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Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions

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Abstract The low impact development (LID) approach has been recommended as an alternative to traditional stormwater design. Research on individual LID practices such as bioretention, pervious pavements, and grassed swales has increased in recent years. Bioretention cells have been effective in retaining large volumes of runoff and pollutants on site, and consistently reduced concentrations of certain pollutants such as metals. However, retention of certain pollutants such as nitrate–nitrogen and phosphorus has been problematic. Porous pavements have been extremely effective in infiltrating stormwater runoff. Concerns have been raised about groundwater contamination, but research has shown that this is not a problem in most settings. Green roofs have been found to retain a large percentage of rainfall (63% on average) in a variety of climates. A common thread across bioretention, green roofs and grassed swales was found: the export of phosphorus. The issue appears to be linked to high phosphorus levels in the soil media, or possibly to fertilization of turf or planted areas. Solutions to this problem have been recommended. Contrary to popular belief, research has shown that bioretention and pervious pavements continue to infiltrate even with frost in the ground. Although issues have been identified with retention of certain pollutants, the LID approach has been found to result in increased retention of stormwater and pollutants on site, mimicking pre-development hydrologic function. Future research needs have also been identified.

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1 Introduction

The effects of traditional development practices on the hydrologic cycle have been well documented. Increases in the impervious surfaces associated with urbanization have resulted in increased surface runoff (Hollis 1977; Jennings and Jarnagin 2002; Waananen 1969), increased runoff velocity, decreased time of concentration (Leopold 1968), and decreased water quality (Makepeace et al. 1995; US EPA 1983). The earliest documentation of increased runoff from urban areas was in the late 1800s (Kuichling 1889), and urban runoff continues to be a leading cause of impairments in the nation's waterways (US EPA 2002).

Low Impact Development (LID) was piloted in Maryland (Prince George's County 1999) as a way to mitigate the negative effects of increasing urbanization and impervious surfaces. The preservation of the pre-development hydrology of a site is the overall goal of LID. In contrast to typical stormwater design, the LID approach advocates for more careful site design in the planning phases. The purpose of the site design is to preserve as much of the site in an undisturbed condition, and where disturbance is necessary, reduce the impact to the soils, vegetation, and aquatic systems on the site. In contrast to traditional stormwater treatment, which typically only mitigates peak flow rates, the use of LID will also help to maintain the pre-development runoff volume. Cluster layouts, grass swales, rain gardens/bioretention areas, and pervious pavements all reduce the "effective impervious area" (Booth and Jackson 1997) of a watershed, or the area that is directly connected to the stormwater system.

Initial research on individual LID practices has shown promising results. However many studies have occurred since an initial EPA literature review was published (US EPA 2000). New successes have been documented, but other unexpected outcomes have also arisen. In addition, questions are frequently raised in regards to the suitability of LID for all sites, groundwater contamination, and winter performance of LID practices. The goal of this literature review is to present relevant research on the various LID practices, and to synthesize the results so that the current status and future research needs of LID investigations can be assessed. The focus of this review was research published in peer-reviewed journals. However, to illustrate a point or corroborate a similar finding, studies published in reports or conference proceedings were occasionally referenced. If used, this research was always referred to as "preliminary" in this review. Also, it is not the intention of the author to endorse one product over another. Product names are only used to provide detail on specific research projects.

2 Bioretention

Bioretention areas, or rain gardens, are depressed areas in the landscape that are designed to accept stormwater. They can be used in residential and commercial settings, and are typically planted with shrubs, perennials, or trees, and covered with shredded hardwood bark mulch. The benefits of bioretention areas include decreased surface runoff, increased groundwater recharge, and pollutant treatment through a variety of processes (Prince George's County 1993). Several municipalities have created bioretention standards. A highly detailed bioretention conservation practice standard is available through the Wisconsin DNR. Site criteria, design specifications, construction guidance, and maintenance recommendations are included in the standard (WI DNR 2006).

Initial bioretention research focused on laboratory prototypes (Davis et al. 2001). High concentration reductions (>90%) were found for copper (Cu), lead (Pb), and zinc (Zn). Nutrient concentrations were also reduced: total Kjeldahl–nitrogen (TKN) retention was 68%, and ammonia–nitrogen (NH_3–N) retention was 87%. The only nutrient not well retained by the system was nitrite + nitrate–nitrogen (NO_3–N), which had a retention of 24%.

