In cooperation with the Wisconsin Department of Natural Resources

A Comparison of Runoff Quantity and Quality from Two Small Basins Undergoing Implementation of Conventional- and Low-Impact-Development (LID) Strategies: Cross Plains, Wisconsin, Water Years 1999–2005

Scientific Investigations Report 2008–5008

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Conversion Factors, Horizontal Datum, and Abbreviated Units of Measurement

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	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
liter (L)	0.2642	gallon (gal)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
	Application Rate	
pounds per acre per year [(lbs/acre)/yr]	1.121	kilograms per hectare per year [(kg/ha)/yr]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Horizontal coordinate information is referenced to the 1991 adjustment of the North American Datum of 1983 (NAD 83/91).

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

Water year is defined as the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends.

Other abbreviations

BMPs	best-management practices
IBI	index of biotic integrity
LID	low-impact development
NOAA	National Oceanic and Atmospheric Administration
RPD	relative percent difference
WDNR	Wisconsin Department of Natural Resources
WSLH	Wisconsin State Laboratory of Hygiene

A Comparison of Runoff Quantity and Quality from Two Small Basins Undergoing Implementation of Conventional- and Low-Impact-Development (LID) Strategies: Cross Plains, Wisconsin, Water Years 1999–2005

By William R. Selbig[1] and Roger T. Bannerman[2]

Abstract

Environmental managers are often faced with the task of designing strategies to accommodate development while minimizing adverse environmental impacts. Low-impact development (LID) is one such strategy that attempts to mitigate environmental degradation commonly associated with impervious surfaces. The U.S. Geological Survey, in cooperation with the Wisconsin Department of Natural Resources, studied two residential basins in Cross Plains, Wis., during water years 1999–2005. A paired-basin study design was used to compare runoff quantity and quality from the two basins, one of which was developed in a conventional way and the other was developed with LID. The conventional-developed basin (herein called "conventional basin") consisted of curb and gutter, 40-foot street widths, and a fully connected stormwater-conveyance system. The LID basin consisted of grassed swales, reduced impervious area (32-foot street widths), street inlets draining to grass swales, a detention pond, and an infiltration basin. Data collected in the LID basin represented predevelopment through near-complete build-out conditions.

Smaller, more frequent precipitation events that produced stormwater discharge from the conventional basin were retained in the LID basin. Only six events with precipitation depths less than or equal to 0.4 inch produced measurable discharge from the LID basin. Of these six events, five occurred during winter months when underlying soils are commonly frozen, and one was likely a result of saturated soil from a preceding storm. In the conventional basin, the number of discharge events, using the same threshold of precipitation depth, was 180, with nearly one-half of those resulting from precipitation depths less than 0.2 inch. Precipitation events capable of producing appreciable discharge in the LID basin were typically those of high intensity or precipitation depth or those that occurred after soils were already saturated. Total annual discharge volume measured from the conventional basin ranged from 1.3 to 9.2 times that from the LID basin.

Development of the LID basin did not appreciably alter the hydrologic response to precipitation characterized during predevelopment conditions. Ninety-five percent or more of precipitation in the LID basin was retained during each year of construction from predevelopment through near-complete build-out, surpassing the 90-percent benchmark established for new development by the Wisconsin Department of Natural Resources. The amount of precipitation retained in the conventional basin did not exceed 94 percent and fell below the 90-percent standard 2 of the 6 years monitored.

Much of the runoff in the LID basin was retained by an infiltration basin, the largest control structure used to mitigate storm-runoff quantity and quality. The infiltration basin also was the last best-management practice (BMP) used to treat runoff before it left the LID basin as discharge. From May 25, 2002, to September 30, 2005, only 24 of 155 precipitation events exceeded the retention/infiltrative capacity of the infiltration basin. The overall reduction in runoff volume from these few events was 51 percent. The effectiveness of the infiltration basin decreased as precipitation intensities exceeded 0.5 inch per hour.

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[1] U.S. Geological Survey, Middleton, Wisconsin

[2] Wisconsin Department of Natural Resources, Madison, Wisconsin

Annual loads were estimated to characterize the overall effectiveness of low-impact design practices for mitigating delivery of total solids, total suspended solids, and total phosphorus. Annual loads of these three constituents were greater in the LID basin than in the conventional basin in 2000 and 2004. Seventy percent or more of all constituent annual loads were associated with two discharge events in 2000, and a single discharge event produced 50 percent or more of constituent annual loads in 2004. Each of these discharge events was associated with considerable precipitation depths and (or) intensities, ranging from 4.89 to 6.21 inches and from 1.13 to 1.2 inches per hour, respectively. These same storms did not contribute as much of the annual load in the conventional basin. With large storms and saturated soils, the ability of low-impact design techniques to reduce runoff, and thus constituent loads, can be greatly diminished.

For both the LID and conventional basins, the temperature of runoff was largely affected by ambient air temperatures. However, the temperature of discharge from the LID basin increased upon runoff cessation. This increase is likely due to solar heating of water that is temporarily stored in the detention pond and infiltration basin.

Introduction

Conversion of rural and agricultural lands to developed urban areas is a leading contributor of nonpoint-source pollution. Contamination from nonpoint sources is now the largest cause of water-quality impairment in the United States because of past and current successes in controlling point sources (U.S. Environmental Protection Agency, 2001). Converting the natural landscape into residential or commercial land use can drastically alter its hydrologic characteristics. Land that was once covered with native vegetation is often replaced with impervious surfaces such as driveways, rooftops, streets, and parking lots. Precipitation that previously infiltrated into surrounding soils is now collected and conveyed by concrete structures into nearby streams, rivers, or lakes to prevent localized flooding. Collectively, impervious areas introduced by traditional urban landscapes lead to more diverse pollutants, reduced pollutant removal during overland flow, reduced infiltration, and increased peak flows which, in turn, can aggravate stream erosion (Davis, 2005). Previous studies have demonstrated that only a small percentage of connected impervious area in a watershed can degrade stream ecology. Wang and others (2001) noted that as the impervious fraction in a watershed exceeded 12 percent, decreases in fish density, species richness, diversity, index of biotic integrity (IBI) score, base flow, and increased bank erosion were measurable.

Although water quality across the country has improved appreciably since passage of the Clean Water Act in 1972, challenges still remain. In 2000, water-quality assessments by states indicated that 39 percent of assessed stream miles, 45 percent of assessed acres of lakes, and 51 percent of assessed estuary areas failed to meet criteria for one or more designated uses (U.S. Environmental Protection Agency, 2002). The top causes of impairment in assessed stream miles were siltation, nutrients, bacteria, metals (primarily mercury), and oxygen-depleting substances. Pollution from urban and agricultural land that is transported by precipitation and runoff was found to be the leading source of impairment (U.S. Environmental Protection Agency, 2002).

Environmental managers are often faced with the task of designing strategies to accommodate expanding development while minimizing adverse environmental impacts. Low-impact development (LID) is one such strategy that attempts to mitigate environmental degradation commonly associated with traditional residential or commercial construction practices. LID attempts to maintain or replicate the predevelopment hydrologic regime through use of design techniques that create a functionally equivalent hydrologic landscape (U.S. Environmental Protection Agency, 2000). LID principles are based on controlling stormwater at the source by incorporating the hydrologic functions of storage and infiltration into small-scale, distributed, structural and nonstructural controls. Some LID practices include, but are not limited to, decreasing impervious surfaces by narrowing street widths, creating micro-scale stormwater retention and detention areas, increasing flow paths, preserving highly permeable soils, incorporating vegetated swales and permeable paving into the building plan, and preventing soil compaction by discouraging the use of heavy equipment (Coffman, 2000; Liaw and others, 2000).

Although individually many of these stormwater controls have been proven to reduce stormwater-runoff volumes and (or) improve water quality, there are very few large-scale studies that evaluate the LID concept. Previous studies used computer-simulated models to attempt to estimate the hydrologic benefits of LID. Results of these studies indicate that it is possible to reduce hydrologic impacts using a LID design instead of traditional, fully connected stormwater systems (Liaw and others, 2000;

Holman-Dodds and others, 2003; Brander and others, 2005). However, environmental limitations, zoning and regulatory statutes, safety and public-health concerns, and economic viability have limited opportunities to apply the LID philosophy (Davis, 2005). For these reasons, the U.S. Geological Survey (USGS), in cooperation with the Wisconsin Department of Natural Resources (WDNR), undertook a study in Cross Plains, Wis. (fig. 1), to evaluate runoff quantity and quality from a LID and a conventional basin. The purpose of the investigation was to determine whether implementing several LID practices in a residential basin could reduce the quantity and (or) improve the quality of stormwater runoff measured at the basin outlet when compared to a nearby residential subdivision that was constructed using more conventional "curb and gutter" techniques.

The WDNR has promulgated a series of performance standards and prohibitions with regard to nonpoint-stormwater sources. These standards are intended to be minimum benchmarks of performance necessary to achieve water-quality goals. For proposed development of new residential areas, the site must be designed to infiltrate at least 90 percent of the predevelopment infiltration volume, based on an average annual rainfall (Wisconsin Administrative Code, 2002). Incorporating low-impact practices as part of residential design may be one way to achieve this State-mandated standard.

Purpose and Scope

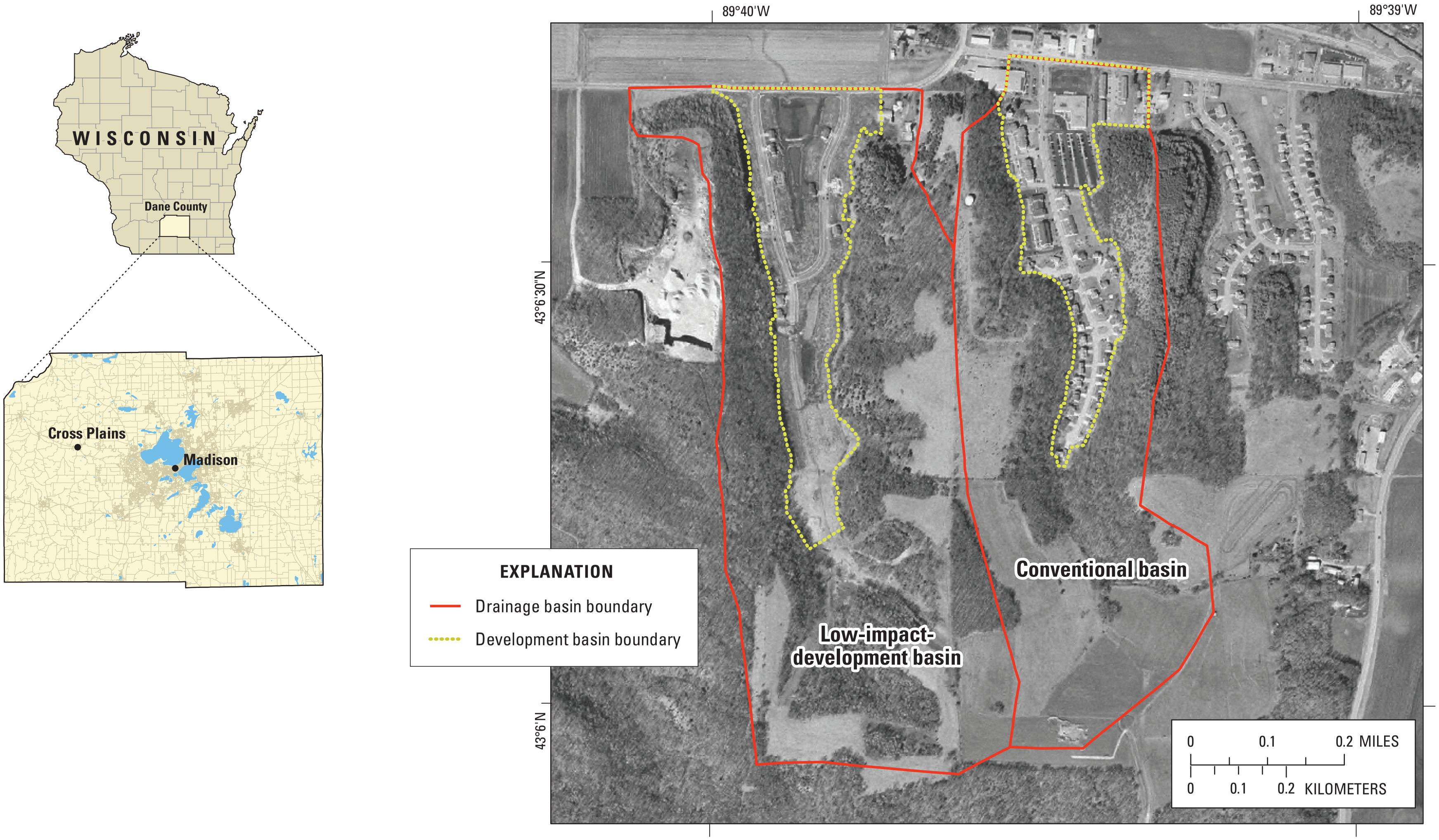
This report describes the methods used in and the results from a study comparing the runoff quantity and quality of a conventionally designed residential basin to one in which LID strategies were implemented. Two basins were selected to represent different construction philosophies. The "conventional" basin, developed in the late 1980s and early 1990s, used traditional engineering practices such as curb and gutter, larger street widths, and a fully connected stormwater-conveyance system. The LID basin, developed in the late 1990s and early 2000s, utilized low-impact design concepts distributed throughout the drainage basin. Automated, intensive stormwater sampling was done during storm-runoff periods from predevelopment through near-complete build-out of the LID basin (October 1998 to September 2005). The objectives of the study were to determine whether using LID techniques in a residential subdivision would reduce the volume as well as improve the quality of stormwater runoff when compared to a residential subdivision built using a more conventional, fully connected stormwater-conveyance system.

Concentrations of total solids, total suspended solids, and total phosphorus in stormwater-runoff samples were used to compute storm loads for each contaminant at the outlets of the two basins. Comparison of constituent loads was made between the conventional and LID basins to evaluate the hydrologic benefits of a low-impact design. Water temperature was measured at the basin outlets to characterize the temperature of stormwater stemming from the concrete storm-sewer conveyance system in the conventional basin and compare it to temperatures from the more natural, vegetated system used in the LID basin. This study supports an ongoing effort by the USGS and WDNR to identify existing and new methods to reduce nonpoint-source pollution from urban areas.

Description of Study Area

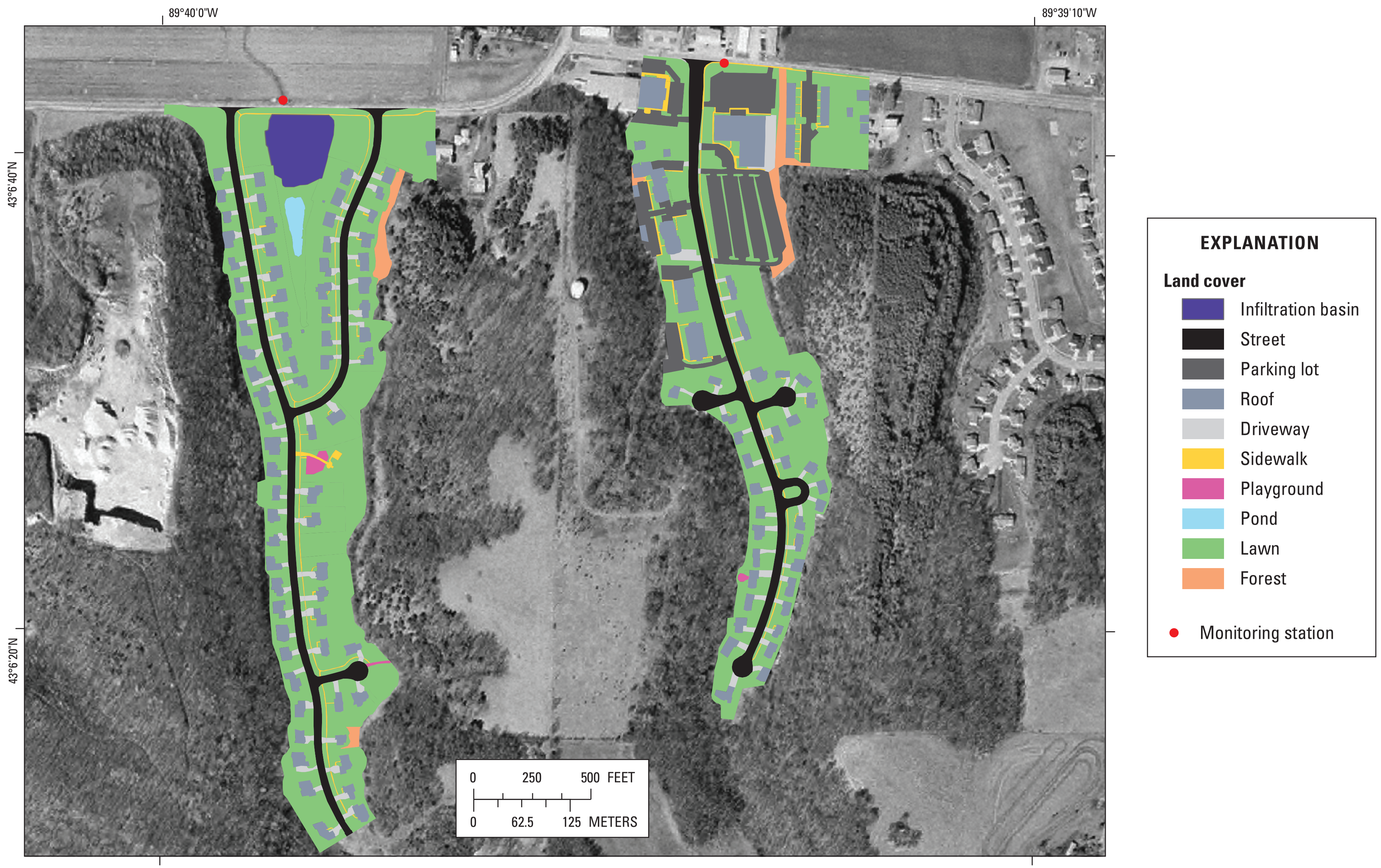
The study area is near the southwest corner of the village of Cross Plains, Wis. (fig. 1). The climate is typical of interior North America, with a large annual temperature range and frequent, short-period temperature changes. Nearly 60 percent of the annual precipitation falls in May through September, with annual precipitation averaging 31.73 in. (National Oceanic and Atmospheric Administration, 1999–2005). The conventional and LID study basins were within ¼ mi of each other to minimize climatic variability between basins. Each basin can be described as a valley with forested upland hills surrounding a valley floor that was previously used for agriculture. The valley floor is composed primarily of silt loam. The valley walls are soil-covered sandstone, limestone, and dolomite bedrock. Each basin drains to nearby Black Earth Creek, a cold-water trout stream that drains the Black Earth Creek watershed, which is generally hilly and has steep-sided valleys.

The conventional basin has a drainage area of 137 acres; 32 acres are developed on the valley floor (fig. 1). The remaining 105 acres are forested uplands. Construction of the conventional basin began in 1988 and was completed by 1991. Land use in the developed portion of the conventional and LID basin is shown in figure 2 and table 1. Land use is mixed, with residential and commercial areas making up approximately 75 and 25 percent of the developed area, respectively. Fifty percent of the basin is pervious; grassed lawns make up the largest percentage (48 percent) of a single land-use classification (table 1). The stormwater-conveyance system is composed of a directly connected network of curb and gutters draining to a large-diameter, concrete storm-sewer pipe that eventually leads to a small detention pond outside the conventional basin.



