

Stormwater; Infiltration, Treat and Use It: Its Time to Stop Giving It Away

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Abstract

The time has come to think of stormwater as a resource to be conserved and saved for future use instead of a waste product to be discharged into our streams, rivers and estuaries. This resource can be managed to minimize runoff, and to replenish our depleted groundwater. Properly managed stormwater can greatly improve the quantity and quality of water available for society. Historically, stormwater has been captured and stored to attenuate the flood peak, and within hours released, thus removing runoff to the downstream watershed. Recent work at Penn State has opened the door to a different way of looking at stormwater. Ten years of sedimentation basin research has resulted in an understanding that sediment laden runoff from most earth disturbance sites can be infiltrated, thus reducing the sediment and water load to our rivers and streams, as well as enhancing our local water supplies. Our Green Roof project has confirmed that by adding extensive green roofs to the flat (and nearly flat) tops of our buildings, we can retain up to 54% of the annual rain that falls. Finally by directing runoff from impervious surfaces (roads, parking lots, etc) into BioRetention Areas (Rain Gardens), the first flush (up to the first 1.0 inch of runoff) from every storm can be treated and, in over 60% of our soils, infiltrated and added to the local water supply. From the assessments we have done, these three BMPs alone can greatly reduce, if not eliminate the need to stormwater basins.

A New Look at Stormwater

Until recently stormwater has been viewed as unnecessary or unwanted water that needed to be disposed of by dumping it into our streams and encouraging its disposal into the nearest river or estuary. In other words “get rid of it”. Thus the focus of stormwater management since the early 1900s has been to build big dams and temporarily store just enough of the stormwater so the peak rate of runoff could be attenuated to the point where economic damage would be minimized. In recent years, this concept was redefined from using large regional dams to requiring the use of small local basins to attenuate the runoff from each individual site as it was developed. But the goal remained the same, get rid of this unwanted stormwater as quickly and efficiently as possible.

Times have changed. The Commonwealth of Pennsylvania and the Susquehanna and Delaware River Basin Commissions are realizing that when we quickly and efficiently dispose of stormwater we are also quickly and efficiently getting rid of the very water that we wish we had to drink, water our cattle, irrigate our crops and gardens, wash our cars and more. We have begun to realize that water flowing down the local stream and river is water we should have been working extra hard to keep for a “non”-rainy day. There is often a direct connection of impervious surfaces, serving as “stormwater superhighways” that quickly conveys stormwater and associated pollutants to receiving streams. Increased stormwater runoff introduces many undesirable effects including:

- 1) More flooding during storm events and less groundwater during dry weather periods,
- 2) Increased land erosion rates and subsequent deposition in streams or flood plains of eroded particles,
- 3) More streambank erosion resulting from higher stream velocities,
- 4) More chemicals and metals deposited by vehicles and equipment, eventually reaching streams,
- 5) Nutrients, such as nitrogen and phosphorus, have easier access to natural water bodies by being carried along by this “efficient” highway,
- 6) Increased numbers of potentially harmful bacteria and other pathogens entering the waters, due to humans, pets, and wildlife whose habitat is reduced, and
- 7) All the pollutants, from sediment to toxic chemicals to bacteria, have a harmful impact on plants and animals living in or near streams, lakes, and estuaries.

Fortunately, there are techniques that minimize flooding, erosion, metals, nutrients and bacteria from entering the runoff waters. These measures are often called stormwater Best Management Practices (BMPs). BMPs can include relatively simple changes in homeowner actions such as annual lawn aeration and proper application of fertilizer; others involve source reduction through site design or mitigation measures implemented by planners and designers such as riparian buffers. Still other BMPs are structural. The most well known structural BMP is the stormwater detention basin. Many others used to treat stormwater include stormwater wetlands, sand filters, grassy swales, and, more recently, bio retention (rain gardens). These BMPs tend to disrupt the “stormwater superhighway” allowing for infiltration and retention of the stormwater.