Field investigations of bioretention have also been performed (Table 1). The first such investigation was

Table 1 Summary of bioretention pollutant retention

Location	TSS	NO_3–N	NH_3–N	TKN	TP	TN	ON	Cu	Pb	Zn	Reference
Connecticut											
Haddam	–	67	82	26	−108	51	41	–	–	–	Dietz and Clausen 2006
Maryland											
Greenbelt	–	16	–	52	65	49	–	97	>95	>95	Davis et al. 2003
Largo	–	15	–	67	87	59	–	43	70	64	Davis et al. 2003
New Hampshire											
Durham	96	27	–	–	–	–	–	–	–	99	Roseen et al. 2006
North Carolina											
Greensboro	−170	75	−1	−5	−240	40	–	99	81	98	Hunt et al. 2006
Chapel Hill	–	13	86	45	65	40	–	–	–	–	Hunt et al. 2006

in Maryland, where synthetic runoff was applied to two different bioretention areas, one in Largo, and one in Greenbelt, MD (Davis et al. 2003). Removal of Cu, Pb and Zn at the Greenbelt site was >95%; however, at the Largo site removal was slightly less. Similar variation in nutrient retention was found between the two sites (Table 1). In Connecticut, nutrient retention by soil media was generally lower, and in the case of total phosphorus (TP), more actually left the system than entered it (Table 1). NO_3–N retention was higher in the Connecticut study than in the Maryland study, especially during the second year (Dietz and Clausen 2006). High Zn, total petroleum hydrocarbon (TPH), and total suspended solids (TSS) retentions were found at another field study in New Hampshire (Roseen et al. 2006). However NO_3–N retention was low, which is consistent with other bioretention research. In North Carolina, high metals retention by bioretention areas was also reported, but variable retention of nutrients was found (Table 1). Export of TSS, TKN, NH_3–N, and TP were found in North Carolina (Table 1).

The export of TP noted in the Connecticut study was attributed to the disturbance of the soils at the beginning of the study, and did decrease over time (Dietz and Clausen 2005). However, phosphorus export from bioretention systems does not seem to be an isolated phenomenon; similar findings have been noted in North Carolina (Hunt et al. 2006), and in preliminary results from Ontario, Canada (Toronto and Region Conservation 2006). In North Carolina, the initial export of phosphorus has been attributed to high phosphorus content in the soil, or a high Phosphorus Index (Hunt et al. 2006). The TP export noted from the bioretention cell in Canada was attributed to leaching of the mulch and organic soil media (Toronto and Region Conservation 2006).

It should be noted that the field studies in Maryland were performed on unlined bioretention areas, whereas the Connecticut study was performed on a lined system. A liner is not a typical component of a rain garden; however it was used in the study in Connecticut for mass balance calculations (Dietz and Clausen 2005). The flow mass balance for the Connecticut rain garden indicated that less than 1% of inflow water overflowed (Dietz and Clausen 2006). In other words, this system, which was sized to contain 2.5 cm (1 in.) of roof runoff, prevented 99% of roof runoff from leaving the site during the 24-month period of study. If this overall retention of flow is used to assess pollutant retention performance, the system in Connecticut retained the vast majority of pollutants along with the flow.

The combination of phosphorus export and an underdrain that is directly connected to the stormwater system could cause more harm than good, if a sensitive water body were downstream. Therefore, to avoid this problem, the phosphorus content of the soil media used in a bioretention area should be examined, and if it is very high, an alternative media should be used. In addition, an underdrain should be installed only when the native soils have a low infiltration capacity. The minimum infiltration rate recommended in the Bioretention Manual is 1 in. h^{-1} (Winogradoff 2002). If it is necessary to use an underdrain, it could be drained to grade in a grassed or wooded area. Another possible solution is to use a capped underdrain or controlled orifice, so that underdrain outflow can be increased if excessive ponding occurs, as recommended by Atchison et al. (2006). This may not be possible in certain situations, so as a last resort the drain could be connected to a standard stormwater system.

Although NH_3–N seems to be well retained by bioretention areas, retention of NO_3–N tends to be low. This is due to the fact that the negatively charged NO_3–N ion does not adsorb well to soil particles. The creation of NO_3–N through mineralization and nitrification of other forms of nitrogen in between infiltration events has also been cited as a possible mechanism for the low retention of NO_3–N (Davis et al. 2001). Several researchers have performed studies designed to increase the ability of a bioretention area to treat NO_3–N. An alternative design was proposed that involved raising the underdrain outlet pipe, to create a saturated zone in the bottom of the garden (Kim et al. 2003). The resulting condition would then be conducive to denitrification reactions, where NO_3–N is converted to nitrogen gas (Korom 1992). In a laboratory experiment, shredded newspapers were found to be the most effective aid to this conversion of NO_3–N in simulated bioretention columns, by providing a carbon source for the denitrification reaction (Kim et al. 2003). This modification was tested in a field study in Connecticut, where increased treatment of total nitrogen (TN) and NO_3–N was found (Dietz and Clausen 2006). In North Carolina, significantly *higher* concentrations of

TKN, NH_4–N, and TN were found in outflow from a similarly modified bioretention cell, as compared to a traditionally designed cell (Hunt et al. 2006). The researchers cite the conversion of organic forms of nitrogen to NH_4–N as the suspected cause of the increased NH_4–N, TKN, and TN concentrations.