Base from Dane County Land Information Office Orthophotography, 1:10,000, 2005, Wisconsin Transverse Mercator projection, NAD 83/91.
Orthophoto from U.S. Geological Survey, 1:12,000, 2000, Wisconsin Transverse Mercator projection, NAD 83/91.

Figure 1. Location of study basins, Cross Plains, Wis.



Base from Dane County Land Information Office Orthophotography, 1:10,000, 2005, Wisconsin Transverse Mercator projection, NAD 83/91.
Orthophoto from U.S. Geological Survey, 1:12,000, 2000, Wisconsin Transverse Mercator projection, NAD 83/91.

Figure 2. Land use in the low-impact-development (left) and conventional-development (right) basins and location of water-quality monitoring stations, Cross Plains, Wis.

The LID basin drainage area is 192 acres; 37.7 acres are developed on the valley floor (fig. 1). The remaining 154.3 acres are forested uplands. Construction of the basin began in May 1999 and was nearly complete at the conclusion of this study (2005). Prior to development, the area had been used for agriculture but was left fallow for approximately 1 year before the study commenced. Land use is dominated by single-family residential lots; however, a small percentage of area zoned for commercial development remained undeveloped during the course of the study and was therefore classified as lawns (table 1). Over two-thirds of the land in the LID basin is considered pervious, a reflection of the low-impact concept. Lawns represent the majority of pervious surfaces (64 percent of the basin area). The LID basin also includes smaller areas that do not fit into one of the major source-area categories. A community park occupies a small percentage of the LID basin (less than 1 percent). This area was not included in the "lawn" category because the physical maintenance and use associated with a public park may be different from that of a typical residential lawn. Similarly, the LID basin includes a large infiltration basin planted with native prairie species. This area makes up nearly 5 percent of the basin area. A detention pond near the center of the basin covers approximately 1 percent of the basin area. Each of these have been lumped into a single "other" source-area category (table 1). Roofs and streets make up the majority of impervious surfaces, with 12 and 10 percent of the basin area, respectively.

Low-Impact-Development Practices in Study Area

A variety of techniques for erosion control and stormwater management were employed in the LID basin. The erosion-control practices included sediment basins, silt fences, use of erosion fabric on street swales, and timely seeding of disturbed areas. Runoff from upland areas was reduced with a combination of earthen berms and rock trenches. The LID basin was designed to maximize infiltration of runoff by locating infiltration practices based on predevelopment soil and permeability rates. Some of the techniques used to manage stormwater in the LID basin include reduction of street widths from 40 to 32 ft to minimize impervious cover, use of grass swales instead of storm sewers, routing of stormwater from street inlets to grass swales, protection of existing woodlands, use of a detention pond to reduce solids loading to the infiltration basin, use of an infiltration trench, and construction of a

Table 1. Breakdown of land use in the developed portion of the low-impact-development (LID) and conventional-development basins.

[Values in parentheses represent percent of developed area rounded to nearest whole number; %, percent; --, land use not present in basin; <, less than]

Characteristic	Study basin		
	LID	Conventional	
	Residential	Residential	Commercial
Drainage area (acres)	37.7	32.0[b]	
Land use (acres)			
Driveway	1.6 (4%)	0.8 (3%)	0.3 (1%)
Lawns	24.4[a] (64%)	13.5 (42%)	1.8 (6%)
Roofs	4.7 (12%)	3.7 (11%)	1.1 (4%)
Sidewalks	0.6 (2%)	0.7 (2%)	--
Streets	3.8 (10%)	2.9 (9%)	0.4 (1%)
Parking lot	--	1.8 (6%)	4.2 (13%)
Forest	0.5 (1%)	0.8 (3%)	--
Park	0.1 (<1%)	--	--
Other	2.0 (5%)	0.03 (<1%)	--

[a] 10 percent of this land-use category was zoned as commercial but was maintained as lawn during study period.

[b] Total drainage area represents a combination of residential and commercial land use.

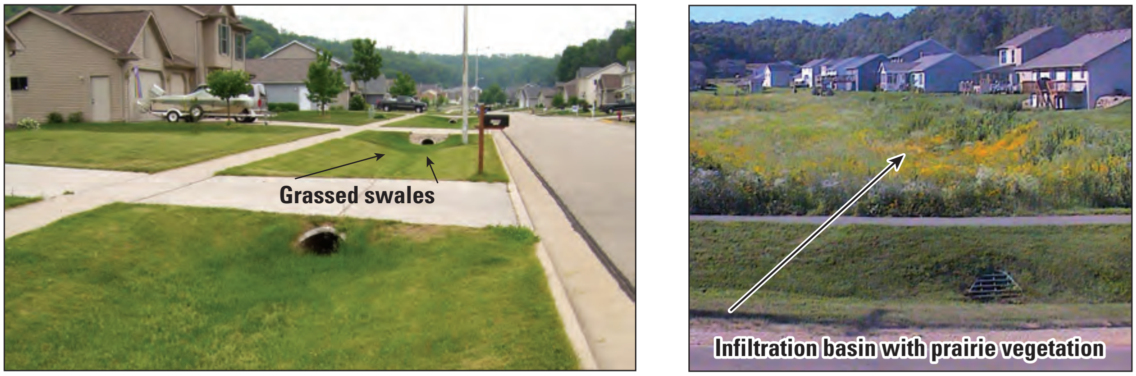


Figure 3. Example of stormwater-runoff controls using low-impact-development practices.

large infiltration basin planted with deep-rooted prairie species native to the area. Some of the practices used in the LID basin are illustrated in figure 3.

Surface runoff was diverted from impervious surfaces to one or more structures for temporary storage and infiltration. This "treatment-train" approach increased the opportunity for stormwater-runoff infiltration and water-quality improvement. For example, runoff originating from the street surface was directed to a grassed swale, where it would then drain into either an infiltration basin or a detention pond for storage during smaller storm events. For larger storm events, a combination of V-notch and broad-crested weirs at the outlet of the detention pond discharged excess runoff into the infiltration basin before the runoff migrated toward the basin outlet.

Methods of Data Collection

During this study, water-quantity and -quality data derived from the two residential basins were collected, characterized, and interpreted. Water-quality concentrations and subsequent loads were collected from the basin outlets (locations shown in fig. 2).

Basin-Outlet Flow Measurement and Calibration

Storm runoff was measured and sampled at the basin outlets in the conventional and LID basins. Locations of the basin-outlet monitoring stations are shown in figure 2. Each monitoring station was equipped with automated water-quality samplers and instruments to measure runoff discharge. Measurement, control, and storage of data were handled by electronic dataloggers. Data were automatically retrieved twice daily by way of telephone modems. Precipitation data were collected at both the conventional and LID basins by means of a tipping-bucket rain gage calibrated to 0.01 in.

Flow Measurement

An automated monitoring station was used to measure flow and collect samples from a 4.50-ft-diameter circular storm sewer at the basin outlet in the conventional basin (fig. 2). Water levels were measured with a bubble-gage system and pressure transducer. Measurements were made at two locations near the pipe floor approximately 20 ft apart. Measuring water level at two locations provided redundancy and minimized the potential for missing data if one of the sensors became inoperable. Ultrasonic velocity sensors were used to measure instantaneous velocity near the locations of the upstream and downstream bubble line. A fifth-order polynomial was used to determine the cross-sectional area of the pipe as a function of water level. Instantaneous discharge was then calculated by multiplying the cross-sectional area of the pipe by the associated mean velocity. Whenever possible, the downstream water level and velocity measurements were used to compute discharge in the conventional basin. Storm-runoff volumes were computed by summing the 1-minute-interval instantaneous discharge over the runoff duration. When water depth at the sensor was less than approximately 1 in., flow calculations were not considered reliable because the velocity sensor and bubble line were not fully submersed. Given the large diameter of the drainage pipe in the conventional basin, all flows occurring at less than 1 in. depth were considered insignificant to the overall event volume.

Figure 4. Parshall flume (left) used to measure discharge at the low-impact-development (LID) basin outlet. The Parshall flume was later replaced by an H-flume (right) to accommodate larger discharge events.

Stormwater runoff leaving the LID basin was routed to a Parshall flume with a 0.25-ft throat width attached to a wooden retaining wall (fig. 4). The Parshall flume was replaced with a 2-ft H-flume on July 14, 2000 (fig. 4), to increase the amount of runoff that could be passed without overtopping the wooden retaining wall. Water levels in both the Parshall and H-flume were measured with a bubble-gage system and pressure transducer. Conversion of water levels to discharge was based on standard rating curves for Parshall and H-flumes of the indicated size. A Flo-Dar device was mounted to the top of the H-flume in April 2001 to record water levels with an ultrasonic-based pulse-echo measurement. Data from the Flo-Dar were used to provide an independent check on the bubble-gage-system and pressure-transducer values, as well as to fill in periods of missing data. Storm-runoff volumes were computed by summing the 1-minute-interval instantaneous discharge over the runoff duration.

Instrumentation was installed in the LID basin to measure both detention-pond and grass-swale runoff volumes prior to drainage into the infiltration basin. Water levels in both the detention pond and grass swales were measured using a bubble-gage system and pressure transducer. Conversion of water levels to discharge was based on rating curves from as-built engineering specifications for the V-notch weir at the detention-pond outlet and published ratings for the trapezoidal flumes placed in the center of each grass swale. Installation of each monitoring station for the detention pond and grass swales was completed in August 2001 and May 2002, respectively.

Calibration of Flows

Water levels were periodically calibrated at the conventional and LID monitoring stations. Water levels were adjusted by applying corrections that represented the difference between water levels measured manually and those measured electronically by the pressure transducer. Corrections were made if the difference between the manual and electronic water-level measurements exceeded 0.02 ft. Because a rated flume was used at the LID basin outlet, water level was the only parameter requiring calibration.

Calibration of the ultrasonic velocity sensor at the conventional-basin outlet was done with a dye tracer and laboratory fluorometer. A known concentration of rhodamine dye was continuously injected at a constant rate sufficiently upstream from the monitoring station to allow for complete mixing during stormwater-runoff events. Samples of the dye were acquired with a dedicated automated sampler. Discrete samples were collected at predetermined, equal increments of rising or falling water levels. Samples were collected and returned to the Wisconsin Water Science Center in Middleton, Wis., for analysis. A detailed description of the methods used to conduct the dye-tracer calibration can be found in Wilson and others (1986). Resulting concentrations of rhodamine dye in each discrete sample were converted into an instantaneous discharge and then compared to the corresponding discharge measured at the basin outlet with the ultrasonic velocity sensor. Figure 5 illustrates the linear relation between the two methods of discharge computation. Of the 38 dye samples collected during the velocity-sensor calibration

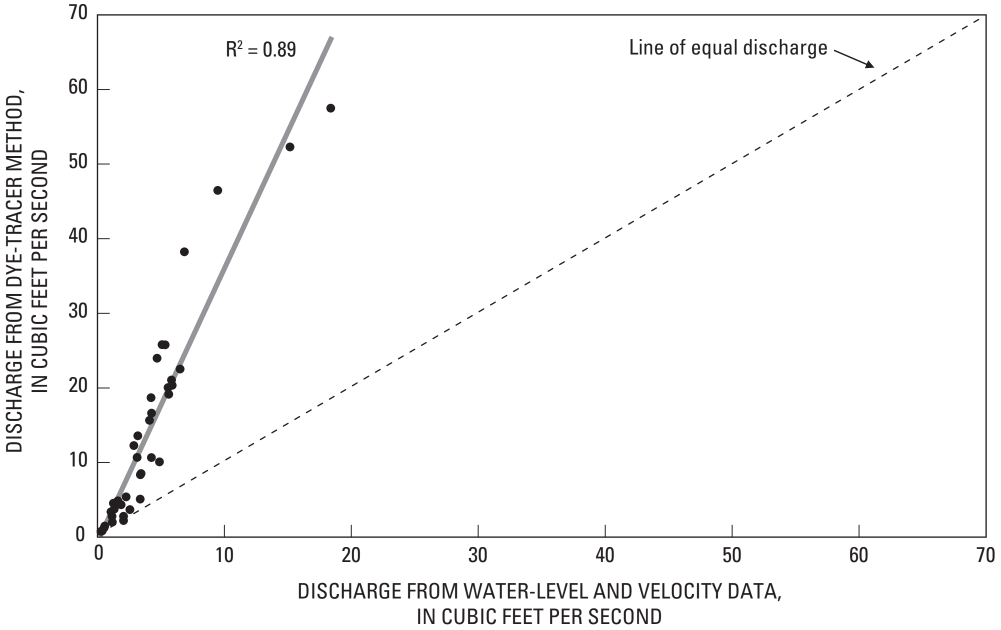


Figure 5. Relation between actual discharge determined using a rhodamine dye tracer and measured discharge, computed by water-level and velocity data, during free-flow conditions at the conventional-development-basin outlet.

period, 35 were associated with water levels less than 1.0 ft. Therefore, determination of discharges by use of a dye tracer for water levels greater than 1.0 ft can only be estimated by extrapolation. However, over 90 percent of all runoff events measured at the conventional basin outlet had maximum water levels less than or equal to 1.0 ft. Figure 5 illustrates that the velocity of runoff measured in the pipe was greatly underestimated, resulting in discharges that were approximately one-third those computed from the dye-tracer measurements. Linear regression was used to derive an adjustment factor for those discharges that were computed by use of the velocity sensor. This adjustment factor was applied to all discharges recorded at the conventional-basin outlet for the entire study period. Church and others (1999) evaluated the bias and variability of several methods of flow measurement, including the sensors used in this study. Velocity sensors using acoustic or electromagnetic detection consistently underestimated actual values. Therefore, errors associated with velocity measurements at the conventional-basin outfall are not unique and highlight the importance of calibrating instrumentation used for water measurements.

Precipitation

Continuous precipitation data were collected by means of tipping-bucket rain gages in the LID and conventional study basins. Each rain gage measured precipitation in 0.01-in. increments. These rain gages were not designed to measure snowfall; however, there were several runoff events during winter months where precipitation was in the form of rain instead of snow. Precipitation data were compiled, and statistical summaries were computed for both rain-gage locations.

Water Temperature

Continuous water temperature was measured with an insulated thermocouple wire during periods of runoff. The LID thermocouple was inside the culvert approximately 5 ft upstream from the H-flume approach section (fig. 4). The conventional-basin thermocouple was in the concrete pipe near the sample-intake orifice.

Runoff-Sample Collection

Sample collection was activated by a rise in water level in the storm-sewer pipe or flume during a storm event. Once the water-level threshold was exceeded, typically a depth of 0.10 to 0.15 ft from the pipe/flume floor, the volume of water passing the station was measured and accumulated at 1-minute increments until a volumetric threshold was reached. At that point, the sampler collected a discrete water sample, and the volumetric counter was reset. The process was repeated until the water level receded below the water-level threshold ensuring adequate coverage of the storm hydrograph.

For the majority of sampled runoff events, the discrete flow-weighted samples were collected and combined into a single water sample, then split and processed for analysis. A Teflon-coated, stainless-steel churn splitter was used to composite and split samples. Processed samples were refrigerated until delivered to the laboratory, usually within 48 hours after runoff cessation, for determination of concentrations of total solids, total suspended solids, and total phosphorus. Mass of a particular constituent, expressed as storm load, was computed by multiplying the event mean concentration by the total storm volume. In some cases, discrete samples were processed individually to determine instantaneous concentrations over the storm hydrograph. For these runoff events, the integration method was used to determine a storm load (Porterfield, 1972).

Field and sample-processing equipment blanks were collected at the control and test basin monitoring stations to evaluate the integrity of the water-quality sampling process, identify whether sample contamination existed and, if so, to identify possible sources. Blank samples were obtained by drawing deionized water through the suction line and sampler into a collection bottle. The Teflon sample line and automatic sampler were not cleaned before obtaining blank samples. Blank water collected in the 1-liter plastic sample bottle(s) was then split through a Teflon-lined churn splitter into plastic laboratory-prepared sample bottles. Samples were placed on ice and delivered to the Wisconsin State Laboratory of Hygiene (WSLH) for analysis. Deionized blank water also was used to isolate individual elements of the sampling process from source to delivery. These samples were not delivered to the WSLH unless erroneous concentrations were found in the original blank sample. Blank-sample results are detailed in appendix table 1-1. Replicate samples also were collected to evaluate the inherent variability in the sampling analyses and methods.

The bias and variability identified by analysis of blanks and replicates were within acceptable limits for total solids, total suspended solids, and total phosphorus. Two of the blank samples collected at the LID-basin outlet had concentrations above the detectable limit; one for total suspended solids and the other for total phosphorus. Because the concentrations of these two constituents were much lower than the majority of those measured in water-quality samples, they were considered insignificant to the overall integrity of the water-quality sampling process. Only one blank sample collected at the conventional basin showed constituent concentrations slightly above the detectable limit. Although the concentrations were within the range of those measured in water-quality samples at this site, a review of field notes indicated the possibility of contamination during sample acquisition. Therefore, the results from this sample were excluded from analysis.

Replicate samples were submitted to verify reproducibility in the sample acquisition and splitting process as well as analytical methods conducted in the laboratory. Replicate samples were checked for precision on the basis of an absolute relative percent difference (RPD). Replicate samples are listed in appendix table 1-2. The RPD values for replicate samples collected at both the LID and conventional basin outlets were within an acceptable range of error (25 percent).

Comparison of Runoff Quantity from the Basins

One of the underlying principles of LID is to maintain or replicate predevelopment hydrologic conditions as closely as possible (Davis, 2005). Advances in structural and nonstructural runoff controls, such as green roofs and reduced impervious area, could provide a way to mitigate storm runoff that might otherwise go untreated. To quantify potential hydrologic benefits of LID, the LID basin, in which a variety of best-management practices (BMPs) was used, was monitored to detect changes in water quantity and quality from predevelopment phase through final build-out. Data from the LID basin were compared to the conventional basin, an existing, fully developed basin built with conventional construction techniques, with a fully connected stormwater-conveyance system.

Precipitation

Differences in rainfall patterns between study basins from one year to the next could potentially affect results from data analyses. An examination of rainfall was done to identify potential sources of bias. Analyses of rainfall patterns were limited to April through October of each water year because rain gages in the study area were not equipped to measure the water equivalency of snowfall. In addition, nearly 75 percent of annual precipitation in the Cross Plains area typically occurs during April through October (National Oceanic and Atmospheric Administration, 1999–2005). The 30-year normal (1976–2005) precipitation for April through October was 23.47 in. at the National Oceanic and Atmospheric Administration (NOAA) weather station at the Dane County Regional Airport in Madison, Wis. (National Oceanic and Atmospheric Administration, 1999–2005). Data from the rain gages in each study basin show that rainfall was above the 30-year normal for 4 of 7 years monitored in the LID study basin (1999, 2000, 2001, and 2004) and below the 30-year normal for 3 years (2002, 2003, and 2005) (fig. 6). Rainfall in the conventional basin was above the 30-year normal for 4 of the 7 years (1999, 2000, 2001, and 2004) and below normal for the remaining 3 years (2002, 2003, and 2005). Rainfall recorded at the Dane County Regional Airport exhibited the same overall pattern (fig. 6).

A Kendall test for trend (Helsel and Hirsch, 1992) was performed on 7 years of precipitation data (1999–2005), covering April through October, collected at the conventional and LID study basins. No significant trend was identified at the 5-percent significance level. A similar test was performed for the precipitation data collected at the Dane County Regional Airport. Again, no significant trend was identified.

