High-Impact Innovation

To meet the growing demand for development that sustains natural systems rather than degrading them, engineers increasingly are embracing the storm-water management approach known as low-impact development. By Jay Landers

In little more than a decade, the storm-water management approach commonly referred to as low-impact development (LID) has progressed from initial concept to a practice that is gaining greater acceptance among municipalities and other entities working to avoid or undo the often deleterious effects of storm-water runoff. Encouraged by a number of successful and increasingly sophisticated LID projects undertaken across the country, engineers have begun working with landscape architects, biologists, ecologists, soil scientists, and others to design and construct innovative and cost-effective solutions that manage storm water and preserve or restore a site's key hydrological functions. Thanks to these efforts, the storm-water management field is rapidly evolving to include a broad array of innovative design techniques that engineers can use to meet the growing demand for new or retrofitted developments that sustain rather than degrade natural systems.

Under natural conditions, most rainfall evaporates or enters the soil close to where it lands. If not absorbed by the roots of vegetation, it percolates farther down to recharge groundwater supplies. On balance, relatively little rainfall leaves the site as surface runoff, and during dry periods streams and rivers benefit from the relatively constant base flows provided by groundwater supplies. However, standard development practices fundamentally alter these natural hydrologic patterns and the water balance. Converting a site from a natural to a developed state greatly increases the efficiency of the drainage system by compacting soils and collecting and conveying runoff using impervious surfaces and pipes. This change reduces a site's ability to absorb precipitation, significantly increasing the volume, frequency, and velocity of runoff leaving the site. On a larger scale, urbanization systematically destroys a watershed's natural capacity to soak up rainfall and impairs the vital terrestrial ecological processes that capture and cycle nutrients and pollutants.

The approach used for decades to manage storm water exacerbates the problem by concentrating and removing water from a site as quickly and efficiently as possible. Such features as roofs, gutters, downspouts, grades, driveways, roads, curbs, and gutters are generally designed to whisk runoff from a site and into a culvert, storm drain, or some other conveyance system. However, as it travels over such impervious surfaces as roads and parking lots, the runoff often accumulates a variety of pollutants. After receiving little or no treatment, the toxic brew typically is discharged into the nearest body of water.

When uncontrolled runoff enters local streams or other small waterways, the larger volume and higher velocity of runoff increase flooding, erode banks, and reduce the amount of water available to recharge groundwater supplies. As a result, natural habitats are degraded, and streams and rivers that once maintained relatively constant water levels throughout much of the year now experience significantly higher peak flows and greatly reduced low flows. For aquatic life unable to adjust to the altered conditions, such changes can spell disaster.

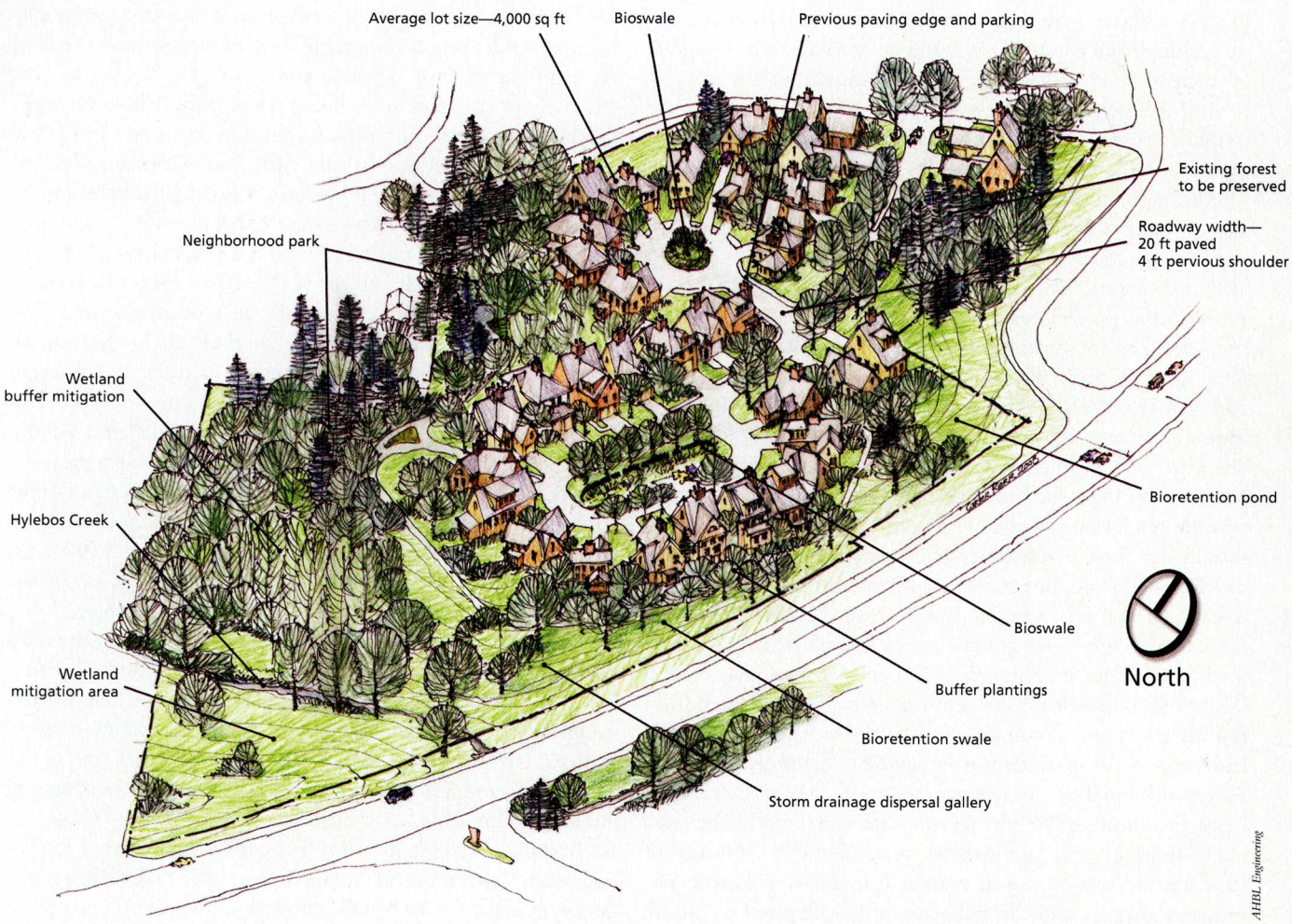
Seeking to address some of these negative effects, many local governments and other property owners in recent years have turned to various centralized, "end-of-pipe" approaches, chief among them detention ponds. Rather than discharge storm water directly to the nearest waterway, ponds are designed to collect and detain runoff for certain periods of time so that sediment and other pollutants can settle out and the flow can be controlled. Although detention ponds have become widely accepted for storm-water management, they are not without their detractors.

