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Effects of Low-Impact-Development (LID) Practices on Streamflow, Runoff Quantity, and Runoff Quality in the Ipswich River Basin, Massachusetts: A Summary of Field and Modeling Studies

Circular 1361

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Massachusetts

U.S. Department of the Interior
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Front cover description: Vegetated green roof on the Whipple Annex, Ipswich, MA

Back cover description: Rain garden on Dexter Street, Wilmington, MA

Effects of Low-Impact-Development (LID) Practices on Streamflow, Runoff Quantity, and Runoff Quality in the Ipswich River Basin, Massachusetts: A Summary of Field and Modeling Studies

By Marc J. Zimmerman, Marcus C. Waldron, Jeffrey R. Barbaro, and Jason R. Sorenson

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Suggested citation:
Zimmerman, M.J., Waldron, M.C., Barbaro, J.R., and Sorenson, J.R., 2010, Effects of low-impact-development (LID) practices on streamflow, runoff quantity, and runoff quality in the Ipswich River Basin, Massachusetts—A Summary of field and modeling studies: U.S. Geological Survey Circular 1361, 40 p. (Also available at http://pubs.usgs.gov/circ/circ1361.)

Library of Congress Cataloging-in-Publication Data

Effects of low-impact-development (LID) practices on streamflow, runoff quantity, and runoff quality in the Ipswich River basin, Massachusetts : a summary of field and modeling studies / by Marc J. Zimmerman ... [et al.] ; prepared in cooperation with the Massachusetts Department of Conservation and Recreation and the U.S. Environmental Protection Agency.
p. cm. -- (Circular ; 1361)
ISBN 978-1-4113-2959-1 (softcover : alk. paper)
1. Runoff--Massachusetts--Ipswich River Watershed. 2. Streamflow--Massachusetts--Ipswich River Watershed. 3. Environmental engineering--Massachusetts--Ipswich River Watershed. 4. Water quality management--Massachusetts--Ipswich River Watershed. I. Zimmerman, Marc James, 1947- II. Massachusetts. Dept. of Conservation and Recreation. III. United States. Environmental Protection Agency. IV. Geological Survey (U.S.) V. Title: Effects of low impact development (LID) practices on streamflow, runoff quantity, and runoff quality in the Ipswich River basin, Massachusetts. VI. Series: U.S. Geological Survey circular ; 1361.
GB991.M4E35 2010
551.48'809744--dc22
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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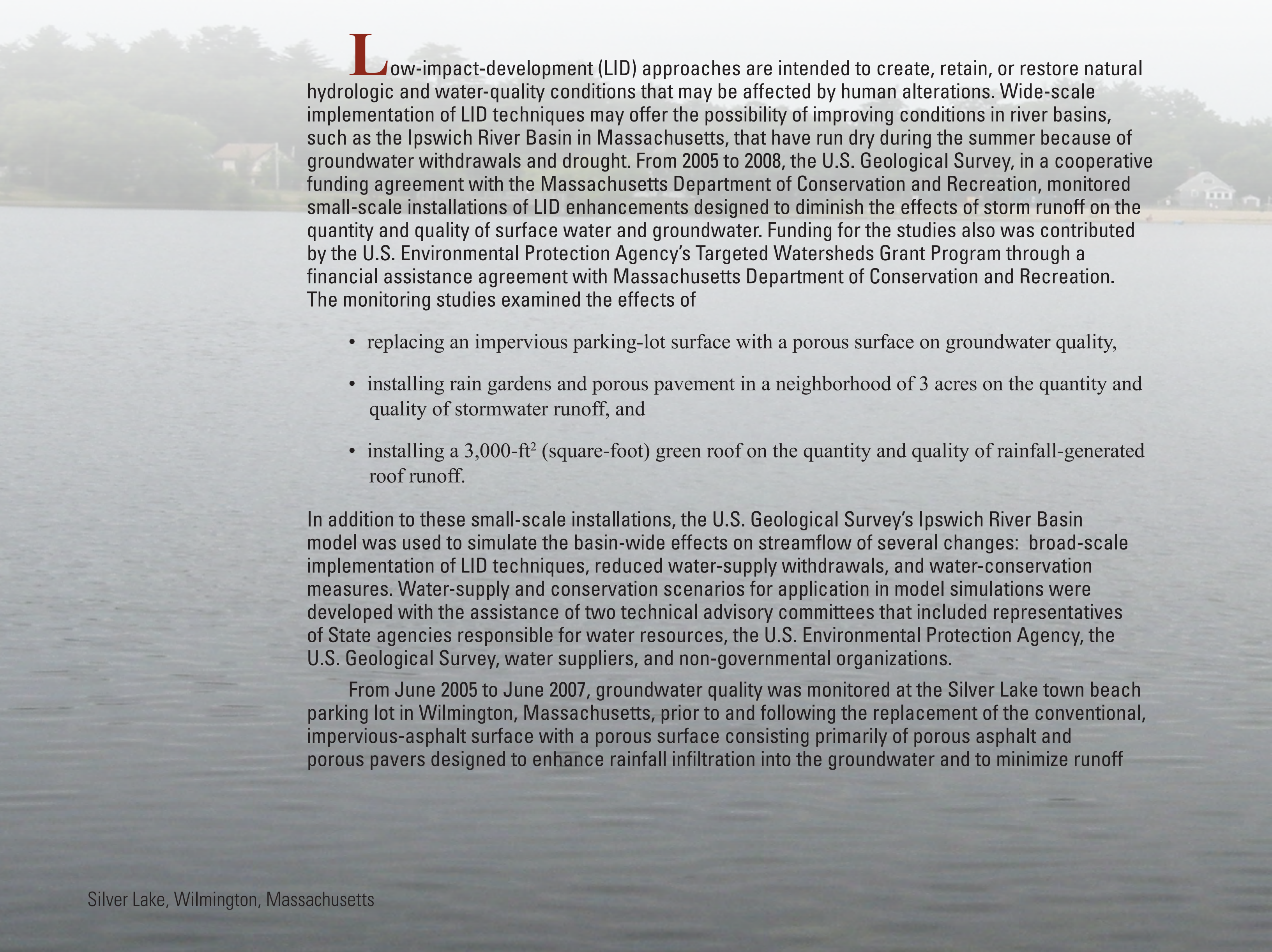
Abstract

Low-impact-development (LID) approaches are intended to create, retain, or restore natural hydrologic and water-quality conditions that may be affected by human alterations. Wide-scale implementation of LID techniques may offer the possibility of improving conditions in river basins, such as the Ipswich River Basin in Massachusetts, that have run dry during the summer because of groundwater withdrawals and drought. From 2005 to 2008, the U.S. Geological Survey, in a cooperative funding agreement with the Massachusetts Department of Conservation and Recreation, monitored small-scale installations of LID enhancements designed to diminish the effects of storm runoff on the quantity and quality of surface water and groundwater. Funding for the studies also was contributed by the U.S. Environmental Protection Agency's Targeted Watersheds Grant Program through a financial assistance agreement with Massachusetts Department of Conservation and Recreation. The monitoring studies examined the effects of

- replacing an impervious parking-lot surface with a porous surface on groundwater quality,
- installing rain gardens and porous pavement in a neighborhood of 3 acres on the quantity and quality of stormwater runoff, and
- installing a 3,000-ft^2 (square-foot) green roof on the quantity and quality of rainfall-generated roof runoff.

In addition to these small-scale installations, the U.S. Geological Survey's Ipswich River Basin model was used to simulate the basin-wide effects on streamflow of several changes: broad-scale implementation of LID techniques, reduced water-supply withdrawals, and water-conservation measures. Water-supply and conservation scenarios for application in model simulations were developed with the assistance of two technical advisory committees that included representatives of State agencies responsible for water resources, the U.S. Environmental Protection Agency, the U.S. Geological Survey, water suppliers, and non-governmental organizations.

From June 2005 to June 2007, groundwater quality was monitored at the Silver Lake town beach parking lot in Wilmington, Massachusetts, prior to and following the replacement of the conventional, impervious-asphalt surface with a porous surface consisting primarily of porous asphalt and porous pavers designed to enhance rainfall infiltration into the groundwater and to minimize runoff



Silver Lake, Wilmington, Massachusetts

to Silver Lake. Concentrations of phosphorus, nitrogen, cadmium, chromium, copper, lead, nickel, zinc, and total petroleum hydrocarbons in groundwater were monitored. Enhancing infiltration of precipitation did not result in discernible increases in concentrations of these potential groundwater contaminants. Concentrations of dissolved oxygen increased slightly in groundwater profiles following the removal of the impervious asphalt parking-lot surface.

In Wilmington, Massachusetts, in a 3-acre neighborhood, stormwater runoff volume and quality were monitored to determine the ability of selected LID enhancements (rain gardens and porous paving stones) to reduce flows and loads of the selected constituents to Silver Lake. Water-quality samples were analyzed for nutrients, metals, total petroleum hydrocarbons, and total-coliform and *E. coli* bacteria. A decrease in runoff quantity was observed for storms of 0.25 inch or less of precipitation. Water-quality-monitoring results were inconclusive; there were no statistically significant differences in concentrations or loads when the pre- and post-installation-period samples were compared.

In a third field study, the characteristics of runoff from a vegetated "green" roof and a conventional, rubber-membrane roof were compared. The two primary factors affecting the green roof's water-storage capacity were the amount of precipitation and antecedent dry period. Although concentrations of many of the chemicals in roof runoff were higher from the green roof than from the conventional roof, the ability of the green roof to retain water generally resulted in decreased differences between the total amounts (loads) of the chemicals that ran off the roofs.

Land-use and water-management changes associated with LID implementation were investigated at multiple spatial scales, using the U.S. Geological Survey's Ipswich River Basin model, to evaluate the effects of

- updated water-supply withdrawals for the towns of Reading and Wilmington (representing new baseline conditions for all simulations),
- potential land-use changes at buildout (potential future development),
- widespread implementation of retrofitting LID techniques,
- basin-scale water withdrawal reductions based on water-conservation pilot programs conducted by the Massachusetts Department of Conservation and Recreation, and
- land-use change and LID applications at a local scale.

The new baseline simulation indicated that reduced water-supply withdrawals for the towns of Reading and Wilmington led to substantially higher medium and low flows in most of the reaches upstream from the South Middleton streamgage in the upper Ipswich River basin.

Overall, simulations pointed to the importance of spatial scale in determining the effects of land-use change and LID practices on streamflow. Potential land-use changes at buildout had modest effects on streamflow in most subbasins (percent differences of less than 20 percent) because relatively little land in the basin was available for development. Results of the simulations conducted to evaluate widespread effective-impervious-area reductions upstream from the South Middleton streamgage indicated that the percentages of urban land use and associated effective impervious area were too small for even a 50-percent reduction of effective impervious area to appreciably affect streamflow in most subbasins. In contrast, the results of the hypothetical local-scale simulations indicated that for smaller streams, with high percentages of urban land use and associated effective impervious area, land-use change, development patterns, and LID practices may have substantial effects on streamflow. Modeling studies concurred with the results of fieldwork in the assessment that LID enhancements would likely have the greatest effect on decreasing stormwater runoff when broadly applied to highly impervious urban areas.

Introduction

Conventional urban and suburban development can profoundly affect the flow and quality of streams and other natural water bodies. Urban development increases the total area covered by impervious surfaces (roofs, roads, sidewalks, driveways, and parking lots) and typically generates higher rates of local stormwater runoff. The goal of traditional stormwater management in urban and suburban areas is to minimize local flooding of streets and other impervious surfaces by conveying stormwater runoff as quickly as possible away from developed areas, usually through networks of storm drains, either to large, offsite detention basins or directly to the nearest stream, river, lake, or coastal water body. While reducing the hazards associated with local flooding, the traditional approach often has unintended consequences, including the alteration of natural streamflow and the degradation of water quality and aquatic habitat in receiving water bodies.

Conventional urban and suburban development can profoundly affect the flow and quality of streams and other natural water bodies.

In the early 1990s, a land planning and engineering design approach known as low-impact-development (LID) began receiving increased attention as a means to reduce the generation of urban runoff at its source. In contrast to the traditional development and stormwater management approach, LID practices seek to develop sites in a manner that mimics the natural hydrology of the undeveloped site (U.S. Environmental Protection Agency, 2009). LID design features, such as rain gardens, permeable pavement, vegetated (or green) roofs, and narrow, uncurbed streets, were integrated into newly developed or existing developed areas to minimize runoff and maximize the infiltration of water into the soil and (or) the transpiration of water by plants.

In 1997, the Ipswich River in northeastern Massachusetts (fig. 1) was designated 1 of the 20 most endangered rivers in the Nation by the environmental organization American Rivers. In recent decades, segments of the upper river have gone dry for extended periods during the summer with serious short- and long-term consequences for aquatic biota (Armstrong and others, 2001). In 2000, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Management (now the Department of Conservation and Recreation, MDCR), conducted a modeling study to evaluate the causes of streamflow depletion in the basin (Zarriello and Ries, 2000). The study concluded that groundwater withdrawals for public water supply, and subsequent exports of water to users outside of the basin, were the largest single factors causing flow depletion in the river and its tributaries.

In 2005, USGS began a study of selected LID practices (vegetated "green" roof, rain gardens, porous pavement, bioretention cells) to evaluate their effects on groundwater quality and runoff volume and quality. This study was funded through a cooperative funding agreement with the MDCR. Funding for the study was also contributed by the U.S. Environmental Protection Agency's Targeted Watershed Grand Program through a financial assistance agreement with MDCR. In addition, the previously developed USGS Ipswich River Basin model was used to quantify the potential roles of LID practices and water-conservation strategies in restoring natural streamflows to urbanized areas. Computer simulations were conducted at both the basin scale (155 mi^2) and at the scale of individual development sites (100 acres). The purpose of this circular is to summarize the results of these studies and their implications for the wider application of LID practices and water-conservation strategies in urbanizing areas of the northeastern United States. A more detailed description of the field studies and modeling simulations can be found in the companion report by Zimmerman and others (2010).

Figure 1. Location of streamgages, weather station, and the low-impact-development study sites in the Ipswich River drainage basin in eastern Massachusetts.

Field Studies of the Effects of LID Practices

Rain garden designed to enhance infiltration at Dexter Street, Wilmington, MA.

