

DESIGN AND PERFORMANCE OF BIORETENTION BEDS FOR REMOVAL OF STORMWATER CONTAMINANTS

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INTRODUCTION

Bioretention basins hold a volume of water that is filtered through sandy soil and allowed to infiltrate into the subsoil or drained to an outlet (Figure 1). Originally, bioretention basins were intended as a site-scale tool to improve the quality of urban stormwater runoff, but they have a demonstrated impact on reduction of runoff volume and time of concentration. Therefore, the design of basins are complicated by a range of possible goals. Recharging groundwater, improving runoff water quality to maintain or restore aquatic ecosystem health, reducing peak storm flows, extending time of concentration, and reducing runoff volume to prevent channel erosion and sedimentation are all possible goal options. Only a few states have guidelines or regulations for bioretention basins. Furthermore, some existing state design requirements do not reflect the range of goals or the research demonstrating the design and performance of bioretention basins. For example, the Idaho Department of Environmental Quality recommendations were published in 2005 but based information from 1993 (IDEQ, 2005). The first section below considers the original purpose—pollutant removal.

KEYWORDS

rain garden, bioretention, stormwater treatment, water quality, infiltration bed

TREATING STORMWATER

Stormwater Characteristics

Stormwater runoff from areas modified from their natural conditions is polluted by various human activities. Research studies provide us with an understanding of the land uses that typically contribute high concentrations of particular contaminants (Table 1).

Other species of pathogenic bacteria, in addition to *E. coli*, are also present in high concentrations in storm runoff. Fecal coliform, total coliform, and *E. coli* bacteria are highly correlated with one another and with turbidity and suspended sediment concentrations (Peters, 2009). Most of the concentrations of nutrients, bacteria, and metals shown in Table 1 are far above U. S. Environmental Protection Agency (EPA) standards. Total nitrogen listed in

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FIGURE 1. Bioretention for treating road runoff on Sandy Blvd. in Portland, Oregon (Austin, 2011).



FIGURE 2. Open water is important for urban biodiversity and aesthetics, but pretreatment in a bioretention bed greatly reduces heavy metals, hydrocarbons, and pathogenic bacteria that road and parking lot runoff contributes to ornamental ponds (Mosberg, Glen Allen, Virginia, 2012).



Table 1 includes organic nitrogen, ammonium, nitrite, and nitrate. While there are no water quality standards for total nitrogen, concentrations of .2 mg/L for nitrite and 1 mg/L for nitrate are generally accepted maximums (Li, 2009).

It seems clear that the pollution levels indicated above would degrade stream water quality. Water quality does diminish as urban and other human uses change watersheds from their natural state. In 2003, the city of Atlanta, Georgia, developed a stream water quality monitoring network that annually gathered data from 21 stations. From 2003 to 2007, data was collected for more than 20 stream watersheds. The degree of watershed urbanization ranged from 69 to 93%. The data from urban watersheds was compared to a small forest watershed and a larger, lightly-developed watershed as references (Peters, 2009).

The study indicates that urbanization does impact stream water quality, but this impact is highly variable. Increased alkalinity and concentrations of calcium and magnesium in urban

TABLE 1. Stormwater runoff pollution concentration and land uses making the greatest contributions

Contaminant	TSS ^a	<i>E. coli</i> ^b	TN ^a	P ^a	Copper ^c	Lead ^c	Zinc ^c
Land-use							
Lawns	602		9.1	2.1			
Commercial Streets	468						
Auto Recyclers	335				103	182	520
Industrial Parking	228						
Landscaping		94,000			94	182	263
Residential Streets		37, 000		.55			
Driveways			2.1	.56			
Urban Highways			3	.32	54	400	329
Rural Highways			22				
Industrial Roofs					62	43	1390
Heavy Industrial Land					148	290	1600
Water Quality Standard	30	126		.05	13	65	120

Kadlec, 2009.

a = mg/L, b = colony forming units per 100 mL, c = micro grams. TSS = total suspended solids, TN = Total Nitrogen, P = Phosphorus

streams were thought to be associated with the weathering of concrete. High levels of chlorine were associated with combined storm and wastewater sewer outflow treated with sodium hypochlorite, as well as drainage from swimming pools and road deicing salts (CaCl_2). The fecal coliform bacteria levels exceeded the EPA standard for primary or secondary use in more than 90% of the test samples taken from urban watershed streams. Nutrient levels in streams were high compared to streams in natural areas, but lower than EPA standards.