Larry Coffman is one of them. An associate director of the Department of Environmental Resources for Prince George's County, Maryland, Coffman is a longtime advocate of LID. He maintains that detention ponds and other centralized approaches to storm-water management possess a number of limitations that ultimately make them "environmentally dysfunctional and economically unsustainable." In particular, Coffman says, ponds fail to replicate the predevelopment hydrology or a watershed's water balance; that is, ponds continue to allow runoff volumes and pollutant loads to increase from a site following development. What is more, Coffman says, they raise water temperatures above levels acceptable to certain sensitive species, expose wildlife to greater levels of toxic substances, sometimes require construction in wetlands, and impose costly maintenance and safety burdens on the communities that use them.

A biologist by training with experience in wastewater systems, Coffman began exploring the idea of using landscaped processes and features to retain and filter storm water in the late 1980s. Using nature as the model, he sought to transfer technology from the wastewater field, in particular, lessons learned from on-site septic drain field systems. As an employee of a local jurisdiction that was rapidly growing but also striving to improve the health of the Chesapeake Bay, the

The Meadow on the Hylebos

Low-Impact Development—Demonstration Project



AHBL Engineering

Anacostia River, and other degraded local water bodies, Coffman was well aware of the need for an approach that would accommodate continued economic development but also protect and restore the ecological integrity of receiving waters. As he analyzed alternative approaches and developed an array of decentralized techniques for managing storm water on-site, Coffman realized that increased runoff and the ecological damage it causes do not have to be unfortunate but inevitable by-products of urbanization. Instead, he says, urban storm-water effects are "a direct consequence and function of the poor state of our conventional technology."

Rather than alter the natural hydrologic conditions of a site undergoing development, Coffman says, LID attempts to integrate hydrologic controls into a site's design to mimic the predevelopment conditions and maintain the terrestrial ecosystem processes and functions necessary to protect receiving waters. Instead of concentrating runoff and conveying it to detention ponds or other large-scale structures, LID attempts to change the form and function of the landscape so that it functions better hydrologically, Coffman says. The precipitation is dispersed through any number of small-scale, integrated control techniques implemented throughout the site. By managing storm water in a way that keeps it as close to the source as possible, LID achieves its basic goal of maintaining a site's predevelopment hydrology.

Seattle Public Utilities, both

This section of a residential street in a northern Seattle neighborhood was chosen to be the site of the first test of the storm-water retrofitting plan dubbed the street edge alternatives approach.

Although LID does not offer a one-size-fits-all approach to storm-water management for new development, Coffman says, the practice can be broken down into five basic steps. First, conventional conservation planning techniques are employed to protect streams, wetlands, forests, recharge areas, and other key environmental features to the fullest extent possible. Second, the design must minimize the amount of soil compaction, clearing, and grading that occurs at a site and limit the extent to which impervious surfaces are directly linked to one another. Third, the paths that storm water will use in traversing a site must be strategically designed to maintain the predevelopment time of concentration; that is, runoff should not leave a site faster than it did before the site was developed. Fourth, integrated management practices designed to capture, use, detain, retain, and treat storm water and enable the water to enter the ground are incorporated into the site. Such techniques may involve open or vegetated swales, also known as bioswales; bioretention cells, or "rain gardens"; porous pavement technologies; dry wells; vegetated buffers and strips; rooftop detention systems, or "ecoroofs"; and rain barrels. Using these and many other site design techniques helps to minimize the change in what is known as the site's curve number—the amount of runoff a site is expected to generate in view of its soil types and land cover. And finally, property owners and the public must be educated to ensure that they become part of the solution by using effective pollution prevention measures and properly adhering to integrated on-site management practices. Although urban environments by their nature often limit the extent to which these steps may be employed, some combination of steps can normally be used to retrofit an existing development.