From 2005 through 2008, widely used LID practices were evaluated to determine their effects on hydrology and water chemistry at three sites in the Ipswich River Basin in northeastern Massachusetts (fig. 1). Two of the sites were in Wilmington, in the upper part of the basin, and the third was in Ipswich, not far from the mouth of the river.

At the town beach at Silver Lake, in Wilmington, approximately one-half of the conventional, impervious-asphalt parking lot was replaced with a porous parking surface, primarily consisting of porous asphalt and porous pavers overlying a 12-in. layer of stone designed to enhance the infiltration of precipitation into the groundwater (fig. 2). The rest of the asphalt was replaced with a new impervious asphalt surface that was graded to drain to the porous asphalt, rather than to the pond, or drain toward the edges of the parking lot. Surface runoff from the impervious asphalt also drained toward rain gardens and bioretention islands that were installed in the porous and impervious areas of the parking lot to enhance infiltration and to filter out sediment and nutrients. Two stormwater-runoff drainpipes were partially daylighted to lessen bacteria loads to the lake near the beach.

The second LID application also took place in Wilmington in the Silver Lake Avenue and Dexter Street neighborhood (“LID retrofit neighborhood”) adjacent to Silver Lake. Initially, Dexter Street had curbs running along its length and several stormwater drains that joined and ran under Silver Lake Avenue and into Silver Lake. Silver Lake Avenue had neither curbs nor stormwater drains. LID retrofitting diverted stormwater through curb cutouts into and through rain gardens and over porous-paver parking areas. The rain gardens and porous paved areas were designed to

Figure 2. Low-impact-development features installed in the parking lot at Silver Lake Beach, Wilmington, MA.

enhance infiltration into the groundwater, thereby decreasing runoff volume and its associated contaminant load entering the storm-drain system leading directly into Silver Lake. The LID features accounted for less than 2 percent of the 3-acre neighborhood area or about 13 percent of the paved-road area. Although the percentage of porous surface created or improved by the LID enhancements was not great, the enhancements were not designed just to receive and infiltrate direct rainfall, but to receive runoff from a large portion of the impervious surface area, potentially having a greater effect on overall runoff than might be expected on the basis of the LID area alone.

The third LID feature studied, a 3,000-ft^2 green (vegetated) roof, designed by K.J. Savoie Architecture, was installed by Magco, Inc., a Tecta America company, on Whipple Annex, a former industrial building renovated for senior housing in Ipswich, MA, by the North Shore Housing Trust. The green roof was designed to retain as much as 1 in. of rainfall and to absorb materials found in precipitation. The vegetation on the green roof was also expected to diminish runoff through evapotranspiration. The green roof runoff characteristics were compared to the chemical characteristics of direct precipitation and to the runoff characteristics of a 5,340-ft^2 section of the conventional, rubber-membrane roof on the Ipswich Town Hall, located across a small parking lot from the Whipple Annex.

Water quantity and quality were monitored to determine whether any changes occurred in association with the LID applications. Water samples were collected to determine concentrations of nutrients, metals, and total petroleum hydrocarbons at all of the study sites. Bacteriological samples were collected from stormwater runoff in a manhole at Silver Lake Avenue. The rates and volumes of runoff were monitored at Silver Lake Avenue in Wilmington and at the green and rubber-membrane roofs in Ipswich.

Vegetated green roof, designed by K.J. Savoie Architecture and installed by Magco, Inc., on the Whipple Annex, Ipswich, MA.

Bacteria in Runoff— A Health Concern

For each of the eight summers prior to the LID renovations, the swimming area at the Wilmington town beach at Silver Lake was closed at least once because of high counts of fecal-indicator bacteria (Sara Cohen, MDCR, written commun., 2008). Waterfowl, attracted to bordering grassy areas and to food offered by beachgoers, were believed to be the primary source of bacteria. Runoff from the parking lot and the bordering neighborhood draining through two pipes directly to the swimming area may have also contributed to the high bacterial counts. As part of the LID enhancements to the beach and parking-lot area, waterfowl were discouraged from visiting the beach area by the removal of the extensive grassy bordering areas and their replacement with vegetated swales. The two drain pipes were partially daylighted to decrease their conveyance of bacteria. Although runoff from these new features was not monitored as part of this study, the approach seemed effective because the beach was not closed due to bacterial contamination for four years following these improvements.

Changes in Groundwater Quality Following the Retrofit of a Conventional Parking Lot with LID Features

A general concern with LID-enhanced infiltration at the Silver Lake beach parking lot was the possibility of groundwater contamination from materials on the parking-lot's surface. The parking-lot retrofit provided useful information about groundwater contaminant transport that could eventually affect the groundwater-fed lake.

Prior to the parking-lot retrofit, four observation wells to monitor water-table altitudes and three multilevel-port, sampling wells (MLSs) were installed to collect groundwater samples in the parking lot (fig. 3). Samples were collected from July 2005 to June 2007, except during the winter and spring of 2006 when the new parking lot was being installed. On each sampling date, routine field measurements of temperature, dissolved oxygen concentration, specific conductance, and pH were made from each sampling port from the top of the water table to the bottom port of the MLS. Water-quality samples for chemical analysis were collected from MLS ports closest to the water table because this was considered the most likely place where infiltrating contaminants could be detected.

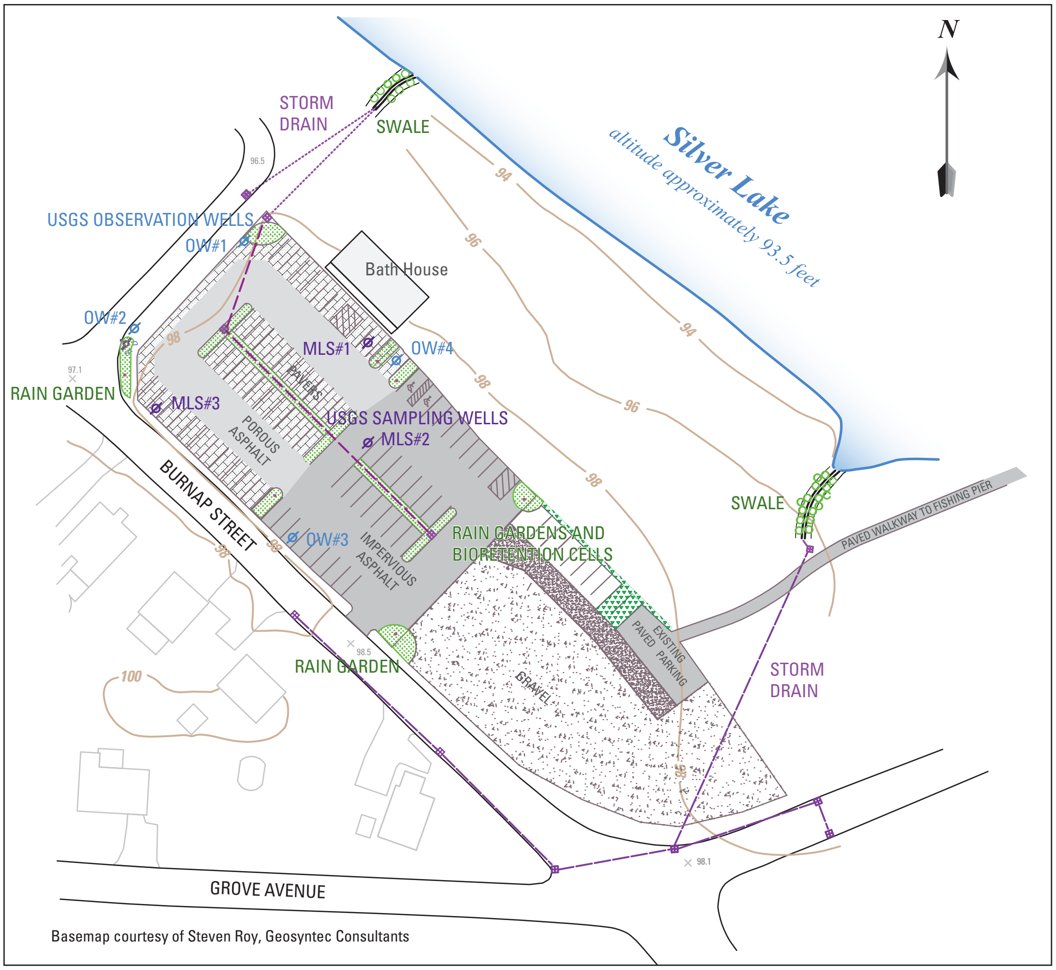


Figure 3. Low-impact-development features of Silver Lake beach parking lot and generalized groundwater-flow direction.

In general, no substantial changes in groundwater-quality conditions were detected after the installation of the porous parking lot and other LID features. Many of the constituent concentrations were at or below detection limits both before and after the installation. Results from sampling well MLS#1 illustrate the minimal changes in groundwater quality. Dissolved oxygen concentrations increased after the LID installation, suggesting a more direct recharge from oxygenated precipitation under the LID-enhanced parking lot than under the conventional impervious parking lot, but the ranges of values before and after installation overlapped considerably (fig. 4). The ranges of total nitrogen and total phosphorus concentrations changed little following installation of the LID retrofits (figs. 5, 6). The highest total nitrogen concentration was detected before installation, and the highest total phosphorus concentration was detected afterward; nevertheless, the overall differences were not great for either constituent. Similarly, the range of concentrations of dissolved copper (fig. 7) did not appear to change after installation. Among all the analytes examined, only nickel concentrations decreased significantly (fig. 8), suggesting that the source was removed during or shortly after the parking-lot construction period.

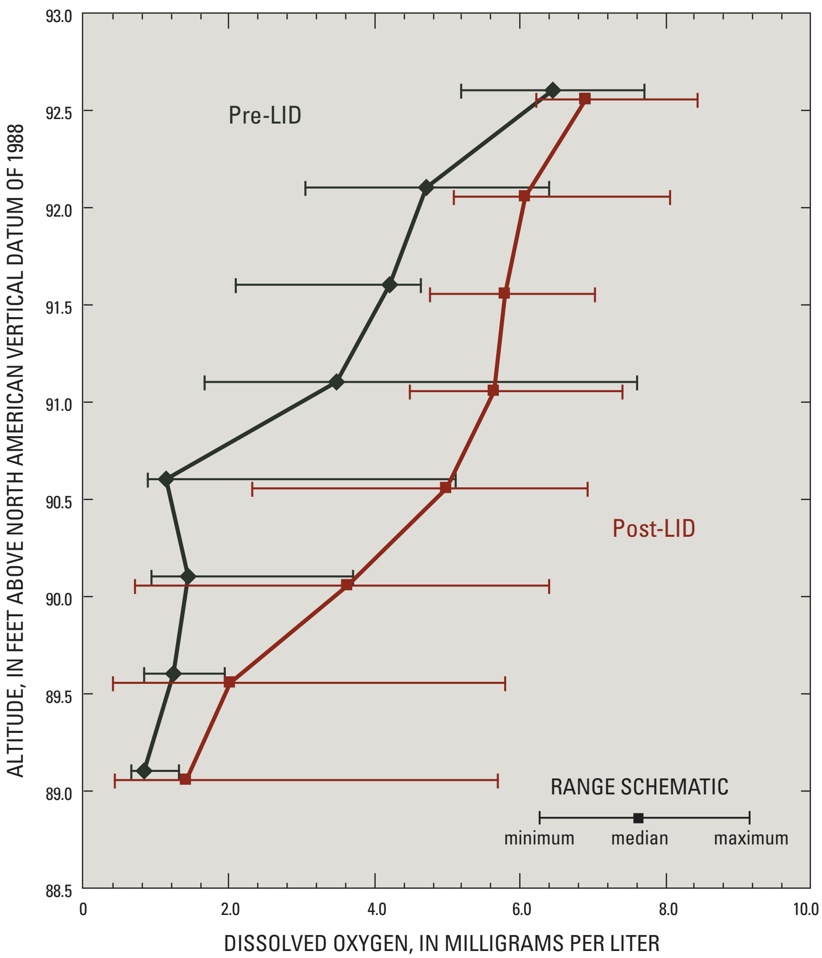


Figure 4. Profiles of median dissolved oxygen concentrations in groundwater at multilevel sampler #1 (MLS#1) beneath the Silver Lake beach parking lot in Wilmington, MA, before (Pre-LID) and after (Post-LID) installation of low-impact-development features, July–December 2005 and June 2006–June 2007, respectively.

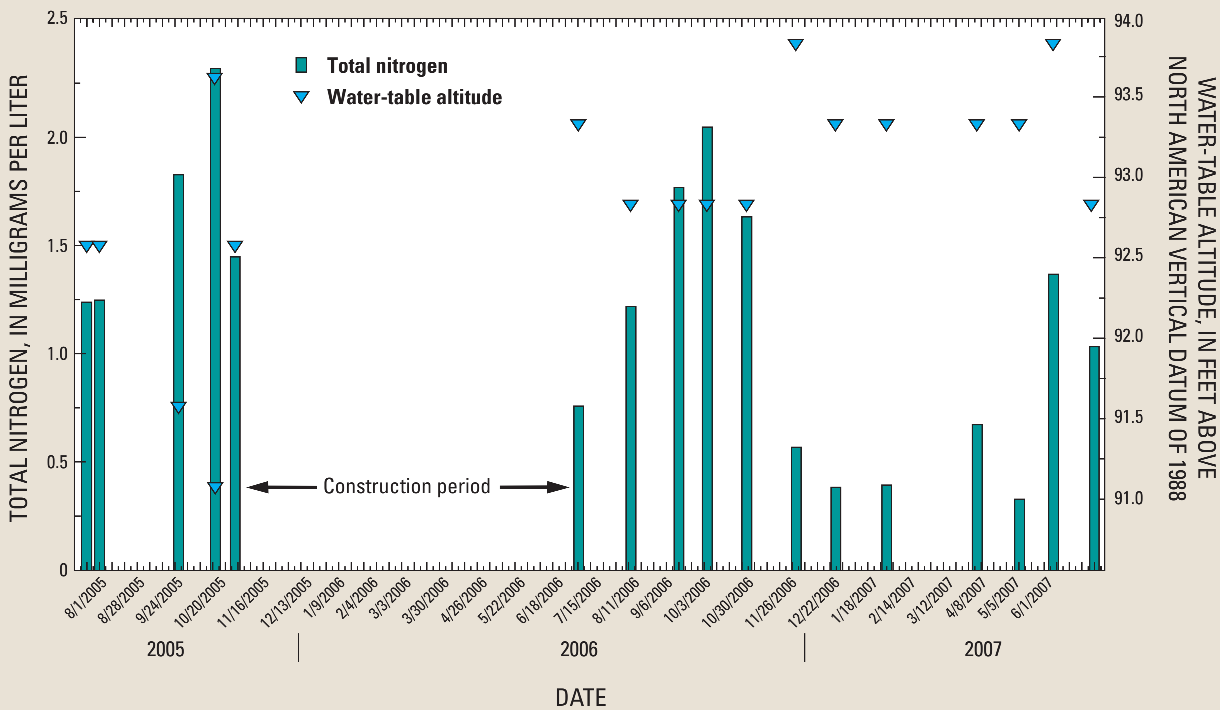


Figure 5. Total nitrogen concentrations in samples from multilevel sampler #1 (MLS#1) before and after installation of porous parking lot at Silver Lake beach, Wilmington, MA.

