TOWARDS GREENER STORMWATER MANAGEMENT

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INTRODUCTION

In the past decade, the focus of stormwater management has moved from a more traditional paradigm to a variety of more ecologically sensitive, "green" stormwater solutions. Because of an increased ecological focus, stormwater management techniques are no longer selected from a one-size-fits-all toolkit, making adjustments only for storage and transport volumes to account for local differences in rainfall and contributing area. Instead, the current generation of stormwater managers has a wealth of options from which to choose, leading to solutions that need to be specifically formulated for or adapted to local soils, ecotypes, topography, and meteorology. Furthermore, there has also been a move away from the more traditional engineered systems toward an increased multi-disciplinary approach. As a result, stormwater can no longer be managed as an afterthought to development. Instead, stormwater managers and developers need to be communicating throughout the design process.

This combination of an ever-increasing range of stormwater management options and a greater reliance on interdisciplinary communication makes it more difficult to sort through the tangle of terminology and practices and to communicate between different groups and disciplines. Therefore, this paper seeks to provide a general understanding of current green stormwater practice and to make sense of the terminology of these different, yet often overlapping stormwater management strategies. To do this, a brief history of stormwater management is reviewed, showing how priorities have changed over time and how the current green stormwater management practices fit into this history. Second, some of the major "flavors" of green stormwater management are described to clarify terminology and practices used by the different groups. Finally, the paper concludes with a discussion of the similarities and differences between the discussed stormwater management options.

A BRIEF HISTORY OF STORMWATER MANAGEMENT

In a sparsely inhabited landscape, like portions of the American Midwest, runoff from rainfall events occurs as a result of high intensity precipitation that overwhelms the infiltration capacity of soils, of precipitation falling on areas of exposed rock or other impervious surfaces, or of precipitation falling on already saturated soils that are unable to absorb additional rainfall. In any of these cases, this overland flow is a natural part of the hydrologic cycle. It is not until population reaches some threshold that stormwater begins to become a "problem" that needs to be managed. In areas of very low population density, it is much easier to find space to live and work in harmony with the natural environment. However, as population densities increase, the need to stay high and dry during rainy weather begins to conflict with the desire to be near a convenient drinking water source or a source of water or energy in support of other human needs. It is this conflict that creates a need for strategies to manage stormwater.

Pre-Development Hydrology

In the years since the 1830s when settlers first started to appear in the Midwest, native vegetation has been converted to agricultural uses and, more recently, urbanized areas. Prior to this time, the landscapes of Iowa, as well as most of the Midwest, were dominated by tallgrass prairie. This can be seen for this area by looking at vegetation and land-use data for Johnson County. The historic vegetation, based on survey data collected from 1832 to 1859, and modern land use, derived from high-altitude aerial photos from 1975 to 1984, are shown in Figure 1. Prior to settlement, this landscape was dominated by prairie along with oak savanna and other wooded areas. By modern times, virtually all of the prairie, as well as much of the wooded areas, had been converted to agricultural uses and, increasingly, urban areas.

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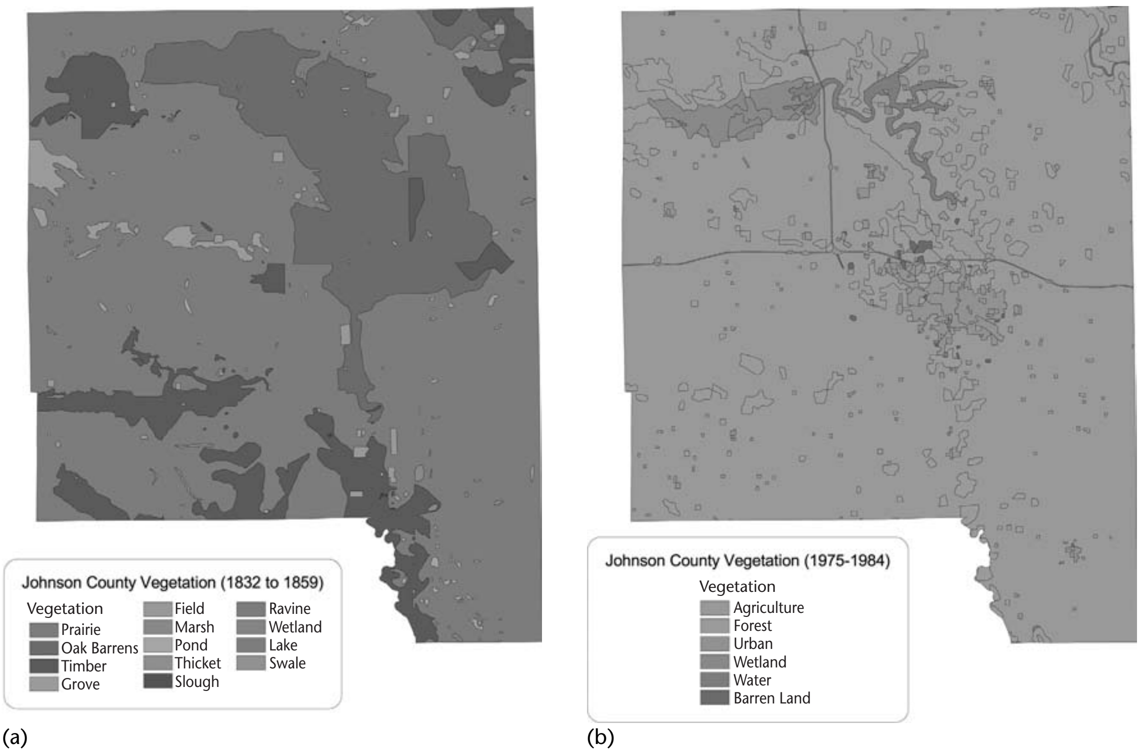
This land-use conversion has significant implications for stormwater management. Tallgrass prairie species were deep-rooted, long-lived, and efficient at using water and nutrients, and consequently maintained very high levels of carbon fixation and primary productivity. In the prairie ecosystem, up to 70% of the biomass was created below ground in highly developed root systems. In contrast, the annual species (corn, soybeans, wheat) or the shallow-rooted, non-native species (bluegrass lawns, brome grass fields) that have replaced the prairies are productive primarily above ground. These changes have modified the capability of the upland systems and small depressional wetlands in the uplands to retain water and assimilate nutrients and other materials that now flow from the land into aquatic systems, streams, and wetlands, thus significantly decreasing the lag time of stormwater runoff and increasing the rate and volume of water leaving the landscape (Apfelbaum 1993).

In pre-settlement times, hydrology was dominated by rainfall and evapotranspiration, a marked contrast with today's surface-dominated hydrology. When overland flow did occur, it was much more diffuse, rather than the concentrated flows seen now (Apfelbaum 1993; Broughton and Apfelbaum 1999). "Before the 1830s, when the Midwest was still considered Wilderness, the first white settlers in our region could hardly recognize the streams that now bear familiar names on the maps of our region. Original land survey records of the U.S. General Land office identified many of the streams we know today only as vegetated swales, wetlands, wet prairies, and swamps" (Broughton and Apfelbaum 1999, p. 10). This is illustrated by the historic vegetation map for Johnson County shown in Figure 1, where rivers and streams are not included as land cover categories; instead, the descriptions rely on categories such as marsh, pond, slough, wetland, lake, or swale, suggestion moist or depressed areas rather than perennial water flow.

FIGURE 1. Comparison of pre-settlement and modern land cover for Johnson County, Iowa: (a) Vegetation data from Government Land Office collected 1832 to 1859. Dominant land covers are prairie (70%), oak barrens (16%), and timber (11%). (b) Land cover data compiled to 1:250,000 USGS GIRAS land-use maps from high-altitude NASA aerial photographs taken between 1975 and 1984. Dominant land covers are agriculture (84%), forest (10%), and urban (3.4%).



Removal of a Nuisance

With increasing population density and the replacement of native vegetation with other ground covers, surface water begins to play a much more substantial role in local hydrology, creating a need for "stormwater management." Early development relied on moving water away from a site as quickly as possible to limit nuisance and flooding potential as increasing volumes of stormwater were generated (Strassler et al. 1999). This approach was feasible prior to 1945, as development generally occurred on a lot-by-lot basis on small parcels of land. Even in the residential boom after World War II, when large tracts of land were completely subdivided, the natural sites would be stripped and replaced by a hydraulically efficient design as a logical extension of the previous approach (Urban Land Institute et al. 1975).

To achieve the primary goal of limiting nuisance and flooding risk, the creation of a highly efficient conveyance system was needed. "Every feature of a conventionally developed site is carefully planned to quickly convey runoff to a centrally located management device, usually at the end of a pipe system. Roadways, roofs, gutters, downspouts, driveways, curbs, pipes, drainage swales, parking, and grading are all typically designed to dispose of the runoff in a rapid fashion" (Prince George's County 1999a, pp. 1-4 to 1-5). A key element of this conveyance system was development of stormwater sewerage, either as separate stormwater systems or combined sewer systems, which direct stormwater into the existing sanitary sewer system (Strassler et al. 1999).

However, as development progressed, it became clear that this kind of practice could not continue indefinitely. "The cumulative effects of such approaches have been a major cause of increased frequency of downstream flooding, often accompanied by diminishing groundwater supplies, as a direct result of urbanization; or have necessitated development of massive downstream engineering works to prevent flood damage" (Urban Land Institute et al. 1975, p. 7). As a result, new strategies were clearly needed to manage stormwater.

Slowing Down Storm Flows

As development became more rapid, it quickly became obvious that the cumulative impact of removing stormwater from a large number of sites in a highly efficient manner led to flooding and other environmental impacts downstream. Receiving streams are frequently unable to convey the large volumes of stormwater collected by stormwater systems without significant degradation (Strassler et al. 1999). Thus it is clear that convenience and safety "are not mutually achievable without extremely high 'cost.' Where we have sought maximum convenience as our first choice in the upper and middle reaches of a watershed, we have created imbalanced systems, and increased hazard and risk of damage along the lower reaches" (Urban Land Institute et al. 1975, p. 8).

As a result, stormwater management systems began to focus on achieving a balance among upstream convenience by avoiding ponding, and downstream safety by avoiding flooding. This has most frequently been achieved using stormwater retention and detention. This allows downstream impacts to be reduced by temporarily increasing upstream inconvenience by retaining and ponding larger storms (Urban Land Institute et al. 1975).

More Than Just Water

In recent decades, water quality concerns have moved to the forefront, and the excess water volume created by urbanization is not the only management issue faced by stormwater managers. In the early years of water quality legislation, point source reduction was emphasized, leading engineers to become increasingly efficient in reducing or eliminating these sources. However, as point sources have been cleaned up, the water quality problems associated with nonpoint sources, especially urban areas, have become more important. There are a number of pieces of water quality legislation that are important to current stormwater management. These are summarized briefly below, drawing from the work of Strassler et al. (1999):

- **Clean Water Act (1972)**—"The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (Clean Water Act (CWA) §101(a)). The original act contains the framework for cleaning up water, but in the early years of the act, the primary focus was on point source regulation. In particular, Title III establishes the program for effluent guidelines, which are national standards for categories of discharges to surface waters. Specific language pertaining to stormwater discharges was included in later amendments.

- **Water Quality Act (1987)**—This group of amendments to the CWA added two sections of particular interest to urban stormwater management. First, section 319 provided a means for assessing non-point source management. Section 319(a) required all states to issue a one-time statewide assessment of runoff problems, preferably on a watershed basis. In addition, biennial reports under Section 319(b) are supposed to cover all water bodies and all relevant pollution sources in each state.