As these concepts were being developed, Prince George's County conducted numerous pilot projects to test and refine various LID techniques. In one early case, Coffman says, the county persuaded a developer of a residential subdivision to intercept street runoff using swales rather than curbs and gutters and to retain groups of trees on individual lots as "conservation areas" to help preserve the development's natural hydrology. The approaches worked well, Coffman says, and the public responded favorably. One subdivision in the county pioneered the use of rain gardens to capture and manage storm water on individual properties. It too succeeded in meeting the county's goals for performance and public acceptance, Coffman says. Based on these and other projects, Prince George's County began developing manuals and other publications to promote what it was referring to as low-impact development. Those efforts culminated in 1999 with the publication of the comprehensive manual *Low-Impact Development Design Strategies: An Integrated Design Approach*.

Meanwhile, on the other side of the country heavily urbanized Seattle was looking for ways to retrofit existing neighborhoods to lessen the harm that unchecked storm-water runoff was inflicting on its remaining natural watercourses. LID approaches would ultimately play a key role in the city's plans, and Seattle has become a model for urban centers looking to improve water quality.

In the past decade the city "has spent a lot of money restoring habitat" within local creek systems, says Denise Andrews, a program manager for Seattle Public Utilities (SPU). The creeks

As part of the street edge alternatives project, the existing street was replaced with a narrower roadway, vegetated swales were installed within the right-of-way, and more than 100 trees and 1,000 shrubs were added to slow and filter storm water.

historically have provided habitat to certain species of salmon listed as threatened in the Endangered Species Act, and they ultimately drain into Puget Sound, the second-largest estuary in the nation and the focus of extensive cleanup efforts. However, it soon became clear that progress in restoring the creeks would not occur unless SPU adopted a "whole new approach to storm water," Andrews says. Rather than continuing to divert runoff to creeks as quickly as possible, the utility recognized that retrofitting certain areas within the right-of-way alongside streets with certain LID techniques could reduce the quantity and improve the quality of runoff entering the local streams and, eventually, Puget Sound. Out of this realization SPU's pioneering natural drainage systems program was born.

Because they constitute the largest holding of public property and the largest source of polluted runoff in Seattle, streets were a logical choice for retrofitting. The natural drainage systems approach involves reconfiguring street layouts and implementing such features as vegetated swales, storm-water cascades, and small wetland ponds to achieve three main objectives: improve water quality by reducing the amount of pollutants reaching streams; protect aquatic life by minimizing the amount that stream levels fluctuate as a result of small storms; and protect creek channels by reducing, where possible, the amount of runoff from larger storms. "We've moved from just utilizing the creek systems as ways to move water out of the city to now trying to mitigate the impacts this drainage has had on our system," Andrews says.

SPU has developed two basic approaches for retrofitting residential streets. Its street edge alternatives (SEA) approach is used on roads with slopes less than 4 percent that do not receive storm water from other areas, Andrews says. It was first employed in 2000 on a pilot basis to retrofit two blocks along a residential street draining a 2.3 acre (0.9 ha) area in a neighborhood in northern Seattle. SPU applied the SEA approach in an attempt to detain enough storm water to reduce the site's peak runoff rate and ensure that the volume associated with a two-year, 24-hour storm would not exceed that under predevelopment conditions.

The existing street was replaced with a narrower, curvilinear roadway that decreased the impervious expanse by 11 percent. The curves maximized the area available in the right-of-way for vegetated swales, says Tracy Tackett, a senior civil engineer with SPU. The contoured swales were carefully graded, and aggregates and soil mixes were added to facilitate retention and detention. Although such traditional drainage elements as catch basins and flow control structures were incorporated to control the flow and discharge of storm water, Tackett says, the swales look and act much like a natural system. More than 100 trees and 1,100 shrubs were added to the site to slow and filter storm water, increase the rate at which evapotranspiration occurs, and provide an aesthetically pleasing appearance. Initial results have been exceptional, Andrews says. Monitoring during the two years after the project was completed revealed that 98 percent of the total volume of storm water was detained and made its way into the soil on-site, she notes.

The second approach developed by SPU is known as the cascade design because it uses a series of stair-step pools constructed in the right-of-way along a residential street. Connected to one another by catch basins, the pools collect and slow runoff from catchments larger and steeper than those served by the SEA approach. First employed by SPU to replace an asphalt-lined culvert system along four blocks of a residential street in 2002, the cascade design reduces flooding, improves water quality by trapping pollutants, and protects receiving waters by reducing the velocity of runoff.

Of particular importance, the approaches used as part of the natural drainage systems program cost significantly less than what the city would pay in trying to achieve the same water quality goals using a conventional street design accompanied by large underground detention tanks or vaults. "It's very expensive to put in vaults and concrete," Andrews says. Despite spending more on grading and landscaping, the natural approaches—depending on which is used—cost $50,000 to $200,000 less per block than traditional alternatives, she says.

In what is called the Broadview Green Grid Project, SPU is applying the SEA and cascade approaches to 15 city blocks in an effort to manage storm water from a 32 acre (13 ha) area. Streets that run east to west will feature the stepped pools, Andrews says, while those running north to south will employ the SEA approach of vegetated swales and reduced impervious areas. "The combination attempts to achieve a very high level of infiltration," she says. The project is scheduled to be completed by mid-2004, and SPU plans to assess its performance by monitoring a number of parameters related to water quality and quantity.

In its most extensive natural drainage systems project so far, SPU is working with the Seattle Housing Authority to integrate LID techniques into a high-density housing project called High Point. The redevelopment effort will begin with the demolition of the existing structures at the 129 acre (52 ha) site. A new street grid featuring 34 streets and related infrastructure will then be built, along with 1,600 residential units. One of the largest developments in Seattle's recent history, High Point affords a rare opportunity for the city to improve water quality and protect streams on a large scale.