So the question emerges, “What new concepts can we implement to better capture and harvest stormwater?” and “What can be done to make this newly captured stormwater as clean as possible?” This paper will review several conceptual design concepts for managing stormwater. It must be remembered that to minimize the economic impact of stormwater, we still need to store or detain this water so the peak rates can be properly attenuated. But the focus needs to be on finding ways to capture and infiltrate this water instead of detaining and releasing this valuable resource.

Selecting an appropriate BMP is dependent upon many factors including available land and its associated cost, homeowner and community attitudes, topography, sources of pollution, soil type, watershed size, land cover, and types of pollutants. In areas where land is limited,

aesthetics are an important concern of the community (or homeowner), nuisances should be avoided at all cost, and “childproof” safety is required, sediment basins that become bioretention areas (rain gardens) and green roofs may prove to be valuable stormwater BMPs.

Sediment Basins

Sediment basins are still, and should remain important “during construction” stormwater BMPs. The goal of sediment basins is to capture construction site sediment laden runoff and detain it long enough for gravitational settling to treat the water before discharging it to the uncontrolled environment. Recent work by Bidelspach and Jarrett (2003) has shown that it is often possible to design and manage sediment basins in such a way that all runoff events smaller than 5-year return period events (PA regulations) can be entirely captured in the basin. Following these storms the basins can be left to dewater by infiltrating the sediment laden water into the bottom of the basins, thus (1) enhancing the local ground water supply, and (2) removing all of the sediment. Questions have been raised about whether water can effectively be infiltrated through the sediment impounded in the bottom of sediment basins. Our data over the past 10 years of research has shown that most sediment leaving construction sites is made up of small aggregates, which contain clay- and silt-sized soil particles. In the absence of free suspended clay there appears to be little or no occurrence of basin sealing. The other concern that might realistically be raised is how long should water be left in a basin to infiltrate? Based on the work of Bidelspach and Jarrett, basins with reasonable Length:Width:Depth ratios will dewater a basin-filling storm in not more than seven days if the soil has an infiltration rate in excess of 3 mm/hr. When soil infiltration rates are less than this value, other approaches should be employed. In cases where larger runoff events occur, the work of Rauhofer et al. (2001) has shown that water expelled from a sediment basin’s broad-crested auxiliary spillway results in a sediment retention efficiency of at least 80%.

Thus the proper design, construction and management of sediment basins can accomplish several important water management objectives: encourage the infiltration and potential recharge of all (or at least most) during construction runoff; and improve runoff quality by capturing essentially all of the sediment leaving the construction site.

BioRetention Areas

Pioneered in Prince George’s County, MD, rain gardens are designed to be landscaped areas that treat the first flush of stormwater runoff from impervious sites. The garden is a shallow depression that temporarily holds the first inch of runoff water from an impermeable area, such as a parking lot or roof. The trees and shrubs selected to grow in the rain garden must be water tolerant. Rain gardens can be installed in a variety of soil types from clayey soils to sands. A typical rain garden is shown in Figure 1. Rain gardens can vary



Figure 1. Typical rain garden. in size and be installed in a corner of your lawn, placed along the edges of roads, or in the medians of parking lots. The size and design of the rain garden

depends upon the area it drains and the type of soil in which the garden is placed. It is well documented that this first flush contains a large portion of the pollutants that leave an impermeable area during each rain. In a rain garden, the first flush is captured, infiltrated into the soil profile, where it is treated and released to the local ground or surface water. When soil percolation rates permit, these treated waters are recharged to the local groundwater. In the rare cases when a rainfall event produces more than one inch of runoff, the runoff in excess of one inch is diverted to the local surface water or stormwater system.