  Second, Section 402 establishes the National Pollutant Discharge Elimination System (NPDES). Specifically, Section 402(p) requires development of a national program for the regulation of stormwater discharges and gives the EPA and state agencies the authority to issue NPDES permits. The stormwater component of the NPDES was implemented in two stages discussed below.
- **NPDES—Phase I (1990)**—The first phase of NPDES stormwater permit application regulations was promulgated on November 16, 1990 (Environmental Protection Agency 1990). This phase covers Municipal Separate Storm Sewer Systems (MS4s) serving a population of 100,000 or more. Construction sites with five or more acres of disturbed land are included in the phase I rule, as one of 11 categories of stormwater discharges associated with industrial activity. These sites must prepare a stormwater pollution prevention plan that describes pollution sources, measures, and controls.
- **Coastal Zone Act Reauthorization Amendments (1990)**—Section 6217 of the Coastal Zone Act Reauthorization Amendments (CZARA) requires states with approved coastal zone management programs to develop and submit coastal non-point pollution control programs to the EPA and the National Oceanic and Atmospheric Administration (NOAA) for approval. In 1993, *Guidance Specifying Management Measures for Sources of Non-point Pollution in Coastal Waters* was issued under section 6217(g) (Environmental Protection Agency 1993). Under this guidance, stormwater discharges regulated under the existing NPDES program do not need to be addressed in Coastal Non-point Pollution Control programs. However, potential new sources, such as urban development adjacent to or surrounding MS4s of 100,000 or more, or construction sites under five acres, that are identified under section 6217 guidance need to be addressed.
- **NPDES—Phase II (1999)**—The second phase of NPDES stormwater permit regulations was promulgated on December 8, 1999 (Environmental Protection Agency 1999a). This phase expanded on the phase I rule to include MS4s with a population of fewer than 100,000 and construction sites having between one and five acres of disturbed land.

Together, these acts and amendments are shaping the current directions of stormwater quantity and quality.

Stormwater Today

A key concept in stormwater management today is sustainability. The Brundtland Commission developed a definition of sustainable development that has become widely accepted: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, p. 43). This definition can certainly be applied to urbanization and associated stormwater management issues. To approach stormwater management from this viewpoint, it is necessary to treat stormwater runoff as a resource to be sustainably managed, rather than a nuisance to be removed as quickly and efficiently as possible. This is best accomplished by recognizing that "[s]tormwater is not a mechanical system or a utility. It is an environmental process, joining the atmosphere, the soil, vegetation, land use, and streamflows" (Ferguson 1990, p. 609).

Many existing stormwater management systems do not meet sustainability criteria. Moving flooding or contaminants to other areas of the watershed for the convenience of one area will limit options for future development, as well as modify local hydrology and compromise ecological systems. While property damage is certainly reduced by these systems, there has been increased degradation in streams due to the larger volume and duration of small storm runoff flows. This can lead not only to the compromise of ecological systems, but also to undermining or sedimentation of engineering structures (Strecker and Reininga 2000).

As a result, stormwater managers need to adopt a broader definition of water resources, beyond basic water quantity and quality control. In the early days of the Clean Water Act, water quality control and water quantity control were generally approached as two separate issues. Only in recent years have we become aware of the effects of stormwater runoff on aquatic life and stream quality (Strassler et al. 1999). Not only is it necessary to address flooding and end-of-the-pipe water quality, but more recently, groundwater recharge, stream base flows, aquatic life, aesthetics, and water supply have also become important stormwater management concerns. In discussing sustainability of urban stormwater management in the United Kingdom, Ellis (1995) defines the objectives of sustainable storm drainage management as combining effective and safe pollution control and floodwater conveyance with self-supporting ecological and aesthetic benefits.

To accomplish this, an integrated approach to stormwater management is needed—one that combines flood control, water quality, natural resources, and aesthetics into stormwater master planning. However, changing the way stormwater master plans are developed and implemented is difficult. For a number of reasons, including institutional inertia, agencies have been slow to give water quality and habitat protection the same emphasis as flood control (Strecker and Reininga 2000). An important element is who should be involved in the process. A truly integrated approach needs an appropriate mix of multi-disciplinary technical specialists. This team is responsible not only for reviewing field conditions to find opportunities to meet objectives and identify existing or suspected future problems, but also for contributing to the design and implementation of stormwater management strategies. Also, it is vital that the appropriate non-technical decision-makers and stakeholders are involved in the process as early as possible (Strecker and Reininga 2000).

IDENTIFYING STORMWATER MANAGEMENT OPTIONS

As stormwater priorities move beyond the traditional water quantity and quality concerns to encompass aesthetics of the urban environment and the ecological function of streams, stormwater management necessarily must follow. A number of groups are implementing these kinds of stormwater management solutions across the country and around the world. However, understanding the terminology of and ideas behind these various approaches can cause confusion to those not directly involved in these practices. Thus, a discussion of some of the major schools of thought in "green" stormwater management follows.

Urban Stormwater Best Management Practices

The term *Best Management Practice* (BMP) refers to any "technique, measure, or structural control that is used for a given set of conditions to manage the quantity and improve the quality of storm water runoff in the most cost-effective manner" (Strassler et al. 1999, p. 5-1). Originally, the motivation for developing BMPs came from the language of the Clean Water Act. Specifically, states have been mandated to identify BMPs for controlling pollution from each category of non-point source in their jurisdictions, as described in reports prepared under Section 319(a) and 319(b) of the Clean Water Act.

BMPs are designed to address one or more of three factors: flow control, pollutant removal, and pollutant source reductions. Flow control involves managing both the volume and intensity of stormwater discharges to receiving waters. In areas of new development, the most effective method of controlling stormwater impacts is to reduce the amount of rainfall converted to runoff. In general, this can be accomplished by on-site storage and infiltration to reduce the amount of directly connected impervious area. Beyond these basic factors, localities are implementing BMPs to improve overall quality of runoff-impacted streams. By reducing hydrologic impacts of urbanization, it is thus possible to also reduce the geomorphic changes that generally accompany land-use change. In addition, pollutant removal and pollutant source reduction are necessary to protect sensitive elements of the ecosystem (Strassler 1999).

BMPs can be categorized as either structural or non-structural. *Structural BMPs* are constructed or engineered systems for controlling the quantity or quality of runoff. They treat stormwater either at the point of generation or the point of discharge to the

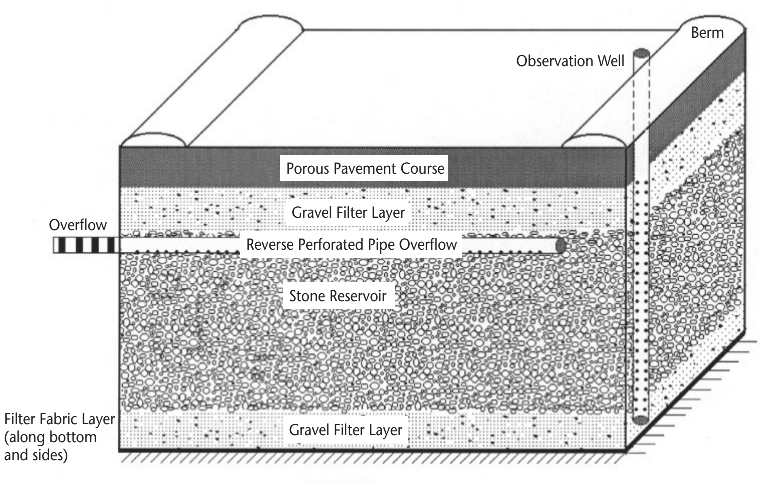


FIGURE 2. Porous pavement (Schueler 1987).

storm sewer systems or receiving water body. *Non-structural BMPs* include a range of prevention, education, or management practices. In general, these practices are designed to limit the volume of stormwater runoff produced or reduce pollution levels in the runoff. Each of these categories is discussed in more detail in the following sections.

Structural Best Management Practices. Structural BMPs include a wide array of engineering approaches to the control of stormwater quantity and quality. The most common categories of structural BMPs are discussed briefly below, drawing from the Environmental Protection Agency's *Preliminary Data Summary of Urban Storm Water Best Management Practices* compiled by Strassler et al. (1999).

Infiltration systems are designed to capture a volume of stormwater runoff, retain it, and then infiltrate it into the ground. Infiltration provides both water quality and water quantity control. Such systems can include infiltration basins, porous pavement systems, and infiltration trenches and wells. An example of a porous pavement system is shown in Figure 2.

Detention systems intercept a volume of stormwater runoff and temporarily store it for gradual release to receiving stream or storm sewer. These systems are designed to empty completely between storm events; thus, they only address stormwater peak flow reduction by changing the timing of the storm runoff with little or no water quality benefits. Examples of detention systems include detention basins (illustrated in Figure 3) or underground vaults, pipes, and tanks.

Retention systems are designed to capture a volume of runoff and retain that volume until it is displaced in part or in total by the next runoff event. Retention systems can provide both water quantity control through temporary storage and water quality control primarily through sedimentation. Retention ponds (shown in Figure 4) or retention tanks, tunnels, vaults, and pipes are examples of retention systems.

Constructed wetland systems are designed to remove pollutants from stormwater using natural vegetation and soil functions. In addition, benefits to water quantity are obtained by temporary storage and slowing of runoff. Wetland systems often need some sort of pre-treatment to reduce sediment,

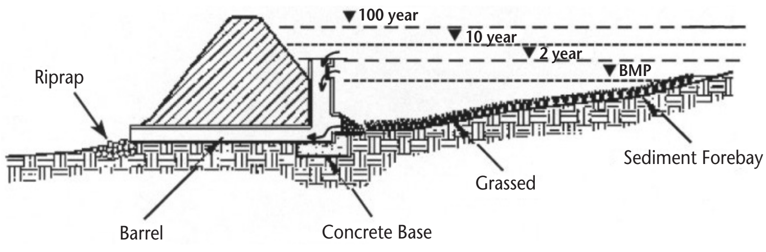
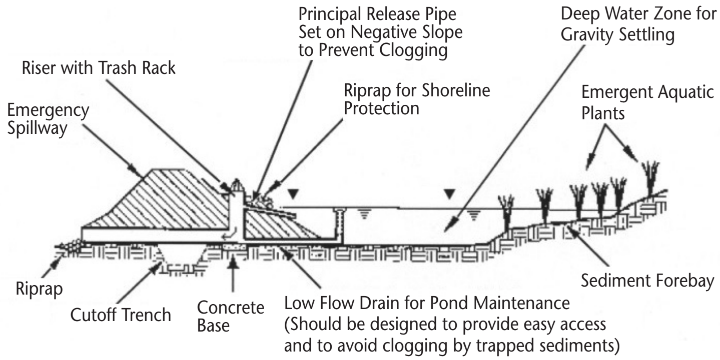


FIGURE 3. Detention basin (NVPDC 1992).

FIGURE 4. Retention pond (NVPDC 1992).



which can impair wetland function. Examples of constructed wetland systems include wetland basins and wetland channels.

Filtration systems are primarily designed for the treatment of water quality. They remove pollutants from stormwater using a media like sand, gravel, peat, or compost to filter runoff. Examples of typical filter media are shown in Figure 5.

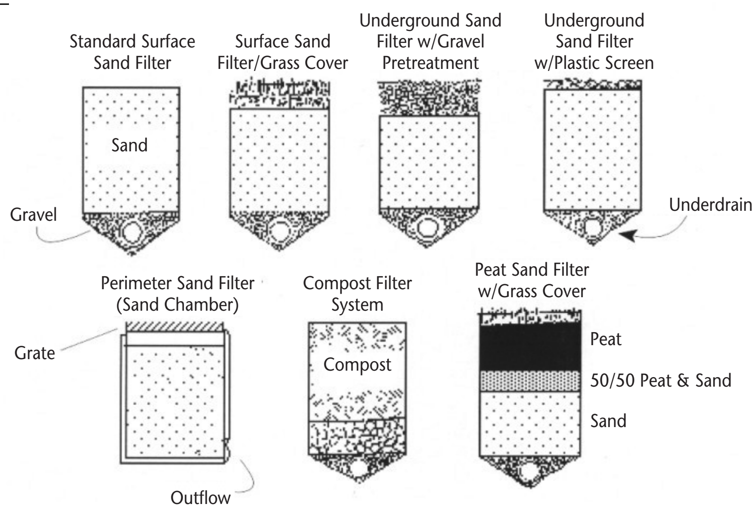
Water quantity control may be incorporated by including a storage component (pond or basin) in the system. Examples of filtration systems include surface sand filters, underground vault sand filters, and biofiltration/bioretention systems (discussed in more detail as follows in conjunction with Low Impact Development). An example of an underground vault sand filter is shown in Figure 6.