High Point differs from other natural drainage systems projects in that a traditional curb-and-gutter system discharging to a detention pond will be included and the site will have a greater degree of imperviousness. As a result, a hybrid approach that will incorporate LID and conventional drainage features to meet water quality and flood control goals has been adopted. In particular, 22,000 linear ft (6,700 m) of vegetated swales constructed along streets throughout the right-of-way will be able to treat runoff from storms with recurrence periods of up to six months and will keep runoff from two-year, 24-hour storms at predevelopment levels. A detention pond will control flows from storms whose recurrence periods exceed 25 years.

Impervious surfaces will constitute nearly 60 percent of High Point's area, making it a challenging site for the application of LID techniques, Tackett says. "That's why we're so excited about it," she says. "We don't think anyone" has designed and constructed a project using LID features on a site with so much imperviousness. Although the demolition of the existing site is under way, construction of the drainage features will not begin until later this year, and the project will not be completed until 2008.

Another major urban center in the Pacific Northwest, Portland, Oregon, also is looking to LID to manage storm water. As in Seattle, the approach has focused on retrofitting the urban environment to reduce the harm caused by impervious surfaces. A few years ago the city began a campaign known as the Clean River Plan to improve water quality and wildlife habitat along the Willamette River and its tributaries. Reducing the flow of storm water into the city's combined sewer system, as well as into the Willamette and local streams, figures prominently in the plan, and Portland has instituted an aggressive program to develop and test a variety of LID approaches. To perhaps a greater extent than any other city in the United States, Portland has explored the possibilities offered by ecoroofs—vegetated roof systems used in place of conventional roofs to reduce runoff and achieve other environmental benefits. Indeed, the approach is becoming a signature element of the city's efforts to manage storm water under the rubric of LID.

Portland's Bureau of Environmental Services (BES) is investigating ecoroofs because they could help solve the problems encountered in any effort to retrofit urban areas, explains Tom Liptan, an environmental specialist with the BES. Like any urban area, Portland has vast expanses of impervious surfaces, and space limitations and real estate costs often allow only techniques with extremely small footprints. Portland estimates that rooftops account for a third of its approximately 60 sq mi (155 km^2) of impervious surfaces. Clearly, minimizing the amount of runoff from rooftops could go a long way toward helping the city meet its storm-water management goals.

Also known as greenroofs, ecoroofs employ vegetation and lightweight soil to intercept and retain rainfall. Rather than immediately descending through the nearest downspout, most of the water evaporates or is used by the vegetation, significantly reducing the amount of runoff. Ecoroofs have been used for years in Europe to manage storm water, but when the BES began considering their application in the 1990s it found no U.S. performance data to guide it. In an effort to conduct an ecoroof test program in 1999, the bureau joined forces with the city's Housing Authority to install an ecoroof on a 10-story building. The roof of the building—the Hamilton Apartments—has two sides: the east side comprises 2,520 sq ft (234 m^2) of vegetated cover while the west side has 2,620 sq ft (243 m^2). Originally planted with more than 75 species of plants in different amounts of lightweight substrate, both sides also intercept drainage from other rooftop structures, increasing the east side's total catchment areas to 3,811 sq ft (354 m^2) and the west's to 3,655 sq ft (340 m^2).

Results so far show that runoff has decreased dramatically. The roof "retains almost seventy percent of the annual average rainfall," Liptan says, and nearly all rainfall from storms that occur during the region's dry period is absorbed. As for the 30 percent that does leave the system as runoff, Liptan says, "its flow rate is dramatically lower than what would occur from a conventional impervious roof." Although he acknowledges that ecoroofs typically cost more than their traditional counterparts, Liptan notes that an ecoroof confers other advantages, among them insulating the building, reducing energy consumption, and helping to lower the temperature in the immediate vicinity of the building.

To encourage the construction of ecoroofs, Portland's planning code makes it possible for developers to use the roofs in meeting some or all of the storm-water management requirements for their sites. What is more, the code contains a "zoning bonus" that allows a development with an ecoroof to be larger than otherwise would have been permitted, Liptan says, and the BES works closely with developers to provide technical and permitting assistance. The encouragement appears to be paying off. As an example, Liptan notes that Portland State University is currently constructing a residential building with a 16,000 sq ft (1,486 m^2) ecoroof. The zoning bonus, he says, "was the reason they did the ecoroof."

Portland of course is employing more than just ecoroofs as it attempts to retrofit its urban environment. The city has worked to install a variety of integrated management

practices, Liptan says. In one prominent example, two apartment complexes—the Buckman Terrace Apartments and the Buckman Heights Apartments—incorporate numerous control techniques to retain and treat storm water and help the water enter the ground.

The adjoining buildings occupy what used to be a parking lot, and all runoff from the site's completely impervious surface previously went directly into the city's combined sewer system. The situation today is quite different. Downspouts on the Buckman Heights Apartments direct storm water to courtyard garden beds, thereby reducing runoff and encouraging groundwater recharge, and a swale extends through the parking area. At the Buckman Terrace Apartments, raised concrete planting boxes, ground-level garden beds, and a swale all help to absorb storm water.