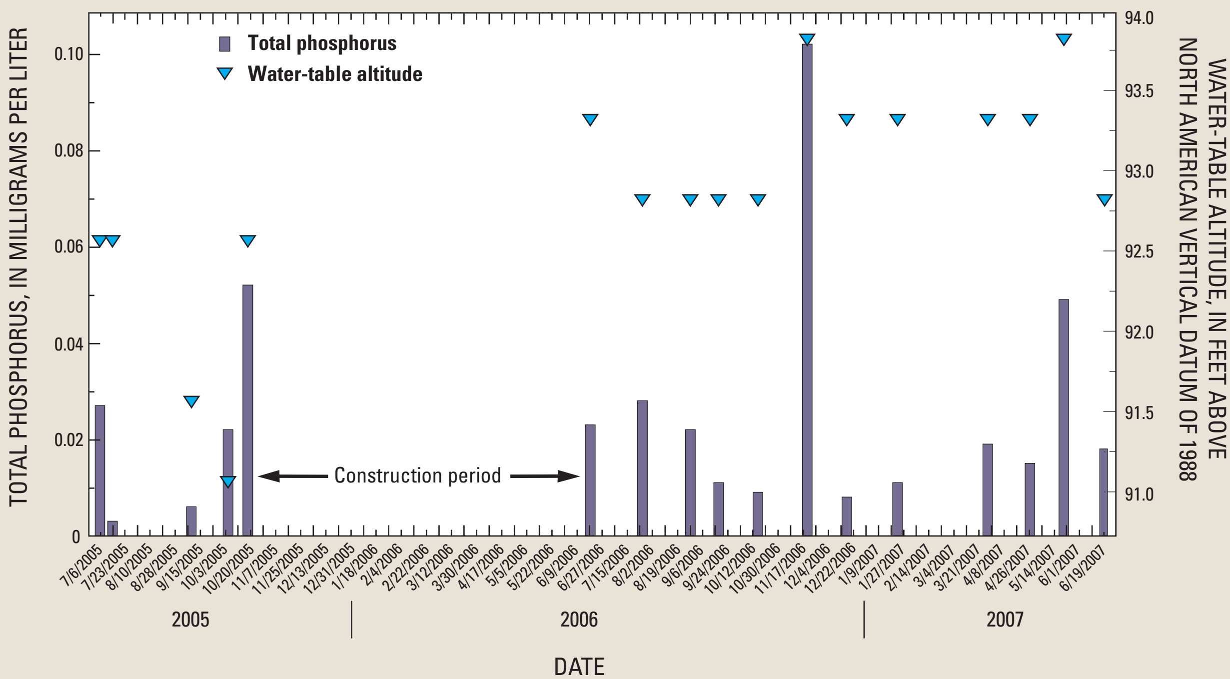


Figure 6. Total phosphorus concentrations in samples from multilevel sampler #1 (MLS#1) before and after installation of porous parking lot at Silver Lake beach, Wilmington, MA.

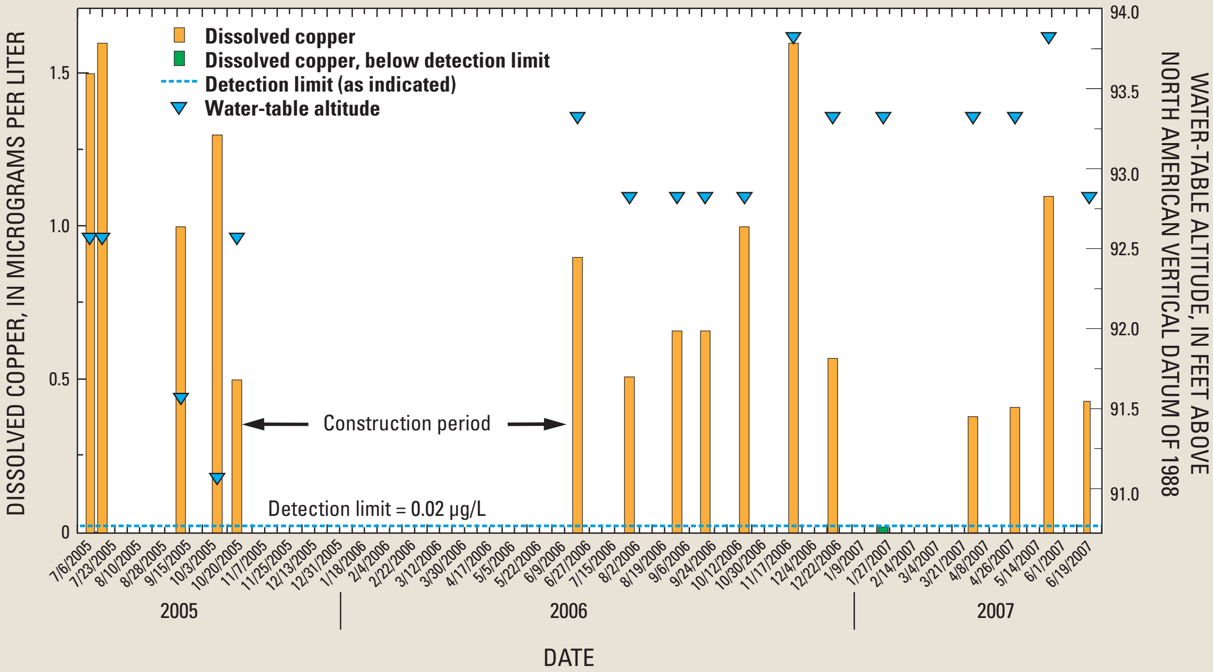


Figure 7. Dissolved copper concentrations in samples from multilevel sampler #1 (MLS#1) before and after installation of porous parking lot at Silver Lake beach, Wilmington, MA.

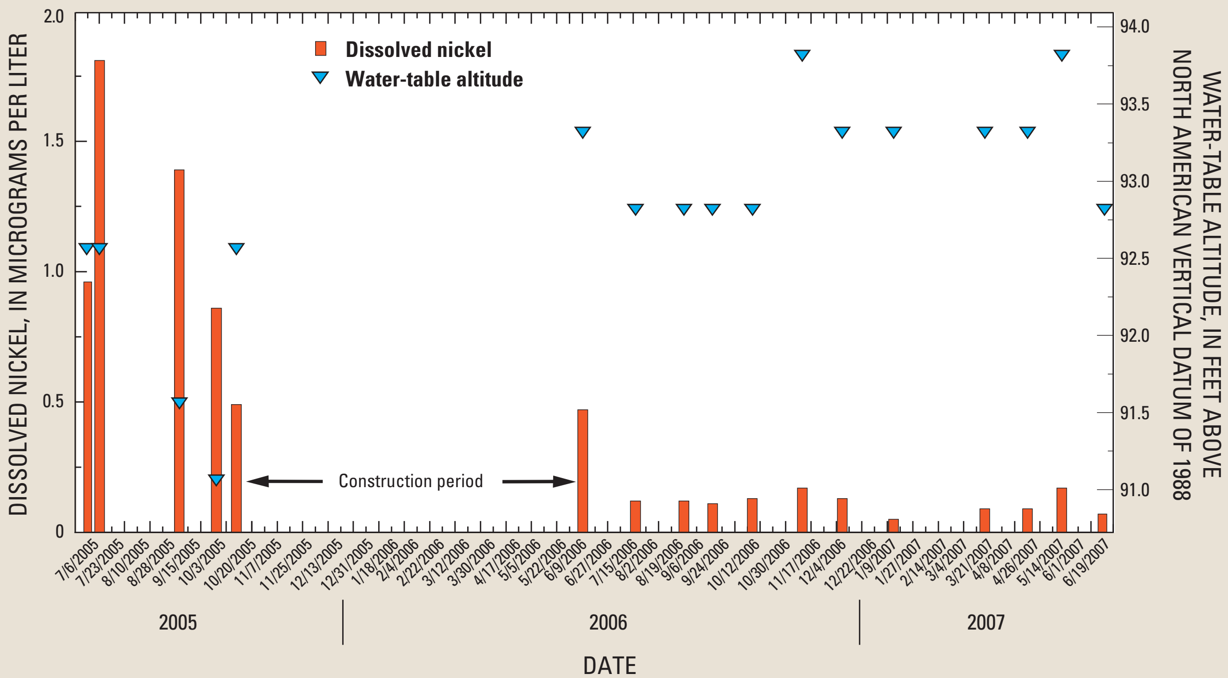


Figure 8. Dissolved nickel concentrations in samples from multilevel sampler #1 (MLS#1) before and after installation of porous parking lot at Silver Lake beach, Wilmington, MA.

Effects of LID Features on Stormwater Runoff Quantity and Quality from a Suburban Neighborhood

Twelve rain gardens and several areas of porous pavers installed in the LID-retrofit neighborhood near Silver Lake (fig. 9) were designed to decrease and delay runoff into storm drains, thus enhancing infiltration and decreasing the loads of nutrients, metals, total petroleum hydrocarbons (TPH), and coliform bacteria transported to Silver Lake. Load is the amount, or mass, of a constituent transported by stormwater (or a stream) during a specific period of time; load is calculated as the constituent concentration multiplied by runoff volume. Runoff was sampled for *E. coli* and total coliform bacteria to evaluate the effects of LID enhancements on bacterial loads to Silver Lake.

Underdrains from the two porous-paved areas and overflow drains from rain gardens were connected to the existing storm-drain system. Combined stormwater quantity and quality from Silver Lake Avenue and Dexter Street were monitored in a manhole on Silver Lake Avenue. The manhole was equipped to monitor stormwater flows and to trigger an automated water sampler to collect flow-proportional samples. Runoff volume was monitored at this location throughout the study to obtain data on storms of all sizes. Water-quality-sample-collection efforts were focused on storms that were likely to generate a sufficient volume of runoff for sample analysis. When the National Weather Service predicted storms of sufficient magnitude for sampling, the automated sampler was programmed manually to collect samples, if enough runoff was measured. Samples for chemical-water-quality analysis and for *E. coli* and total coliform testing were collected from August to November 2005, before the LID enhancements were installed, and from August 2006 to November 2007, the post-LID period.

Figure 9. Low-impact-development (LID) features installed in the LID-retrofit neighborhood along Dexter Street and Silver Lake Avenue, Wilmington, MA.

Differences in pre- and post-LID stormwater-runoff quantity and quality were generally small and subtle. Rainfall-runoff (RR) coefficients before and after LID installation were not statistically different, even for storms with antecedent dry periods exceeding 100 hours. Sorting storms into four size classes (fig. 10) also did not reveal statistically significant differences between pre- and post-LID RRs. However, median runoff coefficients for the small storms (less than or equal to 0.25 in. of rain) did show an appreciable difference: the pre-LID median RR was slightly greater than 0.1 and greater than the post-LID median RR of about 0.045 (fig. 11). The median post-LID RR for storms with 0.26 in. or more precipitation was about the same as the pre-LID median RR. Thus, the estimated effective impervious area (EIA), that is, the area that transmits stormwater directly to Silver Lake with no opportunity for infiltration, decreased from about 10 percent of the drainage area to about 4.5 percent as a result of the LID retrofits.

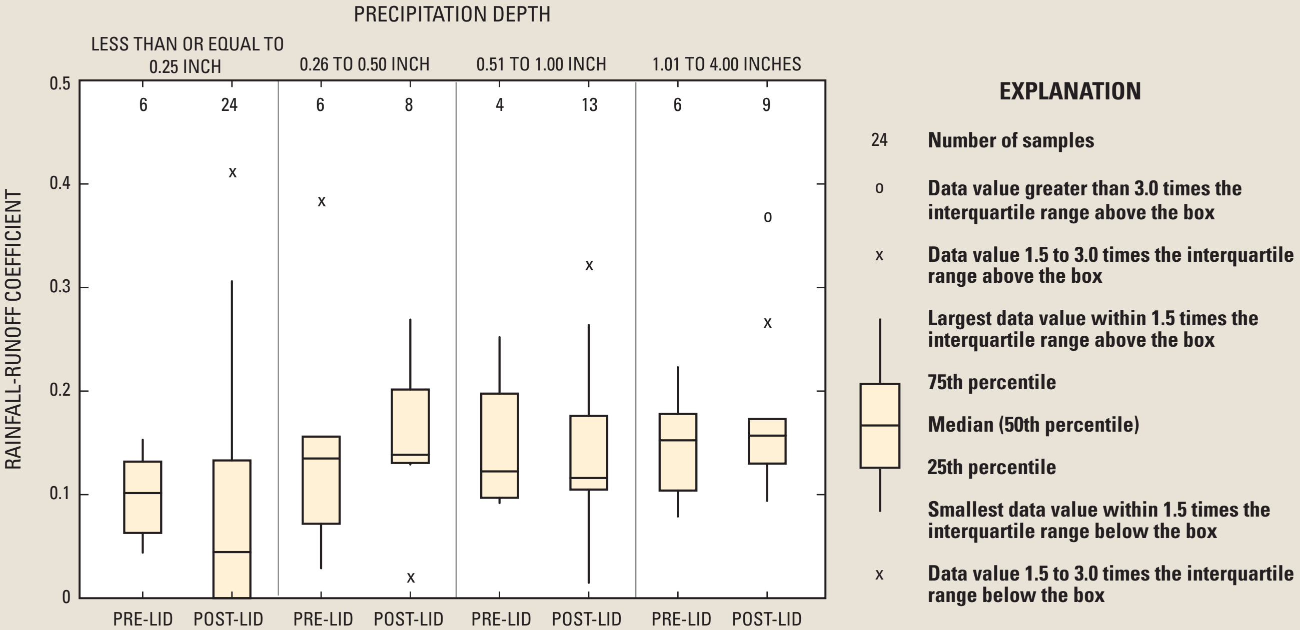


Figure 10. Rainfall-runoff coefficients for storms that occurred before (PRE) and after (POST) installation of low-impact-development (LID) features in the LID-retrofit neighborhood along Silver Lake Avenue and Dexter Street, Wilmington, MA. Rainfall-runoff coefficients are sorted by precipitation depth.