The Design Process

In sandy, highly permeable soils the rain garden should be located where it can receive water from the impermeable area(s). Areas with seasonally high water tables should be avoided. The rain garden is a small depression with a maximum depth of between 9 and 12 inches. This 9- to 12-inch depth will receive up to a 6-inch depth of runoff from the area because the rain garden should be one-sixth of the area of the impermeable surface. Thus the one-inch first flush will fill an area $1/6^{\text{th}}$ its size with six inches of runoff. It is important that a discharge pathway be created to channel excess runoff water away from the rain garden. It is important that a high degree of vegetative diversity exist in the rain garden.

When it rains, the runoff from the impermeable area flows to the rain garden. The one-inch first flush will fill the rain garden to a depth of six inches. If the rain event has a depth greater than 1.0 inch, the runoff in excess of this first flush will exit the rain garden via the overflow structure. This water may require capture and attenuation depending on the stormwater regulations of the municipality. The first flush, now ponded six inches deep in the rain garden, will slowly infiltrate into the organic matter enhanced soil of the rain garden over the next 6 to 24 hours. If the natural soil is as or more permeable than the soil in the rain garden, this treated water can be left to continue to percolate downward toward the groundwater. If, on the other hand, the natural soil is less permeable than the soil in the rain garden, the treated water will be captured by an under drain system and channeled to the surface water or a stormwater detention basin.

Permeability greater than 0.20 inch/hour. When the least permeable layer of the natural soil below the rain garden has a permeability greater than 0.20 inches/hour, the water percolating through the rain garden will simply continue to percolate downward toward the groundwater table. No under drain system should be needed.

Permeability slower than 0.20 inch/hour. When the least permeable layer of the natural soil below the rain garden has a permeability slower than 0.20 inches/hour, the water percolating through the rain garden will pond on the interface between the rain garden soil and the natural soil below. In this case it will be necessary to design and install an under drain system at the rain garden-natural soil interface to collect the treated water as it passes through the rain garden. This under drain system must outlet this water to the downstream channel or a stormwater detention basin.

Rain Gardens are not intended to be wetlands. They are designed so that the soil is not regularly saturated or the garden is not inundated for long periods of time. Therefore, rain gardens are too dry for many obligate wetland plants, such as cattails, common reed, and water lilies to survive. Conversely, rain gardens are designed to receive stormwater runoff; therefore, the vegetation must be able to withstand brief periods of water inundation. Typically, neither obligate wetland nor obligate upland vegetation is appropriate for rain gardens.

Organic mulch should be added to the rain garden as needed. This keeps up the appearance of the rain garden (minimizing weeds) and continues to provide a key water quality function. During drought times it may be important to water the garden. As with any garden, the more care given, the more able the plants will be to survive. It is reasonable to assume that vegetation will need to be replaced every 10 years, but this is not verifiable.

Impact of Rain Gardens

Rain gardens have been shown to have a dramatic effect on the stormwater regime of developed sites. Assuming rain gardens are used to collect and treat the first flush from all impermeable surfaces (roofs, parking, roads, etc) on the site, it has been shown that rain gardens alone can satisfy the stormwater attenuation expectations of most municipalities. The small storage of the rain garden delays the outflow peak and attenuates it to the level of the pre-development peak.

Green Roofs

Another BMP that is relatively new and has been shown to provide considerable reduction of the volume of stormwater leaving a developed site is green roofs. Extensive green roofs are a surface treatment for rooftops, typically less than 150 mm in depth, involving the addition of several layers of growth media and plants to create a contained green space.