The Buckman complexes represent more than just a state-of-the-art LID project. They also illustrate the complications that can arise when existing building codes seemingly preclude the use of an LID approach, Liptan says. The city's building code requires that an area be at least 15 ft (4.6 m) wide before a swale or other feature for managing surface storm water can be constructed. One side of one of the Buckman buildings had only 6 ft (1.8 m) of space separating it from the adjoining building, technically ruling out the use of a swale. However, the BES thought that installing a swale there would be "a very practical thing to do," Liptan says. After an analysis of the building's design, foundations, and soils indicated that the swale could be safely included, the bureau worked for months to obtain a waiver from the city department that oversees the building codes. As a result, the site today includes a 400 ft (122 m) long, 6 ft (1.8 m) wide swale along the side of the building to convey, filter, and infiltrate runoff.

Whenever possible the BES looks for ways to overcome such "institutionalized barriers" that could prevent LID techniques from being used on a project, Liptan says. Of course, the BES will not pursue LID solutions if they pose a risk to people or property, he says, but before it rejects a potential LID application the bureau is sure to "take a closer look."

Efforts by such cities as Seattle and Portland to retrofit their existing built environments to better manage storm water offer a "lesson for developing jurisdictions," SPU's Andrews says. Cities and towns will be better off—financially and environmentally—if they employ LID techniques to manage storm water as they grow rather than try to remedy problems later, she says. "We hope that this message goes to developing areas because it really applies to them," she says.

Fortunately, a number of jurisdictions are getting the message and acting accordingly. This is particularly true in the Puget Sound region, thanks in large part to the efforts of the Puget Sound Action Team, a partnership of Washington state agencies and local government bodies. The team has developed a management plan for protecting and improving the sound's water quality and biological resources. The plan

Seattle Public Utilities

As part of its Broadview Green Grid Project, Seattle Public Utilities is managing storm water in part by constructing a series of connected, stair-step pools located in the right-of-way along residential streets.

emphasizes LID to achieve storm-water management goals, says Bruce Wulkan, the Puget Sound Action Team's storm-water program leader. The team has been working with local governments to help them adopt LID-friendly ordinances, Wulkan says, and approximately 10 jurisdictions have so far done so. As a result, "we're seeing more and more projects that are incorporating LID techniques around Puget Sound," he notes.

One such project—the Meadow on the Hylebos residential subdivision soon to be built in Washington's Pierce County—is an ambitious effort to incorporate LID techniques into a new development on a large scale. Located along the southern end of Puget Sound, the county recently amended its regulations to facilitate the use of LID. The change was instrumental in convincing the developer to employ a host of LID features in what otherwise would have been a conventional subdivision, says Len Zickler, a principal of AHBL Engineering, of Tacoma, Washington, which designed the project. As it turns out, switching to LID benefited the developer as well in that it expedited the environmental review process. "Our proposal to employ LID techniques greatly enhanced the approval and entitlement process for us," Zickler says. "It was attractive to Pierce County because these are technologies

that they have been encouraging and trying to help define." Construction of the project is expected to begin this spring.

To be located on a 9 acre (3.6 ha) site along Hylebos Creek—a locally important salmon-bearing stream—the development will include 35 single-family homes. The site also features steep slopes and dense glacial till soils, Zickler says, making it an excellent test case for LID projects in the area. "I think that's the beauty of this particular site," he says. "It's so characteristic of the constraints we are encountering across the Puget Sound region."

By clustering the homes, the design for the Meadow on the Hylebos will make it possible for slightly more than half the site to remain open space. Portions of the property that have been environmentally degraded will be extensively rehabilitated with native vegetation, and a 150 ft (46 m) buffer will help protect the stream. The layout of the site will also take into account the property's many steep slopes. "The more sensitive steep slopes have all been preserved," Zickler says. The roadway design presented another opportunity to employ LID principles. Although the local fire marshal stipulated that the roadway be at least 24 ft (7.3 m) wide to accommodate emergency vehicles, the design was still able to reduce the amount of impervious area associated with the road by specifying a road width of 20 ft (6 m) and a 4 ft (1.2 m) wide shoulder of pervious concrete on one side.

Roof drainage from homes will be directed to on-site dry wells or trench drains that will lead to a bioswale system constructed along either side of the access drives. Approximately one-third of the individual lots will contain rain gardens. Drainage from the swales, in turn, will be directed to a detention pond, one of the few conventional storm-water management techniques included in the design. Upon leaving the pond, water will be directed to a terrace system designed to carefully release the drainage down a slope to the creek.

Employing the LID techniques will save money for the developer while delivering environmental benefits, Zickler says. The Meadow on the Hylebos project was originally slated to have wide roadways, sidewalks on both sides of the streets, and a piped conveyance system leading to a "very, very large detention pond," Zickler says. However, with the LID features at the site the pond is approximately one-third the size of what a conventional design would require, Zickler says. Through such changes as reducing the size of the streets and the pond and eliminating the piping, "we were able to achieve a cost savings of about nine percent," he says.

To evaluate the performance of the project's many LID features, a comprehensive monitoring program will be employed at the site for at least three years following construction, says Curtis Hinman, a Puget Sound water quality field agent at Washington State University at Tacoma. Hinman has been monitoring the site for more than a year so that he will be able to compare the site's hydrological performance before and after construction. An on-site weather station measures the amount of rainfall at the site, and numerous sensors and wells assess the flow of water on and below the surface. "It's one of the most extensively monitored sites in the country," Hinman says. Besides providing a basis for assessing the project's performance, the results from the monitoring program will probably be used by Washington's Department of Ecology as it develops guidelines for LID, he says.