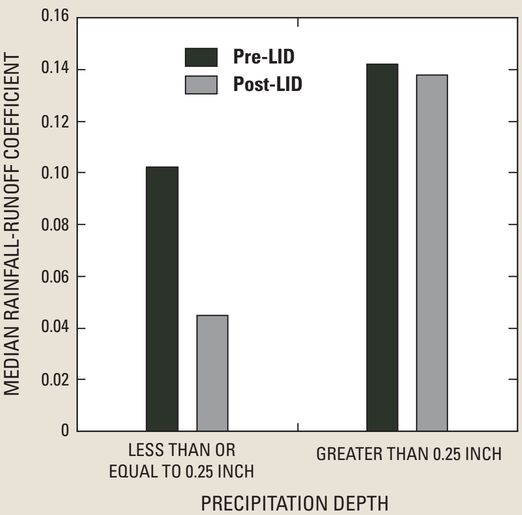


Figure 11. Median rainfall-runoff coefficients for storms that occurred before (Pre-LID) and after (Post-LID) installation of low-impact-development (LID) features in the LID-retrofit neighborhood along Silver Lake Avenue and Dexter Street, Wilmington, MA.

Rainfall and Runoff

The relation between rainfall and runoff is crucial for determining the ability of LID techniques to diminish stormwater runoff by enhancing infiltration. That is, the more effective the techniques are at directing precipitation into the ground, the less water will run off into storm drains. A standard calculation of this relation is the rainfall-runoff coefficient (RR), or the ratio of the amount of runoff to the amount of precipitation during a storm. For example, if 1 in. of water fell on a specific drainage area, and 0.75 in. of that water "ran off" the land surface instead of infiltrating, the RR coefficient would be 0.75, or 75 percent. Thus, the RR can range from 1 (all precipitation runs off—a completely impervious surface) to 0 (all precipitation infiltrates—no runoff, or a completely porous surface).

A notable difference between runoff conditions before and after the LID-retrofit in the Silver Lake neighborhood was the absence of any runoff from 7 of 21 post-LID storms (33 percent) with 0.25 in. or less precipitation (fig. 12). Of the seven pre-LID storms of up to 0.26 in. of precipitation, all had some measurable runoff. No specific factor, such as antecedent dry period, storm duration, or storm intensity, seemed to be associated with the absence or presence of runoff. These results indicate that even relatively small reductions in EIA, in an area underlain by highly permeable, sandy soils, such as the LID-retrofit neighborhood, can produce measurable reductions in stormwater runoff for small storms. In the case of this study site, that threshold was about 0.25 in. of precipitation.

Differences between estimated pre- and post-LID stormwater loads of nutrients, metals, total petroleum hydrocarbons, and coliform bacteria to Silver Lake were inconsistent. None of the differences between pre- and post-LID median loads were statistically significant. The median loads of nitrogen analytes increased after LID implementation, whereas median phosphorus-analyte loads decreased (fig. 13). Among the metal analytes, median loads of lead and zinc decreased and median loads of cadmium, chromium, copper, and nickel increased (fig. 14). The median of total coliform bacteria loads increased slightly, and the median of *E. coli* loads decreased somewhat. However, none of the changes from pre- to post-LID median loads for any of the chemical and biological constituents were statistically significant.

These results indicate that even relatively small reductions in EIA, in an area underlain by highly permeable, sandy soils, such as the LID-retrofit neighborhood, can produce measurable reductions in stormwater runoff for small storms.

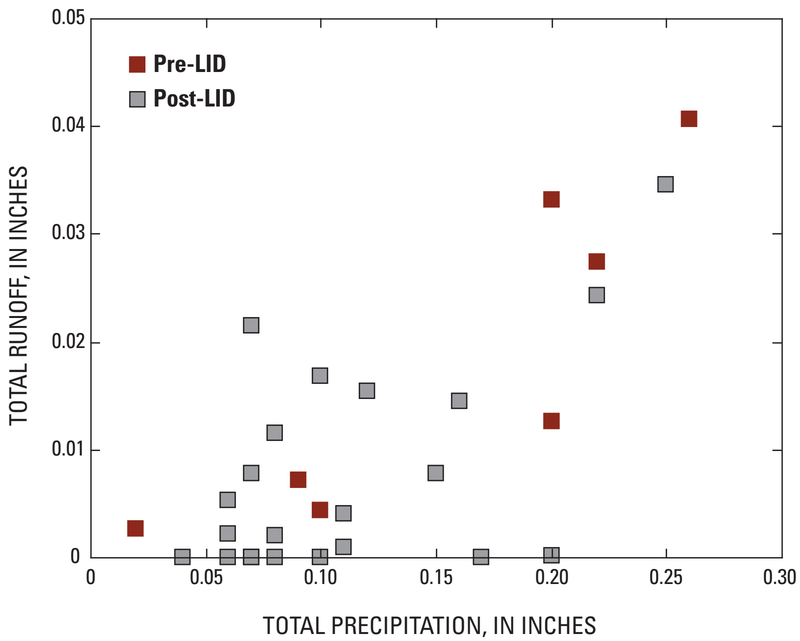


Figure 12. Total runoff in relation to total precipitation for storms of less than 0.26 in. in the LID-retrofit neighborhood along Silver Lake Avenue and Dexter Street, Wilmington, MA.

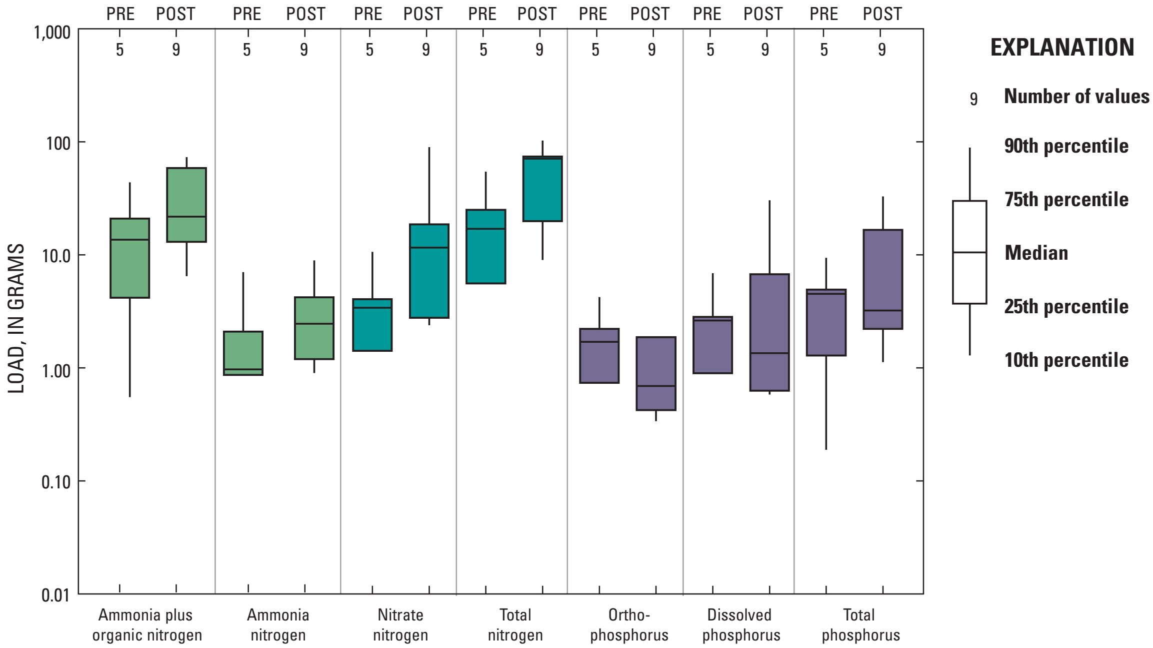


Figure 13. Estimated loads of selected nutrients from storms that occurred before (PRE) and after (POST) installation of low-impact-development (LID) features in the LID-retrofit neighborhood along Silver Lake Avenue and Dexter Street, Wilmington, MA.

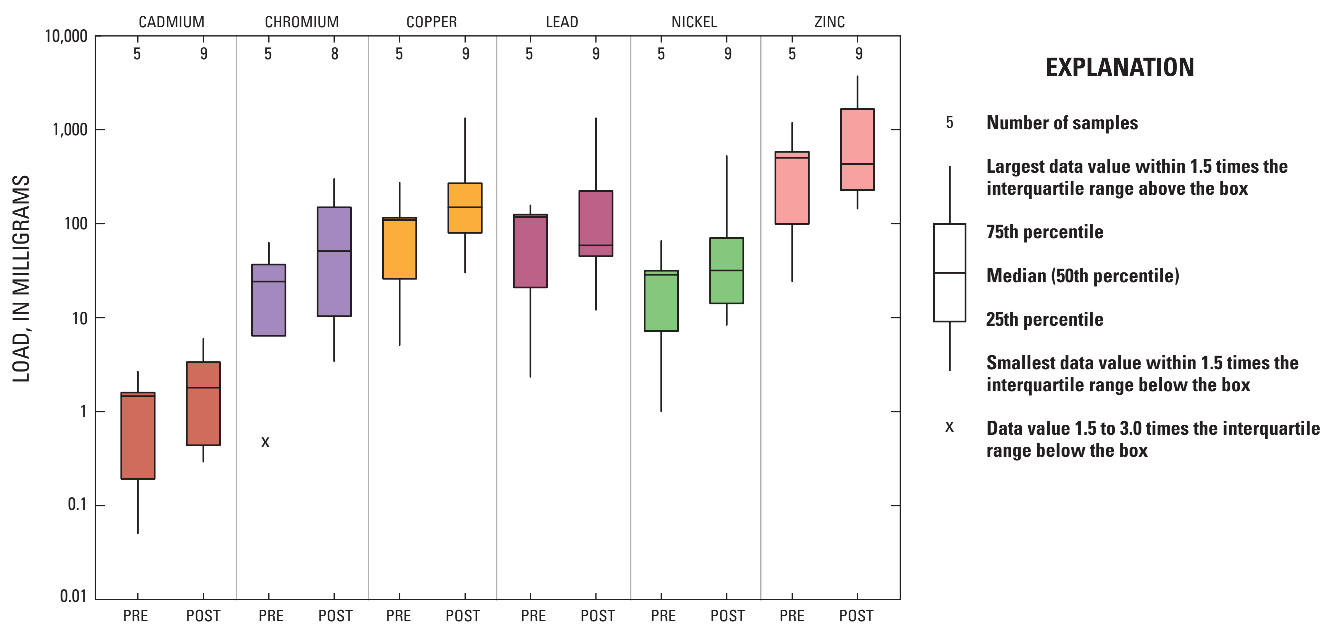


Figure 14. Estimated loads of selected metals from storms that occurred before (PRE) and after (POST) installation of low-impact-development (LID) features in the LID-retrofit neighborhood along Silver Lake Avenue and Dexter Street, Wilmington, MA.

Ability of a Green Roof to Alter the Quantity and Quality of Stormwater Runoff

Although green roofs have been used in Europe for some time, they are relatively new in North America where they are finding application for mitigating problems related to stormwater runoff (Berghage and others, 2007). Green roofs are reported to substantially reduce runoff volume and attenuate, or slow down, runoff when compared to standard roofs. The plants and growing medium on the roof, through absorption and evapotranspiration, make runoff reduction and attenuation possible. The growing medium may also neutralize acidic precipitation through its inherent buffering capacity and retain atmospheric pollutants that affect the quality of runoff.

Figure 15. The green roof installed on the Whipple Annex next to the Ipswich, MA, Town Hall, summer 2007.

The green roof on the Whipple Annex building in Ipswich (fig. 15) consists of a waterproof membrane, a plastic drainage layer, filter fabric, a layer of growth medium (crushed clay plus organic matter), and plants, including *Talinum calycinum* (fameflower), *Allium schoenoprasum* (chive), and eight species of *Sedum* (a drought-tolerant succulent). Ipswich Town Hall has a rubberized membrane roof (fig. 16). Both roofs were instrumented (fig. 17) so that rates of stormwater runoff could be monitored and samples of stormwater could be collected in proportion to the volume of runoff and analyzed chemically. A continuous precipitation gage and a data recorder were installed on the Ipswich Town Hall roof to monitor rainfall.

Rainfall on and runoff from the two roofs were monitored for a period of 18 months in 2007 and 2008. Storms producing less than 0.04 in. of rain were not included in the analysis, nor were most winter storms or any runoff resulting from snowmelt because of the uncertainties caused by freezing, thawing, and snowfall. In all, 70 storms provided data suitable for comparison of stormwater runoff from the green and conventional roofs.

Figure 16. The conventional, rubberized-membrane roof on the Ipswich, MA, Town Hall.

The ability of a vegetated green roof to reduce the volume of runoff from a particular storm depends on the amount, duration, and intensity of storm precipitation, and on the amount of water present in the plants and growing medium at the start of the storm (referred to as "antecedent" conditions). Water retained from a previous storm will slowly evaporate from the green roof surface or transpire into the atmosphere through the plants (hence the term "evapotranspiration"). As the length of the antecedent dry period increases, more of the previously retained water is removed and the roof's capacity to store new rainfall increases. Conversely, if the antecedent dry period is brief, less storage is available, likely resulting in some runoff from the roof. However, the timing of the release of runoff from a green roof may be different from that of a conventional roof.

The differences in the responses of the green roof and rubber roof to antecedent conditions and storm size are shown in graphs of precipitation (hyetographs) and runoff (hydrographs) during two storms in September 2007 (figs. 18, 19). The September 9, 2007, storm (fig. 18) followed an extended dry period of 22 days, lasted about 17 hours, and produced 0.61 in. of rainfall that fell in two bursts about 11 hours apart. Runoff from the conventional roof began almost as soon as the rain began (fig. 18) and totaled 273 ft^3. In contrast, runoff from the green roof totaled only 13 ft^3. One hundred percent of the rainfall on the conventional roof became runoff, whereas more than 85 percent of the rain on the green roof was retained; that is, less than 15 percent of the rain that fell on the green roof became runoff. There was also a noticeable delay in the initial response of runoff from the green roof relative to the start of precipitation (fig. 18). Runoff from the green roof did not increase appreciably until about 1 hour after the storm began.