The first flush of impervious surfaces resulted in high concentrations of copper, lead, and zinc. Copper and zinc in most of the streams exceeded Georgia's chronic and acute standards (chronic levels damage aquatic organisms when exposure exceeds 4 days, acute levels damage aquatic organisms when exposure exceeds 1 hour). Lead was detected at chronic levels. These metals are common in highway runoff and industrial land use. Vehicle tire particles and decayed metal fittings used in building construction are the common sources of these metals. Cadmium exceeded state standards only in a small percentage of tests.

Removal of Contaminants

Vertical subsurface flow (VSF) constructed wetlands developed to treat domestic sewage are the model for the design of bioretention basins. In bioretention basins stormwater filters vertically through a sandy substrate, fully saturating the filter material, and even ponding on the surface temporarily before infiltrating into the subsoil or being drained by pipes below the bed. Like the VSF wetland, bioretention beds are intended to dry (and renew their oxygen content) between storms. Filtration, chemical, and biological processes all contribute to the removal of contaminants in the stormwater. Suspended solids in stormwater (as high as 602 mg/L, according to Table 1) are very effectively filtered by the soil media. Removal of suspended solids is important since heavy metals and pathogenic bacteria attach themselves to

even very small particles. Beneficial bacteria in the soil filter are responsible for the consumption of organic material and the conversion to ammonia, nitrite, and nitrate before removal as nitrogen gas. Soil bacteria are also major agents in the removal of pathogens. Chemical characteristics of the soil media may cause ammonia and phosphorus to be retained. This full set of treatment processes makes the bioretention basin much more effective in the removal of contaminants than detention or retention (wet pond) stormwater basins (Figures 2, 6 and 7). In fact, typical stormwater basins have little, or even a negative, water quality improvement benefit (Davies, 2001; Mallin, 2002; Hathaway, 2009). The example below illustrates the water quality improvement data from one monitored bioretention basin (Table 2).

The bioretention basin was constructed at the Hal Marshall Municipal Services Building in the City of Charlotte, North Carolina, to treat 1" (25.4 mm) of rainfall (the 2 year, 24 hour storm is 3.36"). The bioretention cell received water from a .92-acre (.37 ha) parking lot. The surface of the infiltration bed was 2,480 ft. (229 m²), which represents 6% of the catchment area. The bed was composed of a 4' (1.2 m) depth of loamy sand (silt/clay = 5.7%) with a 6" diameter corrugated under-drain. The soil permeability was .43 in/hr and the basin was planted with a variety of water tolerant species (see Figure 3 for a section of a typical bioretention basin). The bioretention bed reduced contaminants significantly with one exception (Table 2). The low total nitrogen removal was due to low organic matter in the runoff (Hunt, 2008).

The increase in nitrite and nitrate to .43 mg/L indicates that the bed provides aerobic conditions for the conversion of ammonium to nitrite and nitrate. However, the removal of nitrate requires an oxygen-depleted environment that is not a feature of this design. A very similar bioretention bed was installed in Greensborough, North Carolina, but the bottom 2' was saturated with water to form an anaerobic zone. This bed performed better, with nitrate removal at 75% and total nitrogen removal of 40%. It is important to remove nitrogen from stormwater since it is toxic to aquatic organisms, causes algae blooms in lakes and the ocean, and is a human health risk in drinking water. The EPA drinking water standard for nitrate is 1 mg/L, but it is harmful to newborn babies at much smaller concentrations.

A University of New Hampshire bioretention basin featured TSS removal of 99% and zinc removal of 99%, which is better performance than the basin data shown in Table 2. The New Hampshire study also reported total hydrocarbon removal of nearly 60% for a 30" deep filter bed and 99% for a 48" deep bed (UNHSC, 2007).