Like the Meadow on the Hylebos project, the Pembroke Woods residential subdivision, in Emmitsburg, Maryland, was originally conceived as a conventional housing development employing a traditional approach to storm-water management. For example, nearly all of the 43 acre (17 ha) site was to have been cleared, and the design called for two storm-water management ponds, one of which would have been located in wetlands. Fortunately for the environment and, as it turns out, the developer, the design for Pembroke Woods was overhauled by the time construction began in 2002. Today the subdivision—one of the first to be designed and constructed using the design manual developed by Prince George's County—"is one hundred percent LID," says Michael Clar, the president of Ecosite, Inc., of Columbia, Maryland, and the designer of the LID features at Pembroke.

The subdivision comprises 70 units on 0.5 acre (0.2 ha) lots, the last of which will be completed this spring. Among the various LID techniques incorporated into the design, Clar says, the "most important" involved what is called site fingerprinting—the practice of locating development sites in such a way as to limit disturbance to natural areas to the fullest extent possible. Approximately 50 percent of this site remained in an undisturbed, wooded condition, reducing the extent to which its natural runoff patterns would be altered. "That was pretty crucial," Clar says. "It helped us to maintain the curve number and the times of concentration."

In keeping with another key LID principle, efforts were made to reduce the expanse of impervious surfaces. For example, a rural road section with dry swales was used in place of an urban road section with curbs and gutters, reducing the width of the paving from 36 to 30 ft (9 to 11 m). Sidewalks were eliminated except along the subdivision's main road. Runoff from rooftops and driveways is directed to such pervious areas as lawns and forested areas. Runoff from streets is collected by the swales, which enhance pollutant removal and offer opportunities for groundwater recharge by having 30 in. (762 mm) of permeable soil over a gravel layer and underdrain. Check dams are included in swales as needed to reduce flow velocities.

The LID features within the subdivision are designed so that during a two-year storm the developed site generates the same volume of runoff as before development. In other words, the basic LID goal of mimicking a site's predevelopment hydrology has been met at Pembroke. However, as part of the regulatory approval process Clar was required to show that the development would not increase flooding

Although LID is gaining favor in a growing number of jurisdictions, significant hurdles remain. Across the country, local building codes and zoning ordinances often present major impediments.

downstream of the subdivision during larger storms. A hydrologic impact analysis was conducted to analyze the site's ability to maintain the predevelopment peak discharge conditions for a range of events, including 10-, 25-, 50-, and 100-year storms. The study found that designing the LID features so that they could manage the runoff volume associated with a two-year storm would achieve peak discharge control for all the storms, Clar says.

Although no attempt has been made to quantify the full savings achieved by converting the subdivision from a conventional to an LID approach, Clar can point to certain savings that were realized. Eliminating the two storm-water management ponds saved roughly $200,000 and obviated the need to mitigate the harm that would have been done to wetlands. Leaving half the site in its natural condition reduced the costs associated with clearing and grubbing by $160,000. At the same time, Clar notes, site fingerprinting substantially reduced the overall costs associated with grading, although these savings have not been quantified. Replacing the curb and gutters with the dry swales reduced construction costs by $60,000, and the use of the narrower roadways reduced paving costs by 17 percent.

Although LID is gaining favor in a growing number of jurisdictions, significant hurdles remain. Across the country, local building codes and zoning ordinances often present major impediments, says Neil Weinstein, the executive director of the Low Impact Development Center, a nonprofit organization based in Beltsville, Maryland, that works to promote the practice. "Conventional zoning and planning schemes don't really have good water quality concepts or tenets in them," Weinstein says. As a result, innovative approaches to managing storm water may fall foul of existing regulations, and developers interested in pursuing LID may opt not to do so in the face of significant regulatory delays.

Steven Roy agrees. An associate with GeoSyntec Consultants, of Boxborough, Massachusetts, Roy has designed numerous LID projects, including an extensive retrofit of the storm-water controls on properties surrounding a seriously degraded lake in Littleton, Massachusetts. (See "A Retrofit for Long Lake, *Civil Engineering,* April 2003, pages 74–79.) Although developers are increasingly embracing LID concepts, Roy says, LID remains a risky proposition because of the potential for delays in the approval process. "If they can get their permits faster by using a conventional approach to managing storm water, they will," he says.

Fortunately, this problem can be resolved, as those jurisdictions that have adopted ordinances to encourage the use of LID have learned. For example, in Prince George's County "developers just want their permits," the Department of Environmental Resources' Coffman notes. "They don't care how they have to manage storm water," he says, as long as the permitting process is not burdensome. With this idea in mind, local jurisdictions across the country—and not just those in such LID "hot spots" as the Pacific Northwest—are working to overhaul their regulations so as to encourage LID.

For example, the Town of Huntersville, in North Carolina's Mecklenburg County, passed an ordinance in 2003 requiring the use of LID for essentially all development. Development in the rapidly growing town—which has a population of about 28,000—is causing non-point-source pollution that is adversely affecting the drinking water supply. To address the problem, the town's ordinance requires that developments include LID techniques to control runoff volume and maintain water quality, says Rusty Rozzelle, the manager of the water quality program for Mecklenburg County.

To make it easier for developers to comply with the requirements, a design manual was created to explain LID practices. In addition, a water quality model was developed so that developers could assess the volume of runoff and pollutants likely to occur as a result of their projects. The model also shows how certain LID techniques used by themselves or in tandem with conventional storm-water management practices can mitigate potential water quality problems. Although it will take several years to assess the effectiveness of the ordinance in helping to address the town's water quality problems, Rozzelle says, developers in the area have adjusted fairly well to the changes.