Vegetated systems are designed to convey and treat stormwater by using grasses and vegetation to filter runoff. Biofilters provide an alternative to traditional curb and gutter and storm sewer conveyance systems. In addition to providing water quality benefits by filtration, water quantity is reduced by storage and infiltration. Vegetated systems can include grassed filter strips and vegetated swales.

Minimizing directly connected impervious surfaces means limiting the amount of storm runoff that flows directly into the storm drainage system. This can occur by directing impervious runoff across vegetated areas and using vegetated swales to replace curb-and-gutter systems. These measures provide water quantity benefits through infiltration, ponded storage, and slowing of runoff, as well as water quality benefits by managing runoff at the source and thus reducing exposure to contaminants.

Miscellaneous and vendor-supplied systems include a wide variety of proprietary and other devices that don't fit in any other category. These systems often incorporate some combination of filtration media,

FIGURE 5. Filter media (Claytor and Schueler 1996).



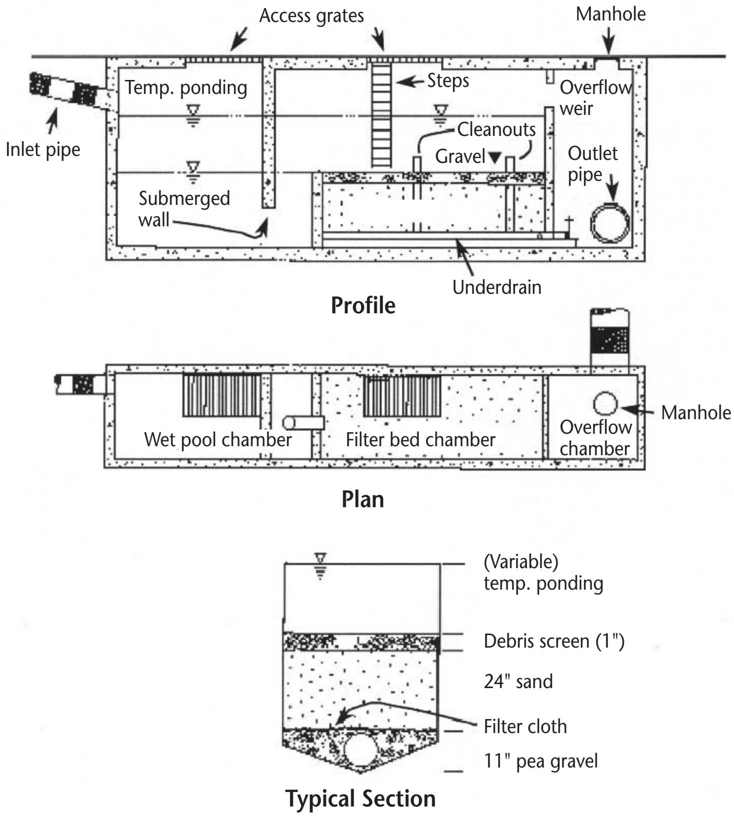


FIGURE 6. Underground vault sand filter (Claytor and Schueler 1996).

hydrodynamic sediment removal, oil and grease removal, or screening to remove pollutants from stormwater.

Non-Structural Best Management Practices. Non-structural BMPs are non-engineered practices designed to reduce pollutants entering stormwater or to reduce the volume of stormwater at the source. Reducing pollution at the source can limit the need for more costly structural end-of-the-pipe treatment. Non-structural practices can generally be divided into two categories as shown in Table 1.

TABLE 1. Non-structural best management practices.

Education, Recycling, and Source Control	Maintenance Practices
• Automotive product discharge	• Catch basin cleaning
• General community outreach	• Road salting and sanding
• Pet waste disposal	• Road and ditch maintenance
• Industrial good housekeeping	• Vegetation maintenance
• Pesticide/herbicide use	• Street and parking lot sweeping
• Storm drain inlet stenciling	• General BMP maintenance
• Commercial and retail space good housekeeping	• Sediment and floatables removal from BMPs
• Illicit discharge detection and elimination	
• Household hazardous material disposal	
• Fertilizer use	
• Lawn debris management	

Source: Strassler, E., J. Pritts, and K. Strellec (1999). Preliminary data summary of urban storm water Best Management Practices. Technical Report EPA-821-R-99-012, Environmental Protection Agency.

The first group—education, recycling, and source controls—is aimed at informing the public of ways to keep common pollutants out of stormwater. Often the public is not aware of the cumulative effects throughout a watershed of day-to-day activities like application of lawn chemicals or improper disposal of pet wastes. The second category, maintenance practices, includes those practices that reduce the contribution of pollutants from the urban landscape, as well as those practices that ensure that the stormwater collection and conveyance systems are operating as designed.

Implementation of Best Management Practices. Since BMPs are being used to meet a national mandate for non-point source pollution reduction, there have been attempts to compile and evaluate practices for nationwide implementation. As a result of the passage of the NPDES Phase II rule in 1999, the EPA has developed a Phase II toolbox to assist smaller municipal separate storm sewere systems impacted by this rule. This toolbox provides, for a wide range of practices, the BMP name, a description, an illustration, applicability and design considerations, limitation, operation and maintenance, effectiveness, cost, and references (Collins and Kosco 2000).

While a compilation of existing BMPs is clearly an important part of national implementation, this is not as straightforward a task as it may appear. Especially troublesome are the evaluation and reporting of BMP effectiveness. In comparing and compiling existing studies, it is apparent that there is little consistency in the study methods, the reporting of design parameters, and the reporting protocols. As a result, with many BMP evaluations it is difficult, if not impossible, to compare BMP design effectiveness among either a group of similar BMPs or a group of very different BMPs (Strecker et al. 2001).

For example, effectiveness is often reported in terms of percent removal of a contaminant. Not only can removal efficiencies vary widely as a result of variations in unreported variables like soil or vegetation type, but there is also a strong dependence on initial concentration of pollutants. A high level of removal efficiency is much easier to obtain with a high initial level of the pollutant. Adams et al. (2000) suggest using more easily comparable metrics. While not endorsing any specific metric, they give examples of metrics that might be adopted: mass of pollutant removal, event mean concentration (flow-weighted sampling), Minton's lines of comparative performance (comparing performance to some feasible lower limit of concentration), or plotting efficiency vs. operating rate (a laboratory evaluation of the technology).

An EPA-ASCE joint research program on reporting BMP effectiveness is attempting to address these issues. This study suggests standards that could be used to compare results from future studies: developing protocols for monitoring and reporting, developing a database of effectiveness studies, and evaluating existing information (Strecker et al. 2000; Strecker et al. 2001).

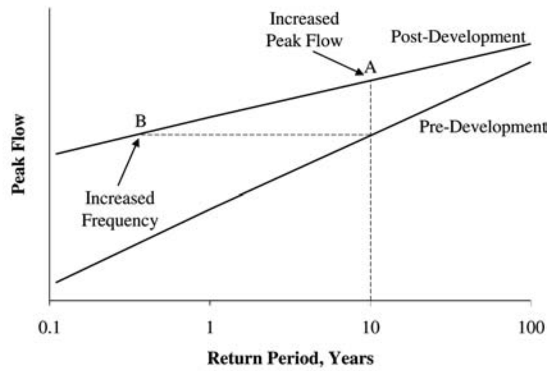
Furthermore, standardized reporting of BMP function is necessary to aid in BMP technology transfer and exchange among diverse groups. "Often BMPs are chosen from a laundry list specified in local or state criteria, rules, regulations, or ordinances; a list that may have been developed without regard to what may be appropriate for the local meteorology, climate, geologic conditions, or the receiving waters that are supposedly being protected" (Urbonas 2001, p. 3). Clearly, it is necessary to evaluate how these regional differences may impact implementation of BMPs that have been demonstrated to be successful in other regions. Some areas of the country have begun to address this problem (e.g., *Minnesota Urban Small Sites BMP Manual* (Barr Engineering Company 2001), *Stormwater Management Manual for Western Washington* (Washington State Department of Ecology 2001).

As individual practices, BMPs are able to provide specific solutions to specific stormwater management needs. However, without an integrated stormwater strategy, it is possible that there may be significant gaps between the intentions of the legislation driving BMP development and the reality of their implementation, especially when combining BMPs to achieve multiple objectives. First of all, it is clear that water quantity, water quality, stream geomorphology, and biological health of an ecosystem are all closely interrelated. Yet, most BMPs address these points individually, with little attention to the ways in which separate technologies interact (Roesner et al. 2001). Furthermore, considering water quantity and water quality separately often leads to systems that are improperly designed hydrologically and hydraulically. To correct this, flow management and water quality need to be considered jointly during the design process (Roesner 1999).

Another issue with BMPs is a problem that has historically plagued stormwater management: the use of a single design storm that focuses on only part of the full spectrum of the flow frequency curve, which often leads to worsening of urban stream conditions. Although water quality BMPs are often designed to address contaminants in the first flush of runoff after a storm commences, flood control BMPs often have an effect on less than 10% of annual storms. For example, if a two-year design storm is used, the facilities will have a significant impact on the hydrograph only once every two years (Roesner 1999).

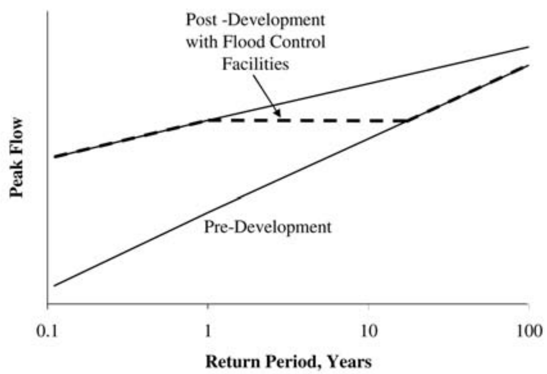
These problems are schematically illustrated in Figure 7. Part (a) shows the effect of urbanization on the flow frequency curve, highlighting both the increase in peak flow for a given return period (point A on the post-development curve), as well as the increase in frequency of a given peak flow rate (point B on the curve). Part (b) shows the effect of controlling solely for peak flow, maintaining the peak flow at the selected design storm level up to the overflow capacity of the facility. Finally, part (c) shows how the addition of water quality BMPs to a flood control facility can actually lead to worsening of flooding over some flow ranges. These failures occur most often as a result of back-to-back storm flows that do not allow BMPs to fully empty between events (Roesner 1999).

While relying solely upon BMPs as a complete stormwater management strategy may not lead to the desired results, BMPs do have an important role to play in the future of more ecologically sensitive stormwater management. As individual components within an integrated stormwater management system, BMPs can provide significant stormwater benefits, especially when selected thoughtfully with regard to site-specific conditions. In many of the practices described below, BMPs (although they might appear under different terminology) are essential building blocks within the broader stormwater strategy.



(a)

FIGURE 7. Effect on flow frequency of poorly designed BMPs: (a) Shift in flow frequency spectrum as a result of urbanization; (b) Effect of controlling for only peak flow over a range of design storms; (c) Effect of over-designed BMPs resulting from combined water quantity and quality controls (Roesner 1999).