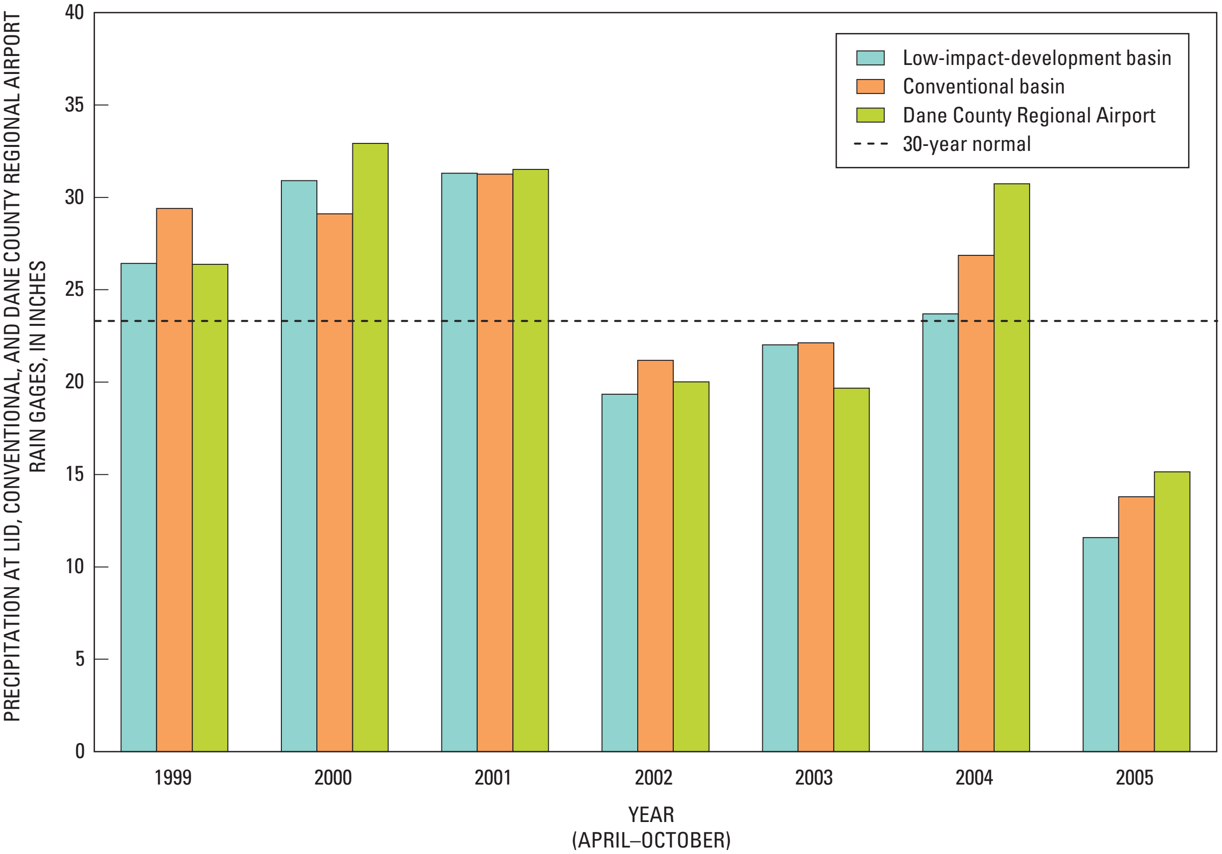


Figure 6. Precipitation totals for April through October at the low-impact-development (LID) and conventional-development basins during each study year. Precipitation measured at the Dane County Regional Airport in Madison, Wis., (approximately 15 miles from the study area) represents a 30-year normal (1976–2005) for the same 5-month span and is represented by the horizontal dotted line.

Event rainfall also was evaluated for differences between study basins. A storm event was defined as any precipitation event greater than 0.1 in. in depth preceded by 6 or more hours of no precipitation. The Wilcoxon rank-sum test (Helsel and Hirsch, 1992), used to test whether one group tends to produce larger observations than a second group, revealed no significant differences (at the 5-percent significance level) in event rainfall between the study basins for each of the 7 years monitored. Climatic characteristics for sampled precipitation events in each basin are detailed in tables 2-1 and 2-2 in appendix 2.

Runoff Volumes

Summary statistics for event volumes measured in the conventional and LID basins are presented in table 2. Hereafter in this report, a “discharge event” is defined as rainfall or snowmelt that results in discharge from the study area. Differences in the number of discharge events, annual discharge volumes, and peak-flow rates were identified between the two study basins. Mean and median annual discharge volumes in the LID basin were less than those in the conventional basin during each study year. Because these values represent runoff from all precipitation events, they reflect the numerous times when there was no discharge from the LID basin; however, those precipitation events that did not generate runoff in the LID basin were excluded from the total number of runoff events described in table 2. The number of precipitation events generating a measurable amount of discharge from the conventional basin far exceeded those in the LID basin (table 2). Smaller, more frequent precipitation events that produced discharge from the conventional basin were retained and infiltrated in the LID basin. Histograms are presented in figure 7 for precipitation events generating a measurable volume of discharge from the conventional and LID basins, respectively. Only six events with precipitation depths less than or equal to 0.4 in. produced discharge from the LID basin. Of these six events, five occurred during winter months when soils are commonly frozen, and one was likely a result of saturated-soil conditions from a preceding storm. In the conventional basin, the number of discharge events, using the same threshold of precipitation depth, was 180, with nearly one-half of those resulting from precipitation depths less than 0.2 in. (fig. 7). The total volume of discharge generated from these 180 events was

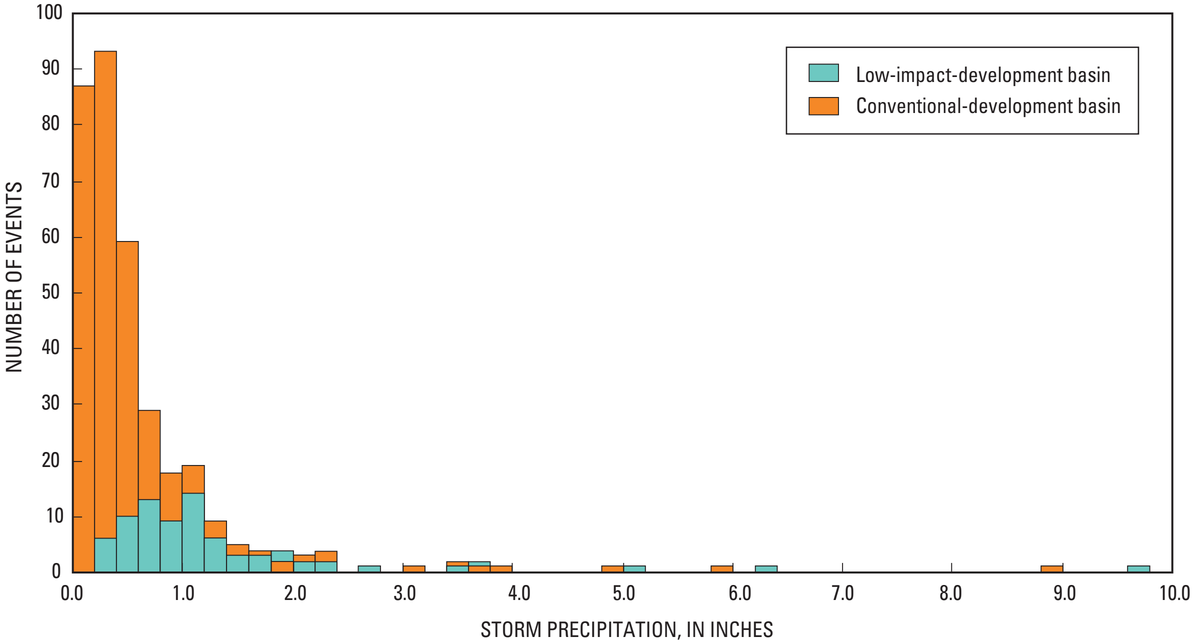


Figure 7. Histograms showing the frequency of rainfall events resulting in discharge from the study area as a function of increasing precipitation depth in the low-impact-development (LID) and conventional-development basins.

nearly 10 times the total volume generated by the 6 events in the LID basin. This difference is likely due to the larger percentage of impervious surface and the fully connected stormwater-conveyance system used in this basin. Stormwater is quickly routed from impervious surfaces into a concrete collection system, with little opportunity for retention and infiltration.

For small, frequent storm events, the hydrologic impact associated with traditional, fully connected systems appears to have been reduced in the LID basin by incorporating structural and nonstructural controls designed to reduce stormwater runoff. Holman-Dodds and others (2003) came to similar conclusions based on model results comparing a fully developed landscape using traditional

Table 2. Summary statistics for measured discharge events at the low-impact-development (LID) and conventional-development basins monitoring stations, water years 1999–2005.

[<, less than; ft^3/s, cubic feet per second]

Statistic	Water year[a]						
	1999	2000	2001	2002	2003	2004	2005
Low-impact-development basin							
Volume (inches)[b]							
Mean	<0.01	0.03	0.03	<0.01	0.01	0.03	0.01
Median	.00	.00	.00	.00	.00	.00	.00
Maximum	.05	.42	1.11	.11	.12	.67	.30
Minimum	.00	.00	.00	.00	.00	.00	.00
Sum	.16	1.51	1.72	.34	.49	1.81	.74
Number of events[c]	13	17	16	11	11	18	12
Peak flow (ft^3/s)[c]							
Mean	.37	4.05	2.62	.66	1.18	1.99	.59
Median	.20	.36	.77	.35	1.05	.73	.23
Maximum	2.19	21.84	22.28	1.93	4.11	10.10	2.20
Minimum	.02	.07	.05	.10	.02	.11	.05
Conventional-development basin							
Volume (inches)[b]							
Mean	.03	.04	.05	.03	.03	.04	.03
Median	.02	.01	.02	.02	.02	.02	.01
Maximum	.12	.33	.83	.13	.24	.30	.37
Minimum	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Sum	1.50	2.22	2.74	1.61	1.40	2.44	1.92
Number of events[c]	49	57	50	55	50	63	58
Peak flow (ft^3/s)[c]							
Mean	9.01	10.16	8.46	7.14	7.73	10.27	5.20
Median	3.87	3.10	3.57	4.97	4.17	5.07	2.74
Maximum	79.30	76.30	78.10	27.20	79.40	96.00	25.80
Minimum	.28	.10	.36	.15	.19	.12	.10

[a] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003, through September 30, 2004).

[b] Represents all precipitation and snowmelt events, including those that did not produce discharge.

[c] Represents only those precipitation and snowmelt events that produced discharge.

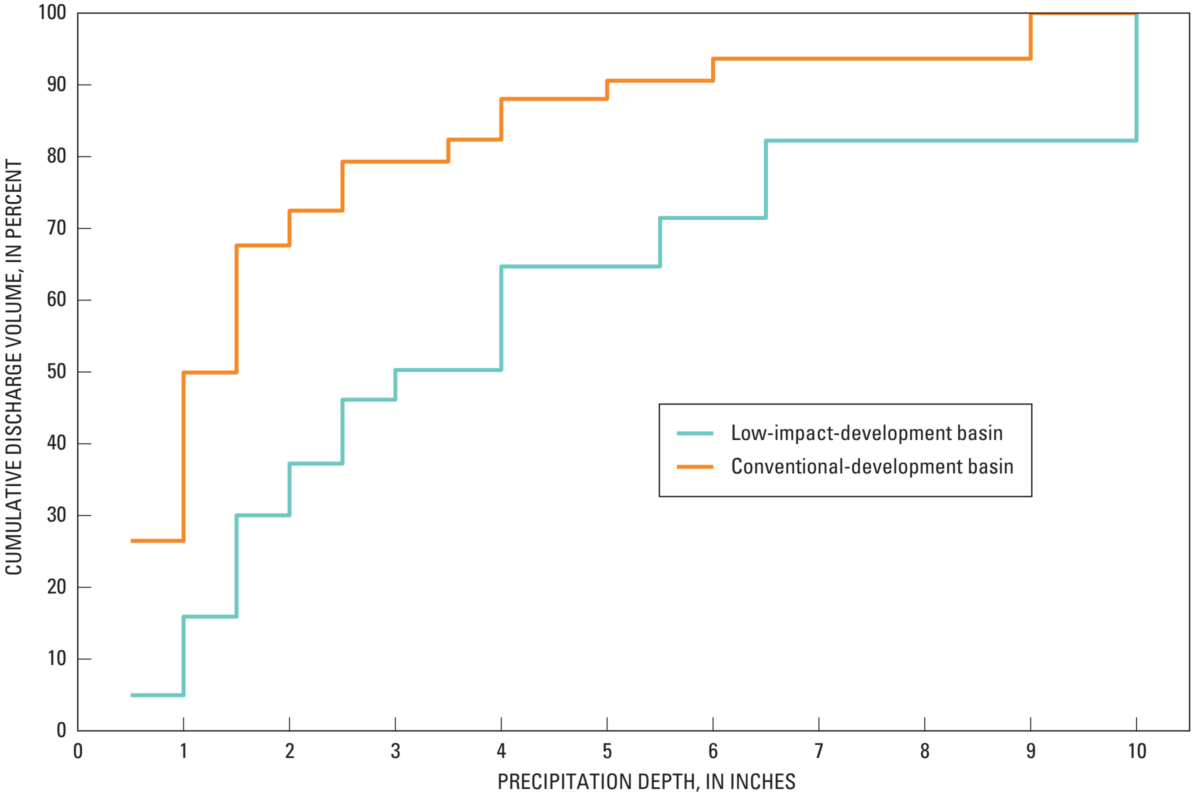


Figure 8. Relation of cumulative-discharge volume, as a percentage of total discharge volume measured between 1999–2005, to increasing precipitation depth in the low-impact-development (LID) and conventional-development basins.

stormwater management as opposed to one that uses infiltration-based, low-impact design. The cumulative effect on discharge volume from these small, frequent precipitation events becomes apparent in each study basin. The annual sum of all discharge events measured in the conventional basin exceeded those measured in the LID basin, in some cases by an order of magnitude (table 2). Total annual discharge volume measured from the conventional basin ranged from 1.3 to 9.2 times that for the LID basin. Cumulative discharge volume measured at the LID and conventional basins as a percentage of total volume with increasing precipitation depths from 1999 through 2005 is shown in figure 8. Fifty percent of discharge volume in the conventional basin was associated with precipitation depths less than 1 in. (fig. 8). This agrees with previous work by Pitt and others (1999) describing the quantity of runoff in Madison, Wis., that can be expected with increasing rainfall depths from a typical medium-density residential development (fig. 9). Compared to the conventional basin, less than 1 in. of precipitation in the LID basin was associated with only 16 percent of cumulative discharge. One-half of total discharge volume was associated with precipitation depths greater than 3 in. compared to 18 percent in the conventional basin (fig. 8). Nearly 20 percent of the total discharge volume from the LID basin came from a single, large event in August 2001. More than 9.5 in. of rain fell within 24 hours, exceeding the 100-year, 24-hour precipitation depth by more than 3 in. (Huff and Angel, 1992). Although precipitation events like this are atypical, they serve as a reminder that the influence of low-impact design practices on runoff becomes less noticeable for large, intense precipitation events or storm events that occur in rapid succession when soils are saturated. Many BMPs are not designed to adequately control the volume of runoff associated with these events.

Similar to discharge volumes, peak-flow rates in the conventional basin were higher than in the LID basin. Precipitation events capable of producing appreciable discharge from the LID basin were typically associated with those of high intensity, substantial depth, or occur-

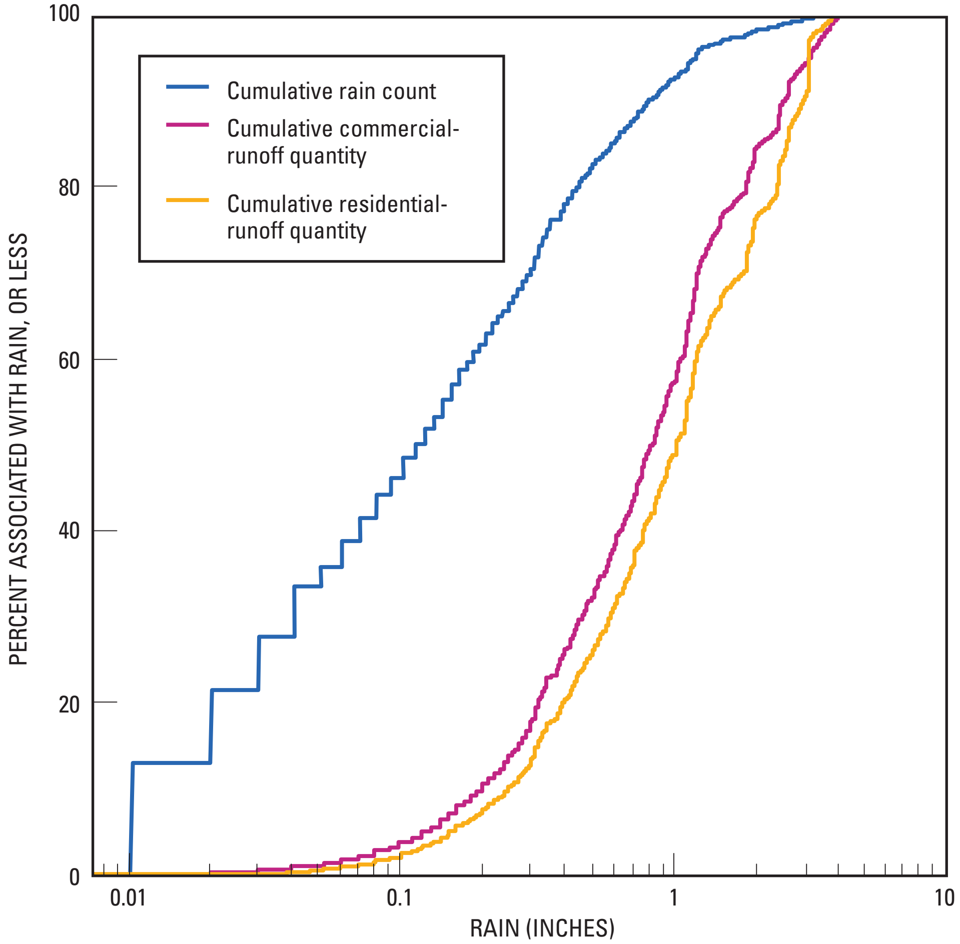


Figure 9. Relation of cumulative-discharge volume to precipitation depth for residential land use in Madison, Wis., based on model predictions (modified from Pitt,1999).

rence after soils were already saturated. The LID basin, when compared to the conventional basin, was effective at reducing discharge volume and peak flows for the first event but was relatively ineffective during the second event (fig. 10). The time of concentration decreases from 24 to 11 minutes during the second event as storage capacity is reduced and soils become saturated. Despite the reduction in the ability to effectively manage discharge during the second event detailed in figure 10, the time of concentration in the LID basin is still greater than the conventional basin where, by comparison, very little time lapses from the onset of rainfall to measurable discharge in the storm sewer. The conventional basin demonstrated a similar hydrologic response during both events, as illustrated in figure 10. Hydrologic characteristics for sampled precipitation events in each basin are detailed in tables 2-1 and 2-2 in appendix 2.

