Low Impact Development strategies use careful site design and decentralized stormwater management to reduce the environmental footprint of new growth. This approach improves water quality, minimizes the need for expensive pipe-and-pond stormwater systems, and creates more attractive developments.

FACT SHEET #7

INFILTRATION TRENCHES AND DRY WELLS

Overview

Infiltration trenches and dry wells are standard stormwater management structures that can play an important role in Low Impact Development site design. Dispersed around the site, these infiltration structures can recharge groundwater and help to maintain or restore the site's natural hydrology. This approach contrasts with conventional stormwater management strategies, which employ infiltration as a secondary strategy that occurs in large basins at the end of a pipe.

Dry wells and infiltration trenches store water in the void space between crushed stone or gravel; the water slowly percolates downward into the subsoil. An overflow outlet is needed for runoff from large storms that cannot be fully infiltrated by the trench or dry well. Bioretention, another important infiltration technique, is discussed in another fact sheet. Infiltration trenches do not have the aesthetic or water quality benefits of bioretention areas, but they may be useful techniques where bioretention cells are not feasible.

Applications and Design Principles

Infiltration structures are ideal for infiltrating runoff from small drainage areas (<5 acres), but they need to be applied very carefully. Particular concerns include potential groundwater contamination, soil infiltration capacity, clogging, and maintenance. Pretreatment is always necessary, except for uncontaminated roof runoff. Trenches and dry wells are often used for stormwater retrofits, since they do not require large amounts of land; directing roof runoff to drywells is a particularly cost-effective and beneficial practice. Whether for retrofits or new construction, multiple infiltration structures will be needed to treat large sites; they are often used in the upland areas of large sites to reduce the overall amount of runoff that must be treated downstream.

Trenches and dry wells are tough to site in dense urban settings, due to the required separation from foundations, and because urban soils often have poor infiltration capacity due to many years of compaction. Infiltration trenches and dry wells should not receive runoff from stormwater hotspots

Management Objectives

- Remove suspended solids, heavy metals, trash, oil and grease.
- Reduce peak discharge rate and total runoff volume.
- Provide modest infiltration and recharge.
- Provide snow storage areas.
- Improve site landscaping.

Metropolitan Area Planning Council

MAPC

arc of innovation

(such as gas stations) unless the stormwater has already been fully treated by another stormwater treatment practice to avoid potential groundwater contamination.

Infiltration structures must be constructed with adequate vertical separation from the groundwater table, generally 2' or more between the bottom of the trench or pit and the seasonally high groundwater table. Soils must be sufficiently permeable (at least 0.3"/hour) to ensure that trenches can infiltrate quickly.

Infiltration trenches and dry wells operate on similar principles, though trenches are linear troughs and dry wells are round or square in plan view. In both cases, the excavated hole or trench, 3'-12' deep, is lined with filter fabric and backfilled with washed, crushed stone 1.5"-3" in diameter. The bottom of infiltration trenches is often filled with a 6"-12" filter layer of washed, compacted sand. A 4"-6" perforated PVC observation well will permit monitoring of the structure and observation of drainage time.

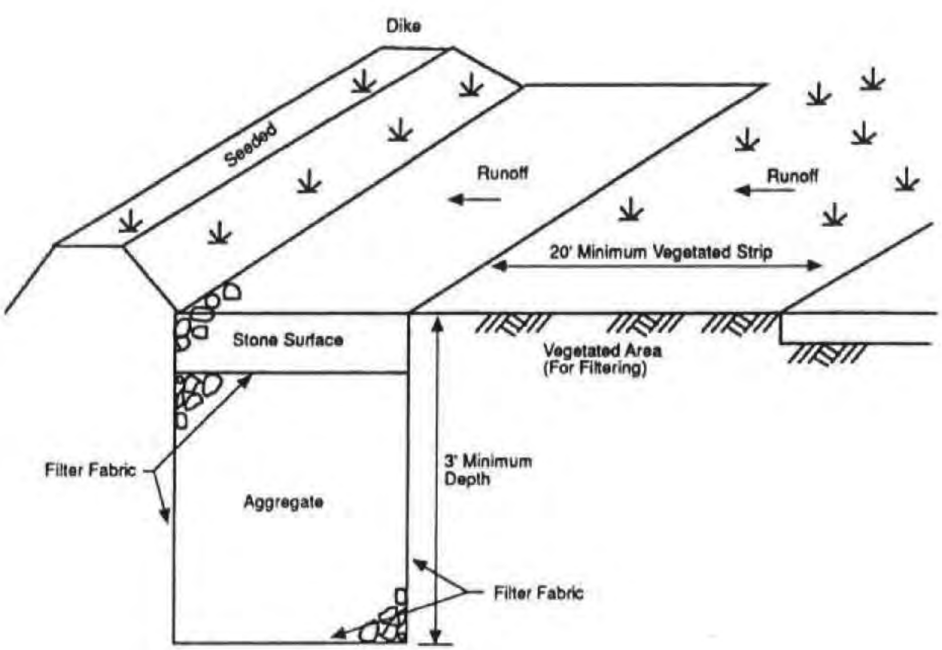
Trenches and dry wells should be designed to store the design volume and infiltrate it into the ground through the bottom of the trench or well within 72 hours. Because of their limited size, infiltration structures are best used to infiltrate the first inch/half inch of runoff from frequent small storms; they are not effective for infiltrating the runoff from large storms. Overflow from trenches and dry wells should be directed to a swale or other conveyance, sized to prevent erosion.