Little data exist on the ability of bioretention areas to reduce fecal coliform (FC) bacteria concentrations, a common indicator species of bacterial contamination. Although some grab sampling for FC bacteria was performed in the Connecticut study, inlet and outflow concentrations were all <10 FCU 100 ml^{-1} (Dietz and Clausen 2005). Preliminary results from a laboratory study indicate an average removal rate of 88% of FC bacteria in simulated bioretention columns (Rusciano and Obropta 2005).

Increases in runoff temperature have been found as rain falls on impervious surfaces (LeBlanc et al. 1997), but there is little data on how well bioretention areas attenuate temperature. In Connecticut, no temperature difference was found between inflow and underdrain outflow from a rain garden (Dietz and Clausen 2005). The rapid infiltration rate of the soils and northerly exposure of the roof (i.e., low influent temperature) were cited as the reasons for this lack of attenuation of the temperature of summer runoff. Preliminary data in North Carolina have shown decreases of 5°F to 10°F as influent stormwater passed through a bioretention cell (Hunt and Lord 2006).

A frequent concern for bioretention areas and infiltration practices in general, is that their performance in the winter months will be reduced, when there may be frost in the soil. Despite measurable frost in the bioretention media in Connecticut (unpublished data), the vast majority of inflow (99%) was either infiltrated or evapotranspired over the course of a 2-year period (Dietz and Clausen 2006). A similar finding has been reported for infiltration practices, including bioretention, at the University of New Hampshire (Roseen, personal communication). Preliminary results from Norway also support the previous findings that bioretention functions well through the winter months: no seasonal differences in retention time or lag time were found (Muthanna et al. 2006). Rapid thawing of soil media has been found to occur when runoff enters bioretention areas. The organic material, macropore structure, and porous nature of bioretention media are likely the reason that infiltration will still occur despite frozen conditions.

Bioretention design recommendations are inconsistent. Most of the guidance has been focused on the engineering community, for larger-scale design. A manual from Wisconsin provides complete, easy to follow guidance for homeowners on siting, sizing, digging, and planting a rain garden (WI DNR 2003). The sizing method used in this manual is based on the WINSLAMM model, and the storage of 2.5 cm (1 in.) of runoff from a roof (Bannerman, personal communication). A similar manual for Connecticut also uses the 2.5 design method (Dietz and Filchak 2006).

The first bioretention design manual originated in Maryland (Prince George's County 1993), and contained recommendations for the what media to use, and how to size bioretention. The more recent manual (Winogradoff 2002) contains updated recommendations for the media, sizing calculations, and ponding time. Detailed engineering specifications for the soil media have also become available, which provide guidance on the percentage/type of sand, percentage/type of compost, and percentage/type of topsoil. Soil pH, soluble salt content, and fertility may also be included in bioretention specifications. Due to problems with clogging of the filter fabric recommended in the earlier manual, the 2002 Bioretention manual recommends the use of a pea gravel blanket around the underdrain pipe instead of filter fabric. The SCS curve number (SCS 1986) continues to be recommended to estimate runoff for bioretention sizing. The RECARGA model (Atchison et al. 2006) provides detailed water budget modeling to customize bioretention size, based on the desired "stay on" volume, or overall retention of precipitation that is desired. The RECARGA model also uses the SCS curve number to estimate runoff from pervious surfaces, although a bioretention area could easily be designed with this model for a totally impervious watershed, such as a parking lot or roof, and the curve number would not be part of the calculation.

The Natural Resources Conservation Service recommends that the curve number approach not be used for rains less than 1.3 cm (SCS 1986). Furthermore, the overall accuracy of the curve number approach for estimating runoff volumes has been brought into question. Large discrepancies have been noted between runoff predicted by the curve number method and actual runoff for small storms (Pitt 1999).

Table 2 Summary of green roof precipitation retention

Location	Precipitation retention (%)	Media thickness (cm)	Roof slope (%)	Reference
Augustenborg, Sweden	63.0	3.0	2.6	Bengtsson et al. 2005
Oregon, USA	69.0	12.7	–	Hutchinson et al. 2003
Michigan, USA	38.6	2.0	2.0	Monterusso et al. 2004
Michigan, USA	58.1	1.0	2.0	Monterusso et al. 2004
North Carolina, USA	62.0	7.6	–	Moran et al. 2004
North Carolina, USA	63.0	10.2	3.0	Moran et al. 2004
Michigan, USA	69.8	2.5	2.0	VanWoert et al. 2005
Michigan, USA	70.7	4.0	2.0	VanWoert et al. 2005
Michigan, USA	65.9	4.0	6.5	VanWoert et al. 2005
Michigan, USA	68.1	6.0	6.5	VanWoert et al. 2005
Average	62.8			

WinSLAMM (Source Loading and Management Model) has been recommended as an alternative design tool for bioretention areas, and LID in general (Pitt 2004). Runoff depths were well predicted by WinSLAMM for a variety of watersheds, and for a wide range of precipitation events (Pitt 1999). Recently, a model called the Western Washington Hydrology Model (WWHM) was constructed (http://www.aquaterra.com/software.html). WWHM is built on the Hydrologic Simulation Program Fortran (HSPF) platform, but it was customized with a simpler interface, and included local soils and precipitation data for western Washington.