Temporal Changes in Runoff Quantity in the Low-Impact-Development (LID) Basin

Changes in hydrologic response in the LID basin were characterized over time from predevelopment to near complete build-out. Predevelopment conditions were monitored from June 24, 1998, through May 14, 1999. Development of the LID basin began on May 14, 1999, with deployment of earth-moving machinery. Because measurements of water quantity and quality during the predevelopment phase of this study did not span a full year, comparison to subsequent years cannot be made. Therefore, an examination of precipitation characteristics, including depth, intensity, and antecedent dry days was done on data collected at a nearby U.S. Geological Survey monitoring station (05406470), located approximately 1.25 miles from

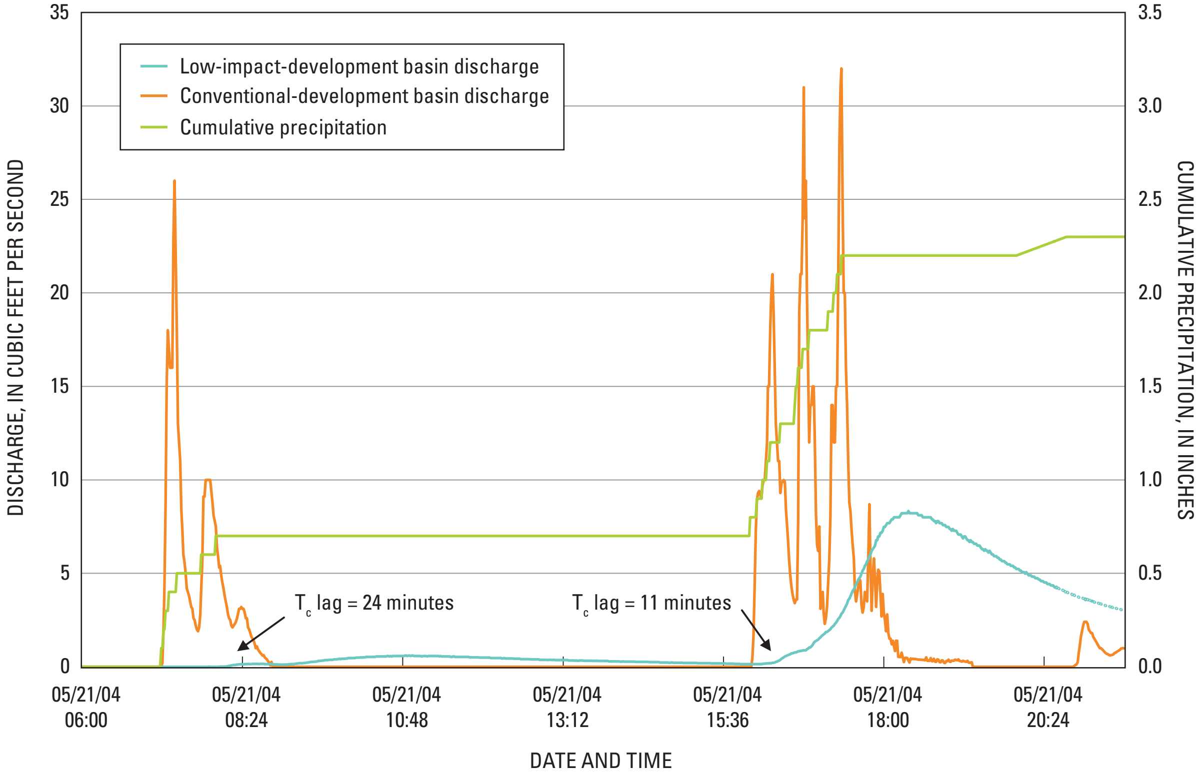


Figure 10. Hydrologic response of low-impact-development (LID) and conventional-development basins to two consecutive precipitation events, Cross Plains, Wis. [T_c, time of concentration]

the LID basin, to estimate hydrologic conditions in the LID basin during May and June 1998. The largest storm event during this period produced 2.27 in. of precipitation in a 24-hour period (June 18, 1998). Two storms with similar characteristics to this storm occurred after the water-quantity and -quality monitoring station was installed in the LID basin. The first storm event occurred on June 27 and the second on September 14, 1998, producing 2.13 and 2.43 in. of rain, respectively, in a 24-hour period. Neither storm produced measurable discharge. Therefore, it was assumed that no discharge occurred during May–June 1998, which was not monitored during the predevelopment phase. For consistency, characterization of hydrologic response to precipitation events in the LID basin during the predevelopment phase, as well as all subsequent phases of build-out, was based on a 12-month period starting in May and ending in April. The hydrologic response of the LID basin during the predevelopment and active construction phases of the study is shown in table 3. For comparison, similar hydrologic characteristics of the conventional basin also are detailed in table 3. However, because monitoring equipment was not installed in the conventional basin until August 1998, data collected during the predevelopment year was incomplete. Unlike the LID basin, nearly every precipitation event in the conventional basin produced measurable discharge, making it difficult to estimate the volume of discharge for storms prior to site installation.

Each year of active construction was differentiated by the level of activity recorded in the basin. Construction activity and housing density in the LID basin during each study year are shown in figure 11. The first year of construction included not only construction of a few single-family homes but also land disturbances typically associated with site grading and installation of infrastructure such as roads, storm sewers, and stormwater-control structures. Estimates of housing density, represented by a percentage of complete build-out of the area illustrated in figure 2 are detailed in table 3. Ninety-five percent or more of precipitation falling in the LID basin was retained during each construction year. The conventional basin consis-

Table 3. Comparison of precipitation and runoff characteristics in the low-impact-development (LID) and conventional-development basins over increasing percentages of basin development.

[--, insufficient data]

	Predevelopment		Year of active development (May through April)											
			1999–2000		2000–2001		2001–2002		2002–2003		2003–2004		2004-2005	
	LID	Conventional	LID	Conventional	LID	Conventional	LID	Conventional	LID	Conventional	LID	Conventional	LID	Conventional
Number of precipitation events[a]	63[c]	--	55	51	61	48	53	58	38	40	48	48	54	57
Total precipitation volume (inches)[a]	35.4	--	26.7	28.5	36.9	33.8	37.6	37.2	19.8	21.8	32.5	33.2	30.5	32.2
Number of discharge events[b]	7	--	10	55	19	51	18	61	7	46	18	60	19	68
Total discharge volume (inches)[b]	.11	--	.19	1.7	1.47	3.4	1.75	4.1	.40	1.9	1.26	2.9	1.61	3.9
Precipitation retained (percent)	100	--	99	94	96	90	95	89	98	91	96	91	95	88
Basin development (percent)	0	--	20	100	35	100	50	100	75	100	85	100	95	100

[a] Does not include snowfall.

[b] Includes snowmelt events.

[c] Includes precipitation events recorded by nearby rain gage for May through June 1998.

tently retained less, ranging from 88 to 94 percent of total precipitation. The percent of precipitation retained in the conventional basin is similar to that measured from other residential basins constructed in a similar style in Madison, Wis. (Selbig and Bannerman, 2007). These figures are slightly underestimated because they include the volume of discharge due to snowmelt but do not account for added precipitation volumes from the water equivalency of snow during winter months. An examination of climatic records collected at the Dane County Regional Airport for December through March of each study year showed a range of 1.3 (2002–2003) to 3.1 (2004–2005) additional inches of precipitation falling on each basin from snow (National Oceanic and Atmospheric Administration, 1999–2005). Adding the estimated water equivalency of snow to the total precipitation amounts detailed in table 3 had little effect on the percentage of precipitation retained during each study year. The largest percentage of total precipitation retained in the LID basin occurred during the predevelopment period. Of the 63 precipitation events measured during this period, only 7 produced any measurable discharge. Three of the seven runoff events occurred during February 1999 and were a direct result of snowmelt. The first year of construction (1999–2000) had the second highest percentage of runoff retained. During this period, the majority of construction activity was related to site grading and infrastructure, and a limited amount of newly created impervious surfaces contributed to discharge volumes. As more houses were built in the basin during each successive construction year, the percentage of runoff retained tended to decrease. One notable exception was the 2002–2003 construction year. Annual rainfall during this period was well below normal. The number of discharge events recorded during the 2002–2003 construction year was similar to that measured during the predevelopment phase. Although the percentage of precipitation retained in 2002–2003 was greater than in previous construction years, it was still less than in the predevelopment period; that is, the natural landscape appears to retain a greater percentage of rainfall than the LID basin does.

Although the LID basin was able to retain a larger percentage of rainfall during each year of construction than the fully developed conventional basin, comparisons are best made during 2004–2005 when the LID basin was nearly 100 percent developed. During this year, more than 3 times as many discharge events were measured at the outfall for the conventional basin. After normalizing by basin area, the volume of discharge leaving the conventional basin was nearly 4 in. compared to 1.6 in. in the LID basin (table 3).

September 1999

September 2000

September 2001

September 2002

September 2003

September 2004

Figure 11. Yearly changes in construction activity and housing density in the low-impact-development (LID) basin, 1999–2004.

In Wisconsin, proposed development of new residential areas must be designed to infiltrate at least 90 percent of the predevelopment infiltration volume (Wisconsin Administrative Code, 2002). The quantity of discharge from the LID basin during predevelopment and the 2004–2005 study periods was compared to estimate whether State infiltration performance standards for new residential development would likely be achieved. Differences in climatic conditions between these two periods could produce large differences in the reduction of runoff volumes. The Wilcoxon rank-sum test (Helsel and Hirsch, 1992) was used to determine whether climatic conditions in the LID basin during the predevelopment phase were different from those measured during 2004–2005, when the basin was 95 percent developed. The test was done on storm-event precipitation depth and 60-minute intensities measured in the LID basin. The null hypothesis states that there is no difference in the distribution of depth or intensity between study periods. The alternative hypothesis is that there is a significant difference, which can be inferred to be a result of climatic variation. Results of the test indicate no difference in precipitation depth or 60-minute precipitation intensities between the predevelopment and 2004–2005 study phases at the 5-percent significance level; therefore, because the LID basin retained 95 percent of rainfall during the period at which it was most developed, the infiltration standard of 90 percent of predevelopment infiltration volume was satisfied (table 3).

Performance of Infiltration Basin

Stormwater in the LID basin was routed to one or more retention structures. Stormwater in excess of retention capacity of lawns and grassed swales was directed to a 1.75-acre infiltration basin along the northern boundary of the development (fig. 2). This was the largest control structure used to mitigate storm-runoff quantity and quality. It was also the last BMP used to treat stormwater before the stormwater discharged from the LID basin.

In May 2002, instrumentation was installed to monitor the quantity of runoff into the infiltration basin. The total volume of water entering the infiltration basin was the sum of runoff volumes contributed from the detention pond, grass swales, and direct precipitation. The reduction in runoff volume attributed to the infiltration basin was determined by comparing total runoff into the infiltration basin to total discharge from the study area. From May 25, 2002, to September 30, 2005, 179 rain and snowmelt events were measured in the LID basin. Of these events, 24 were either snowmelt or a combination of rainfall and snowmelt. The percentage volume reduction by the infiltration basin for those 24 events could not be determined because the volume of water entering (and within) the infiltration basin as snowmelt could not be quantified. Precipitation characteristics and the volume of runoff entering and leaving the infiltration basin for the remaining 155 precipitation events are detailed in table 4. The overall volume of runoff into the infiltration basin was reduced by 51 percent before leaving the study area as discharge. The majority of precipitation events produced a small amount of runoff that was completely retained by the infiltration basin. Much of the potential runoff volume was intercepted prior to entering the infiltration basin. A combination of storage, retention, and infiltration by forested hillslopes, lawns, grassed swales, and a detention pond within the LID basin provided an overall decrease in the potential volume of runoff of 96 percent prior to reaching the infiltration basin (table 4). In general, precipitation from low-intensity, long-duration storm events was absorbed by the surrounding landscape, whereas precipitation generated from high-intensity storm events typically exceeded infiltration rates of underlying soils, resulting in larger volumes of runoff leaving the LID basin as discharge.

A stepwise multivariate linear-regression analysis incorporating precipitation depth, 15-, 30-, and 60-minute precipitation intensities, and antecedent dry days was done to test whether a relation existed between percent runoff-volume reduction in the infiltration basin and climatic variables. Results of the test indicated that 60-minute precipitation intensities were able to explain 29 percent of the variation in the percentage of runoff volume reduced in the infiltration basin at the 5-percent significance level. There was a negative relation between 60-minute precipitation intensities and the percentage reduction between influent and effluent runoff volumes in the infiltration basin; therefore, the effectiveness of runoff-volume reduction in the infiltration basin, and perhaps the LID basin in general, decreased with increasing precipitation intensity. The mean and median runoff-volume reductions by the infiltration basin when grouped by increasing ranges of 60-minute precipitation intensities are shown in table 5. The effectiveness of the infiltration basin decreased as precipitation intensities exceeded 0.5 in. per hour. Only the 24 events that produced enough stormwater to exceed the retention and infiltrative capacity of the infiltration basin (table 4) were used to provide data for table 5. The inability of the LID basin to retain precipitation events of appreciable depth and (or) intensity might be a result of one or a combination of several factors, which may include the rate of precipitation exceeding the maximum

Table 4. Reduction of runoff volume in the low-impact-development (LID) basin by the infiltration basin, 2002–2005.

[mm/dd/yyyy, month, day and year; min., minute; ft^3, cubic foot; --, no data]

Storm date (mm/dd/yyyy)	Storm duration (hours)	Precipitation depth (inches)	Precipitation intensity (inches per hour)			Antecedent dry time (days)	Total volume IN (ft^3)	Total volume OUT (ft^3)	Volume reduction (percent)	
			15-min.	30-min.	60-min.				Infiltration basin	Rest of LID basin
05/25/2002	6.4	0.69	0.32	0.26	0.22	12.1	6,028	0	100	0
05/28/2002	6.2	.15	.24	.18	.11	3.4	958	0	100	0
06/02/2002	2.0	.19	.24	.18	.15	4.6	1,214	0	100	0
06/03/2002	58.3	2.38	1.52	.90	.53	.3	132,703	74,036	44	93
06/10/2002	1.6	.28	.68	.38	.23	5.3	2,430	0	100	0
06/13/2002	4.7	.32	.60	.42	.27	2.8	3,621	0	100	0
06/14/2002	8.0	.11	.32	.16	.08	.6	703	0	100	0
06/26/2002	4.2	.54	1.08	.66	.35	11.4	3,450	0	100	0
07/20/2002	.4	.37	1.23	--	--	24.3	2,370	0	100	0
07/22/2002	6.8	.84	1.54	.90	.50	1.4	6,690	0	100	0
07/27/2002	4.7	.17	.14	.09	.06	4.9	1,092	0	100	0
08/04/2002	8.2	.60	1.42	.83	.44	7.7	4,142	0	100	0
08/11/2002	1.1	.63	.98	.65	.55	7.3	5,825	0	100	0
08/12/2002	9.7	.32	.18	.18	.14	1.1	2,161	0	100	0
08/17/2002	.7	.16	.48	.29	--	4.0	1,291	0	100	0
08/21/2002	3.1	.25	.67	.46	.24	4.4	11,648	0	100	0
08/22/2002	6.0	.31	.14	.13	.11	.3	19,132	0	100	0
09/02/2002	4.6	.56	.25	.23	.22	10.7	5,252	0	100	0
09/10/2002	1.1	.15	.25	.20	.14	8.2	977	0	100	0
09/19/2002	4.0	.30	.32	.22	.14	8.5	1,897	0	100	0
09/19/2002	1.2	.14	.36	.22	.13	.3	862	0	100	0
09/20/2002	14.0	.18	.29	.16	.08	.6	1,150	0	100	0
09/25/2002	.0	.33	--	--	--	4.9	2,121	0	100	0
09/28/2002	7.9	.40	.18	.18	.11	3.3	3,036	0	100	0
10/01/2002	35.5	.53	.24	.16	.13	2.5	6,936	0	100	0
10/03/2002	32.2	1.11	1.28	.88	.64	.8	56,117	23,777	58	94
10/24/2002	26.5	.47	.16	.14	.10	19.7	3,003	0	100	0

Table 4. Reduction of runoff volume in the low-impact-development (LID) basin by the infiltration basin, 2002–2005—Continued.

[mm/dd/yyyy, month, day and year; min., minute; ft^3, cubic foot; --, no data]

Storm date (mm/dd/yyyy)	Storm duration (hours)	Precipitation depth (inches)	Precipitation intensity (inches per hour)			Antecedent dry time (days)	Total volume IN (ft^3)	Total volume OUT (ft^3)	Volume reduction (percent)	
			15-min.	30-min.	60-min.				Infiltration basin	Rest of LID basin
11/10/2002	9.1	.49	.20	.20	.16	15.9	3,131	0	100	0
11/18/2002	5.9	.25	.16	.12	.08	7.3	1,597	0	100	0
12/17/2002	15.0	.57	.32	.16	.14	29.1	3,642	0	100	0
01/31/2003	4.9	.18	.08	.06	.06	43.8	1,150	0	100	0
03/28/2003	16.7	.37	.08	.06	.05	8.2	3,486	0	100	0
04/19/2003	18.0	.22	.08	.06	.05	12.9	1,406	0	100	0
04/30/2003	52.1	2.12	1.32	1.22	.70	9.8	98,363	61,949	37	94
05/04/2003	13.4	.46	.24	.18	.17	2.4	7,003	0	100	0
05/07/2003	22.6	.42	.44	.34	.20	1.8	11,446	492	96	97
05/09/2003	28.4	.51	.32	.28	.24	.9	22,676	10,143	55	94
05/10/2003	60.9	1.48	2.28	1.26	.98	.7	96,171	81,268	15	92
05/14/2003	23.9	.61	.20	.18	.15	.8	15,858	4,614	71	97
05/28/2003	5.6	.22	.40	.20	.20	13.1	1,406	0	100	0
05/30/2003	12.9	0.38	0.68	0.56	0.30	2.1	2,681	0	100	0
06/06/2003	7.7	.26	.28	.20	.14	6.2	1,661	0	100	0
06/08/2003	1.8	.25	.60	.34	.18	1.3	1,630	0	100	0
06/08/2003	.6	.37	.72	.70	--	.6	5,298	0	100	0
06/18/2003	1.5	.24	.48	.34	.21	10.1	1,533	0	100	0
06/22/2003	.2	.11	.44	--	--	3.9	703	0	100	0
06/24/2003	1.7	.30	.56	.36	.22	1.4	1,917	0	100	0
06/24/2003	.2	.11	--	--	--	.4	703	0	100	0
06/25/2003	7.7	.39	.84	.54	.29	.9	2,572	0	100	0
06/28/2003	11.1	1.01	.80	.54	.39	2.1	14,386	0	100	0
07/03/2003	5.2	2.21	3.96	3.90	2.12	4.8	14,119	0	100	0
07/04/2003	1.2	.22	.36	.22	.18	.7	1,406	0	100	0
07/05/2003	2.0	.30	.24	.24	.20	.9	2,670	0	100	0
07/06/2003	55.8	1.82	3.88	2.04	1.04	1.3	73,453	41,562	43	95

Table 4. Reduction of runoff volume in the low-impact-development (LID) basin by the infiltration basin, 2002–2005—Continued.