Because dry wells and infiltration trenches can be prone to clogging, pretreatment of stormwater runoff is a necessity. Where dry wells accept roof runoff through a system of gutters and downspouts, screens at the top of downspouts should suffice. For runoff from paved surfaces, designers should use grass swales, filter strips, settling basins, sediment forebays, or a combination of two or more strategies to pretreat stormwater before it is discharged to an infiltration trench or dry well. In groundwater protection areas (Zone II and Interim Wellhead Protection Areas) infiltration may only be used for uncontaminated rooftop runoff.

Above, top: A perforated pipe delivers rooftop runoff to the full length of this infiltration trench, under construction. After completion the area will be covered with sod and the trench will be invisible. *Photo: Cahill Associates, Inc. 2004*

Above: A roadside infiltration trench that receives runoff via periodic curb cuts; this trench may be prone to clogging because there is no pretreatment. *Photo: Lower Columbia River Estuary Partnership*

Right: A schematic section of an infiltration basin. *Image: American Groundwater Trust, Plainfield CT Stormwater Manual*



Above, and Cover: The parking lot runoff directed to this infiltration basin is pretreated by a vegetated filter strip. Note concrete level spreader (at right) to facilitate sheetflow across filter strip. *Photo:California Stormwater Quality Association*

Benefits and Effectiveness

- Dry wells and infiltration trenches reduce stormwater runoff volume, including most of the runoff from small frequent storms. Consequently, downstream pipes and basins are smaller, and the local hydrology benefits from increased base flow.
- Dry wells and infiltration trenches also reduce peak discharge rates by retaining the first flush of stormwater runoff and creating longer flow paths for runoff.
- Infiltration structures are moderately expensive to construct and can help to reduce the size of downstream stormwater management structures.
- These techniques have an unobtrusive presence; they do not enhance the landscape (like bioretention areas do), but they have a lower profile than large infiltration basins.

Limitations

- Infiltration trenches and dry wells cannot receive untreated stormwater runoff, except rooftop runoff. Pretreatment is necessary to prevent premature failure that results from clogging with fine sediment, and to prevent potential groundwater contamination due to nutrients, salts, and hydrocarbons.
- Infiltration structures cannot be used to treat runoff from portions of the site that are not stabilized.
- Rehabilitation of failed infiltration trenches and dry wells requires complete reconstruction.
- Infiltration structures are difficult to apply in slowly permeable soils or in fill areas.
- Where possible, the design should maintain a minimum separation from paved areas (generally 10', depending on site conditions) to prevent frost heave.
- Unlike bioretention areas, infiltration trenches and dry wells do not help meet site landscaping requirements.

Above: Precast concrete drywell inserts prior to installation.
Photo: Lower Columbia River Estuary Partnership

Maintenance

- After construction, inspect after every major storm for the first few months to ensure stabilization and proper function.
- On a monthly basis, remove sediment and oil/grease from pretreatment devices, overflow structures, and the surface of infiltration trenches.
- Semi-annually, check observation wells 3 days after a major storm. Failure to percolate within this time period indicates clogging
- Semi-annually, inspect pretreatment devices and diversion structures for sediment build-up and structural damage.
- If ponding occurs on the surface of an infiltration trench, remove and replace the topsoil or first layer of stone and the top layer of filter fabric.
- Upon failure, perform total rehabilitation of the trench or dry well to maintain storage capacity within 2/3 of the design treatment volume and 72-hour exfiltration rate.