Research on bioretention has produced positive results, and provided insight into the mechanisms of pollutant retention. Despite certain problems with phosphorus export and low TN retention, bioretention areas have proven to significantly reduce stormflow volumes and concentrations of many pollutants. Longer term, field based research is still necessary to provide data on how these systems perform over time, and under varying seasonal conditions. The use of specific media and/or design variations to reduce certain target pollutants is a research area that should be further explored. Although metals and nutrient retention in bioretention systems have been studied in detail, research on bacteria retention and water temperature attenuation are other possible research areas.

3 Green Roofs

Vegetated roof systems, or green roofs, have been in use in Europe for many years. Historically, green roofs consisted of a thick soil layer with plants, grass, and/or trees, and extra structural support was required. These “intensive” green roofs are being replaced by “extensive” green roofs, which have a much thinner, lighter media (thus fewer structural requirements), and different plants (Davis and McCuen 2005). A variety of research projects on the energy benefits of green roofs have been performed, however only the research related to stormwater will be highlighted here.

Retention of precipitation on a green roof is a combination of storage in the media and evapotranspiration by plants. Research on green roofs in a variety of locations has consistently shown between 60% and 70% retention of precipitation, with an average retention of about 63% (Table 2). The study green roofs have used media with different thicknesses, and one researcher has specifically investigated the effects of media thickness and slope on precipitation retention (VanWoert et al. 2005). Although increased media depths and lower slopes resulted in slightly higher (statistically significant) retention, the gain in retention was not large. In general, for the studies examined, the thickness of the media, ranging from 2 cm to over 12 cm did not result in any noticeable gain in precipitation retention (Fig. 1). This suggests that to minimize installation costs and structural requirements, a thinner media may be acceptable for the purposes of stormwater retention. However, thinner media depths (5 cm) have been found to result in winter frost injury of perennial plants than thicker media (10 or 15 cm) in Ontario, Canada (Boivin et al. 2001). *Sedum* spp. are typical plants used in green roofs, due to their drought tolerance. Although Boivin et al. (2001) did not

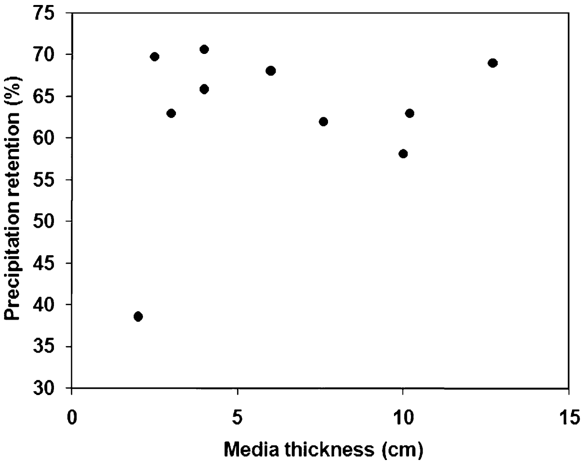

Fig. 1 Green roof media thickness (cm) vs precipitation retention (%)

examine *Sedum* spp., other researchers have found that *Sedum* spp. planted in 10-cm thick media were found to be suitable for use in Michigan, with minimal winter damage and irrigation requirements (Monterusso et al. 2005).

The roofs with the lowest reported retention were from a preliminary study (Monterusso et al. 2004), and may have been the result of a low sample number (n=4), and two rainfall events that were very close to each other. It should also be noted that certain green roofs had extra water storage built into the structure. For example, an extra water holding capacity of 2 and 4 l m^{-2} was reported for the green roofs studied by VanWoert et al. (2005), and Moran et al. (2004), respectively. Although average retention values are presented in Table 1, wide-ranging retention percentages for individual storms were reported by several researchers, depending on the intensity of the storm, and the time of year. In addition to overall retention of flow, reductions in peak flow rate and increases in lag time were also reported for several green roofs (Hutchinson et al. 2003; Moran et al. 2004; VanWoert et al. 2005).