[mm/dd/yyyy, month, day and year; min., minute; ft³, cubic foot; --, no data]

Storm date (mm/dd/yyyy)	Storm duration (hours)	Precipitation depth (inches)	Precipitation intensity (inches per hour)			Antecedent dry time (days)	Total volume IN (ft³)	Total volume OUT (ft³)	Volume reduction (percent)	
			15-min.	30-min.	60-min.				Infiltration basin	Rest of LID basin
07/09/2003	7.0	.11	.20	.10	.06	1.1	4,480	0	100	0
07/15/2003	2.9	.94	1.76	1.70	.93	4.8	47,182	0	100	0
07/21/2003	28.2	.97	1.68	1.02	.73	5.8	48,248	31,467	35	94
08/02/2003	.2	.14	--	--	--	11.4	894	0	100	0
08/16/2003	.3	.18	.68	--	--	14.2	1,150	0	100	0
08/20/2003	1.7	.11	.12	.10	.08	4.0	703	0	100	0
08/28/2003	.9	.46	1.44	.88	--	8.0	3,168	0	100	0
09/12/2003	61.5	3.56	1.00	.68	.48	14.5	135,824	57,344	58	95
09/22/2003	2.6	.11	.28	.20	.10	7.8	703	0	100	0
10/11/2003	1.9	.25	.36	.22	.17	18.9	1,608	0	100	0
10/13/2003	11.2	.66	.28	.26	.21	2.0	4,631	0	100	0
10/24/2003	4.8	.51	.36	.32	.30	10.3	3,535	0	100	0
11/01/2003	21.7	1.35	.44	.30	.20	8.0	8,625	0	100	0
11/03/2003	70.8	3.64	1.28	1.00	.76	.5	518,093	306,858	41	80
11/17/2003	13.5	.24	.08	.04	.04	11.6	1,533	0	100	0
11/22/2003	33.5	2.05	1.48	.88	.63	4.5	280,524	123,068	56	81
12/04/2003	13.0	.14	.04	.04	.03	10.7	894	0	100	0
12/09/2003	23.2	1.17	.20	.18	.16	4.0	160,625	19,362	88	81
12/27/2003	5.2	.18	.16	.10	.07	11.6	1,150	0	100	0
03/10/2004	4.3	.11	.12	.06	.05	4.3	703	0	100	0
03/13/2004	5.0	.23	.16	.10	.08	2.9	1,469	0	100	0
03/24/2004	4.5	.32	.24	.16	.11	6.5	2,044	0	100	0
03/25/2004	39.1	1.07	.76	.68	.51	1.4	55,745	35,087	37	93
03/28/2004	8.5	.33	.24	.18	.14	1.2	2,108	0	100	0
04/16/2004	.1	.12	--	--	--	19.2	1,222	0	100	0
04/20/2004	5.6	0.47	0.20	0.18	0.17	3.6	4,442	0	100	0

Table 4. Reduction of runoff volume in the low-impact-development (LID) basin by the infiltration basin, 2002–2005—Continued.

[mm/dd/yyyy, month, day and year; min., minute; ft^3, cubic foot; --, no data]

Storm date (mm/dd/yyyy)	Storm duration (hours)	Precipitation depth (inches)	Precipitation intensity (inches per hour)			Antecedent dry time (days)	Total volume IN (ft^3)	Total volume OUT (ft^3)	Volume reduction (percent)	
			15-min.	30-min.	60-min.				Infiltration basin	Rest of LID basin
04/24/2004	17.6	.29	.24	.14	.07	4.0	1,853	0	100	0
05/08/2004	3.4	.11	.28	.14	.07	12.8	703	0	100	0
05/08/2004	4.6	.42	.64	.38	.22	.4	2,922	0	100	0
05/10/2004	12.8	.45	.48	.34	.22	1.1	5,693	0	100	0
05/13/2004	5.5	.48	.76	.50	.27	2.8	12,223	0	100	0
05/14/2004	7.6	.27	.12	.08	.07	.5	1,725	0	100	0
05/17/2004	6.9	.75	2.24	1.36	.71	3.3	24,734	4,985	80	96
05/21/2004	74.7	6.21	2.40	1.68	1.13	3.2	503,562	469,610	7	89
05/25/2004	1.5	.18	.44	.24	.17	.6	1,150	0	100	0
05/29/2004	65.3	1.67	1.24	.80	.54	4.2	66,551	27,994	58	95
06/09/2004	6.0	.12	.32	.18	.09	8.9	767	0	100	0
06/10/2004	20.6	.94	.56	.44	.29	.3	12,619	0	100	0
06/12/2004	2.1	.42	.84	.72	.39	.7	13,606	2,411	82	96
06/16/2004	10.0	.48	.36	.30	.24	4.8	3,299	0	100	0
06/21/2004	3.2	.21	.20	.14	.09	4.1	1,342	0	100	0
07/03/2004	21.0	1.08	1.20	.98	.61	12.1	32,841	6,532	80	97
07/09/2004	1.2	.17	.36	.24	.16	5.0	1,258	0	100	0
07/16/2004	24.0	1.05	1.72	1.20	.62	6.9	98,939	59,435	40	87
07/21/2004	2.6	.39	.56	.34	.19	3.9	2,598	0	100	0
07/29/2004	7.4	.28	.32	.18	.12	8.0	1,789	0	100	0
07/30/2004	1.6	.14	.32	.20	.11	.7	894	0	100	0
08/01/2004	1.2	.35	.72	.40	.33	1.7	2,417	0	100	0
08/02/2004	2.0	.38	.72	.52	.28	1.1	2,890	0	100	0
08/03/2004	20.2	1.20	3.84	2.02	1.09	1.2	68,053	36,253	47	93
08/18/2004	.9	.33	.76	.58	--	14.1	2,672	0	100	0
08/24/2004	.4	.12	.44	--	--	6.1	767	0	100	0

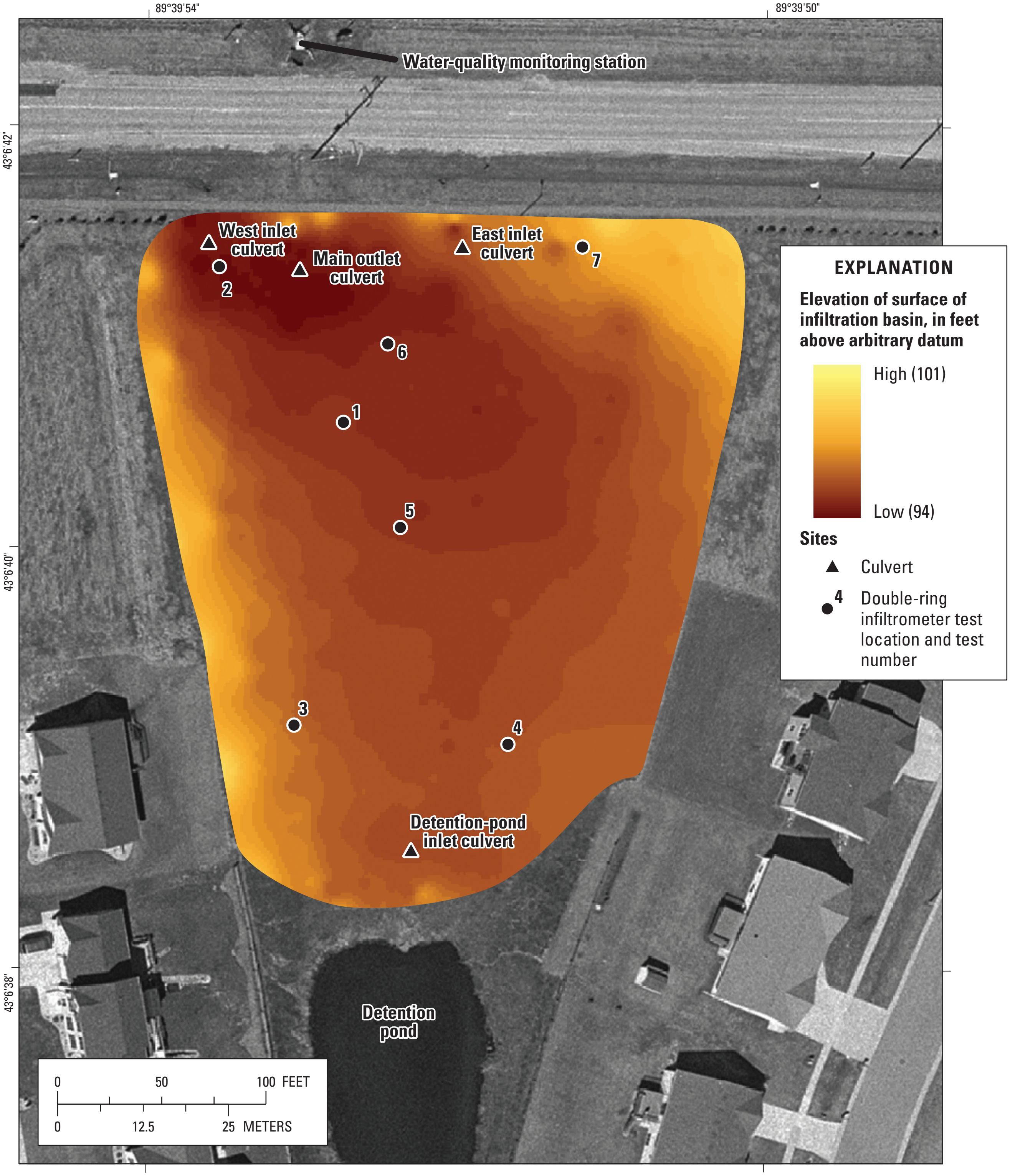
rate of infiltration, contribution of additional stormwater from forested uplands that normally have little to no runoff from smaller precipitation events, saturated soil from prior storms, or frozen soil.

Infiltration rates in the infiltration basin were measured at various locations during the summers of 2000–2004 (except 2001). Infiltration tests also were done in 2005 but were considered unreliable and were not used. A double-ring infiltrometer was used to quantify the steady rate of infiltration, which is often equated to the saturated hydraulic conductivity of underlying soils (Dierks, 2007). The approximate location of each double-ring infiltrometer test is shown in figure 12. The estimated infiltration rates at each location are provided in table 6. Infiltration rates varied within locations from one year to the next and between locations in any given year. Variation in infiltration rates could be a function of changing vegetation and root growth, clogging of pores and openings as a result of sedimentation during periods of episodic inundation, or simply inconsistent location of the double-ring infiltrometer from prior tests. Attempts were made to minimize errors associated with reproducing the test location by identifying each site with latitude and longitude coordinates acquired by a handheld global positioning system. These devices were accurate to within 20 ft, thereby allowing for slight inaccuracies in placement of the infiltrometer. Infiltration rates are much lower along the western edge of the infiltration basin as was determined at points 2 and 3 (fig. 12 and table 6). The reduced infiltration rates are likely a result of the sloping topography of the infiltration basin. Ideally, runoff entering the infiltration basin from the detention pond would spread evenly across the width of the infiltration basin before leaving the site as discharge through the main culvert on the northern edge; however, because the infiltration basin was not level, runoff would move preferentially along the western boundary of the infiltration basin and pond near the northwest corner. Field surveys were done in September 2001 to confirm the overall slope of the infiltration basin. The contours of the infiltration basin and locations of the detention-pond inlet, grassed-swale inlets, and main-culvert outlet are shown in figure 12. As suspected, the lowest elevation was in a small area near the main-culvert outlet. Over time, fine silts and clays suspended in runoff near this area settled out and clogged the upper layers of soil, effectively reducing the infiltrative capacity of underlying soils. A layer of silt that has developed over time near the western grassed-swale-culvert inlet and main-culvert outlet is shown in figure 13. Had runoff into the infiltration basin been spread across a uniform, level surface, it is likely some of the precipitation events that produced stormwater in exceedance of the retention capacity of the infiltration basin may have instead been completely retained. The volume of runoff capable of being stored in the infiltration basin was estimated based on survey data and the depth of water required before reaching the H-flume invert. The infiltration basin should have been able to receive approximately 39,000 ft^3 of runoff (assuming a level surface and no infiltration). Based on data from table 4, 8 of the 24 precipitation events that produced enough runoff to leave the basin as discharge may have been fully retained.

Table 5. Runoff volume reduction by the infiltration basin as a function of increasing precipitation intensity.

[>, greater than]

Statistic	Percent reduction in potential runoff for indicated precipitation intensity, 60-minute (inches per hour)		
	0–0.5	0.5–1.0	>1.0
Mean (percent reduction)	69	43	32
Median (percent reduction)	71	44	43
Number of events	8	13	3



Base from Dane County Land Information Office Orthophotography, 1:10,000, 2005, Wisconsin Transverse Mercator projection, NAD 83/91.

Figure 12. Approximate locations of double-ring infiltrometer tests in the infiltration basin in the low-impact-development (LID) basin. Note how color-shaded contours change from yellow to brown, revealing a preferential pathway for water to move from the detention-pond inlet toward the main outlet. Elevation data obtained by a total-station survey.

Figure 13. Layer of silt that has formed from excessive ponding of runoff near the west-inlet and main-outlet culverts in the infiltration basin in the low-impact-development basin (April, 2001).

Table 6. Infiltration rates measured at seven locations in the infiltration basin, 2000–04. Locations of tests shown in figure 12.

[--, test not performed]

Infiltration test location	Infiltration rate by year (inches per hour)				Average
	2000	2002	2003	2004	
1	--	0.62	1.47	2.12	1.40
2	0.19	.26	.16	.37	.25
3	.49	.18	1.2	.26	.53
4	.86	22.5	6.3	5.81	8.87
5	--	1.06	--	4.11	2.59
6	1.22	1.37	.34	.41	.84
7	.91	1.36	--	1.02	1.10

Comparison of Runoff Water Quality from the Basins

Storm Loads

In addition to water quantity, changes in the quality of stormwater were measured to determine whether low-impact design practices could reduce sediment and sediment-associated constituent loads and yields at the basin outfall compared to those measured in the conventional basin. Loads were computed by multiplying the event mean concentrations by storm-runoff volumes. A complete list of sampled event-mean concentrations and loads can be found in tables 2-3 through 2-6, respectively, in appendix 2.

In many cases, the variability in storm loads is large enough to mask potential differences in conventional and low-impact design practices. In addition, because the development and implementation of BMPs used in the LID basin spanned several years, differences in storm loads from one year to the next could result from differences in hydrologic conditions rather than from the BMPs. Furthermore, because not every runoff event was sampled, comparison of constituent loads between the conventional and LID basins using only those runoff events that were sampled could be misleading. One solution is regression analysis relating storm loads to variables representing climatologic and seasonal conditions. If the explanatory variables represent the climatologic and seasonal conditions, then the variability remaining in the regression residuals represents the combination of lack-of-fit for the regression model and changes induced by the low-impact design practices (Graczyk and others, 2003). Using methods described in Graczyk and others (2003), stepwise regressions were done for each basin and constituent to estimate loads for storm events that were not sampled. The final regressions were based on log transformations of measured storm loads and climatologic and seasonal variables. The outcome of the regression analysis is shown in table 7.

Descriptive statistics for solids and phosphorus loads measured and estimated at the conventional and LID-basin outfalls during each study year are summarized in table 8. Mean total and total suspended solids loads were greater in the LID basin than in the conventional basin two of the seven study years. Mean total phosphorus loads were greater in the LID basin for four of the seven study years. Examination of the LID- and conventional-basin loads revealed a highly skewed distribution. Large precipitation events can skew the distribution of solids loads. One such event occurred in August 2001 when more than 9.5 in. of rain was recorded in the study area within 48 hours. Similarly, precipitation events that did not produce any discharge from the study sites were included in the dataset used to develop table 8. The sediment and phosphorus loads associated with these events were zero. The effect of including these events is represented by the median value in table 8. Because of the numerous precipitation events that did not produce runoff from the LID basin, median values for total solids, total suspended solids, and total phosphorus loads were less than those for the conventional basin for all seven years of the study.

Table 7. Regression results for storm loads in the low-impact-development (LID) and conventional-development basins.

[P, precipitation depth; Peak Q, peak discharge; I_n, n-minute maximum precipitation intensity; API_n, antecedent rainfall n days before the storm; T, starting serial date of runoff period; cos, trigonometric cosine function; sin, trigonometric sine function; R^2, fraction of variation explained by the regression]

Dependent variable	Independent variable	Sample size	Adjusted R^2	Standard error
Conventional-development basin				
Total solids	Peak Q, cos(T)	28	0.767	0.79
Total suspended solids	I_{15}, Peak Q, cos(T)	28	.778	.89
Total phosphorus	I_{15}, Peak Q, sin(T)	25	.883	.5
LID basin				
Total solids	P, I_{15}, Peak Q, sin(T)	66	.614	.77
Total suspended solids	P, I_{15}, Peak Q, sin(T), P+API_5	66	.689	.71
Total phosphorus	P, I_{15}, Peak Q, sin(T), P+API_3	62	.694	.56

Table 8. Storm-load summary statistics at the low-impact-development (LID) and conventional-development-basin outfalls, water years 1999–2005.

[<, less than]

Statistic	Water year[a]						
	1999	2000	2001	2002	2003	2004	2005
Low-impact-development basin							
Total solids (tons)[b]							
Number of observations[c]	9	17	15	11	9	12	6
Minimum	.00	.00	.00	.00	.00	.00	.00
Maximum	.55	5.25	11.63	.52	.85	6.86	.55
Median	.00	.00	.00	.00	.00	.00	.00
Mean	.02	.27	.28	.03	.06	.22	.09
Standard deviation	.08	.92	1.60	.10	.17	.99	.09
Total suspended solids (tons)[b]							
Number of observations[c]	9	17	15	11	9	12	6
Minimum	.00	.00	.00	.00	.00	.00	.00
Maximum	.39	2.95	10.33	.20	.41	4.00	.02
Median	.00	.00	.00	.00	.00	.00	.00
Mean	.01	.13	.22	.01	.03	.11	<.01
Standard deviation	.06	.49	1.42	.03	.08	.58	<.01
Total phosphorus (pounds)[b]							
Number of observations[c]	9	17	15	11	9	12	6
Minimum	.00	.00	.00	.00	.00	.00	.00
Maximum	.94	54.13	31.56	1.19	2.46	19.76	.67
Median	.00	.00	.00	.00	.00	.00	.00
Mean	.04	1.42	.81	.08	.21	.80	.03
Standard deviation	.14	7.23	4.35	.22	.52	3.01	.13

[a] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003 through September 30, 2004).

[b] Represents only those precipitation events, excluding snowmelt, that produced discharge.

[c] Represents all precipitation events, excluding snowmelt, including those that did not produce discharge.

Table 8. Storm-load summary statistics at the low-impact-development (LID) and conventional-development-basin outfalls, water years 1999–2005—Continued.

[<, less than]

Statistic	Water year[a]						
	1999	2000	2001	2002	2003	2004	2005
	Conventional-development basin						
Total solids (tons)[b]							
Number of observations[c]	46	43	43	52	42	47	42
Minimum	<.01	<.01	.01	<.01	<.01	<.01	<.01
Maximum	3.84	2.46	20.85	8.89	.70	1.76	1.03
Median	.07	.03	.13	.07	.06	.06	.04
Mean	.19	.21	.77	.28	.12	.18	.12
Standard deviation	.58	.51	3.16	1.21	.15	.35	.21
Total suspended solids (tons)[b]							
Number of observations[c]	46	42	43	52	42	51	48
Minimum	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Maximum	.69	2.04	1.53	.28	.30	.52	.20
Median	.03	.02	.04	.03	.03	.02	.02
Mean	.06	.15	.10	.05	.05	.07	.04
Standard deviation	.11	.43	.25	.05	.07	.11	.05
Total phosphorus (pounds)[b]							
Number of observations[c]	46	42	43	52	42	51	48
Minimum	.01	.01	.02	.01	<.01	<.01	<.01
Maximum	1.76	5.36	6.25	.75	.78	1.49	1.29
Median	.14	.08	.15	.16	.12	.13	.12
Mean	.22	.45	.43	.19	.20	.27	.23
Standard deviation	.28	1.08	1.00	.16	.19	.33	.31

[a] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003 through September 30, 2004).