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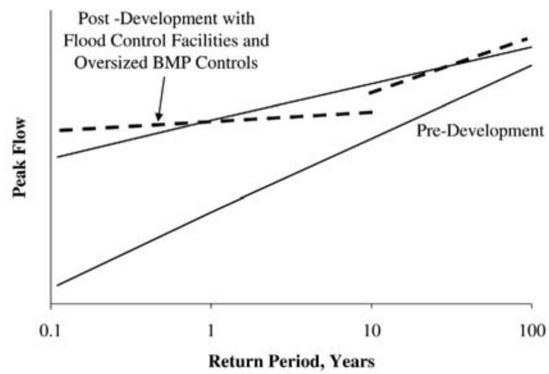


(c)

Low-Impact Development

Low-impact development (LID) is the term applied to the stormwater management strategies developed by Prince George's County, Maryland (Prince George's County 1993; Prince George's County 1999a; Prince George's County 1999b). The overall goals of LID are to "protect surface and ground water quality, maintain the integrity of aquatic living resources and ecosystems, and preserve the physical integrity of receiving streams" (Prince George's County, 1999a, p. ix). This is accomplished by trying to maintain a hydrologically functioning landscape that mimics predevelopment hydrology, by using techniques that store, infiltrate, evaporate, and detain runoff to reduce off-site runoff and maintain groundwater recharge. By distributing numerous small stormwater controls near the source of impacts throughout the entire basin, it may be possible to reduce, if not eliminate, the need for centralized, end-of-the-pipe stormwater facilities. In addition to controlling stormwater quantity, LID also provides stormwater quality benefits by capturing and treating the highly polluted "first flush' of stormwater at the source.

Implementing Low-Impact Development. LID is more than simply a method for managing stormwater quantity and quality. It represents a novel approach to development, based on the five fundamental concepts shown in Table 2 (Prince George's County 1999a). All five of these concepts center around maintaining hydrologic function of a landscape in the face of development. First, the development needs to conform to local hydrology by maintaining natural drainage ways and protecting and preserving sensitive areas that affect the hydrology. This includes streams and their buffers, floodplains, wetlands, steep slopes, high-permeability soils, and woodland conservation zones. Second, LID emphasizes small-scale stormwater controls distributed throughout the catchment, seeking to maintain hydrologic function, including infiltration, depression storage, and interception. Third, source control allows these functions to occur throughout a site, much as they would in an undeveloped landscape. Fourth, the use of non-structural methods reduces the use of steel, concrete, and other engineering materials, resulting in reduced construction costs. In addition, natural materials like native plants and soils are more easily integrated into the landscape, making a more aesthetically pleasing environment. Fifth, when designed within an LID framework, roofs, streets, parking lots, and green spaces serve not only their primary functions, but can also contribute to stormwater detention, retention, filtration, or travel time.

To accomplish these goals by employing the LID concepts, changes to the planning process are needed. The steps in this process are enumerated in Table 3. Basically, this process requires that hydrologic impacts and functions be considered throughout the design process. These steps are applied iteratively, attempting to match post-development hydrology to pre-development hydrology to as great a degree as possible. In their most general form, the hydrologic tools used to accomplish this are shown in Table 4.

TABLE 2. Fundamental concepts of low-impact development.

Concept 1:	Using hydrology as the integrating framework
Concept 2:	Thinking micromanagement
Concept 3:	Controlling stormwater at the source
Concept 4:	Utilizing simplistic, non-structural methods
Concept 5:	Creating multifunctional landscape and infrastructure

Source: Prince George's County (1999a). Low-Impact Development design strategies: An integrated design approach. Technical report, Department of Environmental Resources, Programs and Planning Division.

TABLE 3. Steps in LID site planning process.

1. Identify applicable zoning, land use, subdivision, and other local regulations
2. Define development envelope
3. Use drainage and/or hydrology as a design element
4. Reduce and/or minimize total site impervious areas
5. Integrate preliminary site layout plan
6. Minimize directly connected impervious areas
7. Modify and/or increase drainage flow paths
8. Compare pre- and post-development hydrology
9. Complete LID site plan

Source: Prince George's County (1999a). Low-Impact Development design strategies: An integrated design approach. Technical report, Department of Environmental Resources, Programs and Planning Division.

Low-Impact Design Hydrologic Analysis. Hydrologic analysis for LID is performed using methods described in the Soil Conservation Service's Technical Release 55 (TR-55) (Soil Conservation Service 1986). The design storm is selected by identifying the greater of (1) the rainfall at which the watershed would first produce runoff were it covered by woods in good condition (i.e., undeveloped) multiplied by a factor of 1.5 or (2) the one-year 24-hour design storm.

An example of how the post-development hydrology can be modified using LID methods is shown in Figure 8 and Figure 9. In both of these figures, curve 1 represents the pre-development runoff hydrograph. In Figure 8, curve 2 shows how development using traditional methods would increase the flows. By reducing imperviousness, the basin curve number is re-

TABLE 4. Tools for maintaining pre-development hydrology.

- Reduce/minimize imperviousness
- Disconnect unavoidable impervious surfaces
- Preserve and protect environmentally sensitive site features
- Maintain time of concentration (T_c)
- Mitigate for impervious surfaces with Integrated Management Practices
- Locate the impervious areas on less pervious soils

Source: Prince George's County (1999a). Low-Impact Development design strategies: An integrated design approach. Technical report, Department of Environmental Resources, Programs and Planning Division.

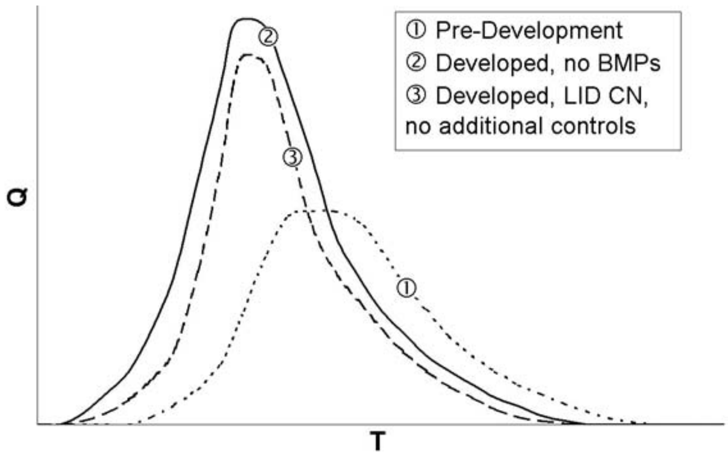


FIGURE 8. Changes in runoff hydrograph as a result of applying Low-Impact Design principles, part 1: reducing curve number (Prince George's County 1999a).

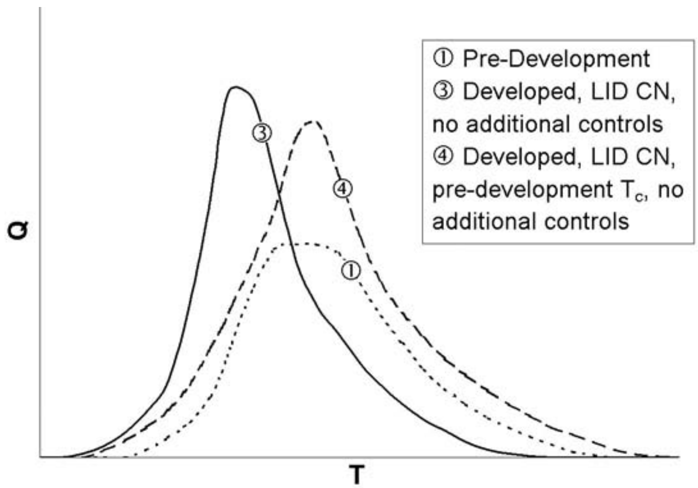


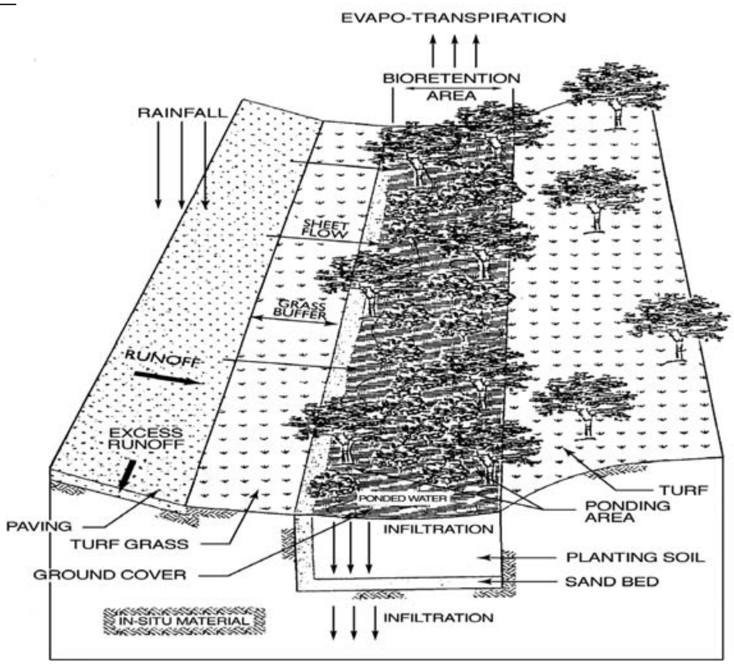
FIGURE 9. Changes in runoff hydrograph as a result of applying Low-Impact Design principles, part 2: decreasing time of concentration (Prince George's County 1999a).

duced, which reduces peak discharge and total runoff volume as shown by curve 3 in both Figure 8 and Figure 9. Next, LID design attempts to increase the time of concentration (T_c). This can be accomplished by storing runoff temporarily, lengthening flow paths, flattening flow slope, and/or increasing flow roughness. This results in a shift in the hydrograph from curve 3 to curve 4 in Figure 9. Finally, the difference in total runoff volume between curve 4 and the pre-development hydrograph (curve 1) can be reduced by placing additional small-scale retention and/or detention controls (IMPs) throughout the watershed (Prince George's County 1999a; Prince George's County 1999b).

Bioretention. One option for providing lot-level retention control is through *bioretention,* the basic technology from which LID was originally developed. In addition to performing the hydrologic functions of infiltration, retention, and evapotranspiration as in a rain garden, bioretention also removes stormwater pollutants through physical and biological processes, including adsorption, filtration, plant uptake, microbial activity, decomposition, sedimentation, and volatilization (Prince George's County 1993; Prince George's County 1999a; Prince George's County 1999b). The basic elements of a bioretention facility, as shown in Figure 10, are a grass buffer strip, a sand bed, a ponding area, a layer of mulch or organic matter, planting soil, and plants. Runoff is directed to the bioretention area as sheet flow, where the grass buffer strip slows the flow. The sand bed further slows the runoff and distributes it evenly over the ponding area, which is graded to provide surface storage with a ponding time of less than four days to prevent both waterlogging of plants and breeding of undesirable vectors. Once ponded, the stored water either infiltrates or evapotranspires. It should be noted that bioretention is not appropriate in areas of shallow groundwater tables (less than 6 feet) or in areas with unstable soils or steep slopes (greater than 20%).

A bioretention pond can be designed as either an "off-line" or an "on-line" treatment. An off-line design directs the polluted first-flush runoff into the bioretention area, but allows larger flows to be diverted to other management options. This ensures treatment of the first flush of pollutants by the bioretention system without having the pollutants washed downstream by subsequent higher flows. An off-line system needs to be graded such that the elevation at which runoff is discharging into the bioretention area is the same as the ponded surface elevation.

FIGURE 10. Bioretention area conceptual layout (Prince George's County 1993).



Guidance for the selection of plants can be found in the *Manual for Use of Bioretention in Stormwater Management* (Prince George's County 1993). A key element of the planting plan is diversity to protect against disease, infestation, and other urban stresses. Most of these guidelines are specific to Prince George's County, using plants from a terrestrial forest community ecosystem. To transfer this technology to other areas, the planting plan would need to be adapted to local native ecotypes.

