4, and 5. The Edgewood Road Bioretention System in Harford County is shown in Figures 3. Two Park and Ride Facilities are shown in Figs. 4 and 5.

The State has provided limited monitoring of the effectiveness of the bioretention cells completed to date, although there are ongoing monitoring efforts. Due to the similarity between dry swales and bioretention cell, the pollutant removal capability should be comparable. The monitoring results of the bioretention cells are shown in Table 2. Determined by the composition of the planting soil and plants installed, the bioretention cells should be capable of managing some petroleum hydrocarbon concentrations typical of urban settings. If there was a high level of pollutant, loading pretreatment should be implemented.

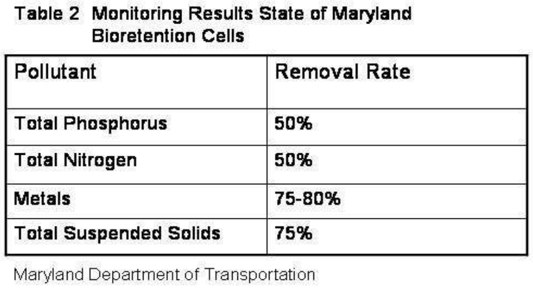

Table 2 Monitoring Results State of Maryland Bioretention Cells

Pollutant	Removal Rate
Total Phosphorus	50%
Total Nitrogen	50%
Metals	75-80%
Total Suspended Solids	75%

Maryland Department of Transportation

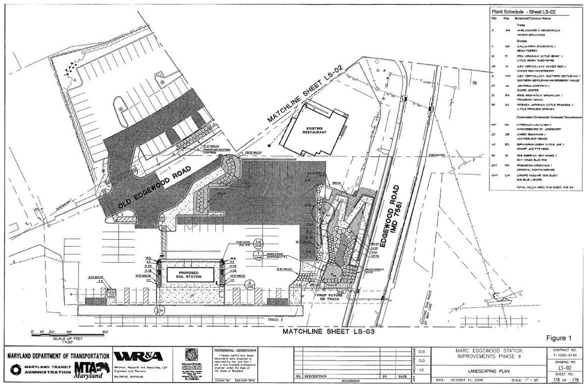

Figure 3. The Edgewood Road Bioretention Facility in Harford County

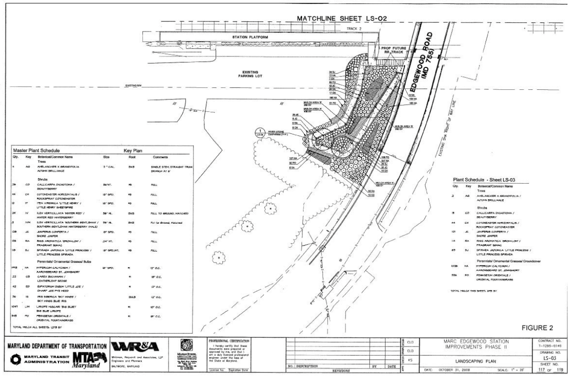

Figure 4. Bioretention Cell at a Park and Ride Facility

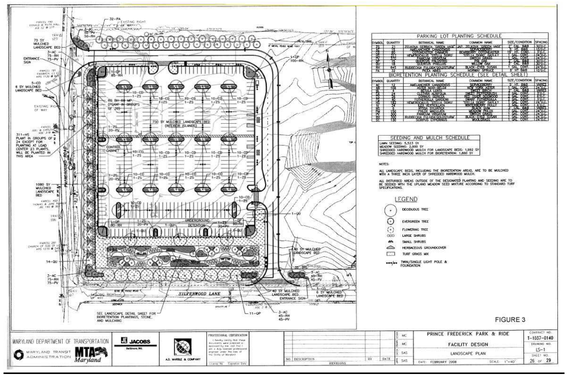

Figure 5. Bioretention Cell at another Park and Ride Facility

4.1 System Optimization Formulation

A system optimization approach will be adapted to show that the infiltration period of the bioretention cell slows down the time from inlet to outlet, which allows time for plant intake and removal of pollutants. Usually this formulation is used to describe the flow pattern resulting from each motorist's choice of the shortest travel-time route from origin to destination (8). A link performance function can be used as follows:

$$t_a(x_a) = t_a^f\left[1+\alpha(\frac{x_a}{c_a})^B\right] \qquad (1)$$

where:

t_a= Predicted runoff flow rate time on pipe a;

$a \in A$

A= A set of pipe in a given drainage network

t_a^f =Free runoff rate of flow on pipe a,

x_a =Peak runoff rate from drainage area

C_a =Capacity of pipe a

L_a =Length of Pipe a

B= Soil permeability rate for the bioretention area.