The September 11, 2007, storm (fig. 19) followed an antecedent dry period of only 10 hours, lasted about 7.5 hours, and produced 1.27 in. of rainfall. In contrast to the September 9, 2007 storm, only 2 days earlier, this storm was about twice as large and delivered more intense rainfall, with much wetter antecedent conditions. Runoff from the conventional roof was similar to that observed in the previous storm, with a direct response to rainfall that produced total runoff of 569 ft^3. All precipitation on the conventional roof became runoff. The runoff response from the green roof was appreciably different from the previous, September 9, 2007, storm. In the first hour of the storm, runoff from the green roof was negligible, but then followed a more direct response to rainfall, producing a total of 251 ft^3, about 80 percent of the total rainfall that fell on the roof (20-percent retention). This response indicates that the growing-medium layer was already nearly saturated from the previous storm, and the time between storms was insufficient for evapotranspiration to allow more than 20 percent retention of rainfall from this storm. This storm also draws attention to the limits of the green roof's design storage capacity of 1.0 in. of precipitation that was exceeded by 0.27 in.

Total storm precipitation and the length of the antecedent dry period determine the effectiveness of a green roof in retaining water. The finite capacity of the green roof is a function of its design limits and the amount of water still retained from previous storms; that amount is controlled by the length of time since the previous storm and the overall potential for evapotranspiration, which varies seasonally. For example, in winter, when plants are dormant, evapotranspiration is minimal, and much precipitation falls in the form of snow that does not immediately result in runoff.

Figure 17. The system, during construction, for collecting stormwater runoff from the Whipple Annex green roof, Ipswich, MA.

A broad view of the green roof performance was obtained by relating storm characteristics to runoff volume for the 70 storms analyzed. The percentage of precipitation retained in relation to total precipitation varied from nearly zero to 100 percent for storms less than 1 in., which was the green roof's design capacity. In general, the green roof retained more than 50 percent of the precipitation from 70 percent of the storms (49 of 70). Of the remaining 21 storms, most had antecedent dry periods of less than 70 hours (fig. 20).

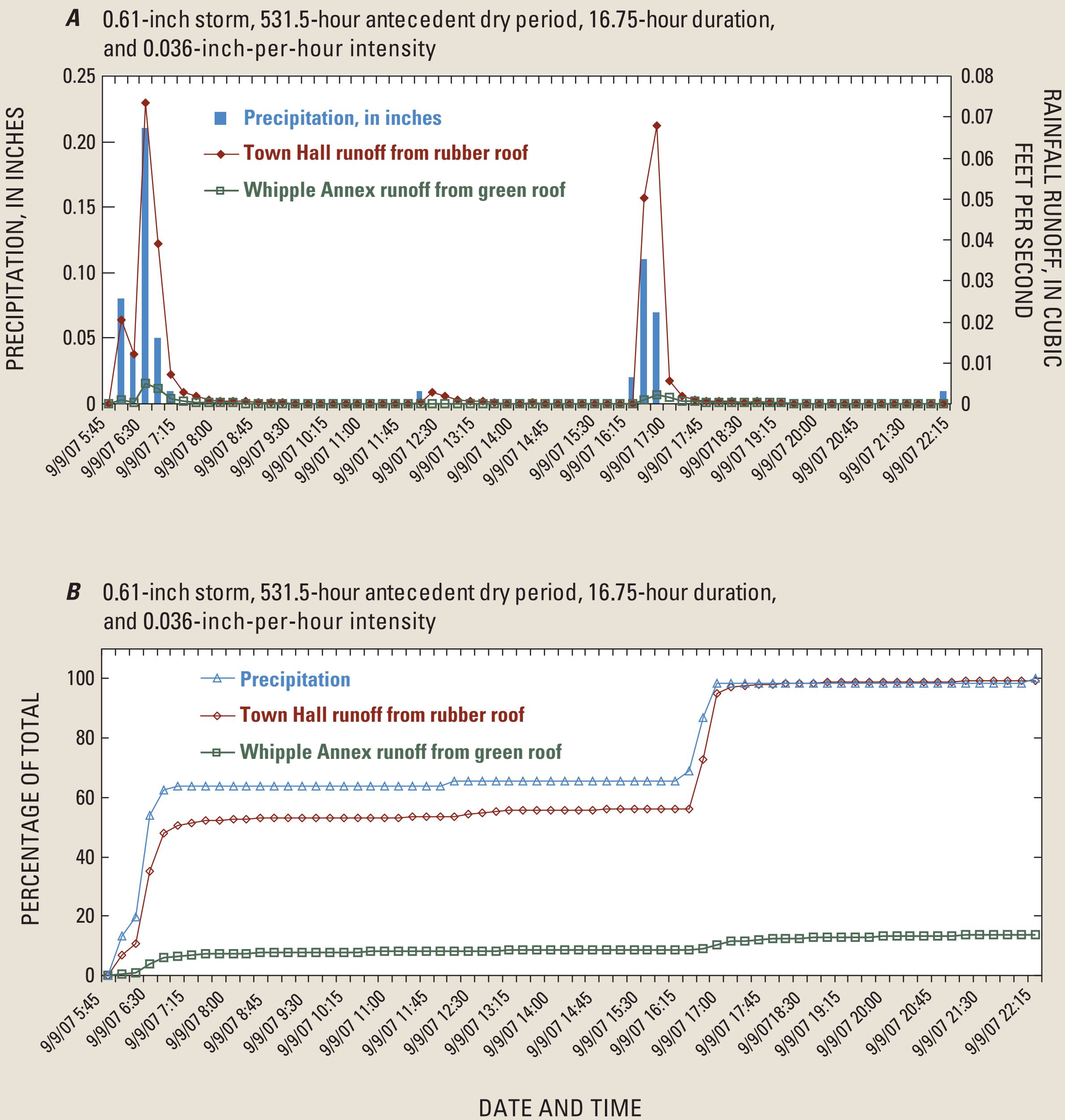


Figure 18. *(A)* Precipitation on and runoff from conventional rubber and green roofs in Ipswich, MA, for the storm of September 9, 2007, and *(B)* cumulative percentages of total precipitation and total runoff from the roofs for the same storm.

A 1.27-inch storm, antecedent dry period 9.75 hours since 0.11-inch event and 32.25 hours since 0.61-inch event, 7.5-hour duration and 0.169-inch-per-hour intensity

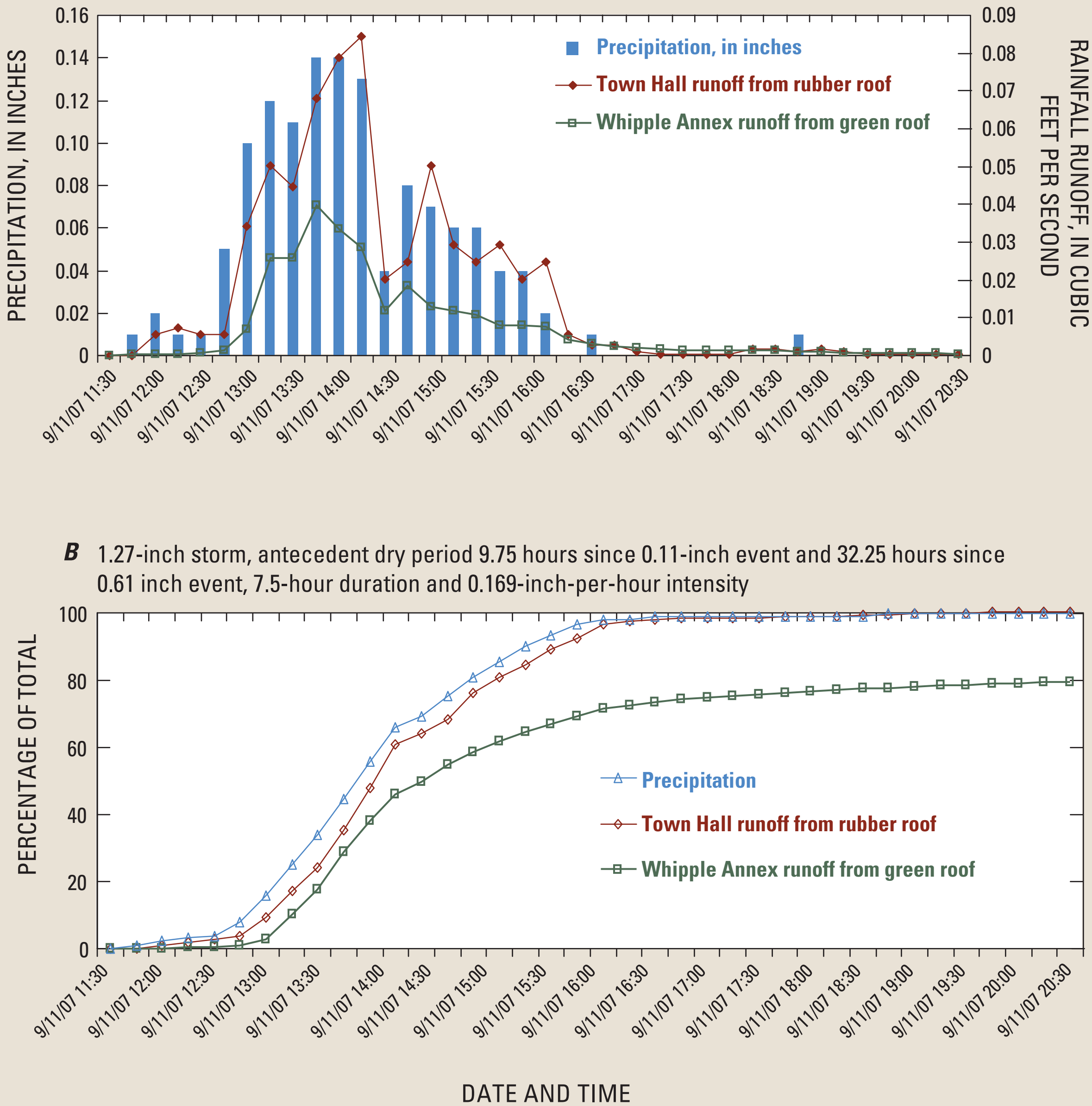


Figure 19. *(A)* Precipitation on and runoff from conventional rubber and green roofs in Ipswich, MA, for the storm of September 11, 2007, and *(B)* cumulative percentages of total precipitation and total runoff from the roofs for the same storm.

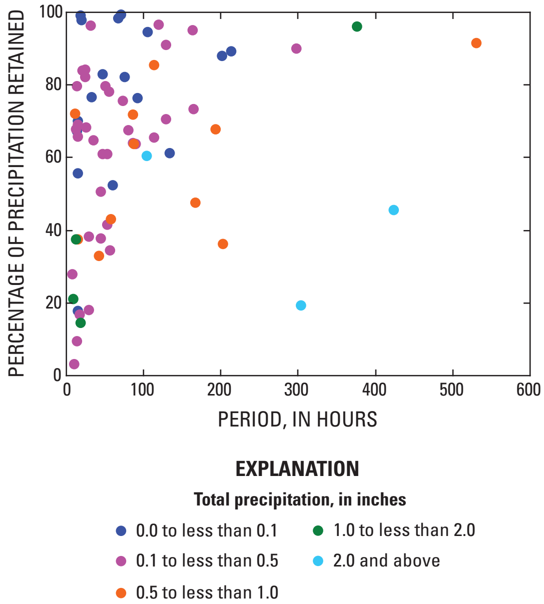


Figure 20. Scatter Percentages of rainfall retained by the Whipple Annex green roof in Ipswich, MA, in relation to the period of dry weather preceding the storm.

Adequate volumes of composite, flow-proportional runoff samples and bulk (direct) precipitation samples were obtained from five storms and analyzed for nutrients (nitrogen and phosphorus), metals (cadmium, chromium, copper, lead, nickel, and zinc), and total petroleum hydrocarbons. (For a compilation of all data, refer to the companion report, Zimmerman and others, 2010.) Median concentrations of total phosphorus and total nitrogen were higher in runoff from the green roof than they were in runoff from the conventional roof, and median concentrations of these constituents in both sets of runoff samples were significantly higher than those in bulk precipitation (fig. 21). The relatively high nutrient concentrations in runoff from the green roof were likely due to nitrogen and phosphorus initially present in the growing medium and to subsequent fertilization of the roof during establishment of the plants. Leaching of nutrients from green roofs has been reported elsewhere (Oberndorfer and others, 2007; Dietz, 2007). With the planned discontinuation of fertilization as the vegetation becomes fully established, the concentrations of nutrients in the green roof runoff should diminish. Likely sources of the constituents found in runoff from the conventional roof include dryfall (particles deposited on surfaces from dry air) between storms and fecal deposits left by birds and insects, in addition to chemicals dissolved in precipitation.