Soil selection is another important design element. The soils need to have an infiltration rate greater than 0.5 in/hr. This generally includes the sandy loam, loamy sand, and loam textures from the USDA textural triangle. Acidity, organic matter, and other chemical constituents need to be at appropriate levels when first placed, and need to be monitored and maintained over time. In addition, mulch may be necessary to provide the organic matter that supports both plant life and soil microorganisms that contribute to pollutant removal. Mulch may not be necessary if the bioretention cell has 70–80% coverage by a dense herbaceous layer or groundcover. In sites underlain with low permeability soils, a drain can be installed under the bioretention bed, which results in the facility acting only as a filtering system rather than as an infiltration device (Environmental Protection Agency 1999b).

LID Evaluation. A number of authors (e.g., Low-Impact Development Center 2000; Hager 2003) describe successful demonstration projects, not only in Maryland and Prince George's County, but also in Virginia, Florida, Pennsylvania, Washington, Minnesota, Massachusetts, and Ottawa, Canada. Application of LID techniques included management of parking lot and highway runoff using bioretention, permeable pavements, and grassed swales, as well as a study of retrofitting vegetated roof cover in a highly urbanized area. These projects showed significant reductions in runoff, as well as good removal of pollutants.

In contrast, mixed results have been seen in the construction phase of the Jordan Cove Project (Phillips 2003). This long-term monitoring project compares three watersheds: a control watershed, a watershed developed using traditional stormwater management, and a watershed developed using LID stormwater management. While the LID watershed showed significant reductions in runoff and peak flows, the results for water quality were poorer than expected, probably due to poor implementation of erosion and sediment control BMPs during the construction phase.

Even with generally good results in demonstration projects, there are still legitimate concerns that need to be addressed. For example, Strecker (2001) notes limitations in the hydrologic analysis. First, the analysis uses only a single design storm, and second, the synthetic design storm represents a single, unique combination of rainfall intensities that may not be a good representation of typical rainfall events. Since basin response varies widely with changing intensities and durations of precipitation, a single design storm (or even two or three) gives a very limited picture of the design hydrology. Third, use of an event-based analysis is much less revealing than continuous simulation, especially with respect to recovery time and antecedent conditions. For example, the response of an LID design to a storm arriving at the end of a string of rainy days would be much different than an identical storm arriving after an extended dry period.

Furthermore, while Coffman (2001) is confident of the ability of individual property owners to maintain LID structures properly, and thus ensure the overall viability of the whole system, other authors express concern over the ongoing maintenance issue. Coffman claims that LID has enough built-in redundancy so that the overall operation of the system will not be adversely affected by the failure of individual elements. However, at some point, enough failures will cross the threshold provided by the built-in redundancy, and the system as a whole will fail to meet design goals. One way to prevent this kind of failure is to have regular inspection and maintenance. However, England (2002) cites as a problem the current workload of municipalities charged with regular inspection and enforcement of standards associated with subdivision-scale stormwater structures. If the number of structures were increased from one per subdivision to one or more per lot, this burden would increase dramatically. Furthermore, the issue of enforcement becomes more difficult when dealing with individual property owners than it would be with contractors or a single homeowners' association.

Conservation Design

In its most general form, described by Arendt (1996), *Conservation Design* seeks to maximize open space without reducing overall building density. The goal of Conservation Design is to designate at least half of the buildable land as undivided, permanent open space. Either clustering houses to maintain a rural sensibility or using a neo-traditional village layout could accomplish this. Up to half of the open space may be used for more formal, intensively managed open space like grassed commons or recreation facilities, but a major goal of Conservation Design is to maximize open space in either undisturbed or restored native landscapes. To maximize the benefits of this open space, the principles of ecology and landscape position shown in Table 5 should be considered when selecting which areas are developed and which are left open.

In addition to maintaining open space in its natural state, providing habitat and other natural ecological functions, Conservation Design also offers attractive quality of life benefits for the human residents as well. Arendt (1996) cites the increasing popularity of living within golf course developments, even among non-golfers, with consumers showing "their clear preference for buying homes that look out onto farmland or other open space, rather than houses where the only view is of their neighbor's picture window or backyard" (p. 11). In addition, Conservation Design developments provide increased recreational and social opportunity. Open spaces provide a place and an opportunity for meeting informally with neighbors or for more formal recreational activities (Northeastern Illinois Planning Commission 2003).

Conservation Design for Stormwater Management. With respect to stormwater management, Conservation Design relies on open space as a strategy for maintaining a more natural hydrologic cycle and incorporates natural site features into the stormwater management plan (Delaware Department of Natural Resources and Environmental Control 1997). This design process integrates stormwater management into the very core of site design, in direct contrast to the traditional development practice of addressing stormwater as a footnote to the design process. To do so requires that the design community treat stormwater as a "resource" rather than a "byproduct" of development.

In following the basic principles of Conservation Design for stormwater management shown in Table 6, Conservation Design seeks to use a wide range of innovative options tailored to a specific site. In contrast, conventional stormwater management tends to use a more standardized approach even as site conditions vary (Horner 2000). Working within the natural landscape can often result in systems that require smaller upfront costs and less maintenance over the long run.

Conservation Design Strategies. In implementing Conservation Design, the site designer can draw from a wide array of practices to achieve stormwater objectives. However, while other stormwater management

TABLE 5. Principles of ecology and landscape position for urban design.

- Old is more valuable than new (wetlands and forests are key resources).
- Complex habitats are more valuable than simple ones.
- Large tracts are more valuable than small tracts (floodplains are key resources).
- Fragmentation reduces ecosystem value.
- The value of small tracts is increased if connected to larger tracts (headwaters are key resources).
- Rare species are important and easily overlooked.
- Our knowledge is limited (need for safety factors).

Source: Delaware Department of Natural Resources and Environmental Control (1997). *Conservation Design for Storm Water Management.*

TABLE 6. Basic principles of conservation design

- Achieve multiple objectives
- Integrate stormwater management early into the site design process
- Prevent first, mitigate second
- Manage stormwater as close to the source of generation as possible
- Engage natural processes within the soil mantle and the plant communities

Source: Horner, W. R. (2000). Conservation Design: Managing stormwater through maximizing preventive nonstructural practices. In *National Conference on Tools for Urban Water Resource Management and Protection*, Chicago, IL, pp. 147–157. U.S. Environmental Protection Agency.

approaches tend to differentiate between structural and non-structural practices, Conservation Design relies on the distinction between preventive and mitigative approaches in classifying specific stormwater strategies. In particular, Conservation Design uses the terminology of *Conservation Design Approaches* (CDAs), which are more preventive in nature, and *Conservation Design Practices* (CDPs), which are more mitigative (Delaware Department of Natural Resources and Environmental Control 1997; Horner 2000). These approaches are briefly discussed below with greater detail available in several sources (e.g., Northeastern Illinois Planning Commission 1997; Delaware Department of Natural Resources and Environmental Control 1997; Horner 2000).

The stormwater management techniques that are preventive in nature, CDAs, tend to be broader in geographical scope, typically involving the entire site. Delaware Department of Natural Resources and Environmental Control (1997) describes four general categories that can be considered preventive. First, through the planning and zoning programs, it may be possible to incorporate open space designs by increasing building density in part of the development, while leaving open space to maintain overall density levels. This works in tandem with the second, consideration of clustering and lot configuration. Clustering allows the site designer to group imperviousness in areas of lower infiltration capacity, while maintaining more pervious areas as open space. Third, imperviousness can be reduced, not only by clustering, but also by reducing road widths or limiting sidewalks to one side of the road. Fourth, site design seeks to minimize disturbance and maintenance by protecting open areas from clearing and disturbance. The use of extensive grading and heavy earthmoving equipment can create significant changes in infiltration capacity. This is captured in hydrologic analysis by changing the hydrologic soil group of areas disturbed by grading and heavy equipment to a less pervious group (i.e., Group B soils are analyzed as C).

In contrast, the mitigative approaches, CDPs, tend to be smaller in scale and more structural in nature. Again, CDPs can be grouped into four general categories (Delaware Department of Natural Resources and Environmental Control 1997). First, using vegetated swales or natural drainageways for stormwater conveyance is effective in slowing the flow and providing some infiltration opportunity. Second, taking advantage of vegetated filter strips, including riparian buffer zones further slows the flow and may provide significant water quality benefits. Third, grading, berming, and terraforming may include the creation of subtle depressions or saucers integrated into the graded landscape or the use of a driveway to create a subtle upslope dam to enhance infiltration and recharge. Finally, the use of natural areas with level spreading maximizes the potential for taking advantage of natural soil and vegetation hydrologic process. This is particularly effective in conjunction either with undisturbed areas or with reforestation and revegetation.

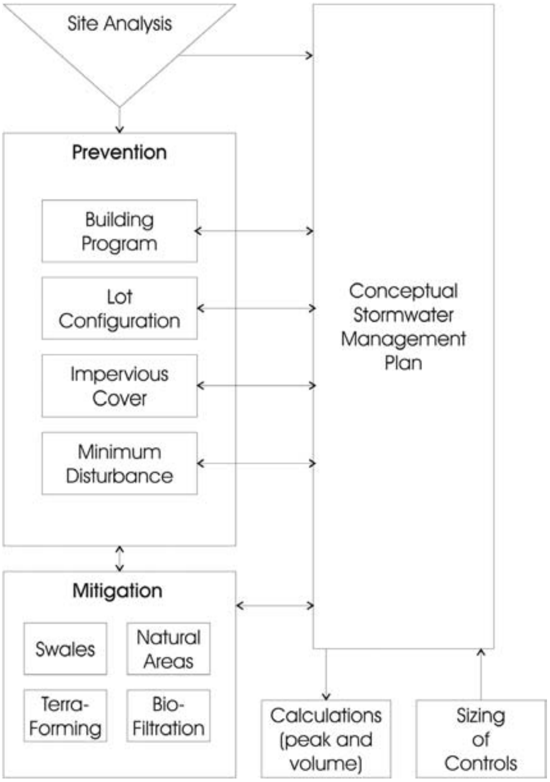
An example of a specific conservation design practice system is the Stormwater Treatment Train[(c)], developed by Applied Ecological Services, Inc. (Broughton and Apfelbaum 1999), which includes an interconnected system of swales, prairies, wetlands, and lakes to treat stormwater. The swales provide initial stormwater treatment, primarily through infiltration and sedimentation.

Then, prairies diffuse the flows conveyed by the swales, and reduce stormwater velocities to maximize the prairies' sedimentation (storing and breaking down contaminants), infiltration (enhanced by the deep root system), and evaporative water treatment. Wetlands then provide both stormwater detention and biological treatment prior to runoff entering the lake. Finally, the lake provides stormwater detention, further solids' settling, and biological treatment.

Implementation of Conservation Design. To ensure successful implementation of a stormwater management plan, Conservation Design requires the developer to consider stormwater at every phase of development. This is shown graphically in Figure 11, which outlines the basic procedure for Conservation Design (Delaware Department of Natural Resources and Environmental Control 1997). The placement of the conceptual stormwater management plan as a concurrent task with all other phases of the design process emphasizes this integration.

Since a primary goal of Conservation Design is to integrate existing site resources into the design and stormwater management plan, a necessary first step is to perform a site analysis. This analysis includes con-

FIGURE 11. Conservation Design procedure. (Delaware Department of Natural Resources and Environmental Control 1997.)



ducting an inventory of site resources and mapping these resources onto the site plan. This inventory allows identification of both limitations and opportunities on the property. Furthermore, the inventory provides the database from which subsequent decisions in the design process can be made (Delaware Department of Natural Resources and Environmental Control 1997; Horner 2000).

Throughout the design process, priority is given to maintaining the natural hydrologic cycle to as great a degree as possible. This is done first by applying the preventive approaches (CDAs) and then, as needed, mitigative approaches (CDPs) as described above. Where quantity reduction and source controls are not adequate, natural mechanisms are used to improve stormwater quality and quantity. By relying on soil and vegetative processes to perform stormwater management functions, Conservation Design provides techniques that will tend to improve in function over time, as vegetation matures and soil structure develops. In contrast, conventional designs like stormwater detention systems tend to diminish in function over time (Horner 2000).