Cost

Infiltration trenches and dry wells are moderately expensive to construct. Because trenches and dry wells can infiltrate stormwater closer to the source, conveyance structures such as swales and pipes can be downsized. It is important that developers and property owners provide a budget for maintenance activities, since lack of maintenance is the primary cause for premature failure of infiltration structures.

Design Details

- Determine infiltration rate of underlying soil through field investigations; use a minimum of one boring at each dry well, two borings at each infiltration trench, with at least one additional boring every 50 feet for trenches over 100 feet. Base trench/drywell sizing on the slowest rate obtained from soil infiltration tests. Determine the infiltrative capacity of the soil through an infiltration test using a double-ring infiltrometer. Do not use a standard septic system percolation test to determine soil permeability.
- Do not use trenches or dry wells where soils are >30% clay or >40% silt clay.
- Use of vertical piping for distribution or infiltration enhancement may cause the trench or drywell to be classified as an injection well which needs to be registered with the state.
- Trim tree roots flush with the trench sides in order to prevent puncturing or tearing the filter fabric. Since tree roots may regrow, it may be necessary to remove all trees within 10 feet of the infiltration structure and replace them with shallow-rooted shrubs and grasses.
- If used, distribution pipes should have perforations of 0.5" and should be capped at least 1 foot short of the wall of the trench or well.
- For infiltration trenches receiving runoff via surface flow, a horizontal layer of filter fabric just below the surface of the trench, covered with 2"-6" of gravel or crushed stone, will help to retain sediment near the surface; this will prevent clogging and allow for rehabilitation of the trench without complete reconstruction.
- Required set backs for surface water supply (Zone 1 and Zone A): 400 feet setback from a source and 100 feet from tributaries. Required setback from private wells: 100 feet
- Required setback from septic systems: 100 feet. Required setback from building foundations: 10 feet for drywells and 20 feet for infiltration trenches.
- Because of clogging problems, infiltration trenches and drywells should never be used to infiltrate runoff from drainage areas that are not completely stabilized. For best performance, contractors, should avoid compaction of soils around trenches and dry wells during construction.

Additional information

Massachusetts Stormwater Management Policy: Volume Two: Stormwater Technical Handbook; MA DEP & MA CZM; 1997

This publication is one component of the Massachusetts Low Impact Development Toolkit, a production of the Metropolitan Area Planning Council, in coordination with the I-495 MetroWest Corridor Partnership, with financial support from US EPA. The Massachusetts Low Impact Development Interagency Working Group also provided valuable input and feedback on the LID Toolkit.

Low Impact Development strategies use careful site design and decentralized stormwater management to reduce the environmental footprint of new growth. This approach improves water quality, minimizes the need for expensive pipe-and-pond stormwater systems, and creates more attractive developments.

FACT SHEET #8

CISTERNS AND RAIN BARRELS

Overview

Cisterns and rain barrels are simple techniques to store rooftop runoff and reuse it landscaping and other nonpotable uses. They are based on the idea that rooftop runoff should be treated as a resource that can be reused or infiltrated. In contrast, conventional stormwater management strategies take rooftop runoff, which is often relatively free of pollutants, and send it into the stormwater treatment system along with runoff from paved areas.

The most common approach to roof runoff storage involves directing each downspout to a 55-gallon rain barrel. A hose is attached to a faucet at the bottom of the barrel and water is distributed by gravity pressure. A more sophisticated and effective technique is to route multiple downspouts to a partially or fully buried cistern with an electric pump for distribution. Where site designs permit, cisterns may be quite large, and shared by multiple households, achieving economies of scale. Stored rain water can be used for lawn irrigation, vegetable and flower gardens, houseplants, car washing, and cleaning windows. When rain barrels or cisterns are full, rooftop runoff should be directed to drywells, stormwater planters, or bioretention areas where it will be infiltrated.

Applications and Design Principles

Cisterns and rain barrels are applicable to most commercial and residential properties where there is a gutter and downspout system to direct roof runoff to the storage tank. They take up very little room and so can be used in very dense urban areas. Rain barrels and cisterns are excellent retrofit techniques for almost any circumstance.

Management Objectives

- Reduce water demand by providing an alternative source for irrigation needs.
- Reduce peak discharge rates and total runoff

Metropolitan Area Planning Council

MAPC

arc of innovation

Above: A low-profile cistern "head house" opens to reveal the electric pumps that distribute water throughout this residential property.
Photo: Rainwater Recovery, LLC

Below, right: Construction of a large underground cistern at a commercial site; this vault consists of a weight-bearing skeleton wrapped in a waterproof membrane. *Photo: Rainwater Recovery Systems, LLC*

Cover, top: A rain barrel at the Discovery Museum in Acton, MA.
Photo: GeoSyntec Consultants, Inc.