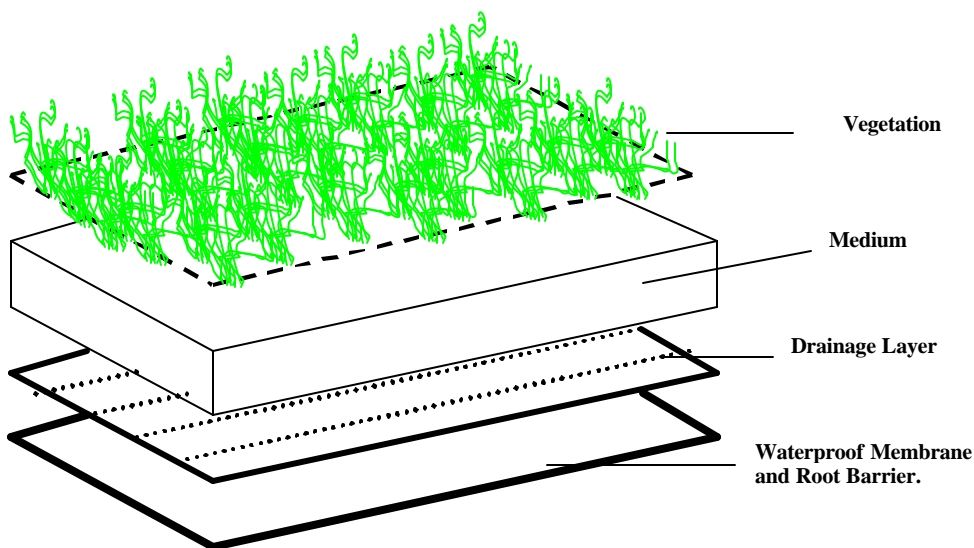


Figure 2. Green Roof Profile.

The stormwater benefits offered by green roofs include increasing the time of concentration, delaying the runoff peak, and decreasing the peak rate of runoff from the site. These benefits, in combination with the limited open space in cities, make green roofs a practical method for easing the pressure on storm sewer systems.

Roof-Layer Properties

DeNardo et al. (2003) showed that the drainage layer has an average porosity of 78% and a field capacity of 5.2%. The growth medium had an average porosity of 55.3% and a field capacity of 33.6%.

Roof Response for Runoff

Figure 3 shows cumulative rainfall and runoff curves for the rain event of October 25, 2002. The October 25, 2002 event had a cumulative rainfall total of 23.9 mm (0.94 in).

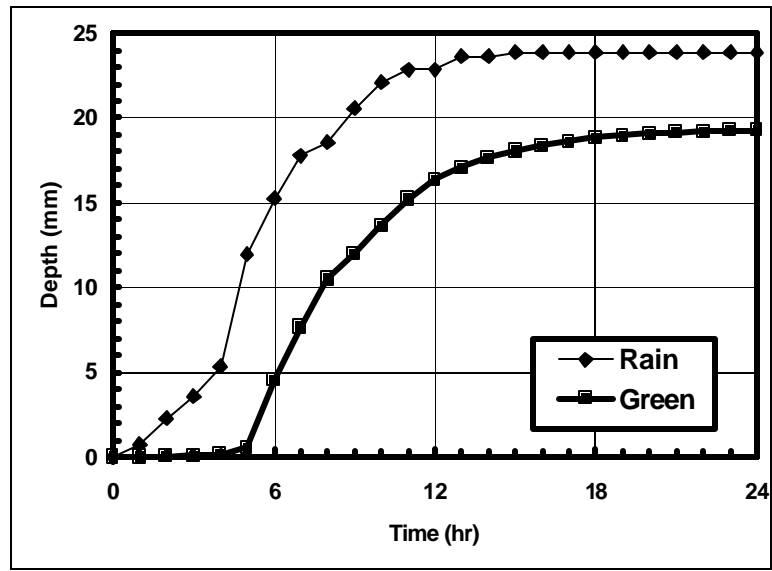


Figure 3: Rainfall and roof response for October 25 storm.

The average cumulative runoff from the green roofs averaged 19.2 mm (0.76 in) as millimeters of depth on the roof. During this storm, which occurred six days after the previous storm, 4.6 mm of the rain (19%) was retained within the layers of the green roof. Figure 3 also clearly shows a delay in the response of the green roof. A period of four hours passed between the start of the rain and when the green roofs began to yield measurable runoff.