Very little data exist on water quality measurements from green roofs. In Oregon, TP concentrations ranging from 0.2 to 1 mg l^{-1} were reported in preliminary measurements of runoff from a green roof (Hutchinson et al. 2003). Mean TP concentrations in green roof runoff ranging from around 0.5 to more than 4 mg l^{-1} were reported in Michigan, although the authors reported that the plots were fertilized (Monterusso et al. 2004). NO_3–N concentrations over 20 mg l^{-1} in roof runoff were also reported for one of the green roof systems in Michigan. TP and NO_3–N concentrations in the precipitation were not reported for these two studies, thus a percent retention could not be calculated. However, in Wisconsin, TP concentrations in roof runoff from residential and commercial areas were 0.15 and 0.20 mg l^{-1}, respectively (Bannerman et al. 1993), which is much lower than the concentrations reported for the runoff from the green roof studies cited above. Preliminary results from North Carolina are showing a similar effect: TP concentrations and mass export in runoff from a green roof were significantly higher than in precipitation, although no significant differences in concentration were reported between green roof runoff and runoff from a traditional roof (Moran et al. 2004). TN concentrations were also significantly higher in runoff from the green roof runoff than in precipitation. No fertilization was reported in the study in North Carolina, but the authors speculate that the export of TP and TN was due to leaching of these nutrients from the media.

Only one study examined Cu concentrations in runoff from green roofs. In Oregon, preliminary results showed that the acute water quality criteria of 9 μg l^{-1} was exceeded three times, although the concentrations were not far above the criteria. Although the Cu concentration in the precipitation was not reported, the authors speculate that the Cu may have come from treated wood used on the roof, or from the soil media itself.

Research has shown that by using a green roof, 60–70% reductions in stormwater runoff volume from a roof are to be expected. This finding may have particular relevance in cities where space for stormwater treatment is costly and limited, and reductions in stormwater flows will provide great relief to overburdened combined sewer overflow (CSO) systems. These benefits may outweigh the high initial cost of green roofs. This has been demonstrated in an analysis for the city of Toronto, Canada, where after installation costs were considered, large cost savings were hypothesized if green roofs were placed on all feasible buildings in the city, due to the reduced stormwater load (Banting et al. 2005).

Despite the reductions in stormwater volume, the export of TP and TN need to be carefully considered when installing green roofs. In many cases, the large reductions in stormwater volumes will offset any increase in concentration. However, plants should be selected that do not require fertilization, as this would increase the TP available for leaching. In addition, more research needs to be performed on the effects of green roof media on the export of pollutants. Research is especially lacking on the treatment and/or export of metals from green roofs.

4 Permeable Pavements

A variety of alternatives to traditional asphalt and concrete paving have become available. Although these products share the same goal (to infiltrate stormwater), there are several design variations. The focus of this paper is research results; a thorough review of the various products and specifications is available in a recent book (Ferguson 2005) for those interested in more background information or specific details.

4.1 Concrete Blocks or Grids

These products are precast concrete that can be in the shape of a grid or a block with open voids to allow for infiltration. They are typically laid down by hand over a specially prepared base, although mechanical installation methods have become available, which reduces the installation cost. The void spaces are typically filled with crushed stone or pea gravel, or some products can be filled with topsoil and planted with turf.

Laboratory monitoring of concrete grid pavers began as early as 1981 (Day et al. 1981). Three products were monitored: Monoslab®, Grasscrete®, and Turfstone®. Runoff coefficients were calculated for a range of simulated precipitation events, up to a 20-year storm. The highest average runoff coefficient for the concrete grid pavers was 0.005, whereas the control concrete slab had an average runoff coefficient of 0.78 (Day et al. 1981). Percolate was also sampled for quality. High retention (>81%) for all metals (Cu, Pb, Zn) was noted, yet phosphorus and nitrogen fractions were inconsistently retained. In some cases, ortho-phosphate (ortho PO_4–P) and NO_3–N were exported from the systems (Day et al. 1981).

More recently, several types of permeable pavements have been monitored in the field in Renton, Washington (Booth and Leavitt 1999; Brattebo and Booth 2003). Two concrete products, Turfstone® (turf infill) and UNI Eco-Stone® (gravel infill) were studied. Over the entire 6-year period of study, negligible surface runoff was noted from both of these products, indicating that virtually all of the precipitation infiltrated (Booth and Leavitt 1999; Brattebo and Booth 2003). Water quality was also improved: copper and zinc concentrations in infiltrate water sampled below all four pavement types were significantly lower (p=0.01) than in concentrations in runoff from an adjacent asphalt lot (Brattebo and Booth 2003). Interestingly, the authors report that from 1996 to 2002, average zinc concentrations in the permeable pavement infiltrate and the asphalt runoff significantly increased, yet two of the permeable systems showed simultaneous decreases in copper concentrations (Brattebo and Booth 2003).

UNI Eco-Stone® was also monitored in Connecticut, where runoff depth from the paver surface was 40% of precipitation depth for the 22-month study (Gilbert and Clausen 2006). Although this is substantially more runoff than reported by Brattebo and Booth (2003), it was still 72% less than the runoff depth from a nearby asphalt driveway. In addition, concentrations of all pollutants measured (TSS, NO_3–N, NH_3–N, TKN, TP, Cu, Pb and Zn) were significantly lower in runoff from the UNI Eco-Stone® driveways than in runoff from the asphalt driveways (Gilbert and Clausen 2006). As would be expected, due to lower concentrations and runoff volumes, mass export for all of the pollutants was also lower for the Eco-Stone® driveways than the asphalt driveways (Gilbert and Clausen 2006). In another study, Unilock® pavers were installed in one section of a large parking lot near Toronto, Canada. Preliminary results indicate that no surface runoff occurred from the Unilock® parking lot for 9 storm events, with a maximum intensity of 31 mm h^{-1} (Toronto and Region Conservation 2006).