The North Carolina studies recorded performance below optimum levels compared to the results of a laboratory experiment that tested 125 biofilter configurations that varied the plant,

TABLE 2. Charlotte, NC Bioretention Basin Water Quality Performance

Pollutant	Removal	Pollutant	Removal
Total Nitrogen	32%	Fecal Coliform Bacteria	69%
Total Kjeldahl Nitrogen	44%	<i>E. coli</i>	71%
Ammonium	73%	Zinc	77%
Nitrite and Nitrate	-5%	Copper	54%
Total Suspended Solids	60%	Lead	31%
Biological Oxygen Demand	63%	Iron	330%
Total Phosphorus	31%		

Source: Hunt, 2008

filter media, media depth, and pollutant concentrations typical of urban stormwater. The significant difference in the best performing biofilter was the presence of *Carex appressa*, which is characterized by deep and fine roots. Under various media and flow conditions, the biofilter removed 99% of TSS, 93% of ammonium, 85%–96% of nitrite and nitrate, 71%–79% of total nitrogen, 93%–96% of total phosphorus, and 87%–98% of particulate phosphorus. Lessons from the study are to use sandy loam as the media, avoid compost or mulch in the media, since this increased total phosphorus in the effluent, and to use plants that are known to remove ammonia and nitrate at accelerated rates (some plants actually increased total nitrogen and nitrogen species in the effluent). The biofilter performed to these standards when sized at 2% of the drainage area (for Melbourne, Australia's climate) (Bratieres, 2008). This study suggests that significant improvements in water quality are possible as the design and construction of bioretention basins are refined.

A second study of the Charlotte, N.C., bioretention basin described above found significantly reduced fecal coliform bacteria (89 %) and *E. coli* (92%). The bioretention basin outflow met EPA recommendations for primary recreation contact for *E. coli* and nearly met the standard for fecal coliform bacteria concentration (Hathaway, 2009). Drying of the soil between storms reduces pathogenic bacteria. Since drainage through the soil media is rapid, even the temporary pool above the soils drops about 1" per hour after a storm. High oxygen levels return to the soil volume quickly and drying is due, in part, to evaporation and transpiration from bioretention beds (Hunt, 2008).

A laboratory-scale study demonstrated 84%–100% removal of the common pesticide, atrazine, in bioretention systems with and without an anaerobic stage (Yang, 2010).

Phosphorus removal in bioretention basins is generally poor, ranging from 5% to 30%. Mulch in the filter media and sands or gravel high in phosphorus cause low removal rates, or sometimes an increase in phosphorus in the outflow. Sedimentation and adsorption are the primary removal mechanisms for phosphorus. Using media with high levels of calcium or magnesium results in good removal of phosphorus, at least in the short term. Eventually the adsorption sites will be filled and removal rates will drop. More research in this area is required. A land farming system in Oregon is producing excellent phosphorus removal from wastewater effluent. This method might be adapted to the site scale under certain soil conditions.

Stormwater Management with Bioretention Basins

The Charlotte, N.C., bioretention basin described above was designed to capture storms of 1" or less. However, for storm volumes of 1.65" (42 mm) the peak storm outflow was decreased by 96% even though the entire catchment area was impervious. During the study, the mean storm was 1.08" (27.4 mm) and the median storm was .95" (24.1 mm) (Hunt, 2008). This performance is confirmed by a study of a bioretention basin constructed at Villanova University in Pennsylvania. Its catchment area is 50,000 sf and is 52% impervious. The 4' deep infiltration basin consistently removes 50%–60% of the storm runoff from the surface waters. In fact, for storms 1.95 inches and less there was rarely any outflow from the basin at all. This is partly because there is infiltration into the subsoil during the entire storm. Even during a 6" storm the retention basin reduced the storm peak (National Research Council, 2009). A University of New Hampshire bioretention basin, comprised of a 30" depth of sandy media, and a 16" depth of gravel below the media, displayed an 82% reduction in peak stormwater flow and a 92 minute delay in the storm peak (UNHSC, 2007).