In most communities, Conservation Design can only be accomplished through the Planned Unit Development (PUD) process. This allows the community a higher level of control over the permitting of unconventional designs. However, a more stringent review process creates a significant disincentive to developers who might otherwise consider a Conservation Design approach. To remove this obstacle, community zoning ordinances may be updated to permit or even encourage the use of Conservation Design (Arendt 1999; Northeastern Illinois Planning Commission 2003).

Better Site Design

In land development, the term *Better Site Design* refers to a collection of techniques seeking to "reduce total paved area, distribute and diffuse stormwater, and conserve natural habitats" (Kwon 2000, p. 253). In so doing, the goal is to improve stormwater management, while creating residential and commercial developments that seek to find a balance between human pursuits and the natural environment.

Better Site Design Philosophy. Specifically, Better Site Design hopes to accomplish three goals at every development site: "to reduce the amount of impervious cover, to increase natural lands set aside for conservation, and to use pervious areas for more effective stormwater treatment" (Kwon 2003, p. 253). To provide guidance in meeting these goals, a national site planning roundtable was convened in 1997 to provide guidelines for implementation and to encourage communities to implement these kinds of practices. Represented at the roundtable were diverse stakeholders in the development process, including the American Society of Civil Engineers, The Conservation Fund, National Association of Homebuilders, National Realty Committee, Natural Resources Defense Council, U.S. Environmental Protection Agency, and a number of others. This group developed and endorsed a set of 22 Better Site Design techniques to provide guidance for developers and communities. The techniques compiled by this committee are enumerated in Table 7.

Application of Better Site Design Practices. Since Better Site Design adheres to a set of stormwater management principles, rather than a more formal design process, the best way to examine how these principles might be applied is to look at examples of how these practices might be implemented in residential or commercial development.

Zielinski (2000b) demonstrates the benefits of better site design by conceptually redesigning a low-density subdivision and comparing key indicators. In this study, Duck Crossing, a large-lot development in Wicomico County on Maryland's Eastern Shore, was redesigned using Better Site Design principles. The comparison is illustrated in Figure 12.

TABLE 7. Principles of better site design.

Residential Streets and Parking Lots (Habitat for Cars)

1. Design residential streets for the minimum required pavement width needed to support travel lanes, on-street parking, and emergency, maintenance, and service vehicle access. Street widths should be based on traffic volume.
2. Reduce the total length of residential streets by examining alternative street layouts to determine the best option for increasing the number of homes per unit length.
3. Wherever possible, residential street right-of-way widths should reflect the minimum required to accommodate the travel-way and the sidewalk, and should be located within the pavement section of the right-of-way wherever feasible.
4. Minimize the number of residential street cul-de-sacs and incorporate landscaped areas to reduce their impervious cover. The radius of cul-de-sacs should be the minimum required to accommodate emergency and maintenance vehicles. Alternative turnarounds should be considered.
5. Where density, topography, soils, and slope permit, vegetated open channels should be used in the street right-of-way to convey and treat stormwater runoff.
6. The required parking ration governing a particular land use or activity should be enforced as both a maximum and a minimum in order to curb excess parking space construction. Existing parking ratios should be reviewed for conformance, taking into account local and national experience to see if lower rations are warranted and feasible.
7. Parking codes should be revised to lower parking requirements where mass transit is available or enforceable shared parking arrangements can be made.
8. Reduce the overall imperviousness associated with parking lots by providing compact car spaces, minimizing stall dimensions, incorporating efficient parking lanes, and using pervious materials in the spillover parking areas where possible.
9. Provide meaningful incentives to encourage structured and shared parking to make it more economically viable.
10. Wherever possible, provide stormwater treatment for parking lot runoff using bioretention areas, filter strips, and/or other practices that can be integrated into required landscaping areas and traffic islands.

Lot Development (Habitat for People)

11. Advocate open space design subdivisions incorporating smaller lot sizes to minimize total impervious area, reduce total construction costs, conserve natural areas, provide community recreational space, and promote watershed protection.
12. Relax side yard setbacks and allow narrower frontages to reduce total road length in the community and overall site imperviousness. Relax front setback requirements to minimize driveway lengths and reduce overall lot imperviousness.
13. Promote more flexible design standards for residential subdivision sidewalks. Where practical, consider locating sidewalks on only one side of the street and providing common walkways linking pedestrian areas.
14. Reduce overall lot imperviousness by promoting alternative driveway surfaces and shared driveways that connect two or more homes together.
15. Clearly specify how community open space will be managed and designate a sustainable legal entity responsible for maintaining both natural and recreational open space.
16. Direct rooftop runoff to pervious areas such as yards, open channels, or vegetated areas and avoid routing rooftop runoff to the roadway and the stormwater conveyance system.

(continues)

TABLE 7 (continued).

Conservation of Natural Areas (Habitat for Nature)

17. Create a variable width, naturally vegetated buffer system along all perennial streams that also encompasses critical environmental features such as the 100-year floodplain, steep slopes, and freshwater wetlands.
18. The riparian stream buffer should be preserved or restored with native vegetation. The buffer system should be maintained through the plan review, delineation, construction, and post-development stages.
19. Clearing and grading of forests and native vegetation at a site should be limited to the minimum amount needed to build lots, allow access, and provide fire protection. A fixed portion of any community open space should be managed as protected green space in a consolidated manner.
20. Conserve trees and other vegetation at each site by planting additional vegetation, clustering tree areas, and conserving native vegetation. Wherever practical, incorporate trees into community open space, street rights-of-way, parking lot islands, and other landscaped areas.
21. Incentives and flexibility should be encouraged to promote conservation of stream buffers, forests, meadows, and other areas of environmental value. In addition, off-site mitigation should be encouraged where it is consistent with locally adopted watershed plans.
22. New stormwater outfalls should not discharge unmanaged stormwater into jurisdictional wetlands, sole-source aquifers, or sensitive areas

Sources: Center for Watershed Protection (1998a). *Better Site Design: A Handbook for Changing Development Rules in Your Community*. Ellicott City, MD.
Center for Watershed Protection (1998b). *A Consensus Agreement on Model Development Principles*. Ellicott City, MD.

In this study, one of the most striking differences is a reduction in lot size, achieved by clustering lots to leave additional common open space. While clustering can be an excellent strategy for reducing impervious areas, many clustering programs have not been designed with hydrologic impacts in mind. As a result, clustering alone might not achieve the desired stormwater management goals, especially if common areas are landscaped with turfgrass or paved over (e.g., for tennis courts) (Schueler 2000b).

However, if the placement and land use of the open space are carefully considered, significant stormwater benefits may be seen. In this example, common open space was able to maintain most of the existing forest, wetlands, and meadows in an undisturbed state. This resulted in a 53% decrease in the area covered by residential lawns. This was complemented by significant reductions in impervious areas by providing narrower access roads, shorter shared driveways, and a loop in the place of the cul-de-sac used for the road turnaround. In addition, paved sidewalks were replaced by a wood chip trail system throughout the open space. An overall 35% reduction in impervious cover was achieved with these practices.

Traditional curb and gutter conveyance to storm drains leading to a detention pond was replaced by a system including dry swale conveyance and a bioretention area incorporated in the road loop. This improved system increased stormwater infiltration by an estimated 12%, decreased stormwater runoff by 23%, and reduced pollution load via filtration. In conjunction with a redesigned septic system with improved location and performance, phosphorus export was reduced by 50% and nitrogen export was reduced by 46%. Finally, cost effectiveness was demonstrated by this design. Although the cost of a more sophisticated stormwater and septic system was more than the traditional counterparts, this was more than offset by the construction cost savings resulting from decreased paving, sidewalks, and curb and gutters. The final price tag showed a 12% decrease when compared to the original design.

In commercial design, where development is dominated by the parking lot, reducing the pavement area becomes an even more important strategy. A study by the city of Olympia, Washington, shows that a 10 to 20% reduction in impervious surfaces is a reasonable goal for many developments (Wells 2000). This can be seen in another study by Zielinski

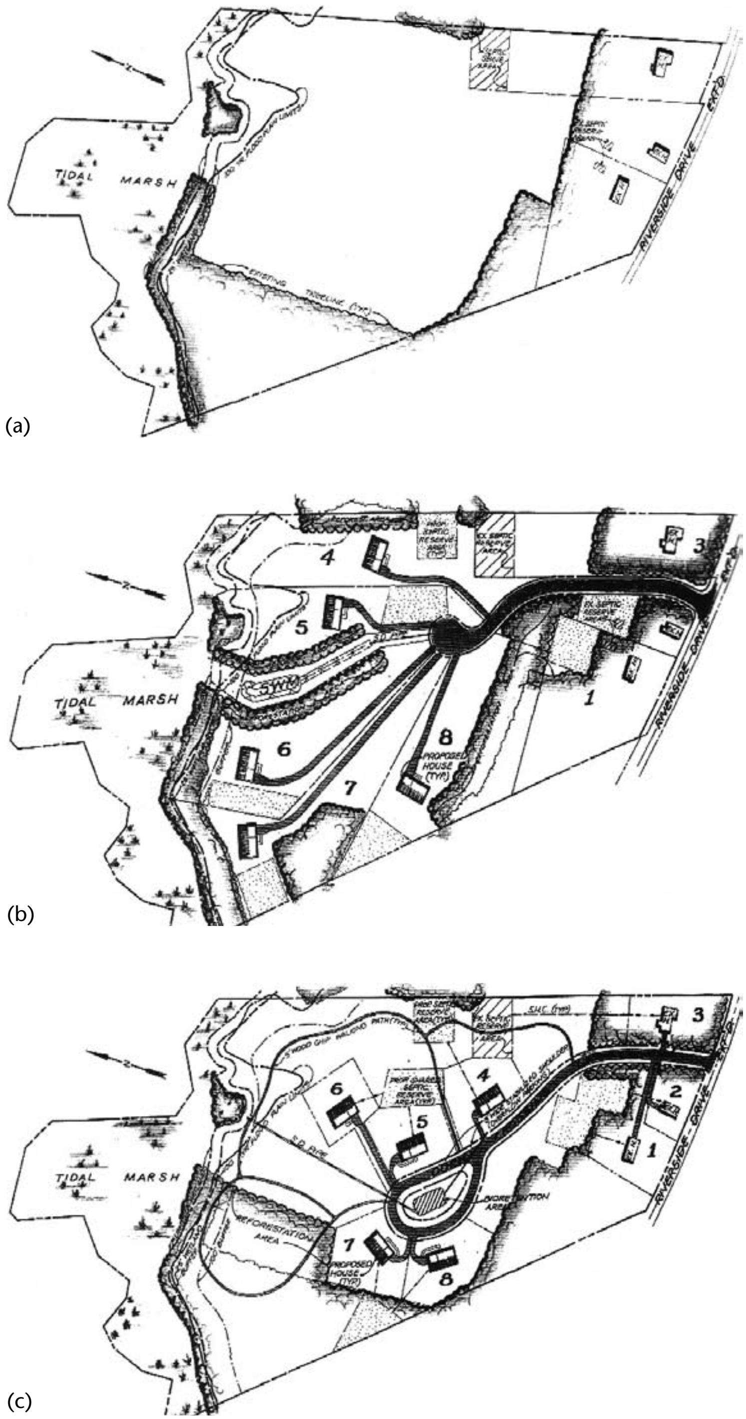
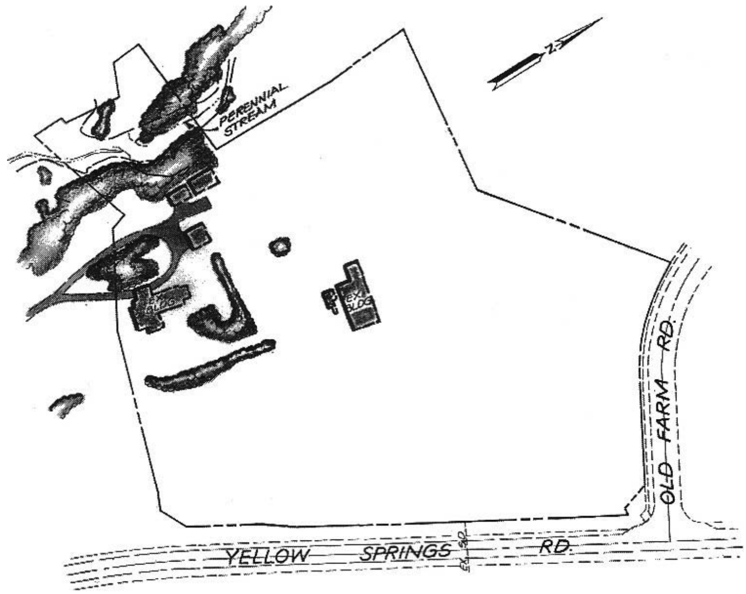


FIGURE 12. Application of "Better Site Design" principles to a residential subdivision: (a) Pre-development conditions at the Duck Crossing site; (b) The low-density conventional subdivision built at Duck Crossing; (c) The open space subdivision that could have been built at Duck Crossing. Example from Zielinski (2000b).