Constituent loads (the total mass of a constituent in stormwater runoff) were computed from concentration data and runoff volumes and divided by roof surface area to account for the differences in area between the two roofs. Estimated constituent loads indicate that the reduction in

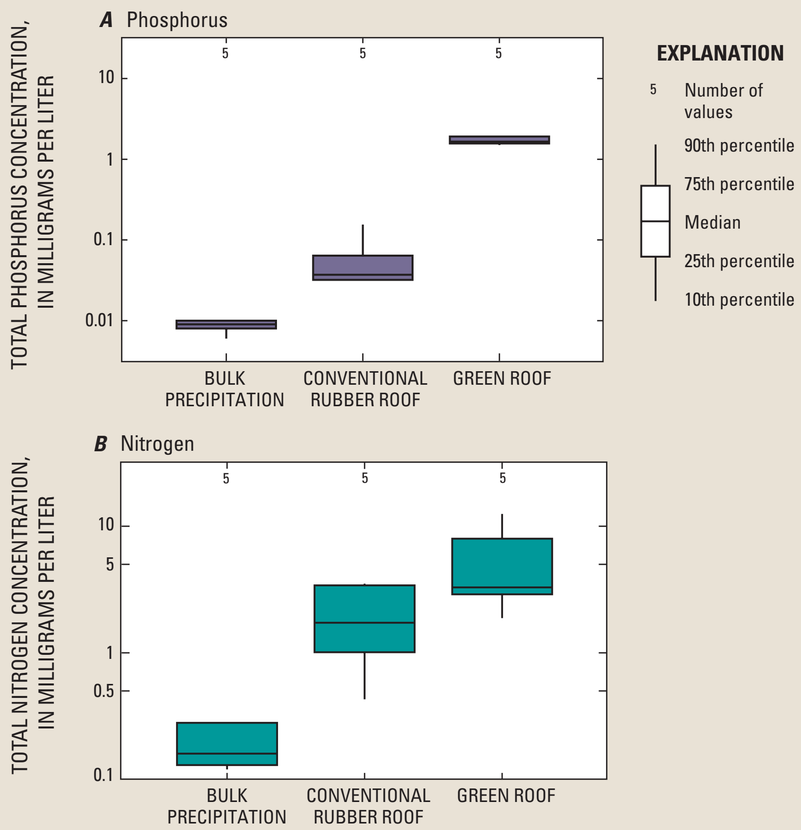


Figure 21. Concentrations of *(A)* total phosphorus and *(B)* total nitrogen in bulk precipitation and rainfall runoff from the Town Hall conventional rubber roof and from the Whipple Annex green roof, Ipswich, MA, from storms sampled during 2007 and 2008.

stormwater volume from the green roof effectively reduced the nutrient loads, even though the constituent concentrations from green roof samples were significantly higher than the constituent concentrations from the conventional roof samples (fig. 22). For example, the median total phosphorus concentration was almost 100 times greater in the green roof runoff than in the conventional roof runoff, but the median total phosphorus loads in runoff from the two roofs differed by only about a magnitude factor of 10. The green roof's median total nitrogen concentration was slightly greater than that of the conventional roof, but the median load was slightly smaller than the median load from the conventional roof. Differences between median total nitrogen loads for the green roof and the conventional roof were not statistically significant.

The median total copper concentration measured in runoff from the green roof (414 micrograms per liter (μg/L)) was about 10 times greater than that in runoff from the conventional roof (41.2 μg/L), and more than 100 times greater than that in bulk precipitation (2 μg/L, fig. 23A). In contrast, the median total lead concentration in runoff from the green roof (1.87 μg/L) was less than 1 percent of that from the conventional roof (589 μg/L) and was not statistically different than the median total lead concentration in bulk precipitation (fig. 23B). These differences in runoff quality are attributed to differences in plumbing and roof-construction materials. The gutters, downspouts, machinery, vents, and copper flashing on the green roof likely all affect runoff water quality. Cast iron drain pipes

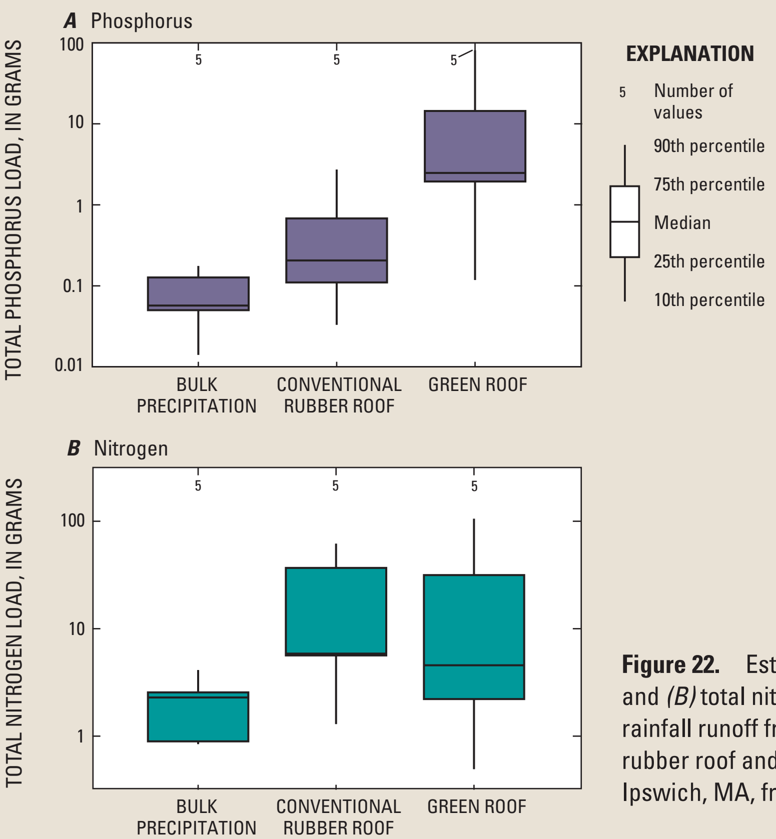


Figure 22. Estimated loads of *(A)* total phosphorus and *(B)* total nitrogen in bulk precipitation and in rainfall runoff from the Town Hall conventional rubber roof and from the Whipple Annex green roof, Ipswich, MA, from storms sampled in 2007 and 2008.

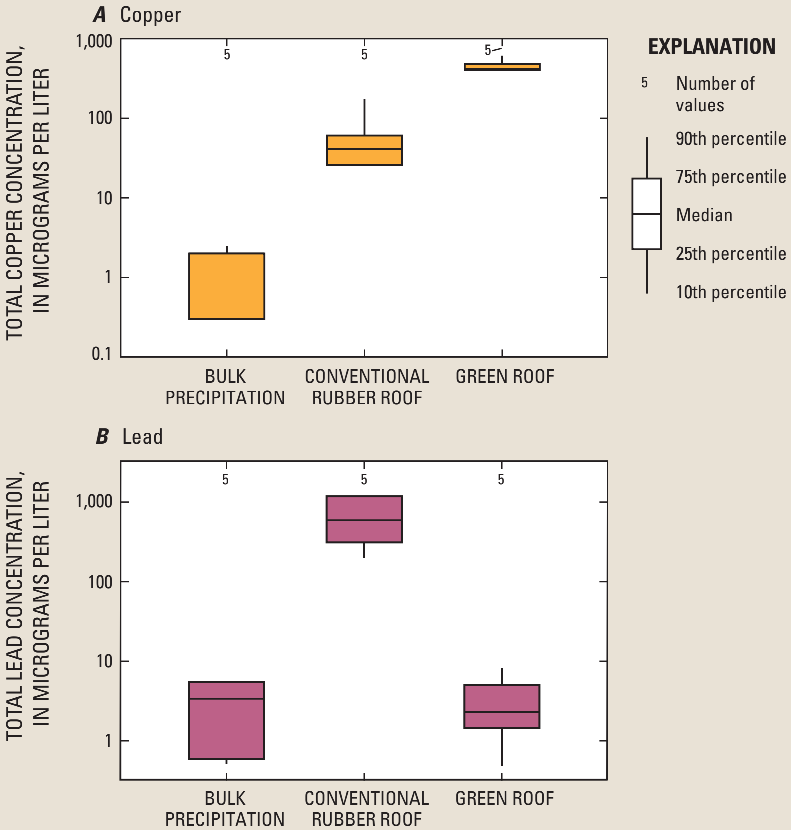


Figure 23. Concentrations of *(A)* total copper and *(B)* total lead in bulk precipitation and in rainfall runoff from the Town Hall conventional rubber roof and from the Whipple Annex green roof, Ipswich, MA, from storms sampled in 2007 and 2008.

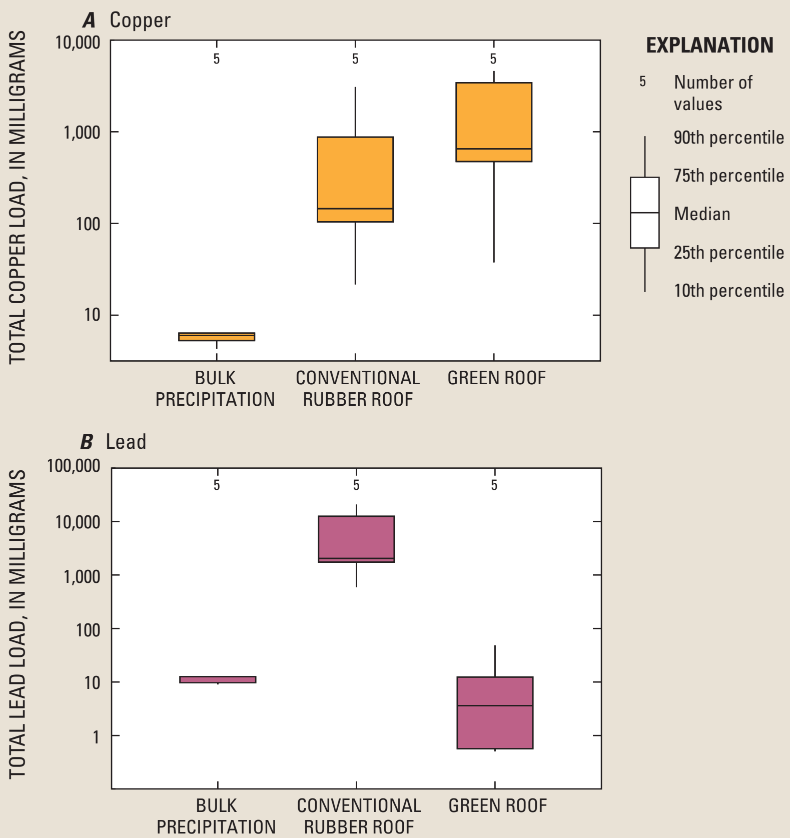


Figure 24. Estimated loads of *(A)* total copper and *(B)* total lead in bulk precipitation and in rainfall runoff from the Town Hall conventional rubber roof and from the Whipple Annex green roof, Ipswich, MA, from storms sampled in 2007 and 2008.

with lead seals likely contribute to the chemical makeup of the conventional roof runoff. In a similar manner to nitrogen, the reduced stormwater volume from the green roof, relative to the conventional roof, resulted in copper loads that were not significantly different from those estimated for the conventional roof (fig. 24A). Lead loads from the conventional roof were much greater than those from the green roof (fig. 24B).

Simulation of the Effects of Land-Use and Water-Management Changes and Low-Impact Development on Streamflow

Urbanization produces changes in land use and stormwater routing that have significant effects on the processes that generate streamflow. Loss of vegetation, increased imperviousness, and water use (water withdrawals, wastewater return flows, and water transfers) affect the entire flow regime, from flood peaks to summer low flows maintained by groundwater discharge. Storm drainage systems, such as catch basins and storm sewers, concentrate and distribute runoff from impervious areas. A computer model of the Ipswich River Basin, called the Ipswich River Basin Hydrological Simulation Program-FORTRAN (HSPF) precipitation-runoff model (Zarriello and Ries, 2000), was modified to simulate the effects of changes in land-use and LID practices on streamflow. To better reflect current conditions, recent changes in public water-supply withdrawals by the towns of Wilmington and Reading were incorporated into the model primarily to bring the model up to date with current water-supply conditions. Several water-withdrawal scenarios representing widespread application of water-conservation strategies were then developed in consultation with MDCR, U.S. Environmental Protection Agency, and the project's technical advisory committees.

Loss of vegetation, increased imperviousness, and water use (water withdrawals, wastewater return flows, and water transfers) affect the entire flow regime, from flood peaks to summer low flows maintained by groundwater discharge.

Watershed computer models, such as HSPF, simplify the complex processes and physical characteristics of a drainage basin. This simplification consequently limits the types of questions that can be addressed with the model. The assumptions, information used to develop and calibrate the model, spatial resolution (degree of detail) of the model, and alternative model structures and parameters (characteristics such as precipitation and housing density) need to be considered when evaluating model results for use in water-resources management decisions. For example, specific LID practices, such as installation of porous pavement, rain gardens, bioretention areas, and green roofs, could not be represented explicitly in the basin-scale Ipswich River Basin HSPF model; instead, substitutes for these practices were simulated by varying the amount of EIA over the entire basin. For more detailed elaboration of the Ipswich River Basin model assumptions and limitations, see Zarriello and Ries (2000).

Simulations were conducted at two different geographic scales for this study (table 1). The first set of simulations examined the effects of land-use change, LID practices, and water-conservation efforts at basin and subbasin scales. The basin-scale simulations generally generally focused on the upper Ipswich River Basin, an area of 44.5 mi^2, upstream from the USGS South Middleton streamgage ((01101500) in fig. 25). However, model simulations represented hydrologic processes in drainage areas ranging from about 0.5 to 125 mi^2 in size. To better represent hydrologic

Table 1. Summary of Ipswich River Basin modeling scenarios and results. (For complete details, see Zimmerman and others, 2010.)

[LID, low-impact development]

Simulation scenario	Area covered	Brief description of selected results of effects of modifying original baseline model
Basin-scale simulations		
Original baseline simulation (Zarriello and Ries, 2000)—average 1989 to 1993 withdrawals (also referred to as original baseline withdrawals), 1991 land use	Entire basin ($155\ mi^2$)	Original baseline model
Updated baseline simulation—average 1989 to 1993 withdrawals with updated withdrawals for Reading and Wilmington (also referred to as updated baseline withdrawals), 1991 land use	Entire basin ($155\ mi^2$)	Increases in low and medium flows upstream from the South Middleton streamgage.
Buildout simulation—updated baseline withdrawals, potential land use at buildout	Entire basin ($155\ mi^2$)	Minor effects on streamflow: 0 to 20 percent change at subbasin scale.
Simulation of LID retrofits upstream from the South Middleton streamgage (station no. 01101500)—updated baseline withdrawals, 1991 land use with effective impervious area reduced by 50 percent	Upper basin ($44.5\ mi^2$)	Minor effects on streamflow: 0 to 20 percent change
Water-conservation simulation—updated baseline withdrawals with rates reduced by 1 to 20 percent to represent water-conservation programs, 1991 land use	Entire basin ($155\ mi^2$)	With 5 percent reduction in withdrawals, effects were minor. With 20 percent reduction in withdrawals, low flows increased slightly.
Local-scale simulations		
Local-scale simulations—no water withdrawals, varying combinations of developed and undeveloped land-use types and amounts of effective impervious area	Hypothetical, 100-acre parcels	**Conventional development:** *(A)* Conversion of forested land use to commercial: increased median 1-day high flow 1,250 percent; decreased median 1-day low flow 33 percent; *(B)* Conversion of forested land use to high-density residential: increased high or medium and low flows, depending on underlying geology; *(C)* Sensitivity of streamflow to effective impervious area: Implementing LID in commercial and high-density residential land-use areas reduced flow alteration more than implementation in low-density residential land-use areas. **Cluster development:** Clustering tended to reduce high flows.