[b] Represents only those precipitation events, excluding snowmelt, that produced discharge.

[c] Represents all precipitation event, excluding snowmelt, including those that did not produce discharge.

Annual loads were computed to better characterize the overall effectiveness of low-impact design practices for mitigating delivery of total and suspended solids and total phosphorus loads. Annual total suspended solids and total phosphorus loads were greater in the conventional basin than the LID basin for all years except 2000, 2001, and 2004 (table 9). Because of the strong association of total phosphorus with sediment, total phosphorus loads tended to increase or decrease with total suspended solids loads (Sartor and Boyd, 1972; Waschbusch and others, 1999; Kronvang and others, 1999). The annual total solids load was greater in the LID basin for water years 2000 and 2004 but was approximately one-half that measured in the conventional basin in 2001. During this year, a single event sampled in the conventional basin had an unusually large total solids concentration of 10,000 mg/L, an order of magnitude higher than that for any other sampled runoff event. An examination of field notes during this combination snowmelt and rainfall event indicated a heavy layer of sediment in the sample containers. Photographs taken a few days later document appreciable street sediment and debris collected in snow piles along the street edge (fig. 14). As snow melted, these concentrated sediments were likely entrained in runoff and washed into nearby storm drains. This event produced more than one-half of the annual total solids load in the conventional basin in 2001. Similarly, closer examination of individual storm loads in the LID basin for water years 2000, 2001, and 2004 showed that the majority of annual constituent loads were attributed to one or two large runoff events. Select runoff events in the LID and conventional basins for water years 2000, 2001, and 2004 are shown in table 10. Two runoff events were responsible for contributing 70 percent or more of all total solids, total suspended solids, and total phosphorus loads in 2000, and a single runoff event produced the majority of constituent loads in 2001 and 2004 (table 10). Each of these events was associated with considerable precipitation depths and (or) intensities. These same storms did not contribute as much of the annual load in the conventional basin. With large storms and saturated soils, the ability of low-impact design techniques to reduce runoff, and thus constituent loads, can, at least in this case, be greatly diminished.

Annual yields were computed by dividing the annual load by contributing drainage area. The annual yields of total solids, total suspended solids, and total phosphorus are shown in table 11. Because both the LID and conventional basins had nearly the same contributing area, comparison of annual yields between the two basins revealed similar conclusions as annual loads. An analysis of annual yields using a drainage boundary defined by developed area only, not including the surrounding undeveloped hillslopes and forested uplands, resulted in similar conclusions. These areas that were not included typically contribute little to no runoff (Montgomery and others, 1997); however, it is likely these areas contributed some volume

Table 9. Estimate of annual loads in the low-impact-development (LID) and conventional-development basins, water years 1999–2005.

Study basin	Water year[a]							
	1999	2000	2001	2002	2003	2004	2005	1999–2005
Total solids (tons)								
LID	1.2	15.5	14.7	1.7	2.4	10.3	1.0	49.8
Conventional	8.9	9.0	33.2	14.3	5.0	8.4	5.1	84.1
Total suspended solids (tons)								
LID	.8	7.4	11.5	.4	1.0	5.3	.0	29.5
Conventional	2.8	6.3	4.5	2.5	2.2	3.4	1.7	23.4
Total phosphorus (pounds)								
LID	2.0	82.6	42.0	4.1	8.2	37.7	1.7	181.3
Conventional	9.9	18.9	18.5	10.0	8.3	13.8	10.8	90.2

[a] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003 through September 30, 2004).

Figure 14. Concentrated sediment in snow piles in the conventional-development basin. As the snow melted, the sediment became entrained in runoff, resulting in unusually high concentrations of solids.

Table 10. Contributions of constituent load as a percentage of annual load for select precipitation events in the low-impact-development (LID) and conventional-development basins.

[mm/dd/yyyy, month, day, and year; in/h, inch per hour]

Water year[1]	Date (mm/dd/yyyy)	Precipitation depth (inches)	Storm intensity (in/h)	Total solids		Total suspended solids		Total phosphorus	
				Event load (tons)	Percent of annual load	Event load (tons)	Percent of annual load	Event load (tons)	Percent of annual load
				Low-impact-development basin					
2000	05/17/2000	5.09	1.2	5.3	32	3.0	35	54.1	65
2000	05/30/2000	4.89	1.14	6.2	38	3.0	35	18.5	22
2001	08/01/2001	9.68	3.15	11.6	74	10.3	83	31.6	73
2004	05/21/2004	6.21	1.13	6.9	61	4.0	63	19.8	51
				Conventional-development basin					
2000	05/17/2000	4.93	1.3	2.1	23	1.9	30	5.4	28
2000	05/30/2000	5.14	.88	2.5	27	2.0	32	4.1	22
2001	08/01/2001	8.82	2.6	2.0	6	1.5	34	6.3	34
2004	05/21/2004	6.71	1.22	3.4	40	1.1	32	3.1	22

[1] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003 through September 30, 2004).

of runoff to the drainage network of the developed basins during one or more events with substantial precipitation depths and (or) intensities. Because these events were responsible for the majority of constituent loading, computations based only on the developed area might result in an overestimation of annual yields in each basin.

Water Temperature

The temperature of urban streams is often affected directly by urban runoff. Previous studies indicate that as rainfall passes over impervious surfaces such as rooftops, driveways, roads, and parking lots, it absorbs some of the energy stored as heat in the surface (Roa-Espinosa and others, 2003). Galli (1990) demonstrated an increase in base-flow water temperature of 0.14°C for every 1-percent increase in watershed imperviousness. Although the LID and conventional basins constitute only a small percentage of the Black Earth Creek watershed area (0.3 and 0.2 percent, respectively), the percentage of impervious surface within each basin is quite different. Runoff leaving each basin eventually drains into nearby Black Earth Creek, a Class I trout stream. The difference in the temperature of runoff between a basin constructed using low-impact techniques as opposed to a more conventional basin could potentially be used to predict impacts to receiving waters given future watershed build-out scenarios. Certain species of fish, such as trout, require low daily mean temperatures of less than 22°C for survival (Lyons and others, 1996) and are particularly sensitive to temperature fluctuations.

A typical response in water temperature to rainfall measured at the LID- and conventional-basin outlets is illustrated in figures 15 and 16, respectively. Water levels in each basin also are shown in figures 15 and 16 to show changes in temperature before, during, and after a rainfall event. The temperature of runoff measured at the conventional-basin outlet is not largely affected by heating of impervious surfaces prior to rain events because of its location. As rainfall first moved into the study basin on May 21, 2004, the temperature of runoff was close to ambient air temperatures (fig. 15). This is likely because rain fell in the early morning hours; impervious surfaces cooled overnight and were not subject to additional heating prior to rainfall. After runoff cessation, temperatures inside the storm-sewer pipe returned to pre-event levels. A second pulse of rainfall moved through the study area

Table 11. Estimate of annual yields of total solids, total suspended solids, and total phosphorus in the low-impact-development (LID) and conventional-development basins, water years 1999–2005.

[lbs/acre, pounds per acre; <, less than]

Study basin	Water year[a]						
	1999	2000	2001	2002	2003	2004	2005
Total solids (lbs/acre)							
LID	13	161	154	18	25	108	11
Conventional	129	132	484	209	72	123	75
Total suspended solids (lbs/acre)							
LID	8	77	120	4	11	55	<1
Conventional	40	92	66	36	32	49	25
Total phosphorus (lbs/acre)							
LID	.01	.43	.22	.02	.04	.20	.01
Conventional	.07	.14	.13	.07	.06	.10	.08

[a] Water year is a 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends (for example, the 2004 water year occurred October 1, 2003 through September 30, 2004).

in the afternoon, just after the air temperature reached its highest point of the day. The temperature of runoff was again similar to air temperatures initially but quickly cooled as rain persisted in the basin. Heating of impervious surfaces during the afternoon hours may have elevated the temperature of runoff somewhat prior to the second pulse of rainfall on May 21, but a drop in air temperature, additional rainfall, and cooler ambient temperatures in the storm sewer produced a cooling effect. Fluctuations in runoff temperatures beyond this point did not exceed more than a couple of degrees despite periods of atmospheric heating with no additional rainfall.

The temperature of runoff in the LID basin is largely controlled by ambient air temperatures, just as in the conventional basin. Runoff temperatures in the LID basin were similar to ambient air temperatures during the cooler morning hours of May 21, 2004. As rainfall subsided, the temperature of runoff measured at the LID outlet increased at nearly the same rate as air temperature (fig. 16). Additional rainfall and cooler air temperatures during the afternoon hours on May 21 resulted in gradually decreasing runoff temperatures; however, unlike the conventional basin, the temperature of runoff in the LID basin increased more dramatically after precipitation ended and air temperatures increased. This warming effect can be seen during the afternoon hours on May 22 and again on May 23 when air temperatures were increasing and there was no additional rainfall (fig. 16). The temperature of runoff follows the same overall trend as air temperature but appears to lag behind by a few hours. This is likely due to the absence of tree canopy for shading and the presence of the wet detention basin in the LID basin. Water in the wet detention basin stores heat during dry periods until runoff from a rainfall event moves the warmer water into the infiltration basin and replaces it with cooler runoff, which is stored in turn. Runoff entering the infiltration basin from the wet detention pond and other drainage areas is spread uniformly over a large surface area to promote infiltration.

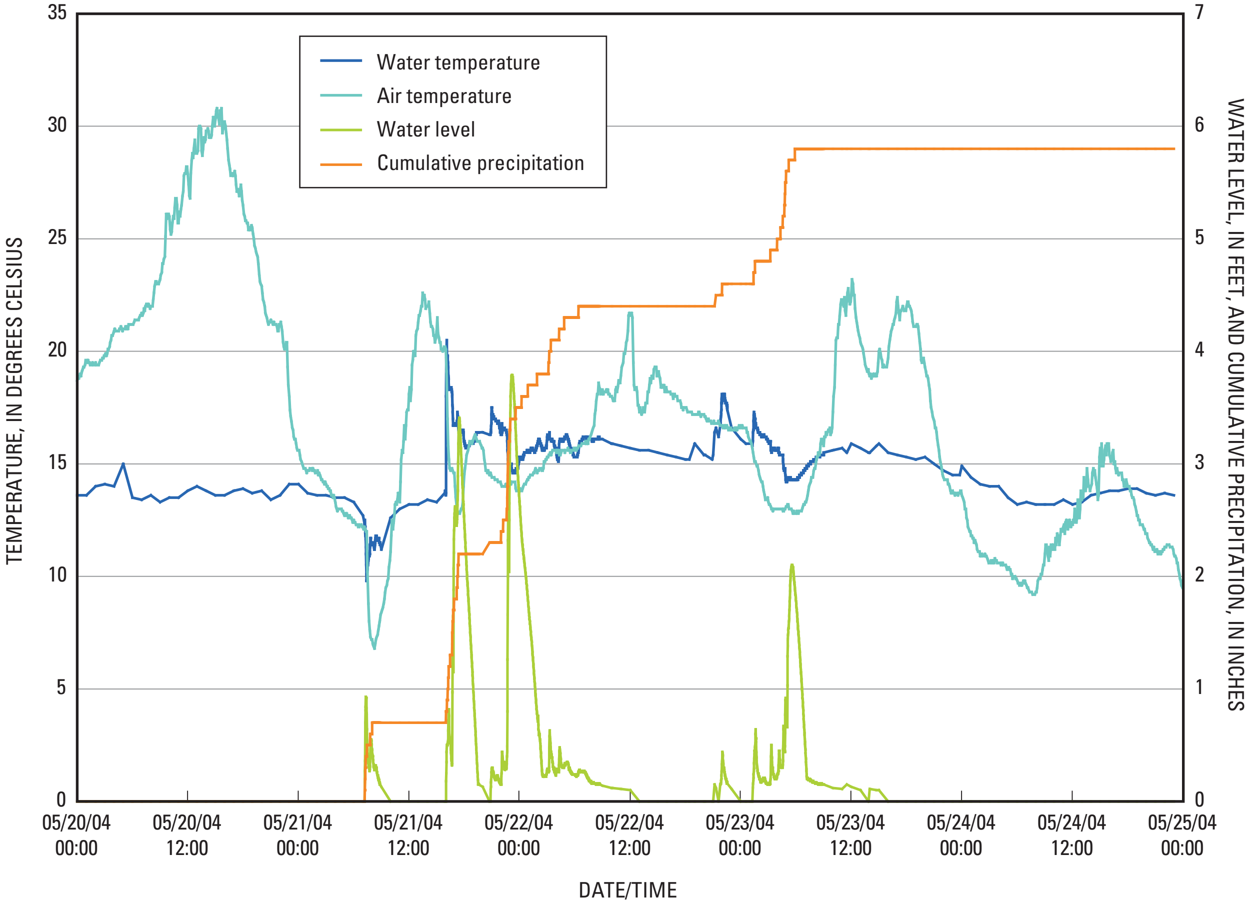


Figure 15. Temperature of runoff, air temperature, cumulative precipitation, and water levels measured in the conventional-development basin.

This water is typically shallow and exposed to direct solar heating, allowing for cooler runoff to warm rapidly during dry periods.

The paired t-test (Helsel and Hirsch, 1992) was used to determine whether daily mean temperatures of runoff in the LID basin were greater or less than those in the conventional basin. The test was done on runoff-temperature data measured in the conventional and LID basins for April through November to eliminate periods of snowmelt. The null hypothesis states that there is no difference in the means of temperature between the LID and conventional basins. The alternative hypothesis is that there is a significant difference that can be inferred to be a result of basin characteristics. Results of the test indicate that the temperature of runoff in the LID basin is greater than that in the conventional basin at the 5-percent significance level.

Water temperature may be considered one of the most important factors in determining the geographic distribution, growth rate, and survival of fish and other aquatic organisms (Bartholow, 1989; Regier and others, 1990; Armour, 1991; LeBlanc and others, 1997). Some of the variables having the most effect on stream temperature include, but are not limited to, riparian vegetation, ground-water discharge, and channel morphology. These variables also are highly influenced by land use. Low-impact design practices appear to mitigate temperature associated with runoff by retaining and infiltrating the majority of stormwater runoff into underlying aquifers, thereby helping to sustain base flow (Pitt and others, 1994). Maintaining a steady supply of ground-water discharge to a stream is important because critical temperature thresholds for aquatic survival are often associated with low-flow periods during summer (LeBlanc and others, 1997).

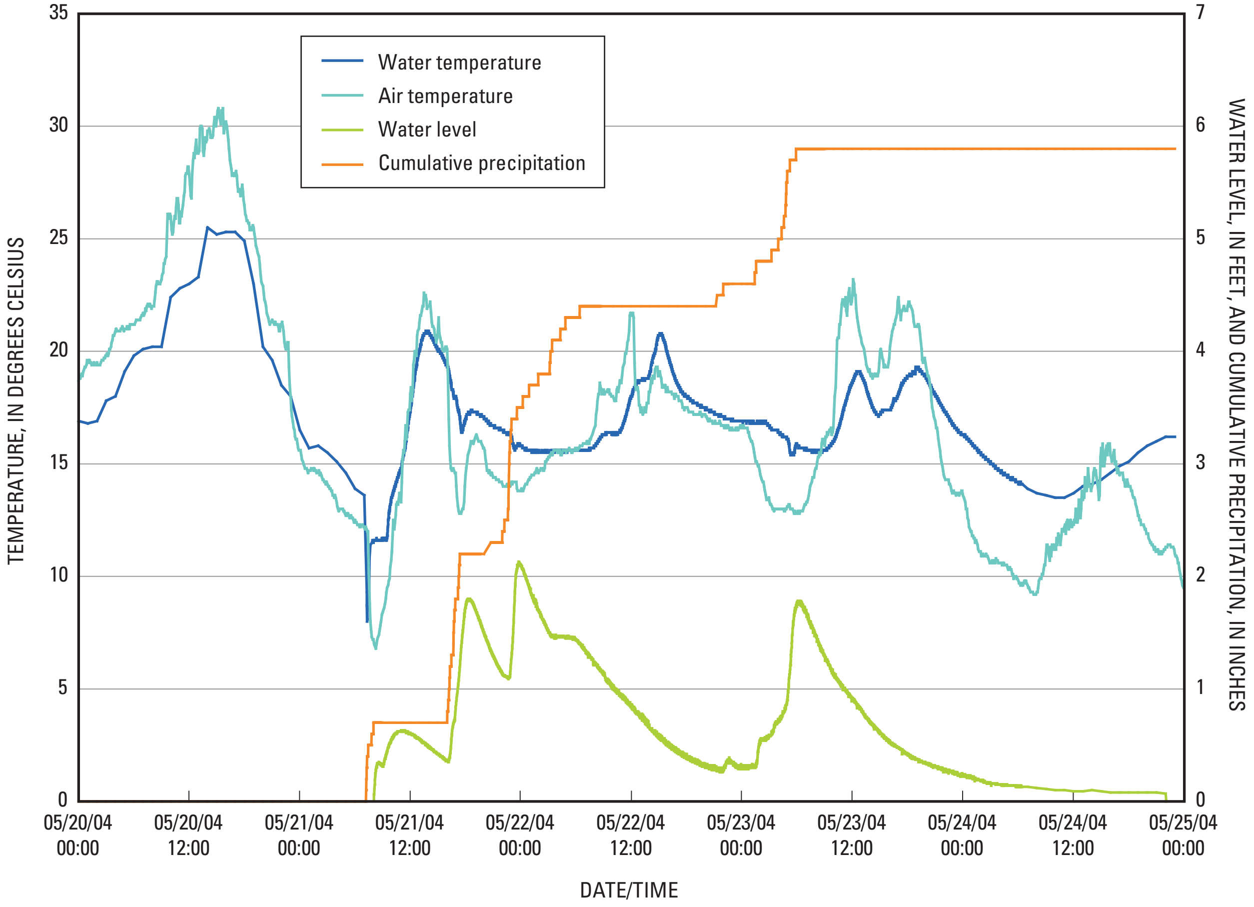


Figure 16. Temperature of runoff, air temperature, cumulative precipitation, and water levels measured in the low-impact-development (LID) basin.

Limitations of This Study and Suggestions for Future Work

This study compared the runoff quantity and quality of a conventionally developed residential basin to an adjacent basin in which LID strategies were implemented. Limitations of this study and suggestions for future work are discussed below.

- Previous studies determined through numerical simulations that developments adopting a low-impact approach, with a large portion of the land kept in a natural condition, produced less runoff than conventional developments (Brander and others, 2005). Unlike in a conventionally developed basin, LID attempts to maintain or replicate the predevelopment hydrologic regime through use of design techniques that create a functionally equivalent hydrologic landscape (U.S. Environmental Protection Agency, 2000). This distinction between construction philosophies became evident in this study when comparing the percentage of impervious surface in the conventional basin to that in the LID basin. The conventional basin had nearly twice the area of mapped imperviousness than the LID basin, largely due to commercial parking lots. The large difference in this factor between these two types of basins presented challenges in this study when comparing runoff quantity and quality. A greater percentage of impervious surfaces in a basin could result in greater runoff volumes.

- During the study period, development activities were continuing in the LID basin; hence, the results from that basin do not necessarily represent fully developed conditions.

- Although the study basins were located relatively close to one another, there were differences in observed rainfall. Slight differences in precipitation totals may lead to differences in stormwater loads and yields.