Monitoring data from warmer climate zones are showing similar results. Preliminary data from North Carolina for three different types of concrete paver blocks indicate reductions in runoff volume, and peak exfiltrate flow rate, as compared to an asphalt lot (Collins et al. 2006).

4.2 Plastic Grids

Several types of plastic grid structures have become available in recent years. Design and installation techniques may vary slightly from the concrete blocks or grids, with the largest difference being the volume of fill material in the pavement structure. In contrast to concrete blocks which are mostly impervious, the plastic grid structure is mostly pervious. The large spaces are designed to be filled either with topsoil and planted with turf, or filled with a small diameter, sharp crushed stone. Installation specifications vary according to the manufacturer, but in general, the base preparation is critical to encourage rapid infiltration into the subgrade. Despite their growing popularity, there are not very many monitoring studies to document the benefits of the plastic grid structures.

Two plastic grid structures, Grasspave® and Gravelpave® were monitored in Renton, Washington (Booth and Leavitt 1999; Brattebo and Booth 2003). The only difference between the two installations was the infill material; topsoil and turf were used in the Grasspave®, and gravel in the Gravelpave® structure. As with the other products monitored at this site, virtually no surface runoff was reported from either of these two products (Brattebo and Booth 2003). The largest amount of runoff reported was from the Grasspave® section, for a long-duration storm, where 121 mm of rain fell, and 4 mm of surface runoff was observed (Brattebo and Booth 2003). Copper and zinc concentrations in infiltrate water below all four pavement types were significantly lower (p=0.01) than asphalt runoff concentrations (Brattebo and Booth 2003). In Georgia, runoff from a Grassy Paver™ plastic grid parking lot filled with sand and planted with grass was 93% less than runoff from an adjacent asphalt lot (Dreelin et al. 2006).

4.3 Pervious Asphalt

Pervious, or permeable asphalt, is a variation on the typical hot mix asphalt (HMA) that is commonly used as a road surface. The mix, which omits the fine portion of the aggregate typically included in HMA, was developed to be installed as a wearing course over a standard asphalt layer. The mix was termed open graded friction course (OGFC), and it has been used around the country since the 1970s because of its ability to dampen road noise and tire spray, and remove water from the surface of a road which reduces the risk of hydroplaning (Fitts 2002). Due to some structural issues, modifications have been made to the mix specs. When stormwater infiltration is desired, the major design difference is that the OGFC material is typically put down over a coarse aggregate storage layer that is designed to rapidly infiltrate and store water.

Research on pervious asphalt began with some EPA funded projects in the early 1970s (Ferguson 2005). Research in Europe began in the 1990s. In France, a street section was repaved with pervious asphalt, and a 61-cm thick crushed stone reservoir was included below the pervious asphalt layers (Legret and Colandini 1999). The authors reported that on average, 96.7% of the storm water volume infiltrated in the soil below the reservoir structure (Legret and Colandini 1999). In Sweden, in a pervious asphalt road section with swales, between 30% and 40% of precipitation ran off the site (Stenmark 1995). The swales were a confounding factor in the study in Sweden; the individual infiltration capacity of the pervious asphalt compared to the swales was not determined.

4.4 Pervious Concrete

Pervious concrete is a variation on the typical concrete mixture. Fine sands are typically omitted from the mix, and the slurry is tamped or rolled in placed, rather than the traditional floating. This type of concrete is much less forgiving than traditional concrete, and a proper installation requires experienced installers. It has been installed in many locations throughout the country, however very little monitoring on pervious concrete installations has been performed.

A pervious concrete parking lot section with a swale in Florida had a runoff coefficient of 0.20, which was lower than the coefficients for an asphalt lot with a swale, and cement lot with a swale, which were 0.35 and 0.33 respectively (Rushton 2001). It should be noted that the asphalt lot also contains a small “garden” area, which the author felt was responsible for the fairly low runoff coefficient from the asphalt lot (Rushton 2001). Pollutant export load from the pervious lot with a grass swale was reduced for TSS, NO_3–N, NH_3–N, and TN by 91%, 66%, 85%, and 42%, respectively, as compared to the asphalt lot with no swale (Rushton 2001). Metal load reductions (Cu, Fe, Pb, Mn, Zn) were all greater than 75%. However, TP loads were only reduced by 3%, despite the large decrease in runoff volume, and some of the systems with grassed swales exported more TP than came in (Rushton 2001). This phenomenon is consistent with the TP export noted earlier from some bioretention systems (Dietz and Clausen 2006; Hunt et al. 2006; Toronto and Region Conservation 2006).