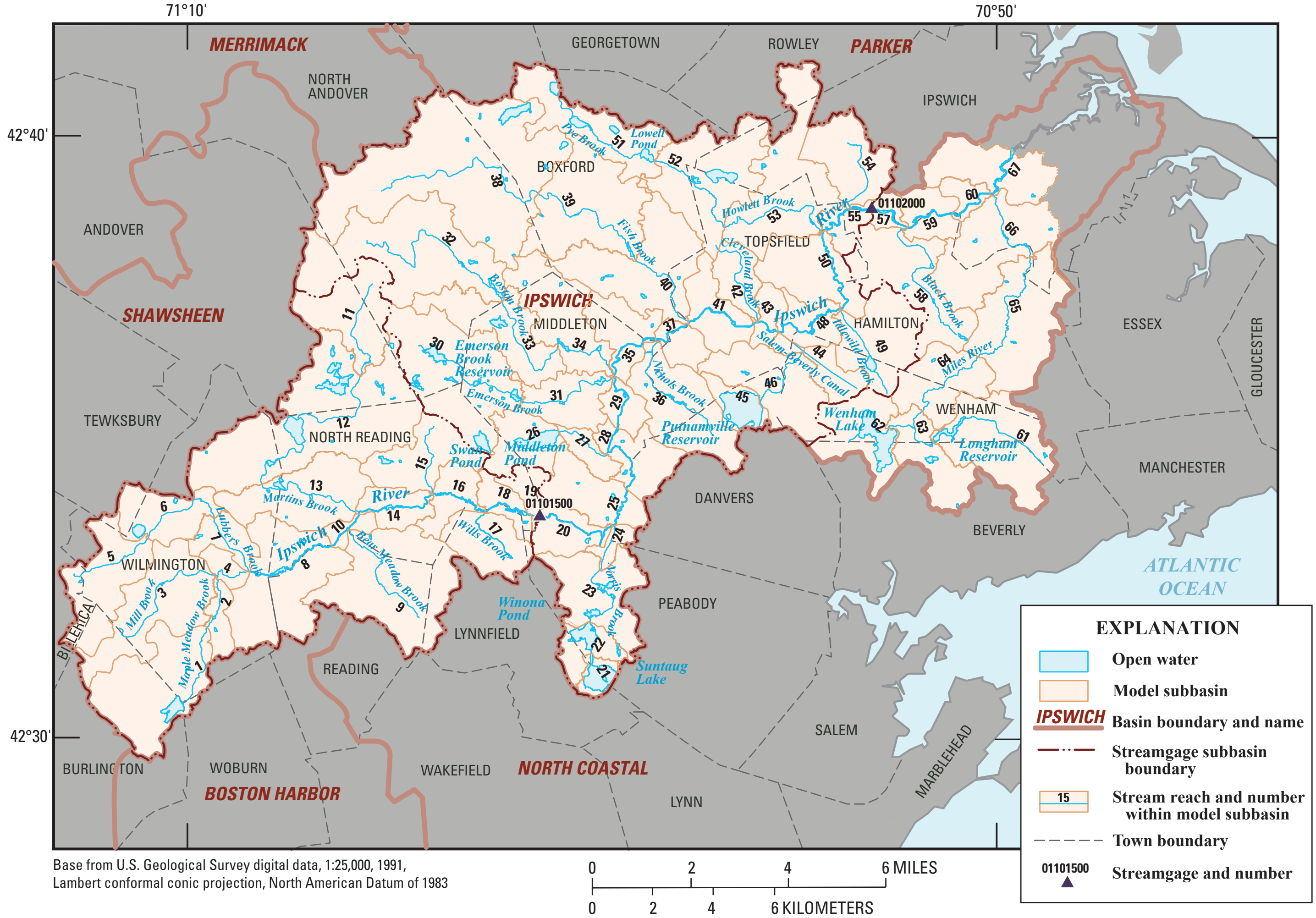


Figure 25. Model reaches and subbasin boundaries in the Ipswich River Basin, MA. (From Zarriello and Ries, 2000)

responses at a local scale, the second set of simulations examined the potential effects of changes in land use, amount of EIA, and incorporation of LID practices, such as clustering development and preserving open space, on streamflow in hypothetical 100-acre (0.16 mi^2) parcels of land. The local-scale simulations were based on homogeneous land uses with different mixes of development density and EIA. Collectively, the simulations represented a wide range of spatial scales and time periods as well as a range of hydrologic responses to land-use change, water-management activities, and various LID practices. (For a complete description of the modeling study, see Zimmerman and others, 2010.)

The baseline simulation in the original Ipswich River Basin modeling study was used to evaluate the effects of average 1989–93 groundwater withdrawals on streamflow over long-term (1961–95) climatic conditions (Zarriello and Ries, 2000). This baseline simulation was updated to incorporate recent changes in groundwater withdrawals for the towns of Reading and Wilmington that had relied on withdrawals from wells in the upper part of the basin. In 2006, the town of Reading began purchasing water from the Massachusetts Water Resources Authority (MWRA) to meet its water needs. To simulate current withdrawals, the 10 well withdrawals by Reading wells were discontinued—a decrease of 2.2 Mgal/d from reach 8 (fig. 25). In anticipation of the town of Wilmington purchasing water from the MWRA in 2008, daily summer withdrawal rates from four active wells were decreased by a total of 1 Mgal/d from reaches 5, 12, and 13 (fig. 25) in the updated baseline simulation.

Total annual withdrawals upstream from the South Middleton streamgage averaged 6.7 Mgal/d in the original baseline simulation (Zarriello and Ries, 2000) and dropped to 3.5 Mgal/d in the updated baseline simulation for the present study.

Table 2. Simulated August median flows in the Ipswich River at the South Middleton streamgage.

Original baseline, cubic feet per second	Updated baseline, cubic feet per second	Percent change
August median flows		
3.42	8.36	144
Median 1-day low flows		
0.74	2.8	278
Median 7-day low flows		
0.983	3.65	271

The decrease in withdrawal led to substantial simulated increases in low and median flows in the Ipswich River at the South Middleton streamgage (table 2).

Effects of Land Development on Streamflow in the Ipswich River Basin

A statewide buildout analysis was conducted by the Massachusetts Executive Office of Energy and Environmental Affairs (EOEEA) in 2001 (Massachusetts Executive Office of Energy and Environmental Affairs, 2008). This analysis provided information to simulate the effects of potential future development, referred to as buildout, on streamflow in the Ipswich River Basin. A buildout analysis determines how a community might develop if all remaining developable areas were fully built out in accordance with current local zoning and other development constraints. Land that is not considered developable includes permanently protected open space such as conservation land and riparian buffers, open water, and land that is already developed. For this study, forested and non-forested wetlands also are considered unavailable for development. The drainage area upstream from the South Middleton streamgage is relatively urban and contains less developable land than other parts of the basin.

Table 3. Land use in 1991 and potential land use at buildout in the Ipswich River Basin, MA.

[Percent change expressed as area at buildout minus area in 1991 over area in 1991.]

Land-use description	1991 land use		Buildout land use		Percent change
	Area (acres)	Percentage of total area	Area (acres)	Percentage of total area	
Forest	36,854.0	38.6	23,113.6	24.2	-37.3
Open	6,675.2	7.0	3,407.0	3.6	-49.0
Open water	2,384.4	2.5	2,384.4	2.5	0.0
Nonforested wetland	6,750.1	7.1	6,750.1	7.1	0.0
Low-density residential	14,471.3	15.2	30,005.4	31.4	107.3
High-density residential	11,486.0	12.0	11,696.3	12.2	1.8
Commercial-industrial-transportation	3,583.5	3.8	4,847.7	5.1	35.3
Forested wetland	13,284.0	13.9	13,284.0	13.9	0.0
Total:	**95,488.5**		**95,488.5**		

To develop new land-use data to simulate future conditions, the zoning codes in the developable areas were related to the land-use categories used for model development. Using 1991 land use as a baseline, the buildout analysis indicated that about 17 percent of the entire Ipswich River Basin was developable. The major changes in the basin were the decline in forested areas from 39 to 24 percent, and the increase in low-density residential development (lot sizes greater than 0.5 acre) from 15 to 31 percent. Other developed land-use categories, including high-density residential (lot sizes less than or equal to 0.5 acre) and commercial, increased slightly at buildout (table 3).

To isolate the effects of land-use change on streamflow, the updated baseline simulation, reflecting 1991 land use, was modified to account for land-use change at buildout. Land-use change associated with buildout generally had minor effects (0 to 20 percent change) on streamflow at the subbasin scale because most of the developable land in the basin was forested or open and zoned for low-density residential development. The EIA associated with low-density residential development was relatively small (2.5 percent in the calibrated Ipswich River Basin HSPF model); therefore, increases in this type of land use were not expected to appreciably change the runoff response to precipitation because the runoff characteristics are similar for forest and low-density-residential land use for a given type of underlying surficial geology. The major difference between simulated forests and low-density residential development was the amount of water lost to evapotranspiration. In humid climates, low water yields in forested watersheds have been attributed to increased canopy-intercepted evaporation and more intensive root-zone transpiration during the growing season (Bent, 2001; Calder, 1993; Robinson and others, 1991). These processes lower the soil-moisture content, reduce recharge, and lower water tables, thus reducing the base-flow (groundwater) contribution to streamflow. Consequently, although low-density residential areas received slightly less infiltration per unit area than forested areas because of EIA, the comparatively small evapotranspiration losses from low-density residential areas are believed to have resulted in slight increases in summer low flows, relative to forested areas with the same surficial geology.

By comparison, conversion of forest to commercial land use in this analysis had a pronounced effect on simulated streamflow, producing increases in peak flows, because the relatively large increases in EIA increased surface runoff. Although this effect of urbanization on flood peaks was relatively clear, the effect of increasing urbanization on low flows showed conflicting results, as also noted by Brandes and others (2005) and Rose and Peters (2001). The lack of clear effects may result because low flows are determined by the net response to complex interactions among climate, land use, water use, and water infrastructure (Claessens and others, 2006; Lerner, 2002; Dow and DeWalle, 2000).

Overall, the buildout simulation assuming conventional styles of development demonstrated only minor effects on streamflow in the basin. Therefore, buildout incorporating LID practices, which would only show subtle effects of development, was not evaluated.

The major difference between simulated forests and low-density residential development was the amount of water lost to evapotranspiration. In humid climates, low water yields in forested watersheds have been attributed to increased canopy-intercepted evaporation and more intensive root-zone transpiration during the growing season (Bent, 2001; Calder, 1993; Robinson and others, 1991).

LID features to increase stormwater recharge and decrease surface runoff.

Simulation of Low-Impact-Development Retrofits in the Upper Ipswich River Basin

The drainage area of the upper Ipswich River Basin, upstream from the South Middleton streamgage (fig. 25), is relatively urban and has less developable land than the rest of the basin. Therefore, this subbasin was used to evaluate the effects of retrofitting existing development with LID features to increase stormwater recharge and decrease surface runoff.

In the LID-retrofit simulation, EIA upstream from the South Middleton streamgage was reduced by 50 percent as a surrogate for the implementation of LID practices that decrease EIA (for example, porous pavement, green roofs, and re-direction of surface runoff from EIA to natural or constructed recharge areas). The simulated 50-percent reduction in EIA was considered a substantial, but reasonable, maximum amount of EIA reduction that could be achieved through the widespread implementation of various LID practices. The 50-percent reduction of EIA upstream from the South Middleton streamgage generally had modest effects on subbasin streamflows (percent differences of less than 20 percent). (Specific details of these differences may be found in the companion report, Zimmerman and others, 2010). Even in this relatively urban part of the Ipswich River Basin, the heterogeneous mix of land uses resulted in changes in the total EIA that were small percentages of the total areas of the 19 subbasins. Thus, the results may indicate that widespread LID practices may not substantially affect flows in large rivers and tributary streams that are characterized by heterogeneous land use and an EIA lower than 50 percent. On the other hand, LID practices that reduce EIA on a local scale may have substantial effects on flows because the EIA as a percentage of the drainage area may be large and a large decrease in EIA may be attainable. This concept is examined further in the section, “Simulations of Land-Use Change at the Local Scale.”

Simulation of Water Conservation Effects

Data from four water-conservation pilot projects conducted by MDCR were used to simulate the effects of widespread application of conservation practices on streamflow. Pilot projects included:

- installation of weather-sensitive “smart” irrigation controller switches on automated sprinkler systems at municipal athletic fields;
- application of soil amendments at a municipal athletic field to improve soil moisture and nutrient retention;
- installation of 800-gallon rainwater harvesting systems for the collection and reuse of rainwater for irrigation; and
- implementation of two concurrent municipal programs offering homeowners free indoor water-use audits, water-reducing retrofit kits, and rebates for low-flow toilets and washing machines.

Features in the first three projects were designed to reduce irrigation demands that affect summer withdrawals in the basin, and the fourth was designed to reduce indoor water use that affects withdrawals year round. Based on per-unit savings calculated by MDCR from the pilot projects and from specific information about each town, for example, acres of irrigated athletic fields and number of households, water suppliers were assigned hypothetical, potentially achievable, town-wide water-withdrawal reductions. (For a detailed description of the assumptions used for these simulations, see Zimmerman and others, 2010.)

Reductions in water use were expected to have their greatest effects on low flows in subbasins in which streamflow depletion was high, relative to the rate of streamflow in the absence of withdrawals (Barbaro, 2007). Hypothetical water-use reductions from the pilot projects in the basin ranged from 1.4 percent (Salem-Beverly water supply) to 8.5 percent (Hamilton) of average 1989–93 withdrawals. Withdrawal reductions of 5 percent had little effect on simulated low flows, and a 20-percent withdrawal reduction resulted in slightly higher low flows. In general, however, the conservation scenarios examined did not indicate appreciable changes from current (1989–93) simulations. This result is consistent with previous reduced-withdrawal simulations for the Ipswich River upstream from the South Middleton streamgage that were conducted with the original baseline withdrawals (Zarriello, 2002). The effects of withdrawal reductions on small streams would likely be more pronounced.

LID practices that reduce EIA on a local scale may have substantial effects on flows.