- Replacing natural landscapes with urban areas can introduce a wide variety of anthropogenic contaminants such as total and dissolved metals, oil and grease, pesticides, and polycyclic aromatic hydrocarbons (Davis, 2005; Bannerman and others, 1996). Because constituents analyzed as part of this study were limited to total solids, total suspended solids, and total phosphorus, little can be inferred about the potential benefits of low-impact design on reducing concentrations of other contaminants. Future work could include comparison of the concentrations and loads of additional contaminants between the LID and conventional basins.

- Daily mean temperatures of runoff in the LID basin were higher than in the conventional basin. Although the frequency of runoff events in the LID basin was less than that in the conventional basin, their duration was considerably longer. The length and magnitude of water temperature excursions above or below a threshold may have an effect on the survival of fish species (Mohseni and others, 1998). For example, Bear and others (2007) measured a drop in survival rates of rainbow trout—which is a common species found in Black Earth Creek—in Montana streams after only a few days when stream temperatures were at or above 26°C. The temperature of runoff leaving the LID basin occasionally exceeded this threshold. Although detailed runoff temperature data from both study basins were collected as part of the current study, additional data would need to be collected to allow prediction of the short- and long-term thermal response in Black Earth Creek during and after storm-runoff events.

- The ability to detect long-term trends in sediment and phosphorus yields was limited given the short period of observation in the continually developing LID basin. Additional data would need to be collected once the LID basin was completely developed in order to fully characterize the water-quantity and -quality benefits of a LID design.

Summary and Conclusions

As development continues to push further into the natural landscape, controlling nonpoint sources of contamination has become a major focus for the regulatory community. During the course of development, land that was once covered with vegetation is sometimes replaced with impervious surfaces that are associated with more diverse pollutants, reduced infiltration, and increased peak stream flows. Environmental managers are often faced with designing strategies to accommodate development while minimizing adverse environmental impacts. Low-impact development (LID) is one such strategy that attempts to mitigate environmental degradation commonly associated with impervious surfaces. By incorporating the hydrologic functions of storage, infiltration, and volume and frequency of discharges into small-scale, distributed, structural, and nonstructural controls, LID principles attempt to control stormwater at the source. Many of the stormwater controls used as part of low-impact design have been successfully evaluated individually. Although hydrologic models have demonstrated the potential environmental benefit of incorporating multiple stormwater controls, there is a paucity of large-scale field studies evaluating the aggregate effect of these practices implicit in a low-impact design.

To that end, the U.S. Geological Survey, in cooperation with the Wisconsin Department of Natural Resources, did a study to compare conventional and LID practices with respect to the quantity and quality of stormwater runoff. Specifically, this study examined the hydrologic response of a residential basin from predevelopment through near-complete build-out. The basin (referred to as the “LID” basin) was developed using several stormwater controls that are often implemented as part of LID, such as reduced street widths to minimize impervious cover, grass swales, street inlets that discharge to grass swales, protection of existing woodlands, a detention pond, an infiltration trench, and a large infiltration basin planted with deep-rooted prairie species native to the area. Water-quantity and -quality data from the LID basin were compared to data from a fully developed residential basin (referred to as the “conventional basin”) that was constructed using a more conventional, fully connected stormwater-conveyance system, such as curbs and gutters and concrete storm sewers.

Results of the study show that the quantity of stormwater discharge leaving a residential basin can be reduced by incorporating LID practices. Precipitation from smaller, more frequent events that produced stormwater discharge from the conventional basin was retained within the drainage boundaries of the LID basin. The cumulative effect of these small, frequent precipitation events became apparent when examining cumulative discharge volumes from each study basin. Fifty percent of total runoff volume leaving the LID basin as discharge was associated with precipitation depths greater than 3 inches compared to 18 percent in the conventional basin. For each study year, annual discharge volume measured from the conventional basin exceeded that from the LID basin, in some cases by an order of magnitude. During the 2004–2005 study year, when the LID basin was near complete build-out, 95 percent of the annual precipitation was retained onsite. Much of the runoff reduction was attributed to a combination of low-impact practices such as lawns, grassed swales, a detention pond, and forested hillslopes.

Runoff in the LID basin was received by a 1.75-acre infiltration basin, the largest control structure used to mitigate runoff quantity and quality. It also was the last structure used to treat runoff before it left the LID basin as discharge. A volumetric mass balance was computed for all stormwater-runoff volumes entering and leaving the infiltration basin from May 2002 through September 2005. During this period, 51 percent of all influent was retained in the infiltration basin. Examination of individual precipitation events showed a relation between the amount of runoff reduced by the infiltration basin and precipitation intensity. Reductions in stormwater runoff in the LID basin diminished as precipitation intensities increased. As precipitation intensities exceeded 0.5 inches per hour, the average percentage reduction in runoff volumes dropped to 43 percent. The failure of the LID basin to fully retain precipitation events of appreciable depth and (or) intensity might be a result of one or a combination of several factors, including the rate of precipitation exceeding the maximum rate of infiltration, additional volume of runoff from forested uplands that normally have little to no runoff from smaller precipitation events, saturated soil from prior storms, or frozen soil.

A comparison of annual loads characterized the overall effectiveness in this study of low-impact design practices at mitigating delivery of total solids, total suspended solids, and total phosphorus loads. Annual constituent loads were greater in the conventional basin than in the LID basin for all but 3 study years, during which more than 50 percent of annual load in the LID basin was associated with one or two discharge events. Although low-impact design practices are able to retain and reduce stormwater runoff, and thus constituent loads, larger, less frequent precipitation events can greatly diminish this capability.

The temperature of runoff in both the LID and conventional basins was largely controlled by ambient air temperatures. A greater percentage of impervious surface area in the conventional basin resulted in slight heating of runoff initially, but cooler air temperatures and precipitation rapidly reduced the temperature of runoff leaving the basin as discharge. Once in the enclosed storm-sewer conduit, the temperature of discharge in the conventional basin remained constant. The absence of storm sewers in the LID basin allowed stormwater runoff retained in the infiltration basin and detention pond to be exposed to direct solar heating. This resulted in elevated discharge temperatures several days after a storm event.

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References

Armour, C.L., 1991, Guidance for evaluating and recommending temperature regimes to protect fish: U.S. Fish and Wildlife Service, Biological Report 90(22), Instream Flow Information Paper 28, 13 p.

Bannerman, R.T., Legg, A.D., and Greb, S.R., 1996, Quality of Wisconsin stormwater: U.S. Geological Survey Open-File Report 96–458, 26 p.

Bartholow, J.M., 1989, Stream temperature investigations—Field and analytical methods: U.S. Fish and Wildlife Service, Biological Report 89(17), Instream Flow Information Paper 13, 139 p.

Bear, E.A., McMahon, T.E, and Zale, A.V., 2007, Comparative thermal requirements of westslope cutthroat trout and rainbow trout—Implications for species interactions and development of thermal protection standards: Transactions of the American Fisheries Society, v. 136, no. 4, p. 1113–1121.

Brander, K.E., Owen, K.E., and Potter, K.W., 2005, Modeled impacts of development type on runoff volume and infiltration performance: Journal of the American Water Resources Association, v. 40, no. 4, p. 961–970.

Church, P.E., Granato, G.E., and Owens, D.W., 1999, Basic requirements for collecting, documenting, and reporting precipitation and stormwater-flow measurements: U.S. Geological Survey Open-File Report 99–255, 38 p.

Coffman, Larry, 2000, Low-impact development design strategies—An integrated design approach: U.S. Environmental Protection Agency, EPA 841–B–00–003, [variously paginated].

Davis, A.P., 2005, Green engineering principles promote low-impact development: Environmental Science and Technology, A-pages, v. 39, no. 16, p. 338A–344A.

Dierks, S., 2007, Not all green space is created equal—The hydrologic benefits of native landscapes: Stormwater, v. 8, no. 2, p. 68–77.

Galli, J., 1990, Thermal impacts associated with urbanization and stormwater management best management practices—Appendix C, Water temperature and freshwater stream biota—An overview: Washington D.C., Metropolitan Washington Council of Governments, [variously paginated].

Graczyk, D.J., Walker, J.F., Horwatich, J.A., and Bannerman, R.T., 2003, Effects of best-management practices in the Black Earth Creek priority watershed, Wisconsin, 1984–98: U.S. Geological Survey Water-Resources Investigations Report 03–4163, 24 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.

Holman-Dodds, J.K., Bradley, A.A., and Potter, K.W., 2003, Evaluation of hydrologic benefits of infiltration-based urban storm water management: Journal of the American Water Resources Association, v. 39, no. 1, p. 205–215.

Huff, F.A., and Angel, J.R., 1992, Rainfall frequency atlas of the Midwest: Midwest Climate Center Research Report 92–03, Bulletin 71, 141 p.

Kronvang, B., Laubel, A., and Grant, R., 1999, Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment, Gelbaek stream: Denmark, Hydrologic Processes, v. 11, no. 6, p. 627–642.

LeBlanc, R.T., Brown, R.D., and FitzGibbon, J.E., 1997, Modeling the effects of land use change on the water temperature in unregulated urban streams: Journal of Environmental Management, v. 49, no. 4, p. 445–469.

Liaw, C., Cheng, M., and Tsai, Y., 2000, Low-impact development—An innovative alternative approach to stormwater management: Journal of Marine Science and Technology, v. 8, no. 1, p. 41–49.

Lyons, J., Wang, L., and Simonson, T.D., 1996, Development and validation of an index of biotic integrity for coldwater streams in Wisconsin: North American Journal of Fisheries Management, v. 16, no. 2, p. 241–256.

Mohseni, O., Stefan, H.G., and Erickson, T.R., 1998, A nonlinear regression model for weekly stream temperatures: Water Resources Research, v. 34, no. 10, p. 2685–2692.

Montgomery, D.R., Dietrich, W.E., Torres, R., Prestrud Anderson, S., Heffner, J.T., and Loague, K., 1997, Hydrologic response of a steep, unchanneled valley to natural and applied rainfall: Water Resources Research, v. 33, no. 1, p. 91–109.

National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Data Center, 1999–2005, local climatological data, Madison, Wisconsin—Annual summary with comparative data: accessed November 6, 2007 at *http://www.ncdc.noaa.gov.*

Pitt, R., Clark, S., and Parmer, K., 1994, Protection of groundwater from intentional and nonintentional stormwater infiltration: U.S. Environmental Protection Agency, Storm and Combined Sewer Program, EPA/600/SR–94/051, 187 p.

Pitt, R., Lilburn, M., Nix, S., Durrans, S.R., Burian, S., Vorhees, J., and Martinson, J., 1999, Guidance manual for integrated wet weather flow (WWF) collection and treatment systems for newly urbanized areas (New WWF Systems): U.S. Environmental Protection Agency, [variously paginated].

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 66 p.

Regier, H.A., Holmes, J.A. and Pauly, D., 1990, Influence of temperature changes on aquatic ecosystems—An interpretation of empirical data: Transactions of the American Fisheries Society, v. 119, no. 2, p. 374–389.

Roa-Espinosa, A., Wilson, T.B., Norman, J.M., and Johnson, Kenneth, 2003, Predicting the impacts of urban development on stream temperature using a Thermal Urban Runoff Model (TURM), *in* Proceedings of the National Conference on Urban Stormwater—Enhancing Programs at the Local Level: U. S. Environmental Protection Agency, National Risk Management Research Laboratory, p. 369–389.

Sartor, J.D., and Boyd, G.B., 1972, Water pollution aspects of street surface contaminants: U.S. Environmental Protection Agency, EPA–R2–72–081, 237 p.

Selbig, W.R., and Bannerman, R.T., 2007, Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2007–5156, 102 p.

U.S. Environmental Protection Agency, 2000, Low impact development (LID)—A literature review: Washington, D.C., Office of Water, EPA–841–B–00–005, 35 p.

U.S. Environmental Protection Agency, 2001, Techniques for tracking, evaluating, and reporting the implementation of nonpoint source control measures—III. Urban: Washington, D.C., Office of Water, [variously paginated].

U.S. Environmental Protection Agency, 2002, National water-quality inventory, 2000 report: Washington, D.C., Office of Water, EPA 841–R–02–001, 207 p., 6 apps.

Wang, L., Lyons, J., Kanehl, P., and Bannerman, R., 2001, Impacts of urbanization on stream habitat and fish across multiple spatial scales: Environmental Management, v. 28, no. 2, p. 255–266.

Waschbusch, R.J., Selbig, W.R., and Bannerman, R.T., 1999, Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin, 1994–95, U.S. Geological Survey Water-Resources Investigations Report 99–4021, 47 p.

Wilson, J.F., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A12, 34 p.

Wisconsin Administrative Code, 2002, Wisconsin Department of Natural Resources—Runoff management: Chap. NR 151 [variously paginated].

Appendixes

Appendix 1. Quality-Assurance and Quality-Control Data

Appendix table 1-1. Results of blank-sample analyses in the low-impact-development (LID) and conventional-development basins.

[mm/dd/yyyy, month/day/year; mg/L, milligram per liter; <, less than; --, no data]

Sample name	Date (mm/dd/yyyy)	Phosphorus, total recoverable (mg/L)	Total suspended solids (mg/L)	Total solids (mg/L)
LID-3	04/17/2001	<0.005	<2	--
LID-3	07/09/2002	--	3	<50
LID-3	06/10/2004	.008	<2	<50
LID-2	06/01/2005	<.001	<6	<6
Conventional-3	04/19/2001	.015	9	--
Conventional-3	07/09/2002	--	<2	<50
Conventional-3	07/02/2004	<.005	<2	<50
Conventional-2	06/01/2005	<.001	<6	<6

Appendix table 1-2. Results of replicate-sample analyses in the low-impact-development (LID) and conventional-development basins.

[mm/dd/yyyy, month/day/year; mg/L, milligram per liter; RPD, relative percent difference; LID, low-impact-development; --, no data; n/a, no value available]

Sample name	Date (mm/dd/yyyy)	Phosphorus, total recoverable (mg/L)	Absolute RPD (percent)	Total suspended solids (mg/L)	Absolute RPD (percent)	Total solids (mg/L)	Absolute RPD (percent)
LID-32	09/08/2001	--	n/a	61	17	196	0
LID-32R[1]	09/08/2001	--		52		196	
Conventional-35	09/07/2001	--	n/a	59	13	98	21
Conventional-35R[1]	09/07/2001	--		68		124	
Conventional-85	05/11/2005	0.142	7	--	n/a	--	n/a
Conventional-85R[1]	05/11/2005	.152		--		--	

[1] Replicate sample.

Appendix 2. Detailed Event Characteristics and Stormwater-Quality Data

Appendix 2

Appendix table 2-1. Hydrologic and precipitation characteristics of sampled discharge events in the low-impact-development (LID) basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
2	10/05/1998	17:19	10/05/1998	20:07	2.8	1.07	1.88	1.68	1.06	423	<1	0.20	0.5
3	02/11/1999	13:27	02/11/1999	16:30	3.0	.63	1.48	.98	.58	1,486	<1	.57	1.8
4	04/22/1999	19:21	04/23/1999	09:52	14.5	1.95	.48	.44	.38	28,080	2	2.19	.2
5	05/16/1999	21:56	05/17/1999	19:31	16.2	1.92	4.28	2.52	1.33	933	<1	.04	.2
6	06/30/1999	23:38	07/01/1999	09:52	5.2	1.05	1.16	.74	.48	1,391	<1	.06	2.1
7	07/17/1999	02:46	07/17/1999	15:10	3.8	1.25	1.48	1.24	.91	484	<1	.04	.2
8	07/20/1999	13:48	07/24/1999	18:40	100.9	1.59	2.48	1.96	1.40	29,315	3	.36	1.9
9	08/23/1999	08:36	08/25/1999	10:35	50.0	1.07	1.60	1.12	.65	7,318	1	.10	4.5
10	02/23/2000	09:00	02/24/2000	22:00	37.0	.29[b]	.12	.10	.08	46,837	23	1.22	44.0
11	02/25/2000	18:14	02/26/2000	12:49	18.6	.72	.80	.48	.30	19,872	4	.59	.8
13, 14, 15[a]	04/20/2000	00:16	04/22/2000	07:42	55.4	1.02	.60	.40	.35	29,039	1	.36	.5
16	05/17/2000	12:49	05/19/2000	21:53	57.1	5.09	4.20	2.32	1.20	294,926	8	21.84	5.4
17	05/30/2000	06:23	06/01/2000	15:00	56.6	3.67	2.48	1.46	.84	264,142	10	11.65	.8
18	06/13/2000	15:36	06/15/2000	02:54	35.3	2.79	2.87	1.60	.93	180,680	9	15.47	1.1
19	07/02/2000	19:34	07/03/2000	17:07	21.5	.90	2.60	1.52	.81	6,428	1	.17	4.0
20	07/10/2000	03:40	07/11/2000	02:25	22.7	.71	.64	.42	.29	4,182	1	.14	.7
21	08/05/2000	11:09	08/06/2000	03:54	16.7	1.84	3.00	2.20	1.46	21,980	2	1.35	4.0
22	08/17/2000	02:23	08/18/2000	01:50	23.4	.92	.88	.68	.50	5,210	1	.17	3.7
23	09/11/2000	07:37	09/12/2000	14:03	30.4	1.08	1.48	.88	.81	8,873	1	.24	7.9
24	09/22/2000	09:16	09/24/2000	03:07	41.9	.55	.28	.22	.17	13,435	4	.28	2.4
25	04/09/2001	23:18	04/10/2001	03:10	27.2	.82	.32	.32	.27	9,634	2	.62	3.1
26	04/11/2001	06:01	04/12/2001	13:48	31.8	.76	.72	.60	.40	36,253	7	1.55	1.1
27	04/21/2001	00:11	04/21/2001	23:55	4.7	.42	.56	.36	.23	8,312	3	.34	.7
28	05/20/2001	23:50	05/22/2001	05:59	30.1	1.71	1.32	1.02	.71	38,431	3	2.10	9.8
29	05/23/2001	01:34	05/23/2001	21:03	12.1	.38	.24	.16	.11	2,195	1	.11	.8
30	06/05/2001	01:29	06/06/2001	06:40	29.2	.66	.56	.42	.33	17,194	4	.69	3.2
31	08/01/2001	18:00	08/03/2001	13:30	43.5	9.68	6.08	4.54	3.15	774,516	11	22.28	7.7
32	09/07/2001	19:05	09/09/2001	00:02	28.9	1.26	2.44	1.52	.81	20,736	2	.84	.3
33	09/18/2001	23:28	09/20/2001	10:48	35.3	1.02	.36	.28	.25	25,350	4	.85	1.5

Appendix table 2-1. Hydrologic and precipitation characteristics of sampled discharge events in the low-impact-development (LID) basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
34	09/22/2001	22:34	09/24/2001	15:23	40.8	1.66	0.92	0.78	0.62	88,344	8	3.90	2.1
35	10/22/2001	14:36	10/23/2001	22:14	31.6	1.21	.84	.66	.44	6,592	1	.25	8.7
36	11/23/2001	22:17	11/25/2001	13:20	39.0	.97	.80	.48	.30	9,798	1	.35	4.8
37	02/18/2002	22:10	02/21/2002	20:19	70.2	1.54	.24	.18	.16	52,842	5	1.07	8.4
38	04/07/2002	15:14	04/09/2002	16:25	49.2	.99	.16	.12	.10	14,826	2	.44	.4
39	03/04/2004	18:04	03/06/2004	12:24	42.3	1.13	.48	.30	.22	78,883	10	1.97	2.0
40	03/25/2004	14:20	03/27/2004	05:25	39.1	1.07	.76	.68	.51	35,087	5	1.43	1.4
41	05/21/2004	07:16	05/24/2004	10:00	74.7	6.21	2.40	1.68	1.13	469,610	11	9.48	3.2
42	05/29/2004	06:41	06/01/2004	00:00	65.3	1.67	1.24	.80	.54	27,994	2	1.18	4.2
43	07/03/2004	15:03	07/04/2004	12:00	21.0	1.08	1.20	.98	.61	6,532	1	.31	12.1
44	07/16/2004	10:01	07/17/2004	10:00	24.0	1.05	1.72	1.20	.62	59,435	8	2.36	6.9
45	08/03/2004	17:51	08/04/2004	14:00	20.2	1.20	3.84	2.02	1.09	36,253	4	1.77	1.2
46	01/12/2005	13:04	01/13/2005	15:38	26.6	.33[b]	.16	.12	.11	27,233	12	1.09	10.0
47	03/21/2005	14:00	03/24/2005	19:10	82.0	snowmelt	--	--	--	21,910	<1	.28	.4
48	03/24/2005	10:00	03/25/2005	21:45	35.8	snowmelt	--	--	--	5,358	<1	.16	.0
49	03/30/2005	13:33	03/31/2005	17:14	27.7	.51	.72	.46	.25	4,095	1	.13	1.1

[a] Single discharge event separated into three sampled periods.