Table 1. Summary of green roof stormwater responses.	
Parameter	Average Response of 7 Oct, Nov, 2002 Storms
Period since last storm	4 Days
Rainfall depth	19.7 mm
Maximum rainfall intensity	4.3 mm/hr
Runoff depth	13.2 mm
Maximum runoff rate	2.4 mm/hr
Maximum runoff rate	56%
Depth retained	6.5 mm
Percent retained	45%
Maximum depth detained	3.8 mm
Delay to start of runoff	5.7 hrs
Peak rain to peak runoff	2 hrs

The important average results from each of the seven storms evaluated during the period of October to November 2002 are shown in Table 1. It should be noted that the green roofs were able to retain an average of 6.5 mm of the rain from each storm. Based on the laboratory determined water retention capacity of 34% for the media used on these green roofs, we can expect the maximum retention for this 89-mm thick green roof to reach as high as 30 mm for any given storm. This assumes the plants have transpired all available water from the media and that evaporation has removed most of the remaining moisture.

Other Stormwater Management BMPs

Any management activity that increases the soils ability to infiltrate rainwater, will reduce the watershed's stormwater response. Requiring that all homeowners aerate their lawns every year has the potential to reduce the SCS Curve Number for the post-development condition from the currently accepted 55 to 75 down to even 15 or 20. Having homeowners capture roof runoff into barrels for lawn and garden watering will have a small impact on stormwater.

Summary of Stormwater BMP Impacts.

Sediment Basins (SB): Based on data for PA, 100% of all earth disturbance site runoff can be infiltrated for storms up to about 5-year return period events on at least 60% of our soils. The differential runoff volumes larger than the 5-year events will have at least 80% of the sediment removed.

BioRetention Areas (BRA): Based on a 6:1 ratio of impervious surface area to BRA, the one-inch first flush of all treated areas can be treated and infiltrated. Storm volumes greater than one inch will be diverted to streams.

Green Roofs (GR): Based on the work of DeNardo et al. (2003), up to 30 mm of rain can be retained on an 89-mm thick roof. Remaining rain runs off, but is delayed several hours and the peak runoff rates are attenuated 56%.

New Approach to Stormwater

It is difficult to figure out what happens when we begin to implement some of these BMPs. To get a better sense of the overall impact a green roof can be expected to have on a specific areas stormwater response a simple check-book model of the water retention capacity within the green roof media was created. By applying the actual daily rainfall totals for the Centre County, PA area of Pennsylvania, the water remaining in the roof media was determined every day after removing water for ET losses and adding any rain. This model used an estimate of monthly ET, which was divided by 30 days/month to yield an average daily ET rate. This model was applied to the daily rainfall record for nine years of readily available data. The results for this simulation are shown in Table 2 for each year simulated.

Of the nine years of rainfall data applied to the green roof with 89 mm (3.5 in) of media, the green roof was able to retain from 48 to 66% and averaged 55% of the annual rain. This simulation accounted for the actual period (number of days) between each rainfall event and it

assumed that ET was removing water at the rate estimated for the month in question. This simulation included all 12 months of each of the nine years. Therefore, there is substantial evidence that green roofs alone can capture and retain about 55% of the annual rainfall.

Table 2. Summary of model showing retention from a green roof and bioretention area in Centre County, PA.

Year	Rain (mm)	Retained On Green Roof (%)	Retained In BioRetention Area (%)
1983	1117.6	47.8	91.0
1984	1251.0	52.0	83.2
1985	996.4	56.5	89.2
1986	1105.4	53.7	91.4
1988	942.6	57.0	85.5
1989	1077.0	54.4	92.6
1990	1248.4	46.6	92.2
1992	817.4	65.3	98.0
1993	938.8	51.9	86.3
Average =	1055.0	53.9	89.9

The same check-book modeling approach was applied to bioretention areas. The assumption was made that the first inch of rain on any day would be captured and infiltrated into an appropriately designed and installed bioretention area. The same rainfall records were applied to these BRAs. If we assume all of the captured runoff (one inch of runoff from an impervious area this is equivalent to a ponding of six inches of water in the BRA) will infiltrate in the 6- to 24-hr period following the storm, the BRAs were able to capture and infiltrate an average of 89.9% of the annual rain, Table 2.