Simulations of Land-Use Change at the Local Scale

Local-scale simulations were conducted to evaluate the hydrologic effects of land-use change, development patterns, and surficial geology on 100-acre parcels of land. The results of these simulations are depicted with flow-duration curves (fig. 26). (See box for explanation of flow-duration curves.) These simulations of the effects of land-use change provided valuable information for assessing the conditions under which LID practices may have the greatest benefits. Specifically, simulations were conducted to evaluate the effect on streamflow of

- uniform land-use change for conventional development (that is, uniform lot sizes);
- cluster development;
- changes in the amount of EIA that represent LID applications; and
- surficial geology. (See Zimmerman and others (2010) for additional simulation details.)

Converting a 100-acre parcel from forested land to developed land increased simulated median 1-day high flows (median of 1-day annual high flows for 1961–95 simulation) by as much as 1,250 percent, depending on the underlying surficial geology and the type of development. Conversion of forested land overlying sand and gravel deposits to commercial development produced the maximum increase in the simulated median 1-day high flow, from 0.49 to 6.60 ft^3/s (1,250 percent.) Converting forest to low-density or high-density residential development resulted in modest increases in the median 1-day high flow and also increased simulated medium and low flows (fig. 26). Medium and low flows increased because both residential densities were simulated to have lower evapotranspiration losses than forested drainage areas, producing more subsurface discharge to streams. Simulations of runoff from a 100-acre parcel with variable amounts of EIA indicate that LID provided the greatest benefit in commercial and high-density residential land-use parcels because of their high proportion of EIA relative to other land uses.

Simulations of cluster development, in which a percentage of the parcel remains forested, or as open space, indicated that this practice reduced high flows and had variable effects on low flows when compared to conventional development with the same number of houses. For low-density cluster developments, leaving a large part of the land forested resulted in slightly lower low flows than for a conventional low-density development with uniform lot sizes because a greater percentage of deep-rooted vegetated area remained undisturbed. Flows from a cluster development more closely approximated flows from forested areas than flows from conventional low-density development on the 100-acre parcel. However, in the absence of LID enhancements, flows from the cluster development itself would closely approximate a high-density development. Simulated streamflow did not vary substantially with variations in the amount of EIA in the cluster development, because the total EIA over the parcel was a relatively low percentage of the area.

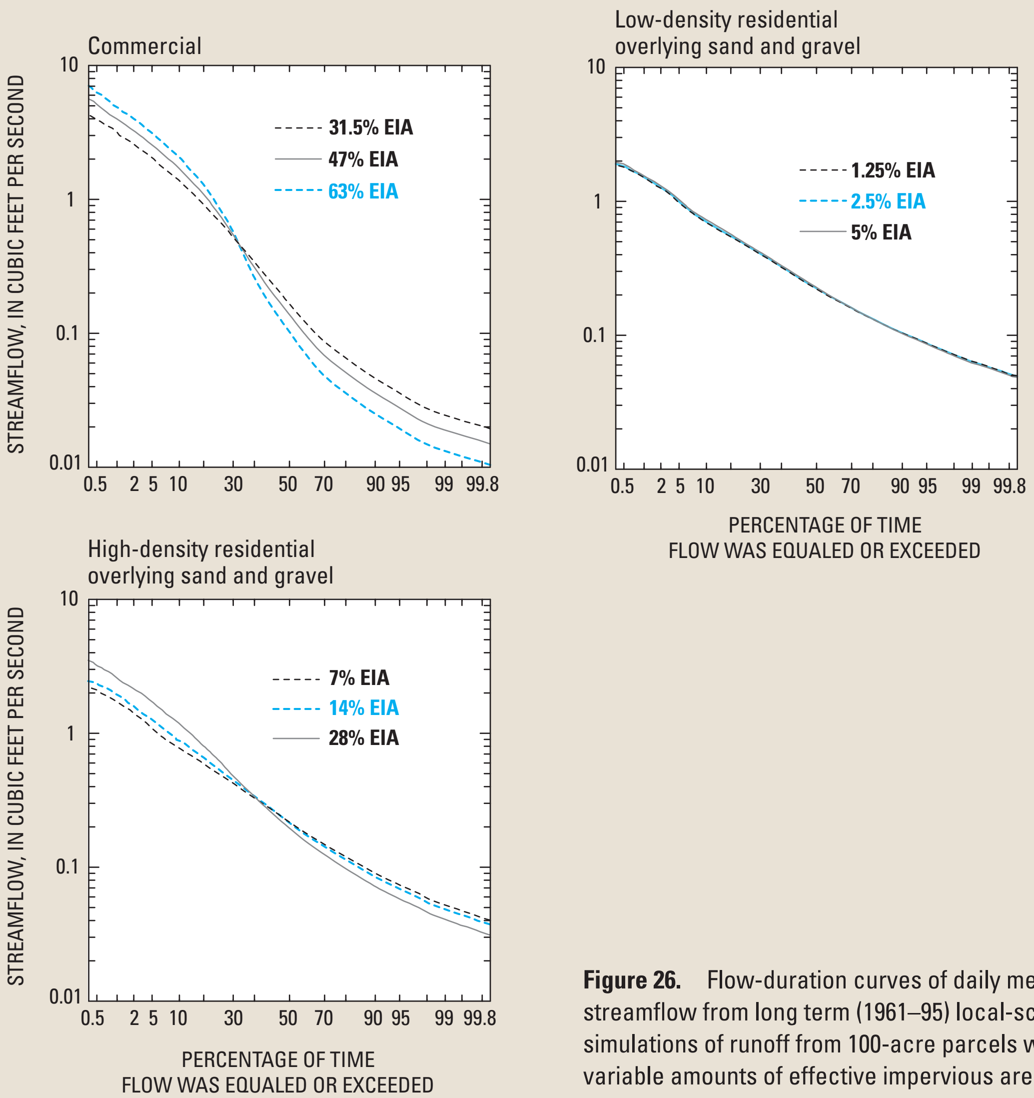
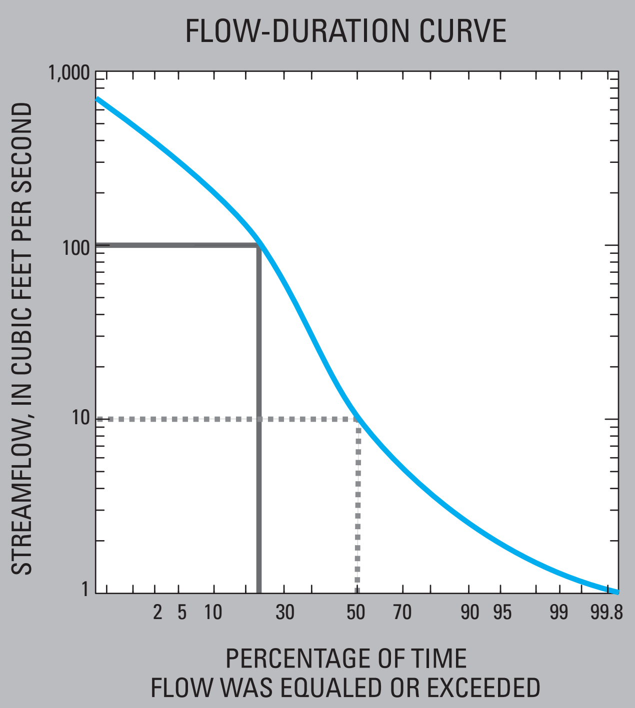


Figure 26. Flow-duration curves of daily mean streamflow from long term (1961–95) local-scale simulations of runoff from 100-acre parcels with variable amounts of effective impervious area.

What is a Flow Duration Curve?

Simply stated, a flow-duration curve shows the percentage of time that a given streamflow is equaled or exceeded. For example, see the solid horizontal line extending from the y axis at 100 cubic feet per second to the point where it meets the curve. A vertical line extended downward from this point meets the x axis at approximately 25 percent. This means that the streamflow of cubic feet per second is met or surpassed about 25 percent of the time. In order to derive the median streamflow (the amount equaled or exceeded 50 percent of the time), see the dashed vertical line extending upward from the x axis at 50 percent to where it meets the curve. A horizontal line extended from this point meets the y axis at 10 cubic feet per second. This means that the median streamflow is 10 cubic feet per second.



Summary and Conclusions

The U.S. Geological Survey, in cooperation with the Massachusetts Department of Conservation and Recreation and the U.S. Environmental Protection Agency, examined the effects of implementing selected low-impact-development (LID) techniques on water quantity and quality in several field studies and a computer-modeling study in the Ipswich River Basin, in Massachusetts, which is adversely affected by low streamflows in the summer season. The field studies monitored

- possible changes in groundwater quality caused by replacing a conventional impervious parking-lot surface with a porous asphalt and paver surface,
- effects on runoff quantity and quality by directing runoff from the street and driveways into a combination of rain gardens and porous parking surfaces in a 3-acre neighborhood, and
- differences in runoff quantity and quality from a conventional rubberized-membrane roof and a neighboring vegetated "green" roof.

The study also examined the potential effects of LID practices and water-withdrawal reductions by modifying a previously developed precipitation-runoff model of the basin.

Enhanced infiltration, particularly from parking lots, has the potential to transport contaminants to the water table. The first LID field site, a parking lot for Silver Lake Beach in Wilmington, MA, indicated no detrimental effects on groundwater quality after the parking lot was retrofitted with porous asphalt, porous pavers, rain gardens, and bioretention cells. At the second field site, in a residential neighborhood adjacent to Silver Lake, installation of LID features (rain gardens and porous pavers) had the most pronounced effect on runoff from small storms (0.25 in. or less of precipitation); the median runoff from such storms was reduced by about 50 percent, consistent with the decrease in effective impervious area from 10 to 4.5 percent after LID implementation. In addition, these LID features decreased the number of small storms producing measurable runoff. At the third field site, the runoff from a green roof retained at least 50 percent of the rainfall from about 70 percent of the storms, relative to a conventional rubber-membrane roof that does not reduce runoff at all. The length of the antecedent dry period and storm size were the controlling factors affecting the green roof's capacity for water retention and runoff attenuation; long, dry antecedent periods increased available storage for the green roof, thus attenuating storm runoff. The relatively high concentrations of nutrients in green roof runoff, affected by fertilizer application during establishment of the vegetation,

were somewhat offset by the decrease in runoff volume. Extending the study duration would demonstrate whether nutrient loads would decrease as the vegetation further matured and fertilizers were no longer applied. Contaminants, such as metals, in the roof runoff were attributed to specific roof and gutter structures.

The modeling studies used the calibrated Hydrologic Simulation Program-FORTRAN Ipswich River Basin precipitation-runoff model to simulate the effects of water-management scenarios and LID practices on streamflow at scales ranging from the local scale (100 acres, or 0.16 mi^2) to the subbasin and basin scale (0.5 to 125 mi^2). Specific LID practices were not simulated; rather, land-use change and associated changes in effective impervious area were used as surrogates for LID practices.

Simulations indicated that, at the basin and subbasin scale, the potential effective impervious area reduction from the application of LID practices was generally too low to appreciably affect streamflow. In contrast, the local-scale simulations of a 100-acre parcel indicated that, where the percentage of urban land use and associated effective impervious area was relatively high, development patterns and LID practices could have substantial effects on streamflow.

In LID-retrofit simulations, reducing effective impervious area by 50 percent minimally affected streamflow in most subbasins analyzed, because the effective impervious area in the subbasin was a relatively small percentage of the overall area. In drainage basins that are characterized by heterogeneous land use, widespread use of LID practices may not have a pronounced effect on streamflow. On the other hand, LID practices that reduce effective impervious area on a local scale may affect streamflow because effective impervious area, as a percentage of the drainage area, may be large, and a relatively large percentage decrease in effective impervious area may be attainable.

Data from water-conservation pilot projects were scaled up to the town level and used to simulate the effects of widespread application of these programs on streamflow. For communities with water withdrawals from the basin, the effects on simulated low flows in most of the rivers and streams in the basin were minor.

In summary, the field studies and model simulations demonstrate that implementation of LID practices can demonstrably affect stormwater runoff quantity and quality; however, their effects may be difficult to discern when the changes in effective-impervious area, as a percentage of total basin area, are small. The benefits of LID practices are greatest when the percentage of effective impervious area is large and the LID enhancements can substantially redirect storm runoff away from conveyances leading to streams or lakes.

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Glossary of terms as commonly used in this circular

Analyte The subject of a chemical analysis

Antecedent conditions Conditions preceding a particular storm

Base flow Streamflow that originates from groundwater

Bioretention cell A man-made feature, containing soil and plants, that functions to remove pollutants from runoff

Bulk-precipitation samples Precipitation samples that directly captured in open containers

Calibrate Modify computer program parameters so the results of a simulation closely match a set of known conditions

Composite, flow-proportional Water-quality subsamples collected and combined at a frequency sampled in proportion to the amount of water that has passed the collection point

EIA Effective impervious area—surface area that does not contribute runoff to groundwater or base flow

Evapotranspiration The sum of evaporation and plant transpiration from a surface to the atmosphere

Flow-duration curve A graph showing the percentage of time that streamflow is likely to equal or exceed a specific value

Hydrograph A graph showing the amount of streamflow over a period of time

Hyetograph A graph showing the amount of rainfall over a period of time

Impervious Incapable of being penetrated by water

Infiltration The process by which water on the surface enters the ground

LID Low-impact development—a planning or design approach to development intended to reduce runoff by enhancing infiltration, thereby retaining or restoring natural hydrological characteristics

Load The total amount of a particular analyte or subject of analysis, such as bacteria

Median In a group of numbers, the middle value above and below which there is an equal number of values

Parameters Characteristic values that can be manipulated in a computer model

Post-LID The time period after the installation of LID features

Pre-LID The time period before the installation of LID feature

Rainfall-Runoff Coefficient (RR) The ratio of the amount of runoff to the amount of precipitation

Scenario A condition, or set of conditions, to be simulated using a computer program

Simulation The implementation of a scenario by running a computer program

Prepared by the Pembroke Publishing Service Center.

For more information concerning this report, contact:

Director
U.S. Geological Survey
Massachusetts-Rhode Island Water Science Center
10 Bearfoot Road
Northborough, MA 01532
dc_ma@usgs.gov

or visit our Web site at:
http://ma.water.usgs.gov

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Zimmerman and others—Effects of Low-Impact-Development Practices on Streamflow and Runoff in the Ipswich River Basin, Massachusetts—Circular 1361

ISBN 978-1-4113-2959-1
9 781411 329591

Printed on recycled paper