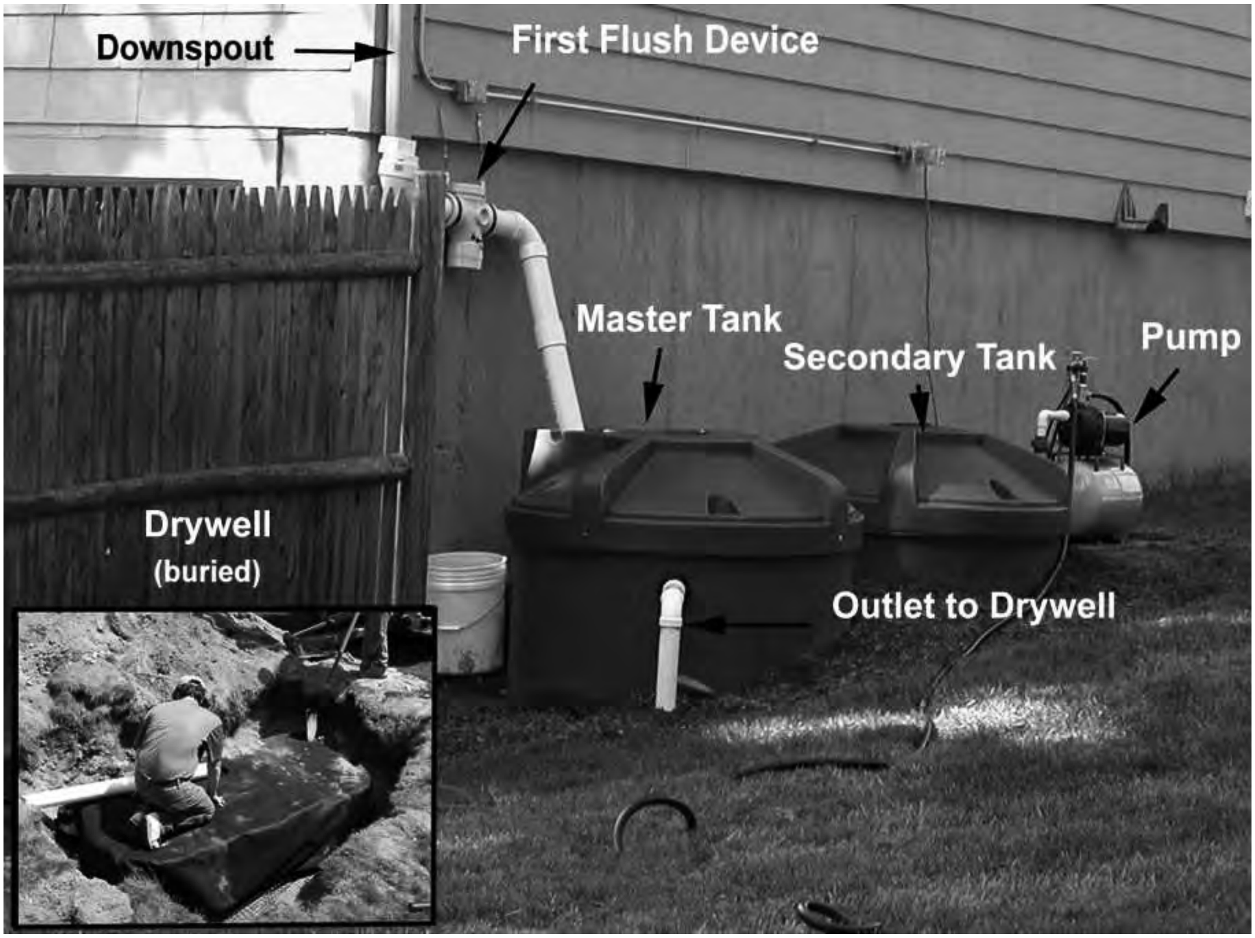
Cover, bottom: A 400-gallon cistern at a group home in Ipswich provides water landscaping and gardening.
Photo: Charles River Watershed Association

Rain barrels are 50-100 gallon covered plastic tanks with a hole in the top for downspout discharge, an overflow outlet, and a valve and hose adapter at the bottom. They are used almost exclusively on residential properties. Since rain barrels rely on gravity flow, they should be placed near, and slightly higher than, the point of use (whether a garden, flower bed, or lawn.) The overflow outlet should be routed to a dry well, bioretention area, or rain garden. It is important for property owners to use the water in rain barrels on a regular basis, or else they fill up and no additional roof runoff can be stored. It is recommended that each house have at least two rain barrels; a one inch storm produces over 500 gallons of water on a 1000 square foot roof.