Meanwhile, efforts also are under way at the federal level to encourage LID. For example, the U.S. Army Corps of Engineers' Norfolk district—which has jurisdiction over most of Virginia and a small portion of North Carolina—is contemplating whether it should require that LID be considered in the design of developments that, because they affect wetlands, need a permit. Following a number of successful LID projects in the Fredericksburg, Virginia, area, the Norfolk district and the Commonwealth of Virginia held a series of workshops in late 2003 to inform the public of the plan. The district intends to issue a report this month that will map out its strategy for moving forward on the issue, says Bruce Williams, the chief of the district's regulatory section for northern Virginia.

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(continued from page 57) The U.S. Environmental Protection Agency (EPA) also is interested in promoting LID. Having funded the development of key LID-related documents, including the design manual developed by Prince George's County, the EPA is looking to encourage the use of LID as a tool that municipalities can use to comply with the storm-water requirements that the agency imposes as part of its National Pollutant Discharge Elimination System. To this end, the EPA is developing materials intended to explain various LID techniques and provide such information as cost and design details and bibliographic information.

The materials will be posted on the agency's Web site in early 2004 as part of an existing "menu" of recommended management practices that municipalities can consider when seeking ways to comply with their storm-water permit requirements, says Jack Faulk, the storm-water permit team leader in the EPA's Office of Wastewater Management. Although municipalities will not be required to implement LID techniques, the EPA expects that including the information on the menu will prompt a greater number of them to do so, Faulk says.

Although there is little debate about the principles underlying LID, concerns are sometimes raised about whether the practice will work under certain circumstances. For example, some engineers question the wisdom of incorporating LID features on privately owned residential property because the features may not be properly cared for by the homeowner. Bob Beduhn, the assistant department manager in the Minneapolis office of HDR, Inc., of Omaha, Nebraska, supports the LID approach, viewing it as particularly helpful in providing water quality benefits. However, he concedes that individual actions ultimately could undermine the long-term effectiveness of certain LID features.

Beduhn notes that homeowners might be tempted to alter a rain garden or swale to shorten the time that standing water remains on their property. He says that in view of the fact that such modifications could occur on a large scale, relying on LID for flood control makes him "as a design engineer a little nervous." For this reason Beduhn prefers to see LID features employed on public property or in large commercial developments, which are easier to regulate. When rain gardens and other LID appurtenances are included on single-family residential properties, he says, "it's a lot harder to be confident that those things are going to stay there."

This sort of uncertainty has led Matt Moore, the administrator of the South Washington Watershed District, of Woodbury, Minnesota, to pursue a hybrid approach to storm-water management. Moore says that in his district he tries to strike a balance between the two, mainly because of concerns regarding flooding. "There's no doubt that on a day in and day out basis" LID features are "probably going to work and provide water quality benefits by treating water where it lands," he says. However, "overall we still need to have the system downstream that can handle overflows" from LID features, Moore notes.

Clar—the designer of the LID features at the Pembroke Woods subdivision—agrees that in certain circumstances LID techniques may need to be paired with conventional approaches to achieve storm-water management goals. "What we've done with LID is add a series of valuable practices and ideas for the design toolbox," he says. "But that doesn't mean we need to throw out everything that we've used in the past." Instead, Clar notes that engineers today are "more likely to use the things we've done in the past but with a little more caution and understanding."

As more projects are constructed and studied and additional research is carried out, concerns that civil engineers and others may have regarding LID will probably be addressed, AHBL's Zickler says. "We're seeing more and more of these projects being built across the country," he notes. "As data is collected it will raise the level of comfort, and I think that the engineering community will embrace these concepts." In areas where local governments have begun to encourage the use of LID, GeoSyntec's Roy says, civil engineers are responding with interest. Indeed, in the Puget Sound region "engineers have been some of the strongest advocates for LID," says Wulkan of the Puget Sound Action Team.

To fully embrace LID, civil engineers will need to become more familiar with such disciplines as landscape architecture, planning, ecology, and soil science, the Low Impact Development Center's Weinstein says. LID takes "more of a multidisciplinary approach to storm-water management" than most engineers might be used to, he says. "It's not just simply mathematical modeling."

Ultimately, growing public demand for ecologically sensitive designs will motivate engineers and landscape architects to collaborate to a greater extent on projects that incorporate LID elements, says Robert France, an adjunct professor of landscape ecology at the Harvard Design School. "Engineers who refuse to partner with landscape architects are going to get less and less work in the future, as they should," he says bluntly. "And landscape architects who continue to do superficial projects without a backbone in engineering science are going to have projects fail, and they're not going to get work." The two professions should be able to unite around LID, France says, because "if done correctly it is very much at the intersection of landscape design and sensible engineering."