The agency with stormwater management jurisdiction will set the requirements for stormwater runoff detention or retention in relationship to predevelopment runoff rates and volumes. Bioretention basins are most often used as site-scale elements instead of watershed-scale measures. Therefore, small basins that are practical for residential and commercial lots are emphasized. Added interest in the recharge of groundwater may add requirements that some post-development runoff is to be infiltrated to meet predevelopment infiltration rates. For example, a wooded site slated for low density residential development might typically have a predevelopment curve number of 55 (based on the US Natural Resources Conservation Service TR-55 runoff calculation method) and a post-development curve number of 70. An infiltration of .22 inches of runoff volume would be required in the developed landscape to meet predevelopment conditions for a 2" storm. Over a 1/2 acre site this would equal approximately 400 cubic feet for a 2" storm and could be accommodated in 20' × 20' bioretention basin (DER, 2007).

DESIGN CRITERIA

Design standards for bioretention basins are either unavailable or outdated in most states. Initially, guidelines were established based on very little research data and a limited set of goals. Monitoring of installed bioretention basins over the last 10 years provides more reliable criteria, installation requirements, and performance expectations (Davis, 2009).

Basin

The area of bioretention basins is typically 5%–8% of the catchment area, but the size varies with the regional rainfall character, the catchment imperviousness, and stormwater goals set for the basin. Suggested maximum widths for bioretention basins (25') are based on the ability to excavate the basin with heavy equipment located outside the basin in order to avoid compaction of the bottom soil. The width could be expanded with post-excavation measures such as ripping the soil or installing boreholes or infiltration trenches (Brown, 2009). The basin includes a portion above the surface (Figure 3) to temporarily pond 70%–75% of the water quality storm. The maximum depth of ponding is a matter of some debate. Most states with regulations set surface pond depth between six and eighteen inches. If the filter media and subsoil have a high infiltration rate, or the basin has an under-drain, then the deeper surface pond is more acceptable. The level of the surface pond should drop at about 1" per hour.

A six- to twelve-inch freeboard above the maximum water level is necessary. The surface of the basin should be covered with three to four inches of wood chips or other mulch. This appears to be particularly important if hydrocarbons are targeted for removal since bacteria in mulch rapidly decompose absorbed hydrocarbons, such as toluene and naphthalene (Davis, 2009). The basin should be deep enough to contain 24" to 48" of sandy filter media. Underneath the filter media, a 6"–16" depth of sand or gravel is sometimes specified to be improve infiltration. However, this is probably not beneficial for a correctly designed and constructed basin. Metals and suspended solids are reduced significantly in the top 8" (20 cm) of the media, which is where much of the pathogenic bacteria are removed also. However, removal of hydrocarbons, total nitrogen, and phosphorus seems to benefit by media depths of at least 30" (Davis, 2009).

When the subsoil has an infiltration rate below .5 inches per hour (in./h), an under-drain in a bed of coarse gravel (1–2" dia.) is recommended (Figure 4). As a transition layer to pre-

FIGURE 3. Bioretention Basin. A. Earth berm with spillway or piped overflow. B. 6"–18" ponding depth. C. 4" wood chip mulch. D. Sandy loam filter media. E. Scarify basin base. F. Existing uncompact subgrade with infiltration of .5 inches per hour. 2' minimum to high water table surface.

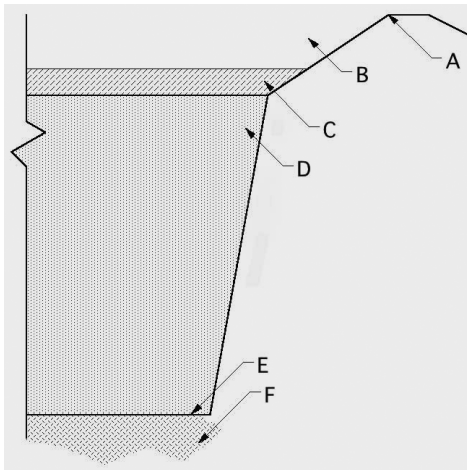
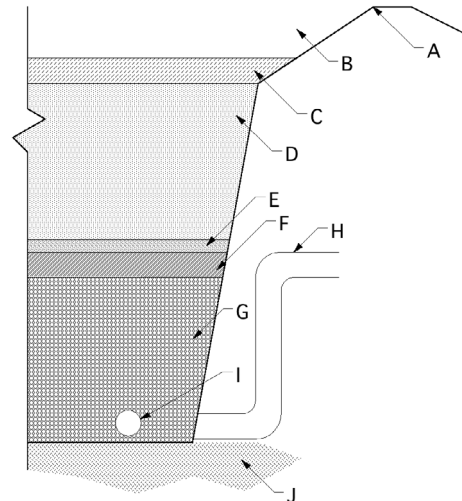