Cisterns are partially or fully buried tanks with a secure cover and a discharge pump; they provide considerably more storage than barrels as well as pressurized distribution. Cisterns can collect water from multiple downspouts or even multiple roofs, and then distribute this water wherever it needs to go through an electric pump. Property owners may use one large tank or multiple tanks in series. Either way, the overflow for the systems should be a drywell or other infiltration mechanism, so that if the cistern is full, excess roof runoff is infiltrated, and not discharged to the stormwater system. Some cisterns are designed to continuously discharge water at a very slow rate into the infiltration mechanism, so that the tank slowly empties after a storm event, providing more storage for the next event.

Benefits and Effectiveness

- Rain barrels and cisterns can reduce water demand for irrigation, car washing, or other nonpotable uses. Property owners save money on water bills and public water systems experience lower peak demand and less stress on local water supplies.
- Property owners who have cisterns and rain barrels can use stored water for landscape purposes, even during outdoor watering bans.
- If installed and used properly, rain barrels and cisterns can reduce stormwater runoff volume through storage, and will also help to reduce the peak discharge rate.



Above, top: The SmartStorm Rainwater Recovery System, developed by the Charles River Watershed Association; the cisterns and pumps can be easily hidden by landscape plantings. *Photo: Charles River Watershed Association.*

Above: A half-dozen 400-gallon cistern tanks installed in series to provide greater storage capacity. *Photo: Rainwater Recovery Systems, LLC*

Limitations

- The stormwater volume/peak discharge rate benefits of cisterns and rain barrels depend on the amount of storage available at the beginning of each storm. One rain barrel may provide a useful amount of water for garden irrigation, but it will have little effect on overall runoff volumes, especially if the entire tank is not drained in between storms.
- Greater effectiveness can be achieved by having more storage volume and by designing the system with a continuous discharge to an infiltration mechanism, so that there is always available volume for retention.
- Rain barrels and cisterns offer no primary pollutant removal benefits. However, rooftop runoff tends to have few sediments and dissolved minerals than municipal water and is ideal for lawns, vegetable gardens, car washing, etc.
- Rain barrels must be childproof and sealed against mosquitoes.
- The water collected is for nonpotable uses only.

Cost

The cost of rooftop runoff storage varies widely, from a homeowner-installed rain barrel to a commercially constructed underground cistern vault. Most rain barrels and cisterns do not retain enough stormwater to downsize the site's

The overflow outlet from this rain barrel drains into an adjacent rain garden. *Photo: GeoSyntec Consultants, Inc.*

stormwater management system, but can provide cost savings because they reduce the demand for potable water for landscaping and irrigation. The cost-benefit ratio will depend on how much landscaping/irrigation water the property owner uses, and the unit cost of water from the local public water supply.

Commercially available rain barrels begin at approximately $60 for a 55-gallon barrel. Larger barrels may be available at correspondingly higher prices. Most rain barrels can be installed by homeowners. Rain barrels can be assembled by homeowners for lower cost but some of the parts may be hard to find. Some watershed associations or municipalities offer rain barrels at a discount or provide rebates.

Cisterns are more expensive due to the larger size and multiple "moving parts." Installation of buried cisterns can also be expensive. One system available in Massachusetts (SmartStorm) costs $3000 for an 800 gallon two-tank system complete with pump and drywell structure. A common cistern shared by multiple properties may result in considerable economies of scale because there is only one excavation, one tank or set of tanks, and one pump.

Design Details

- Because of the low pressure of the discharge, rain barrels are most effectively used with a drip irrigation system.
- Rain barrels should be childproof and secured against disturbance by people or animals. Any openings should be sealed with mosquito netting.
- If present, a cistern's continuous discharge outlet should be placed so that the tank does not empty completely, ensuring water availability at all times, while also providing at least some storage capacity for every storm.
- A diverter at the cistern inlet can redirect the "first flush" of runoff which is more likely to have particulates, leaves, and air-deposited contaminants washed off the roof.
- Minimize leaves and debris in the storage tank by placing a screen at the top of the downspout.
- Screen rain barrels and exposed cisterns with shrubs or other landscaped features.
- Direct overflow from rain barrels and cisterns to a dry well, infiltration trench, rain garden, bioretention area, or grassed swale sized to infiltrate the overflow volume. Use pond routing to account for retention of early runoff in the storage tank. MA Stormwater Policy does not require treatment of most roof runoff prior to infiltration.