Based on her experience with Seattle's natural drainage systems projects, SPU's Tackett recommends that other engineers give greater consideration to LID because of the numerous benefits it can offer. With LID, engineers can manage storm water in a manner that is not only functional but also pays aesthetic dividends, Tackett notes. At the same time, she says, it simply makes sense environmentally. "I think the idea of trying to get closer to replicating nature in our designs is bound to have a better effect for the environment we're trying to protect," she says. "It's hard to engineer nature, so using nature's approaches seems to be the good approach to go with. We've been trying to do it the straight engineering way for a while and we're not getting it too closely." ■

(continued from page 63) with drainboards—to ensure groundwater drainage of the system—was then placed over the nails and exposed cut face. Next, the soil nails were connected together by horizontal and vertical waler reinforcement bars with plates attached to the ends of the nails. Shotcrete was then placed to develop a complete structural reinforcement system. The sequence continued in a top-down manner so that no more than 4 to 5 ft (1.2 to 1.5 m) of vertical excavation was exposed during construction. As earth pressures develop behind the shotcrete facing system, the load is transferred through the facing system to the soil nail bars. The soil nail bar in turn transfers the load into the bonded section of the nail. Small deflections at the top of the walls are generally anticipated and have been allowed for in the design. A final precast panel was then attached over the wall face. The total area of permanent soil nail walls constructed on this project is approximately 56,600 sq ft (5,258 m^2).

Many areas along the existing slopes were too steep to effectively support with soil nail walls, and in those areas it was necessary to use ground anchor (tieback) support. The ground anchors consisted of multiple-strand tendons ranging in length from 35 to 70 ft (10.7 to 21.3 m). The bond lengths of the ground anchors averaged 20 ft (6.1 m). Given the overall low bond strength of the colluvial materials, it was necessary to place the bond lengths of the anchor systems in bedrock or alluvial materials. The ground anchors were set on an 8 ft (2.4 m) horizontal by 8 ft (2.4 m) vertical spacing. One to three rows of permanent tiebacks were used to provide excavation support and to satisfy overall stability where necessary. The ground anchor support panels consisted of 8 by 8 ft (2.4 by 2.4 m) rebar-reinforced sections that were shotcreted in place.

Like the soil nail walls, the ground anchor walls were constructed in a top-down manner. Approximately 35,000 sq ft (3,252 m^2) of permanent ground anchor tiebacks were used on this project.

In sections of the project where the side slopes were in excess of 1H:1V and the bedrock quality was relatively low, double tee retaining walls with micropile foundation support were used. These walls ranged in height from 14 to 36 ft (4.3 to 11 m) and extended for a total distance of approximately 1,700 ft (518.2 m). The original foundation design called for 30 in. (762 mm) diameter caisson (drilled shaft) support of the wall system with a 10 to 12 ft (3 to 3.7 m) spacing between the caissons. The foundation design was modified to use 7 in. (178 mm) diameter micropiles with spacing varying from $2\frac{1}{2}$ to $8\frac{1}{2}$ ft (0.8 to 2.6 m), depending on the wall height. The casing of the micropiles—approximately 7 in. (178 mm) in diameter with a wall thickness of $\frac{1}{2}$ in. (12.7 mm)—was drilled a minimum of 2 ft (0.6 m) into the bedrock. A "rock socket" was then drilled into the bedrock to form the bond zone of the micropile. The bond zone ranged from 20 to 37 ft (6.1 to 11.3 m), depending on the installation method. A #14 threaded bar was placed inside the 7 in. (178 mm) casing and extended into the bond zone. The inside of the casing and the rock socket were then grouted. Plates were attached to the top of the threaded bar and the system was incorporated into the poured foundation for the double tee walls. To provide additional external wall and overall stability it was necessary to incorporate permanent ground anchors into the foundation system. Ground anchors were placed between the uphill row of micropiles.

Most of the slopes above the highway alignment consist of colluvial materials; however, certain sections of the alignment are next to steep bedrock cliffs. In these areas, kinematic slope stability analyses and the Colorado Rockfall Simulation Program, developed by the Colorado DOT and the Colorado School of Mines, were used to evaluate the rockfall potential. Typical rockfall mitigation included spot bolting, pattern bolting, and the use of draped mesh in critical sections.

Construction of the up-valley lanes began in 2001 and was completed in the fall of 2003. Work on the down-valley lanes began in 2002, and completion is expected late this year. The total construction phase costs for the up-valley and down-valley lanes will be approximately $93 million. The geotechnical investigation, retaining wall, and foundation design costs were approximately $1.3 million, of which approximately $1 million went toward remote drilling operations.

Evaluating and designing the wall and foundation systems for the Snowmass Canyon project required detailed subsurface information at the wall and foundation locations. This information was obtained with the aid of borings from helicopter-transported drill rigs. The helicopters made it possible to work at sites that otherwise would not have been accessible until construction commenced. Without this extensive geotechnical study and the support and cooperation of the Colorado DOT, it would have been extremely difficult to evaluate the various conditions present at the site, and more conservative—that is, more expensive—retaining and foundation systems would have been considered. Close cooperation and good communication between the Colorado DOT, the contractors, and the designers prior to and during construction were of cardinal importance in accommodating changes and variations in the subsurface properties and thus ensuring compliance with the design assumptions. Good communication is vital since the long-term performance of the wall systems is greatly affected by the subsurface material properties. Many of the retaining walls along the alignments have been instrumented, making it possible to assess the performance of the wall systems over time. The wall and foundation systems that have thus far been constructed appear to be performing in conformity with the designs. ■

Benjamin P. Arndt, P.E., P.G., A.M.ASCE, is a project manager, Richard Andrew, P.G., a vice president, and Shan-Tai Yeh, P.E., the president of Yeh and Associates, of Denver.

Project Credits

Owner: Colorado Department of Transportation

Roadway and structural design engineer: Parsons, Denver

Geotechnical design engineer: Yeh and Associates, Denver

Prime construction contractor: Ames Construction, Aurora, Colorado