A large pervious concrete plaza was installed at Villanova University. Although there were some problems with the installation of the material and some sections had to be reinstalled (Traver et al. 2005), the problems have been corrected, and the site has shown promising results. The site takes runoff from adjacent standard concrete areas, several rooftops, and grassed areas. To date, the site has successfully captured and infiltrated runoff from all storms 5 cm or less in size (Kwiatkowski et al. 2007). Water quality measurements were also taken at the site; chloride concentrations were found to be highest during winter months, as deicers were applied to pedestrian areas. In addition, concentrations of copper in roof runoff were fairly high (Kwiatkowski et al. 2007). However, neither copper nor chloride concentrations in groundwater below the pervious concrete were high enough to be of concern. The authors concluded that with proper siting, an infiltration BMP such as the pervious concrete would not adversely impact the groundwater (Kwiatkowski et al. 2007).

4.5 Other Concerns

4.5.1 Clogging of Surfaces

A frequent concern with porous pavements is the clogging of the surface over time. Rather than particles becoming lodged in the internal structure of the pavement, clogging of pervious asphalt pavements seems to be confined to the surface 2 cm of the pavement (Baladès et al. 1995). The specifications for these types of products (e.g., pervious asphalt, pervious concrete) state that the pavement surface should be cleaned out with vacuum suction on a specified maintenance interval, so that the infiltration rate can be maintained. A more intensive vacuuming, high pressure washing, and suction removal of the remaining sludge was found to greatly improve the infiltration rate of a partially clogged pervious asphalt in France (Legret and Colandini 1999). The maintenance recommendation for UNI-Ecostone® pavers is the removal and replacement of the infill material. The time interval for the replacement depends upon the local conditions, and the loading of fine particles on to the pavement surface. Research on pervious pavement sites in North Carolina, Maryland, Virginia, and Delaware (Bean et al. 2007) has shown that although the infiltration capacity of concrete grid, concrete block, and pervious concrete pavements may decrease if fine particles are loaded on to the surface, they can still infiltrate large quantities of water (comparable to grassed sandy loam), and the infiltration rate can be improved with replacement of the infill material. In place of sand, the authors recommend the use of crushed aggregate as an infill material to help encourage high infiltration rates (Bean et al. 2007). A laboratory experiment on pervious concrete found that even when the surface of the material was clogged with fine sand, the vast majority of simulated rainfall (up to a 100-year event for the Columbia, SC region) was infiltrated (Haselbach et al. 2006).

4.5.2 Winter Performance

Another concern with pervious pavements, just as with bioretention, is the ability of the system to perform in the winter. Numerous studies on pervious pavements in cold climates (e.g., Connecticut, Washington, New Hampshire, and Ontario Canada) have been performed or are ongoing. Research findings support the claims of manufacturers that with a proper base and proper installation, the system will continue to infiltrate through the winter, and the surface can be plowed, although some care should be exercised with sanding (to avoid clogging of the pores) and salting (to avoid potential groundwater contamination).

4.5.3 Soils

In addition to concerns about winter performance, fine grained soils with slow infiltration rates have been cited as a reason why a pervious pavement or bioretention cannot be used. However, research has shown that with appropriate design, pervious pavements can be used in clay soils. A previously cited example in Georgia (Dreelin et al. 2006) was installed over well-drained soils with clayey subgrade that could contain as much as 35–60% clay. An underdrain system was installed in the subgrade, below a 10-in. thick layer of open graded gravel. Runoff from the underdrain was only observed one time, during a 1.85 cm precipitation event (Dreelin et al. 2006). Just as with bioretention (Winogradoff 2002), in areas where native soils may not have high infiltration rates, a thicker reservoir of coarse aggregate can be installed beneath the pavement structure and underdrain. This provides a greater storage capacity, and a longer time for water to exfiltrate to the native soils before underdrain flow would begin.

4.5.4 Groundwater Contamination

Due to the fact that stormwater runoff is known to contain a wide variety of pollutants (Makepeace et al. 1995), concerns of groundwater contamination have been raised where infiltration practices such as pervious paving or bioretention have been recommended. The results from a multiyear research project sponsored by the US EPA on this topic have been summarized (Pitt et al. 1999). For residential and light commercial applications, the pollutants of concern are typically nutrients, petroleum residue from automobile traffic, heavy metals, pathogens, and possibly pesticides. Due to the fact that these pollutants are usually found in fairly low concentrations in stormwater, and are well retained by soils, the contamination potential is low or moderate (Pitt et al. 1999). Two exceptions to this general finding exist: pathogens may be present in high concentrations, and may not be well attenuated in the soil. Fecal coliform bacteria was well retained by bioretention columns in the previously cited preliminary laboratory study (Rusciano and Obropta 2005), however field research on bacteria and virus removal in bioretention or pervious paving systems is lacking. Also, chloride may be present in stormwater, and concentrations may be high during winter months (Pitt et al. 1999). Chloride is also very mobile in soil, and can easily travel to shallow groundwater. Research is showing that concentrations of chloride have been increasing in local waterways in New England (Kaushal et al. 2005), and if current trends continue, chloride levels in streams will reach dangerous levels, threatening aquatic life. The ability of LID systems to treat bacteria and chloride needs to be investigated further.