Additional information

http://www.rainwaterrecovery.com/about.html
www.crwa.org (Charles River Watershed Association)

This publication is one component of the Massachusetts Low Impact Development Toolkit, a production of the Metropolitan Area Planning Council, in coordination with the I-495 MetroWest Corridor Partnership, with financial support from US EPA.
The Massachusetts Low Impact Development Interagency Working Group also provided valuable input and feedback on the LID Toolkit.

Low Impact Development strategies use careful site design and decentralized stormwater management to reduce the environmental footprint of new growth. This approach improves water quality, minimizes the need for expensive pipe-and-pond stormwater systems, and creates more attractive developments.

MASSACHUSETTS **LOW IMPACT DEVELOPMENT** TOOLKIT

FACT SHEET #9

GREEN ROOFS

Overview

A green roof is a low-maintenance vegetated roof system that stores rainwater in a lightweight engineered soil medium, where the water is taken up by plants and transpired into the air. As a result, much less water runs off the roof, as compared to conventional rooftops. Green roofs have been in use in Europe for more than 30 years; they are easy to incorporate into new construction, and can even be used on many existing buildings.

Green roofs provide an extra layer of insulation that reduces heating and cooling costs, and they are likely to last much longer than conventional roofs, since the roofing material itself is shielded from ultraviolet light and thermal stress. The vegetation on green roofs also improves air quality, enhances the appearance of the building, and reduces the urban "heat island" effect.

There are two distinct types of green roofs: extensive green roofs require less than 6" of soil medium and support mostly herbaceous plants; these utilitarian "roof meadows" generally have no public access and require little maintenance. In contrast, intensive green roofs include shrubs and small trees planted in more than six inches of growing medium; they are often designed as accessible building amenities. This fact sheet focuses on extensive green roofs and their stormwater management benefits. Both types of green roofs seek to transform rooftops from "wasted space" into a form of infrastructure that has environmental, economic, aesthetic, and social benefits.

Applications and Design Principles

Green roofs are appropriate for commercial, industrial, and residential structures, especially those with a wide roof area. They can be incorporated into new construction or added to existing buildings during renovation or re-roofing. Most green roofs are built on flat or low-angle rooftops, but some have been installed on pitched roofs up to 40% slope, with special design features to prevent slumping and ensure plant survival.

Green roofs are appropriate anywhere it is desirable to reduce the overall amount of stormwater runoff. They are an excellent technique to use in dense urban areas, in areas where infiltration is difficult due to tight soils or shallow bedrock, or on sites where infiltration is undesirable due to existing soil contamination. Because green roofs return rainwater to the atmosphere,

Management Objectives

- Reduce total runoff volume through rainwater storage and evapotranspiration.
- Reduce peak discharge rates.
- Reduce heating and cooling costs through roof insulation.
- Extend roof life.

MAPC Metropolitan Area Planning Council

arc of innovation

Above, top: The Ford Dearborn Truck Assembly Plant in Dearborn Michigan has a 10-acre green roof that is a 2004 Green Roof Awards of Excellence Winner.
Photo: William McDonough + Partners

Above, bottom: The Fencing Academy of Philadelphia was retrofit with a 3.5″-thick green roof, installed over the existing roof structure.
Photo: © 2005, Roofscapes, Inc. Used by permission; all rights reserved.

Right: A schematic diagram of a green roof system. *Image: City of Portland, OR Environmental Services.*

Cover, top: A green roof at the Yorktown Square Condominiums in Falls Church, VA. This installation was a 2005 Green Roof Awards of Excellence Nominee.
Photo: Building Logics, Inc.

Cover, bottom: This green roof at the Heinz 57 Center in Pittsburgh is located on the 14th floor and requires no irrigation. It is a 2005 Green Roof Awards of Excellence Nominee.
Photo: © 2005, Roofscapes, Inc. Used by permission; all rights reserved.