FIGURE 4. Bioretention Basin. A. Earth berm with spillway or piped overflow. B. 6"–18" ponding depth. C. 4" wood chip mulch. D. 24" sandy loam filter media. E. 2" coarse sand layer. F. 4" pea gravel layer. G. 24" layer of 2" dia. drain rock with waterproof liner. H. 4" dia. PVC drain. I. 4" dia. perforated PVC under-drain. J. Existing subsoil.



vent media wash out, the coarse gravel should be separated from the filter media by a 2"–4" layer of 1/4" dia. gravel (pea gravel). Some installations even include a coarse sand transition between the filter media and the pea gravel (UNHSC, 2007).

A bucket with teeth should excavate the final 12" of the basin, in order to limit compaction of the basin bottom. Research shows that infiltration into loamy sand subsoil is 2.6 in./h when the basin is dug with a rake bucket compared to 1.2 in./h for a basin dug with a flat edged bucket. This translates into a basin drawdown of 12 hours and 27 hours for the rake and flat edge bucket, respectively. Similarly, infiltration will be higher if the basin is dry when dug (Brown, 2009).

Filter Media

Originally the bioretention basins were planted with a mix of shrubs, ground cover, and trees to resemble a native forest. Concern that using coarse sand or gravel, as in a vertical subsurface flow wetland, would be too infertile and dry too quickly, led to initial specifications for loam soil. This caused the bioretention basins to clog quickly, as did the use of filter fabrics to separate the media layers in the basin (UNHSC, 2007). Most specifications today require 80 to 88% sand for the main filter layer. Small amounts of shredded bark, mulch, and loam soil are generally specified, but fines (silt and clay) are limited to 7%. However, an effective bioretention basin with a sandy clay loam soil (54% sand, 26% silt, 20% clay) and 12.2% of organic matter performed better in removal of most pollutants than a basin with sandy loam soil (80% sand, 13% silt, 7% clay, 5.7% organic matter). In this study, performance testing over 14 months began only one month after the basin was completed, so the long-term infiltration

rate is not known. Compost should be used with caution since it can increase the amount of nitrogen and phosphorus in the outfall. Specifications should require that all gravel be triple washed and media with a low phosphorus index should be used. A bioretention basin at Villanova University in Pennsylvania has been in operation for seven years with no reduction in the infiltration rate. The filter media in this basin is composed of 50% sand and 50% existing site soil (National Research Council, 2009).

Subsoil

Infiltration of water treated in a bioretention basin may be desirable for groundwater recharge, to maintain base flow in the soil, or to reduce stormwater runoff volumes. Where groundwater recharge is implemented, high water quality should be achieved before infiltration. Nitrates are poorly removed from bioretention basins constructed without a water impoundment below the media (see Figure 4 for a section of a basin with a flooded storage zone, F and G). Nitrates are also not held in the soil and therefore are likely to drain into groundwater, especially if it is within several feet of the surface. Therefore, agricultural drainage areas, brownfields, or industrial land uses are poor locations for bioretention basins with infiltration due to elevated levels of nitrates or toxic chemicals.