It should be noted that LID advocates a distributed approach to treatment practices, rather than an “end of pipe” approach. If this strategy is adhered to, the stormwater will have less of a chance to accumulate large masses of pollutants. Therefore, the likelihood of having high concentrations of pollutants will be reduced if the distributed approach is used, and concentrations of pollutants will largely be driven by atmospheric deposition rates. Collecting and treating stormwater from high traffic areas or areas with high potential pollutant loads, while infiltrating “cleaner” runoff from buildings and low traffic areas, may provide a good margin of safety where groundwater contamination is a concern.

5 Large-scale LID Studies

Many large-scale housing projects utilizing LID techniques have been installed around the country. However, to date only one such project has had monitoring of stormwater quantity and quality to investigate the cumulative impact of LID systems. The Jordan Cove Urban Watershed Project in Waterford, Connecticut was designed to monitor the effects of a traditional (17 lots) and LID (12 lots) subdivision. Grassed swales, bioretention areas, pervious pavements and a cluster layout were among the practices utilized in the LID subdivision. Large increases in runoff and pollutant export were found as the traditional subdivision was developed, however no change in runoff depth or nitrogen or phosphorus export was found as the LID subdivision was developed (Dietz and Clausen 2007). Stormwater runoff lag times were also significantly greater in the LID subdivision, indicating that the LID practices were effective in increasing the time of concentration in the watershed, and maintaining the hydrologic function of the undeveloped site (Hood et al. 2007).

6 Conclusions

LID is a relatively new suite of practices and is constantly evolving. To date, the research on LID practices has not been as extensive as the research on agricultural or traditional urban stormwater best management practices. The LID practices investigated in this review have shown great promise in mitigating the impacts of development on downstream water bodies. However, as this paper shows, some strong conclusions can be drawn from the research to date when LID practices are used in developed areas. The research cited in this paper has shown generally that LID practices are effective at preserving the natural hydrologic function of a site, and retaining pollutants. Also, some frequently voiced concerns about the function of pervious pavements and bioretention areas have been shown to be inaccurate: pervious pavements and bioretention have been found to work effectively in cold climates, with frost in the ground. Proper base design and installation are critical to this function. In addition, substantial infiltration in tight soils beneath pervious pavers has also been found. Again, proper design and installation are critical components of LID systems in *any* application, not just cold climates or tight soils.

There are certain conditions where it may not be appropriate to use an LID practice that relies on infiltration. Areas with high contaminant loading such as recycling centers or gas stations, or brownfield areas with high soil contamination, may not be appropriate for infiltration, due to increased risks of contaminating the groundwater. Conditions such as steep slopes, shallow (<3 ft) depth to bedrock or seasonal high water table are also places where traditional pavement and stormwater management practices may be more appropriate. However, rarely is an entire site composed of such limiting conditions, and LID practices can be used wherever possible to reduce to cumulative impact on downstream water bodies.

A common thread across green roofs, bioretention, and grass swales has been noted: the export of phosphorus. This issue appears to be linked to high phosphorus levels in the media (for bioretention and green roofs), or possibly to fertilization of turf or planted areas. This can be a concern in areas where underdrains or roof leaders are tied into a stormwater system; in these cases the excess loading of TP to surface waters may worsen an existing problem. Care should be taken to ensure that in cases where a drain is directly connected and is likely to be utilized, the media does not contain high levels of phosphorus. Proper education of maintenance personnel and homeowners can also address the issue of excessive fertilization.

Although the individual practices often have detailed specifications, it seems that engineers to do not have a consistent design tool that can credit the runoff reductions that LID components can provide, that is also based on research results. The standard curve number calculation (SCS 1986), while fairly easy to apply, does not have the flexibility to give credit for the variety of LID components available, and its accuracy has been brought into question. Engineers are using models like RECARGA, WinSLAMM, and P8 to design LID practices, although they may use another model such as SWMM for hydraulic routing on a site. The Western Washington Hydrologic Model is accurate, easy to use, and provides credits for LID practices. The widespread adoption of an accurate model to give proper credit to LID components is critical for widespread adoption of LID techniques.

Future research needs have been identified. Longer term studies for all of the practices are justified, as very few studies exist on how these systems perform for long periods of time. In addition, investigations on the effect of different media mixtures for bioretention and green roofs to minimize the risk of phosphorus export are needed. Also, further research on the ability of LID systems to retain and destroy bacteria and viruses is needed. Despite limitations in certain situations, it seems clear that LID is a viable stormwater treatment option that has broad applicability.

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