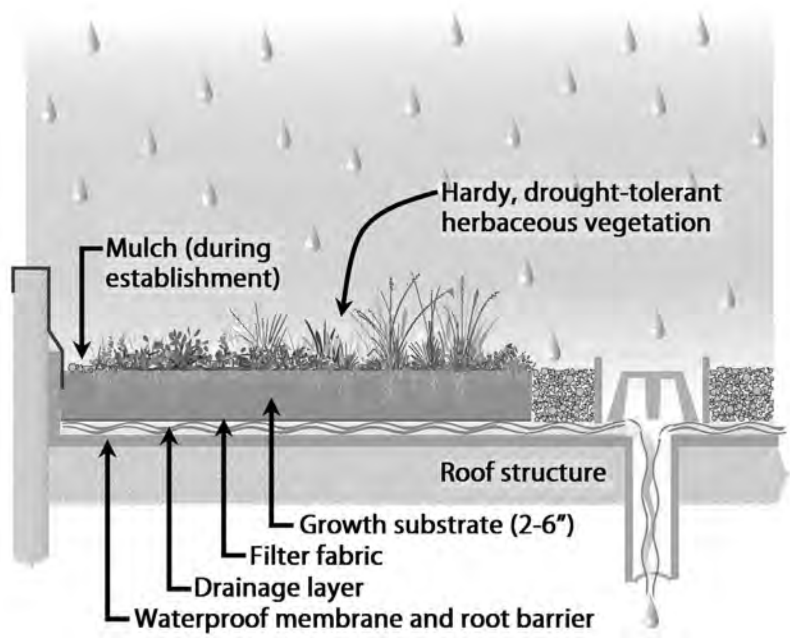
Opposite top: Workers conduct semi-annual maintenance at the Life Expression Wellness Center in Pennsylvania.
Photo: © 2005, Roofscapes, Inc. Used by permission; all rights reserved

they should not be used in situations where groundwater recharge is a priority, such as in stressed basins with chronic low-flow conditions. In these circumstances, roof runoff should be infiltrated whenever feasible.

Like conventional roofs, the basic element of a green roof is a waterproof membrane over the roof sheathing. The system also includes a root barrier; a drainage layer; filter fabric; and 2”-6” of a lightweight growth substrate consisting of inorganic absorbent material such as perlite, clay shale, pumice, or crushed terracotta, with no more than 5% organic content. Substrates should not be too rich in organic material such as compost, because of the potential for settling, nutrient export, and too-rapid plant growth. Gravel ballast is sometimes placed along the perimeter of the roof and at air vents and other vertical elements, in order to promote drainage and facilitate access.

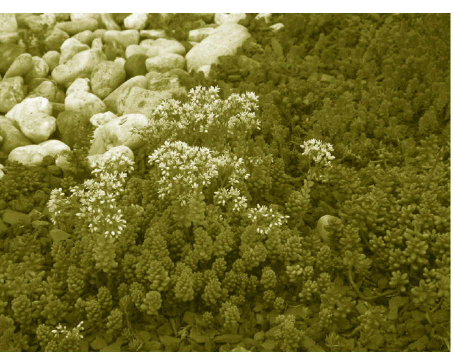
Extensive green roofs require moderate structural support which can be easily accommodated during design for new construction; existing roofs may be adequate or may require additional structural supports that can be added during re-roofing or renovation. An extensive green roof may weigh approximately 10-25 pounds per square foot when fully saturated, whereas a conventional rock ballast roof weighs approximately 10-12 pounds per square foot (neither figure includes potential snow load.)

Vegetation on extensive green roofs usually consists of hardy, low-growing, drought-resistant, fire-resistant plants that provide dense cover and are able to withstand heat, cold, and high winds. Varieties commonly used include succulents such as sedum (stonecrop) and delosperma (ice plant.) During dry periods, these plants droop but do not die back; when it rains, they quickly revive and absorb large



amounts of water. Grasses and herbs are less common on green roofs because to survive dry periods they require either irrigation or deeper substrate that retains more water.

A common concern about green roofs is the potential for leaks. The performance of green roofs has improved dramatically since the 1970s, when many leak problems were associated with the first generation of green roofs. Current waterproofing materials, root barriers, and rigorous design and construction standards have largely eliminated these problems; low-cost electronic grids installed under the membrane during construction can also help to pinpoint leaks and minimize repair costs.



Above, middle: A photo of the green roof at the Bruker Deltronics Headquarters in Billerica, MA. *Photo: © 2005, Roofscapes, Inc. Used by permission; all rights reserved.*

Above, bottom: A close up of low-growing, spreading green roof vegetation. *Photo: Building Logics, Inc.*

Benefits and Effectiveness:

- Green roofs effectively reduce stormwater runoff. Researchers at North Carolina State have found that a 3" green roof can retain approximately 0.6" of rain for each rainfall event, even when storms come on consecutive days. The Center for Green Roof Research at Penn State University reports that a 4" green roof can retain 50% of total rainfall over a series of storm events.
- Green roofs reduce peak discharge rates by retaining runoff and creating longer flow paths. Research indicates that peak flow rates are reduced by 50% to 90% compared to conventional roofs, and peak discharge is delayed by an hour or more.
- Green roofs lower heating and cooling costs because the trapped air in the underdrain layer and in the root layer help to insulate the roof of the building. During the summer, sunlight drives evaporation and plant growth, instead of heating the roof surface. During the winter, a green roof can reduce heat loss by 25% or more.
- Because green roofs shield roof membranes from intense heat and direct sunlight, the entire roofing system has a longer lifespan than conventional roofs.
- The presence of a green roof helps to reduce air temperatures around the building, reducing the "heat island" effect and reducing the production of smog and ozone, which forms in the intense heat (175 degrees) over large conventional roofs. The vegetation on green roofs also consumes carbon dioxide and increases the local levels of oxygen and humidity.
- Green roofs have demonstrated aesthetic benefits that can increase community acceptance of a high-visibility project; they may also add value to the property if marketed effectively.

Above: Installation of eight inches of soil medium using pneumatic equipment at the Oaklyn Branch Library in Evansville, IN. *Photo: © 2005, Roofscapes, Inc. Used by permission; all rights reserved.*

Limitations

- Load restrictions are usually the main limitation for green roofs in retrofit applications. A professional engineer must assess the necessary load reserves and design a roof structure that meets state and local codes.
- Slopes greater than 15% require a wooden lath grid or other retention system to hold substrate in place until plants form a thick vegetation mat.
- Green roofs should not be used where groundwater recharge is a priority, such as in aquifer recharge areas or watersheds experiencing low-flow stresses.
- The initial construction cost is higher than conventional roofs.

Maintenance

- Green roofs require some support during establishment and then yearly maintenance thereafter. Plants or sprigs should be irrigated until established, and additional plants or sprigs added to ensure good plant coverage if necessary. With drought-resistant vegetation, irrigation of an extensive green roof is rarely necessary after the two-year establishment period.
- Weeding and mulching may be needed during the establishment period and periodically thereafter over the life of the roof. Any woody plants which become established on the roof need to be removed regularly.
- If necessary (many roofs can survive on deposition of airborne nitrogen and biomass breakdown), application of a slow-release fertilizer once a year will ensure continued vigorous growth of the vegetation. Soluble nitrogen fertilizers and compost should not be used due to the potential for nutrient and bacteria export.

Cost

Green roofs start at $5 per square foot. They generally cost more to install than conventional roofs, but are financially competitive on a life-cycle basis because of longer life spans (up to 40 years), increased energy efficiency, and reduced stormwater runoff. If the application is a retrofit, structural upgrades may increase the cost somewhat.

Design Details:

- Waterproof membranes are made of various materials, such as modified asphalts (bitumens), synthetic rubber (EPDM), hypolan (CPSE), and reinforced PVC. The most common design used in Europe is 60-80 mil PVC single-ply roof systems. Modified asphalts usually require a root barrier, while EPDM and reinforced PVC generally do not. Attention to seams is critical because some glues and cements are not always root impermeable.
- The underdrain layer may be constructed of perforated plastic sheets or a thin layer of gravel. Pitched roofs and small flat roofs may not require an underdrain.
- Vegetation should be low-growing, spreading perennial or self-sowing annuals that are drought tolerant. Appropriate varieties include sedum, delospermum, sempervivium, creeping thyme, allium, phloxes, anntenaria, ameria, and abretia. Vegetation may be planted as vegetation mats, plugs or potted plants, sprigs (cuttings), or seeds. Vegetation mats are the most expensive but achieve immediate full coverage. Potted plants are also expensive and labor intensive to install. Sprigs are often the most cost effective option, even considering that initial irrigation is necessary and repeat installations may be required due to mortality. Conventional sod should not be used because it requires irrigation, mowing, and maintenance.
- Access routes should be identified during the design phase, and access paths of gravel or other inert materials provided, as well as safety harness hooks for inspection and maintenance personnel.

For more information

www.greenroofs.org (Green roof industry association; training and design courses)
www.greenroofs.com (The Green Roof Industry Resource Portal)
www.bae.ncsu.edu/greenroofs/ (North Carolina State University)
hortweb.cas.psu.edu/research/greenroofcenter/ (Penn State University)
www.greeninggotham.org/home.php
www.roofmeadow.com (North American Green Roof Provider)

This publication is one component of the Massachusetts Low Impact Development Toolkit, a production of the Metropolitan Area Planning Council, in coordination with the I-495 MetroWest Corridor Partnership, with financial support from US EPA. The Massachusetts Low Impact Development Interagency Working Group also provided valuable input and feedback on the LID Toolkit.