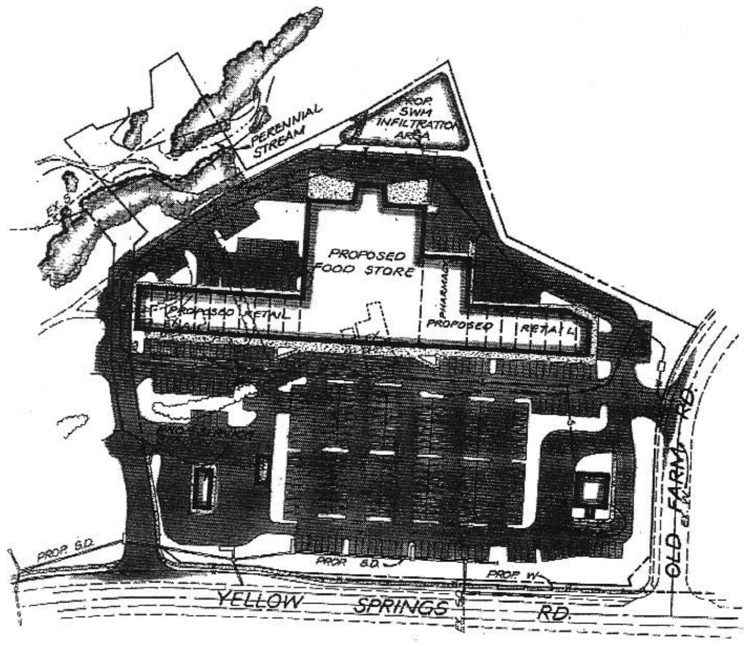
(2000a), which evaluates a redesigned commercial development. Figure 13 shows the Old Farm shopping center site in the city of Frederick, Maryland. This typical "strip" shopping center was constructed in 1992 and covers most of the 9.3-acre site.

While maintaining the same amount of gross floor area, the redesigned shopping center was changed to a U-shaped configuration to reduce walking distances between stores. Parking was reduced from 5.2 spaces to 4.4 spaces per 1000 ft^2, based on

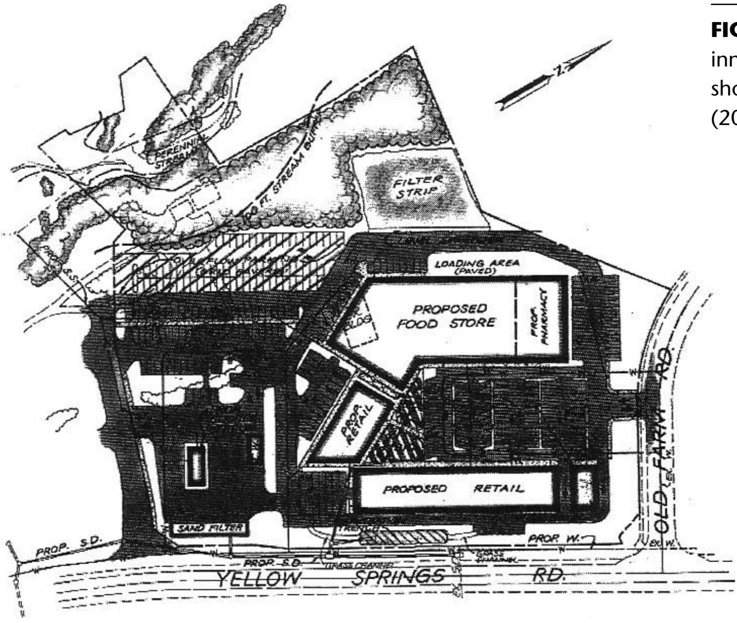
FIGURE 13. Application of "Better Site Design" principles to a commercial development: (a) Pre-development conditions at the Old Farm shopping center site. (b) The conventional design of the Old Farm shopping center. (continues)



(a)



(b)



(c)

FIGURE 13 (continued). (c) The innovative design of the Old Farm shopping center. Example from Zielinski (2000a).

local municipality requirements, with an additional reduction based on actual annual parking demand. In addition, 17% of the stalls were reduced in size for compact car parking. Furthermore, 25% of the parking area was designated "spillover" parking and substituted grid pavers (capable of storing the first few tenths of an inch for rainfall events) for normal paving material. Together, these changes resulted in an 18% reduction in impervious cover.

Stormwater management was enhanced by taking advantage of the reduction in paved areas to design more effective landscaping and stormwater treatment. This included larger parking lot islands that were converted to stormwater bioretention areas, as well as stormwater infrastructure that included a sand filter, a filter strip, and an infiltration trench. Combined with the reduction in impervious cover, these elements resulted in an estimated 17% reduction in stormwater runoff, a 46% reduction in phosphorus export, and a 42% reduction in nitrogen export. Although the reduced amount of pavement cost less to develop, the additional landscaping, the more sophisticated stormwater practices, and the use of the more expensive grid pavers mostly offset these savings. As a result, the redesigned shopping center ended up with only a 2% decrease in cost.

Together, these examples demonstrate that it is possible to realize significant hydrologic and water quality benefits through the use of Better Site Design. Through these principles, it is possible to consistently increase stormwater infiltration, reduce runoff, and reduce nutrient export while maintaining or even decreasing construction costs (Zielinski 2000a; Zielinski 2000b).

Smart Growth

Smart Growth is a movement in urban development resulting from the frustration with the sprawling development patterns that often occur as a result of current governmental policies. These policies facilitate the decentralization of people and jobs and the decline of urban centers. In general, the goals of Smart Growth are "to slow decentralization, promote urban reinvestment, and promote a new form of development that is mixed use, transit-oriented and pedestrian friendly" (Katz 2002, p. 15).

While Smart Growth has traditionally focused on transportation needs and issues, a number of authors have approached Smart Growth from the stormwater management viewpoint. Beach (2004) identifies urban sprawl as one of the leading causes of water pollution and endorses Smart Growth principles as the solution. "Encouragingly, the patterns of growth that will sustain our nation's waters will also advance other community goals—goals such as affordable housing, social equity, transportation efficiency, and fiscal responsibility. The requisite development patterns are similar to those promoted by smart growth advocates, but they are further shaped by the needs of watershed protection" (Beach 2004, p. 3). To address the needs of watershed protection, McCuen (2003) enumerates seven principles that form the basis of the hydrologic Smart Growth philosophy, summarized in Table 8. Not surprisingly, many of these principles overlap with other approaches discussed above.

Furthermore, Smart Growth advocates selection of multiple metrics for evaluating stormwater management plans, over and above the standard metric of maintaining end-of-pipe flow rates. Specific metrics should be chosen locally to reflect community priorities and conditions. Examples may include sub-basin storage, stream channel maintenance, groundwater recharge, or maintenance of travel times (McCuen 2003).

Other Stormwater Management Options

Most of the practices described above have been developed in the United States. However, other parts of the world have been designing and implementing green stormwater solutions as long or longer than in the United States. Therefore, a discussion of a few international practices is included. Finally, a couple of examples from a single region of the United States that do not necessarily adhere to just one of the above-described practices are described, before turning to a more general discussion of green stormwater management.

TABLE 8. Hydrologic philosophy of Smart Growth.

1. Control runoff at microwatershed level
2. Consider hydrologic processes in microwatershed layout
3. Maintain first-order receiving streams
4. Maintain vegetated buffer zones
5. Control spatial pattern of hydrologic storage
6. Control upland flow velocities
7. Control temporal characteristics of runoff

Source: McCuen, R. H. (2003). Smart growth: Hydrologic perspective. *Journal of Professional Issues in Engineering Education and Practice 129*(3), 151–154.

The International Experience. The Europeans have long been at the forefront of ecologically sensitive stormwater management. Thus, we include some examples from Europe, including Germany, Denmark, Sweden, and the Netherlands, as well as other areas of the world, including Japan and Australia.

The Germans have extensive experience with integrating storm drainage into "green planning." For example, Ristenpart (1999) describes the development of a large city-planning project (27 ha), accomplished without creating significant changes in the local hydrology. Grotehusmann et al. (1994) describe a System of INterconnected Infiltration POnds and Trenches (SINIPOT) implemented in the city of Gelsenkirchen, Germany. The low infiltration capacity of the natural soil at the case study site (in the range of 10^{-6} – 10^{-7} m/s in most areas) severely limits the potential for decentralized infiltration. Instead, rainwater is directed to an infiltration pond and filtrates through an intermediate soil strata into an underlying trench for temporary storage. Vegetation in the soil strata can improve the quality of the storm runoff. From the trench, the water can—depending on soil permeability—either infiltrate or flow slowly through the connected trench system to the receiving water body after a significant delay.

In Denmark, Mikkelsen et al. (1999) explore the potential for on-site reuse of collected rainwater. While this study is primarily concerned with reducing use of the municipal water supply to maintain sustainable groundwater extraction, the system also provides for a reduction in stormwater runoff from house roofs. In this design, water from the roof is captured and stored in a tank for future use for flushing of toilets and washing of clothes. While it may be impractical to collect all rainfall due to excessively large storage requirements to contain large, rare events, much of the annual rainfall can be captured and reused in this manner.

In Sweden, the greatest challenge with respect to stormwater management is the cold climate. Stenmark (1995) notes that frost heave damage and ice blockages often occur within the stormwater system in cold climates. This paper describes a field study designed to address these problems by replacing existing road and storm sewer systems with permeable pavement and wider vegetated roadside swales. The pavement is one-meter-thick, coarse macadam with 35–40% porosity, lined with geotextile to reduce clogging by fine sediment. The thick asphalt and homogeneous sub-base significantly reduce frost heave damage, while the use of swales reduces the problem of backwater effects due to ice blockage. Together the pavement and swales performed well in reducing runoff, especially during the critical snowmelt period.

Geldof et al. (1994) compiled and compared infiltration practices in Japan, Denmark, and the Netherlands and concluded that infiltration can be a successful approach to solving a variety of urban runoff problems in diverse settings as a part of integrated water resources management. In particular, using similar techniques, infiltration-based approaches have been implemented successfully to deal with flooding problems in Japan, water quality problems resulting from combined sewer overflows in Denmark and the Netherlands, and subsiding groundwater levels in the Netherlands.

By taking advantage of an extensive system of Quaternary and Tertiary aquifers beneath the city of Adelaide, Australia, it is possible to store water infiltrated during the rainy winters for retrieval and use during the summer. All residential surface runoff is collected in a swale system, which filters sediment and other contaminants and conveys stormwater, providing a degree of temporary storage. As stormwater travels along the swale, it is infiltrated into a gravel-filled trench beneath the swale that serves as a conduit to the aquifer system (as well as additional storage). In addition to storing stormwater for retrieval during dry periods, this system also enhances soil moisture storage for a greener streetscape throughout the year (Argue 1994).