To determine the peak rate of runoff the following Rational Method is used:

$$q = CiA \qquad (2)$$

where:
q = peak runoff rate, in cubic feet per second
$\left(ft\,{}^{3}\!/_{s} \;\; or \;\; cfs \right)$
C= dimensionless coefficient (between 0 and 1)
i = rainfall intensity, inches per hour (iph) for the design storm frequency and for the time of concentration of the drainage area
A=area of drainage area

4.2A Numerical Example

The following data are given:

Drainage area: 3 ac of pavement, 3 ac of lawn, 3 min. travel time over pavement, 30 min. travel time over lawn, 2.8iph (rain fall intensity), T_c =45min. (time of concentration), C=0.3, Soil permeability rate= 0.5iph, Storm duration=20min

Calculation of Peak runoff rate:

$$q = (0.30\times 2.8\times 3.0) + (0.80\times 2.8\times 3.0)$$
$$= 2.5\, ft\,{}^{3}\!/_{s} + 6.72\, ft\,{}^{3}\!/_{s}$$
$$= 9.2\, ft\,{}^{3}\!/_{s} \tag{3}$$

Calculation of Maximum flow rate

$$q = C\times C_A \times i\times A\times Dur / T_c$$
$$q = 0.3\times 1\times 2.8\times 6\times 20/45$$
$$q = 5.04\, ft\,{}^{3}\!/_{s} \tag{4}$$

Predicted runoff flow rate using Eq. (1) and considering the soil permeability rate=0.05

$$t_a(x_a) = t_a^f\left[1+\alpha\left(\frac{x_a}{c_a}\right)^B\right]$$
$$t_a(9.2\, ft\,{}^{3}\!/_{s}) = 5.04 + \left(\frac{9.2}{.03}\right)^{0.05}$$
$$t_a(9.2\, ft\,{}^{3}\!/_{s}) = 20.37\, ft\,{}^{3}\!/_{s}$$
$$t_a = 2.2\, ft\,{}^{3}\!/_{s} \tag{5}$$

Predicted runoff flow rate considering the soil permeability rate=1

$$t_a(x_a) = t_a^f\left[1+\alpha\left(\frac{x_a}{c_a}\right)\right]$$
$$t_a(9.2\, ft\,{}^{3}\!/_{s}) = 5.04\ \left(\frac{9.2}{.03}\right).$$
$$t_a(9.2\, ft\,{}^{3}\!/_{s}) = 311.7\, ft\,{}^{3}\!/_{s}$$
$$t_a = 33.88\, ft\,{}^{3}\!/_{s} \tag{6}$$

5. CONCLUSIONS

The System Optimization (SO) approach in the above numerical example shows that when infiltration time caused by the use of bioretention is included the predicted runoff rate (t_a) is increased (Eq. (6) above). This is most likely due to the decrease in volume loss through evapotranspiration, absorption and plant uptake.

The most important technical difference in conventional facilities and bioretention system is the infiltration period which allows for absorption, plant uptake, and filtration. Bioretention faculties provide several advantages. Some of them can be listed as:

a) Varying pollutant removing mechanisms which include:
   1. Filtration
   2. Absorption to soil particles
   3. Biological up take to plants
b) Stormwater treatment that enhances the quality of downstream water bodies by temporarily storing runoff and releasing it overtime. This is due to a slow rate of flow allowing the pollutant removing mechanisms to be affective.
c) Vegetation used in bioretention provides shade and wind breaks, absorbs noise and improves the site's landscape.

d) Cost and energy savings are provided

The proposed SO approach will be applied in a underground drainage network in future works.

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