If we were to assume the runoff from the green roofs was channeled to a bioretention area instead of into a local stream or stormwater conveyance system, the combined retention was (using the same daily rain described above) 95%.

A Closer Look

The question every land developer is asking is “what does this mean?” Does this mean we can get rid of stormwater detention basins? Extrapolating the results shown in this paper to any specific development site requires that the design rain events be applied to each BMP or combination of BMPs. The analysis shown above was based on daily rainfall totals. There was no attempt to include travel times or watershed times of concentration. These timing parameters will make each site different. When you change from what happens to daily rain to what happens to a specific design storm hydrograph, the timing and the details of how each BMP accommodates the water in retention and detention will differ. If these BMPs are to be implemented into our land development designs, engineers are going to need to go back to the basics and forget many of the off-the-shelf models we have been using.

We believe that with creative effort, much of the rain that falls in a humid region, like Pennsylvania, can be harvested captured (retained) and infiltrated locally. This approach is highly dependent on the local soils and their permeability. Soils that have steady-state infiltration rates less than 3 mm/hr (0.12 in/hr) will probably need to continue to use many of the same stormwater BMPs. On the other hand, sites having soils with infiltration rates greater than 3 mm/hr, should find bioretention areas attractive. Sediment basins on these sites should also be capable of dewatering under the influence of infiltration alone. The implementation of these types of stormwater BMPs will greatly enhance our groundwater supplies as this new water percolates to the watertable. Springs that have not flowed in years may start flowing again. Stream baseflow can be expected to increase somewhat. The flow of water in our streams and rivers can be expected to increase during periods of drought and decline during periods of heavy rain. All of these responses are good and society should benefit greatly.

Conclusions

On land development sites with soils having steady-state infiltration rates (permeabilities) greater than about 3 mm/hr, there are a host of BMPs available to manage stormwater. BMPs such as sediment basins can be designed and constructed to dewater the design runoff event from earth disturbance sites entirely by infiltrating the captured sediment-laden water. This dewatering approach also captures 100% of the sediment for all storms smaller than or equal to the design storm.

Once the construction activities have been completed, bioretention areas can be sited in the same areas once used for stormwater detention basins. These shallow depressions can be designed to capture the one-inch first flush all impervious surfaces (parking lots, roofs, walks, roads, etc) from each storm. The first flush will then infiltrate into the soil and be treated and delivered to the local ground water. For those rare runoff events, that produce more than one-inch of runoff, some traditional stormwater conveyance system maybe needed.

Another BMP that can greatly reduce and delay stormwater flows, both peak rates and volumes greatly, is green roofs. Green roofs have the potential to retain up to about 35% of their media depth from each rain event. The potential is there to retain as much as 54% of all rain in Central PA. The use of green roofs, however, does not harvest the rain water for future use.

References

Bidelspach, D. A. and A. R. Jarrett. 2003. Delayed Dewatering Of Sediment Basins Improves Water Quality. Proceeding of the 2003 Pennsylvania Stormwater Symposium, Villanova University, October 15-17, 2003.

DeNardo, J. C., A. R. Jarrett, H. B. Manbeck, D. J. Beattie, R. D. Berghage. 2003. Green Roofs: A Stormwater BMP. Proceeding of the 2003 Pennsylvania Stormwater Symposium, Villanova University, October 15-17, 2003.

Rauhofer, J, A. R. Jarrett and R. D. Shannon. 2001. Effectiveness of Sedimentation Basins that do not Totally Impound a Runoff Event. Trans. ASAE 44(4):813-818.