Regional Case Studies. Lehner et al. (1999) have compiled case studies of successful integrated stormwater management strategies from across the United States. Criteria for inclusion in this compilation included environmental gains, economic advantages, and community benefits. Environmental gains include biological, hydrological, or chemical improvements; economic advantages include cost savings or increased property values; and community benefits include aesthetic or recreational enhancement, administrative or institutional success, or improved community relations. Here, two examples are taken from the Midwest, but examples from other regions of the United States may also be found in this compilation.

The Prairie Crossing project, a 4.1 mi^2 development in Grayslake, Illinois (20 miles northwest of Chicago), uses Conservation Design techniques to reduce quantity and improve quality of stormwater runoff. Clustered lot design significantly reduces the length of roads, which helps to reduce runoff quantity, while use of native vegetation with no fertilizers and only limited spot-application of herbicides significantly reduces stormwater contamination. Likewise, Prairie Crossing's homeowner covenants require that private lots be managed in an environmentally sensitive way. An environmental coordinator, who manages the open areas, is also available to aid homeowners in adhering to these practices. In addition to stormwater benefits, Prairie Crossing has demonstrated an initial capital cost savings of an estimated $1.6 to $2.7 million. Further, home sales performance has been comparable to or better than conventional developments in the region (Apfelbaum et al. 1995; Lehner et al. 1999).

The Prairie Waterway project is comprised of a two-mile constructed waterway with constructed wetlands and ponds in Farmington, Minnesota, located in the southern outskirts of the Minneapolis–St. Paul metropolitan area. This waterway was designed to address existing storm-related flooding in the Farmington community, as well as to accommodate the nearby construction of a proposed 500-unit subdivision to be built on 200 acres. The project used previously undevelopable land to provide drainage and water storage capacity for the area. In addition to the stormwater benefits provided by the waterway, the developer of the new subdivision also incorporated on-site elements to help resolve water quality and quantity concerns. This included compact development and narrower streets to reduce imperviousness and stormwater retention incorporated into each block using depressions in adjoining backyards and common spaces. Not only did this project help to minimize impacts of the new development, it was also successful in reducing the flooding in existing developments (Lehner et al. 1999).

DISCUSSION

Having explored a variety of green stormwater management strategies, it is useful to compare and contrast these practices. While there are certainly differences among the strategies, common themes also appear. First, we look at some of the differences, which range from minor to substantial. Then we look at ideas that seem to be common to most integrated stormwater management schemes.

Comparing Options

In stormwater management, "Best Management Practice" seems to be both the broadest and the most general term. In fact, many of the specific technologies employed by the other approaches (e.g., bioretention, minimizing directly connected impervious areas) are included under the umbrella of BMPs. However, by itself, BMP is not as comprehensive as many of the other options, in the sense that it contains only the individual tools without a guiding vision or philosophy for integrated implementation.

Another striking difference that separates BMPs from the rest of the approaches is the difference in how the stormwater management issues are approached. BMP literature focuses more on human ingenuity and highly complex, engineered structures for the solution of stormwater problems. In contrast, the other approaches show a preference for working within the natural landscape and seeking to maintain or mimic the natural hydrologic cycle to maintain the ecological integrity of the landscape. This difference most likely results from who has been leading the respective discussions. Many BMP researchers and experts draw heavily from an engineering background, while other approaches reflect a much more interdisciplinary approach, drawing expertise from not only engineers, but also landscape architects, biologists, ecologists, etc.

Furthermore, the approaches vary in the degree to which they are able to work within the existing zoning and plan review framework. The approaches discussed in this chapter seem to lie along the full spectrum. BMPs, for the most part, require no special treatment in their implementation. LID also is fairly straightforward in application, although minor revision or waivers to the building code may be required. Next is Conservation Design, which adds the need for special consideration for clustering development while maintaining overall site density. Better Site Design advocates work actively to enact changes ranging from redefining parking and transportation requirements to overhauling building and zoning codes and ordinances at the community level. At the far end of the spectrum is Smart Growth, which seeks fundamental changes to how urban planning and development proceed, demanding a complete overhaul of major governmental policies on land use, infrastructure, and taxation.

A final notable difference is one of semantics and classification. Many of the approaches appear to have a greater degree of variation than they actually do, due to variation in terminology and classification. For example, LID differentiates between small-scale practices implemented throughout the basin at the lot level (Integrated Management Practices) and centralized, end-of-the-pipe practices (Best Management Practices). In contrast, BMP literature would include all of these practices under the term "Best Management Practices." Further, Conservation Design offers yet another way of dividing stormwater management techniques: preventive practices, often broader in geographical scope (Conservation Design Approaches) and mitigative practices, which tend to be smaller in scale and more structural (Conservation Design Practices). Thus, the same general body of stormwater management technology can be divided in a number of different ways: CDAs vs. CDPs (Conservation Design), IMPs vs. BMPs (LID), or structural vs. non-structural (BMP).

Furthermore, Coffman (2001) draws a distinction between LID and other techniques like Conservation Design and Better Site Design: while other techniques tend to mostly focus on reducing runoff through reductions in impervious area or minimization of impacts, LID is focused on the more fundamental goal of retaining or restoring hydrologic function. It is not clear whether this is a real difference or merely a difference in language, as the end results of the different practices are often quite similar. Although such differences in semantics or classification seem to be relatively minor, they may become important if these differences make clear communication among practitioners of different approaches difficult.

Common Themes

In spite of differences in vocabulary and usage, there are clearly a number of common themes and strategies that can be seen when comparing different approaches. First, there are a couple of concepts that appear throughout the green stormwater management literature: maintaining infiltration function and managing stormwater at the source. In addition, there are implementation issues that need to be considered regardless of which approach one follows.

Maintaining Infiltration Function. The first theme that seems to be common to the successful implementation of any of these stormwater strategies is the importance of maintaining infiltration function. Although maintenance is an important component to keep most stormwater strategies functioning as designed, maintenance of infiltration practices is especially important as it may mean the difference between function and failure, rather than just reduced effectiveness.

The primary causes of failure of infiltration-based strategies are excessive compaction and improper erosion and sediment control during construction, or excessive sedimentation due to lack of pretreatment BMPs like filtering or sedimentation (Livingston 2000; Cahill 2000; Schueler 2000a). The likelihood of failure, however, can vary regionally depending on soil type. Areas with coarser and more permeable soils are generally more resilient to adverse impacts (Hilding 2000).

Lack of routine maintenance is another cause of failure. Maintenance should include routine observation of infiltration capacity, as well as special attention to pretreatment sedimentation pits. Although the significant accumulation of sediment indicates the importance of the pretreatment facility, the quantity of sediment in the pit eventually stops increasing over time, indicating washout of sediment beyond this volume. Without routine removal of sediments, sedimentation pits will become ineffective for reducing sediment (Schueler 2000a).

Another risk with infiltration techniques is the risk of groundwater contamination. Pitt (2000) has observed that the risk of contamination varies with the quantity and type of contaminant. Organic compounds and heavy metals may be removed by percolation through the soil column. These contaminants, as well as pesticides, also respond well to pretreatment prior to infiltration. However, salts appear to be a chronic risk, regardless of pretreatment.

Additional care is required for porous pavement. Often excessive sedimentation during construction can cause irreversible failure due to plugging of the pavement and the underlying recharge bed. Restricting the use of porous pavement to low traffic areas also reduces the risk of plugging. Also, if it is not possible to pretreat sediment-laden flows, they need to be redirected away from porous pavement. Finally, routine vacuum cleaning of porous pavements can prevent buildup of unavoidable sediments (Cahill 2000).

Managing Stormwater Problems at the Source. Another common theme is the importance of source management, whether considering water quantity or water quality. The primary means of source control for water quality is pollution prevention. A wide range of prevention measures "dramatically and cost-effectively reduce the quantity and concentration of pollutants winding up in stormwater" (Lehner et al. 1999, p. 12).

Minimizing imperviousness and the use of small-scale infiltration practices through a watershed are the two primary ways to address water quantity concerns. In addition, by managing stormwater quantity at the source, additional source control of water quality can also be realized. In reviewing earlier infiltration practices, Mikkelsen et al. (1994) conclude that the best way to reduce pollution risk is through the use of small-scale distributed infiltration systems that treat quantities of pollutants small enough to avoid overwhelming natural treatment processes in the soil and vegetation. Natural systems are better able to manage small, localized contributions of pollutants, rather than trying to cope with greater quantities of accumulated contaminants at the end of the pipe. Like pollution prevention, minimizing imperviousness "is more cost-effective than treating stormwater runoff and much more cost-effective than restoring waterbodies after they have been polluted or damaged" (Lehner et al., p. 66). In addition, by implementing small-scale source control practices, the stormwater system can be integrated into site landscaping, maintaining site hydrology, and aesthetics at the same time (Ellis 1995).

Although these practices agree that source management is of utmost importance, the approaches vary as to how this might be accomplished. For example, in LID, managing stormwater at the source means implementing practices at the level of the individual lot. This means that responsibility for maintenance of the stormwater control belongs to the individual property owners. In contrast, in Conservation Design, managing stormwater at the source means placing controls in common open areas. This places the responsibility for maintenance on the municipality or homeowners' association (Low-Impact Development Center 2000).

Successful Implementation. Finally, by examining successfully implemented green stormwater management systems, such as those described in Lehner et al. (1999), it is possible to identify important elements that are required regardless of which philosophy or approach is chosen. Themes common to successful projects are summarized in Table 9. Critical elements include an emphasis on pollution prevention, which is both effective and inexpensive, supplemented with structural treatment when necessary; preservation of natural features and processes; informing the public and encouraging citizen involvement; a framework that creates and maintains accountability; an equitable funding source; and strong leadership and effective administration (Lehner et al. 1999; Clarke et al. 2000).

TABLE 9. Themes common to successful stormwater management strategies.

1. Pollution prevention
2. Preserving and utilizing natural features
3. Education and informing the public to improve program effectiveness
4. Strong incentives, routine monitoring, and consistent enforcement
5. Financial stability
6. Strong leadership
7. Effective administration

Sources: Lehner, P. H., G. P. Aponte Clark, D. M. Cameron, and A. G. Frank (1999). Stormwater strategies: Community responses to runoff pollution. Technical report, Natural Resources Defense Council.

Clarke, G. A., P. H. Lehner, D. M. Cameron, and A. G. Frank (2000). Community response to stormwater pollution: Case study findings with examples from the Midwest. In *National Conference on Tools for Urban Water Resource Management and Protection*, Chicago, IL, pp. 124–131. U.S. Environmental Protection Agency.

CONCLUSIONS

Like many branches of engineering and science, stormwater management has been moving away from a narrowly defined, clearly separate discipline of its own. Instead, it is just one piece of a complex system of many interacting elements. As a result, the literature becomes more diverse and requires collaboration between disciplines, each with its own vocabulary and understanding. Although many of the groups practicing green stormwater management use similar techniques to achieve similar goals, there are differences between groups that need to be clarified. Some of these differences are relatively minor variations in semantics and classification, while other differences are more substantial (e.g., how stormwater management is integrated into the design process). By exploring the state-of-the-art in Best Management Practices, Low Impact Development, Conservation Design, Better Site Design, and Smart Growth, as well as a number of specific examples, we can begin to understand some of the advantages and limitations of specific strategies. In particular, source management of both runoff and pollution is proving to be both an effective and relatively inexpensive stormwater management strategy. Clearly, infiltration-based techniques, along with reduction of imperviousness, form the foundation for controlling runoff quantity at the source. However, in looking at implementation of infiltration-based technologies, it also becomes apparent that infiltration areas need special attention both during and after construction. There is a significant potential for problems if the infiltration areas are subjected to sediment-laden or heavily polluted stormwater flows. Finally, successful implementation of green stormwater practices require elements like effective administration and strong leadership that transcend the specific design approach.

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