If infiltration is desired, then the character of the soil below the bioretention basin is important. Generally, a subsoil infiltration rate of .5 in./h is required to drain the saturated basin. The saturated hydraulic conductivity of loam is .52 in./h, while for silty loam and sandy loam it is .27 in./h and 1.2 in./h, respectively. Hydraulic soil groups A and B, as defined by the U.S. Natural Resources Conservation Service, are most suitable, but silty loam soil (type C) might be suitable under certain design conditions. A temporary pond 13" deep in a bioretention basin will be eliminated in 48 hours if the subsoil is a silty loam, while in a loam soil this takes only 24 hours. A sandy loam soil will draw down 24 inches of ponded water in 24 hours. It is important to reduce the standing water in the bioretention basin rapidly so that capacity is available for storms occurring at short intervals. However, an excessive infiltration rate of more than 3 in./h is not desirable, since this reduces treatment time and also indicates a soil unsuitable for most plants. If .5"–1" of water from every storm is infiltrated to recharge groundwater, this typically meets or exceeds predevelopment infiltration rates (Davis, 2009).

Under-drains

Under-drains are used when the infiltration rate of the native soil is less than .5 in./h, or when the groundwater is seasonally within three feet of the bioretention basin bottom. When there is limited infiltration, perforated, polyvinyl chloride (PVC) pipe in a coarse gravel drainage layer discharges the treated stormwater to the surface waters.

When reduction of nitrate is an important goal, then a permanently saturated 24" deep layer of gravel is included below the main filter media. This creates an anaerobic zone that encourages the growth of bacteria that use carbon instead of oxygen as an energy source. In the process nitrate is converted to nitrogen gas that escapes to the atmosphere. In Figure 4, the elevated discharge pipe, H, will cause water to be retained in the gravel beds, F and G. Inflow from the subsequent storm causes the retained water to be discharged. Therefore, a volume of water is held for longer treatment. Within about one hour oxygen in the retained water will be depleted by organisms, creating anaerobic conditions that are suitable for denitrification of nitrates by bacteria. This is the final step in a complex sequence including organic matter > ammoniaification > nitrite > nitrate > denitrification > nitrogen gas.

Where organic matter, ammonium, or nitrates are at high concentrations, such as in agricultural runoff, solid carbon (wood chips) in a horizontal subsurface flow bed has proven to be very effective for removal of nitrates (Schipper, 2010). A laboratory study demonstrated an 87% reduction of nitrate when carbon was added to the media of a saturated biofilter (Yang, 2010). This is a topic requiring additional research.

Pretreatment

The failure of bioretention basins is most often due to construction errors and clogging of the filter media. Therefore, a sedimentation basin, swale, or tank is recommended to remove as much sediment and suspended organic material as possible. The recommended 70%–75% storage of the water quality storm in the pond above the bioretention basin can include the temporary storage in the sedimentation pool. The use of a wide grass filter strip that was initially required by some states was related to the single circumstance of basins along roads and is generally not necessary.

CONCLUSION

Bioretention basins can be positive contributors to the aesthetics and biodiversity of cities if native plants are used thoughtfully (Figure 5). Achieving these secondary benefits is important for acceptance by the homeowner or developer. Bioretention basins are effective landscapes for the treatment of pollutants, stormwater management and groundwater recharge. The basin design must be adapted to site conditions and the primary implementation goal, but are more effective than stormwater detention and retention basins (Figure 7). Lower than desired removal of nitrates, phosphorus, and chloride require design modification or additional treatment methods. Use of a saturated volume within the bioretention basin improves nitrate removal. Even higher performance might be achieved (as it is in the treatment of wastewater) if a sequence of treatment stages is implemented (Langergraber, 2009). This might be configured as a lined aerobic bioretention basin followed by a lined anaerobic horizontal subsurface wetland and then an infiltration bed (Austin, 2010).

FIGURE 5. A sequence of bioinfiltration basins separated by check dams clean water from a school parking lot (Austin 2011).



FIGURE 6. In contrast to wet ponds, bioretention basins require a sedimentation forebay or a nearly flat turf slope to intercept sediment and suspended solids to prevent clogging of the infiltration surface. (Mosberg, Glen Allen, Virginia, 2012).



FIGURE 7. Wet ponds (retention basins) provide more stormwater treatment than detention basins since a volume of water is held until the next storm replaces it. However, the absence of emergent macrophytes or submerged plants reduces the treatment effectiveness dramatically. (Mosberg, Glen Allen, Virginia, 2012).



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