[b] Combination rainfall and snowmelt event.

Appendix table 2-2. Hydrologic and precipitation characteristics of sampled discharge events in the conventional-development basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed; n/a, data not available]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
1	10/05/1998	18:01	10/05/1998	19:55	1.9	1.10	2.00	1.68	1.09	35,420	6	30.8	n/a
3	04/21/1999	20:58	04/26/1999	03:50	102.9	3.42	4.28	2.22	1.17	81,005	5	11.4	1.2
4	05/16/1999	16:25	05/17/1999	22:45	30.3	2.39	4.56	2.62	1.38	81,361	7	79.3	10.0
5	06/06/1999	14:24	06/07/1999	04:24	14.0	.89	1.68	1.30	.77	33,741	8	18.2	2.1
7	07/16/1999	20:34	07/18/1999	02:00	29.4	1.86	1.36	1.30	1.01	69,510	8	17.0	7.8
8	07/20/1999	13:07	07/21/1999	20:07	31.0	2.00	3.00	2.42	1.69	63,393	6	29.6	1.3
9	08/23/1999	08:35	08/24/1999	14:45	30.2	1.27	1.72	1.32	.76	44,820	7	18.3	4.5
12	04/19/2000	07:45	04/19/2000	12:40	4.9	.52	.28	.26	.20	9,125	4	3.3	23.6
12[a]	04/20/2000	00:18	04/21/2000	10:00	32.5	1.02	.60	.40	.35	46,039	9	10.8	.5
13	05/17/2000	12:47	05/21/2000	15:15	98.5	4.93	4.54	2.57	1.34	232,123	9	76.3	4.8
14	05/26/2000	22:14	06/01/2000	18:13	122.4	5.14	2.76	1.58	.88	209,190	8	45.7	5.3
15	06/12/2000	05:50	06/15/2000	22:15	88.4	3.18	2.87	1.60	.93	199,351	13	70.6	7.0
16	07/02/2000	19:36	07/04/2000	21:07	37.4	.91	2.60	1.54	.83	53,295	12	43.2	3.9
17	07/10/2000	03:41	07/11/2000	16:00	36.3	.67	.63	.42	.28	46,576	14	9.3	.7
18	08/05/2000	11:10	08/07/2000	17:00	53.8	2.02	3.28	2.38	1.59	80,440	8	38.7	4.1
19	08/17/2000	02:23	08/19/2000	06:00	51.6	.91	.94	.67	.47	44,139	10	11.6	3.7
20	09/11/2000	07:38	09/13/2000	17:00	57.4	1.10	1.43	.86	.79	52,536	10	25.1	7.9
21	09/22/2000	09:36	09/24/2000	00:30	38.9	.61	.29	.22	.17	28,450	9	4.9	2.5
22	01/29/2001	11:08	01/31/2001	03:00	39.9	.83	.29	.22	.19	66,804	16	3.7	61.3
23	02/08/2001	14:47	02/10/2001	16:00	49.2	1.18	.32	.29	.26	82,153	14	4.4	8.5
24	02/24/2001	09:21	02/25/2001	11:50	26.5	.24	.11	.09	.07	31,240	26	2.7	13.7
25	04/10/2001	22:49	04/14/2001	00:20	73.5	.78	.67	.51	.35	29,384	8	14.2	.0
26	04/21/2001	00:10	04/22/2001	15:00	38.8	.47	.63	.40	.25	20,409	9	10.4	.7
27	05/10/2001	19:40	05/12/2001	21:50	50.2	.65	1.28	.77	.46	41,351	13	22.1	.7
28	05/20/2001	23:58	05/23/2001	01:27	49.5	1.62	.96	.78	.52	70,074	9	10.6	8.1
29	05/23/2001	01:28	05/24/2001	22:00	44.5	.37	.20	.16	.11	23,065	13	3.5	.0
30	06/05/2001	01:29	06/07/2001	12:00	58.5	.70	.68	.50	.38	63,906	18	7.9	3.2
31	06/11/2001	22:04	06/13/2001	21:10	47.1	2.33	2.24	2.06	1.51	172,661	15	38.9	1.9
32	07/18/2001	07:21	07/20/2001	13:00	53.6	.90	2.80	1.64	.88	38,983	9	27.4	.9

Appendix table 2-2. Hydrologic and precipitation characteristics of sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed; n/a, data not available]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
33	08/01/2001	18:00	08/04/2001	23:00	77.0	8.82	4.87	3.67	2.64	581,107	13	78.1	7.7
34	08/24/2001	19:05	08/27/2001	04:00	56.9	1.11	.94	.86	.72	49,664	9	12.7	2.2
35	09/07/2001	12:19	09/11/2001	20:00	103.7	2.35	2.54	1.60	.83	116,172	10	35.3	.9
36	09/18/2001	23:44	09/22/2001	17:00	89.3	1.22	.32	.29	.25	91,392	15	9.7	1.5
37	09/22/2001	22:34	09/25/2001	06:00	55.4	1.61	1.01	.80	.61	64,039	8	26.0	.2
38	10/22/2001	14:38	10/24/2001	08:09	41.5	1.10	.86	.61	.41	34,534	6	8.6	8.8
39	11/23/2001	22:17	11/25/2001	19:00	44.7	.80	.70	.41	.25	32,721	8	8.9	4.8
40	02/18/2002	22:13	02/23/2002	21:00	118.8	1.44	.22	.18	.16	93,388	13	2.5	8.4
41	03/08/2002	16:53	03/12/2002	19:00	98.1	.25	.36	.25	.14	21,812	17	5.3	.5
42	04/07/2002	03:39	04/07/2002	06:48	3.1	.26	.25	.22	.14	20,005	15	2.5	4.3
43	08/04/2002	02:25	08/04/2002	10:33	8.1	.66	1.60	.92	.48	23,214	7	18.0	7.7
44	08/11/2002	16:34	08/11/2002	17:44	1.2	.98	2.04	1.14	.91	38,108	8	27.2	7.3
45	08/21/2002	18:01	08/22/2002	13:00	19.0	1.01	1.88	1.02	.51	30,426	6	17.1	4.5
46	09/02/2002	03:46	09/02/2002	11:01	7.2	.99	1.04	.80	.52	43,075	9	12.3	10.6
47	09/28/2002	21:44	09/29/2002	05:29	7.8	.67	.96	.66	.34	25,552	8	14.5	8.2
48	03/04/2004	17:40	03/05/2004	11:28	17.8	1.20	.52	.34	.24	74,929	13	7.7	2.9
49	03/25/2004	20:09	03/26/2004	03:17	7.1	1.10	.68	.66	.51	48,617	9	9.1	1.6
50	05/08/2004	06:31	05/09/2004	00:53	18.4	.61	.84	.48	.28	22,379	7	14.5	12.7
51	05/10/2004	02:24	05/10/2004	15:05	12.7	.51	.56	.40	.25	17,935	7	6.9	1.1
52	05/17/2004	20:01	05/18/2004	03:01	7.0	.77	2.28	1.36	.72	23,862	6	22.8	3.3
53	05/21/2004	07:16	05/21/2004	08:28	1.2	.80	1.92	1.02	.75	32,735	8	25.7	3.2
54	05/29/2004	06:54	05/29/2004	12:05	5.2	.64	.28	.24	.21	26,030	8	3.2	4.2
55	05/30/2004	07:58	05/30/2004	10:42	2.7	.71	1.28	.84	.58	27,061	8	13.5	.8
56	05/31/2004	06:54	05/31/2004	21:00	14.1	.19	.16	.14	.10	15,345	16	8.0	.8
57	06/09/2004	21:42	06/10/2004	12:15	14.5	.46	--	--	--	16,194	7	7.7	9.0
58	06/10/2004	14:15	06/11/2004	05:00	14.8	.69	--	--	--	26,353	8	6.8	.1
59	06/12/2004	00:06	06/12/2004	02:04	2.0	.45	.80	.76	.42	16,232	7	7.5	.8
60	06/16/2004	20:26	06/17/2004	03:46	7.3	.52	.36	.32	.25	20,274	8	5.6	4.8
61	06/24/2004	06:04	06/24/2004	11:21	5.3	.39	.32	.22	.16	14,529	7	4.7	2.7

Appendix table 2-2. Hydrologic and precipitation characteristics of sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed; n/a, data not available]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
62	07/03/2004	15:06	07/04/2004	00:04	9.0	1.40	1.72	1.24	0.76	53,015	8	31.6	5.8
63	07/09/2004	11:33	07/09/2004	12:43	1.2	.35	.76	.58	.33	11,141	6	7.1	5.5
64	07/16/2004	10:01	07/16/2004	16:41	6.7	1.94	5.08	2.96	1.50	83,778	9	96.0	4.8
65	07/21/2004	07:49	07/21/2004	10:36	2.8	.39	.44	.28	.16	15,284	8	5.3	4.6
66	07/29/2004	13:07	07/29/2004	17:31	4.4	.26	.32	.16	.12	8,334	6	4.5	8.1
67	08/01/2004	05:59	08/01/2004	07:08	1.2	.32	.68	.40	.30	12,909	8	8.2	1.7
68	08/02/2004	10:00	08/02/2004	11:43	1.7	.45	.88	.62	.35	16,702	7	8.4	1.1
69	08/03/2004	17:51	08/04/2004	01:25	7.6	1.20	3.84	2.02	1.09	45,887	8	60.9	1.3
70	08/18/2004	17:14	08/18/2004	18:40	1.4	.47	1.20	.86	.46	17,594	8	12.3	14.7
71	09/01/2004	03:48	09/01/2004	05:39	1.9	.50	.96	.56	.40	19,549	8	11.8	5.1
72	09/15/2004	09:29	09/15/2004	15:32	6.0	.56	1.08	.56	.28	21,598	8	18.4	14.2
73	10/07/2004	23:24	10/08/2004	06:29	7.1	.87	.64	.58	.48	39,630	9	10.8	6.1
74	10/22/2004	17:14	10/23/2004	09:23	16.2	.76	.24	.20	.19	33,845	9	3.9	3.5
75	10/29/2004	22:38	10/29/2004	23:07	.5	.49	1.64	--	--	17,514	7	25.8	3.1
76	11/26/2004	22:08	11/27/2004	16:24	18.3	.48	.12	.08	.07	8,736	4	1.1	6.9
77	12/05/2004	21:12	12/06/2004	07:29	10.3	.34	.20	.16	.14	11,047	7	1.7	8.2
78	12/07/2004	00:44	12/07/2004	11:18	10.6	.57	.16	.16	.14	26,418	9	2.8	.7
79	01/01/2005	19:30	01/02/2005	18:00	22.5	snowmelt	--	--	--	54,887	<1	10.9	22.0
80	01/12/2005	06:46	01/13/2005	02:00	19.2	1.54[b]	.80	.70	.61	47,572	6	3.2	9.5
81	03/22/2005	12:00	03/23/2005	19:00	31.0	snowmelt	--	--	--	47,696	<1	2.7	.6
82	03/24/2005	12:00	03/24/2005	19:00	7.0	snowmelt	--	--	--	23,262	<1	2.1	.7
83	03/30/2005	13:31	03/30/2005	18:18	4.8	.53	.84	.52	.27	16,617	6	10.5	1.0
84	04/06/2005	18:54	04/06/2005	20:38	1.7	.42	.76	.56	.37	15,664	7	7.4	7.0
85	05/11/2005	03:50	05/11/2005	10:04	6.2	.77	.32	.30	.28	40,592	11	6.4	1.9
86	05/13/2005	00:49	05/13/2005	06:34	5.7	.4	.56	.40	.31	18,933	10	8.8	1.6
87	05/18/2005	21:36	05/19/2005	03:14	5.6	.39	.36	.30	.20	15,701	8	5.4	5.6
88	06/05/2005	01:06	06/05/2005	03:44	2.6	.34	.48	.38	.27	384	<1	.3	8.6
89	06/24/2005	18:38	06/25/2005	04:44	10.1	.49	.28	.18	.12	1,336	1	1.2	9.9
90	06/30/2005	01:41	06/30/2005	01:45	.1	.11	--	--	--	1,686	3	.2	4.0

Appendix table 2-2. Hydrologic and precipitation characteristics of sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; in/h, inch per hour; ft^3, cubic foot; %, percent; ft^3/s, cubic foot per second; <, less than; --, not computed; n/a, data not available]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Duration (hours)	Precipitation depth (inches)	15-minute precipitation intensity (in/h)	30-minute precipitation intensity (in/h)	60-minute precipitation intensity (in/h)	Total event volume (ft^3)	Runoff (%)	Peak flow (ft^3/s)	Antecedent dry time (days)
91	07/21/2005	08:45	07/21/2005	13:28	4.7	1.42	3.28	2.30	1.25	37,675	5	21.1	0.9
92	07/25/2005	00:47	07/26/2005	02:20	25.5	1.69	2.48	1.32	.78	49,441	6	23.3	1.5
93	08/11/2005	07:12	08/11/2005	23:41	16.5	.42	.32	.20	.18	11,118	5	3.5	16.2
94	08/26/2005	19:29	08/26/2005	20:30	1.0	.24	.40	.38	.23	10,045	8	7.0	8.4
95	09/13/2005	16:17	09/13/2005	16:35	.3	.23	.88	--	--	7,750	7	16.7	17.8
96	09/19/2005	05:07	09/19/2005	07:18	2.2	.56	1.28	.80	.43	16,137	6	13.4	5.5
97	09/22/2005	02:49	09/22/2005	12:29	9.7	.4	.56	.36	.26	15,362	8	9.2	2.8
98	09/25/2005	09:46	09/25/2005	21:08	11.4	1.06	1.64	1.02	.61	37,292	7	21.8	2.9

[a] Single discharge event separated into two sampled periods.

[b] Combination rainfall and snowmelt event.

Appendix table 2-3. Event mean concentrations for sampled discharge events in the low-impact-development (LID) basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; mg/L, milligram per liter; --, not computed; n/a, data not available]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (mg/L)	Total suspended solids (mg/L)	Total phosphorus (mg/L)
2	10/05/1998	17:19	10/05/1998	20:07	152	82	--
3	02/11/1999	13:27	02/11/1999	16:30	3,110	2,550	--
4	04/22/1999	19:21	04/23/1999	09:52	n/a	n/a	n/a
5	05/16/1999	21:56	05/17/1999	19:31	926	300	1.77
6	06/30/1999	23:38	07/01/1999	09:52	1,270	108	--
7	07/17/1999	02:46	07/17/1999	15:10	880	974	--
8	07/20/1999	13:48	07/24/1999	18:40	n/a	n/a	--
9	08/23/1999	08:36	08/25/1999	10:35	n/a	n/a	n/a
10	02/23/2000	09:00	02/24/2000	22:00	n/a	n/a	n/a
11	02/25/2000	18:14	02/26/2000	12:49	n/a	n/a	n/a
13, 14, 15[a]	04/20/2000	00:16	04/22/2000	07:42	n/a	n/a	n/a
16	05/17/2000	12:49	05/19/2000	21:53	570	320	2.94
17	05/30/2000	06:23	06/01/2000	15:00	356	91	.53
18	06/13/2000	15:36	06/15/2000	02:54	434	132	.59
19	07/02/2000	19:34	07/03/2000	17:07	352	212	.57
20	07/10/2000	03:40	07/11/2000	02:25	216	84	.28
21	08/05/2000	11:09	08/06/2000	03:54	804	600	1.03
22	08/17/2000	02:23	08/18/2000	01:50	134	44	.27
23	09/11/2000	07:37	09/12/2000	14:03	350	252	.71
24	09/22/2000	09:16	09/24/2000	03:07	80	22	.27
25	04/09/2001	23:18	04/10/2001	03:10	228	35	.30
26	04/11/2001	06:01	04/12/2001	13:48	260	82	.36
27	04/21/2001	00:11	04/21/2001	23:55	182	40	.28
28	05/20/2001	23:50	05/22/2001	05:59	148	72	.25
29	05/23/2001	01:34	05/23/2001	21:03	108	12	.11
30	06/05/2001	01:29	06/06/2001	06:40	108	22	.16
31	08/01/2001	18:00	08/03/2001	13:30	n/a	n/a	n/a
32	09/07/2001	19:05	09/09/2001	00:02	196	61	--
33	09/18/2001	23:28	09/20/2001	10:48	116	8	.30
34	09/22/2001	22:34	09/24/2001	15:23	176	54	.39
35	10/22/2001	14:36	10/23/2001	22:14	116	16	.56
36	11/23/2001	22:17	11/25/2001	13:20	114	13	.35
37	02/18/2002	22:10	02/21/2002	20:19	222	21	.24
38	04/07/2002	15:14	04/09/2002	16:25	182	14	.22
39	03/04/2004	18:04	03/06/2004	12:24	252	77	.31
40	03/25/2004	14:20	03/27/2004	05:25	288	82	.44
41	05/21/2004	07:16	05/24/2004	10:00	468	273	.67
42	05/29/2004	06:41	06/01/2004	00:00	206	80	.32
43	07/03/2004	15:03	07/04/2004	12:00	112	31	.27
44	07/16/2004	10:01	07/17/2004	10:00	382	224	.66
45	08/03/2004	17:51	08/04/2004	14:00	348	175	.84
46	01/12/2005	13:04	01/13/2005	15:38	646	22	.37
47	03/21/2005	14:00	03/24/2005	19:10	136	23	.44
48	03/24/2005	10:00	03/25/2005	21:45	164	15	.31
49	03/30/2005	13:33	03/31/2005	17:14	156	25	.24

[a] Single discharge event separated into three sampled periods.

Appendix table 2-4. Event mean concentrations for sampled discharge events in the conventional-development basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; mg/L, milligram per liter; --, not computed; n/a, data not available; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (mg/L)	Total suspended solids (mg/L)	Total phosphorus (mg/L)
1	10/05/1998	18:01	10/05/1998	19:55	138	125	--
3	04/21/1999	20:58	04/26/1999	03:50	n/a	n/a	n/a
4	05/16/1999	16:25	05/17/1999	22:45	n/a	n/a	n/a
5	06/06/1999	14:24	06/07/1999	04:24	118	80	--
7	07/16/1999	20:34	07/18/1999	02:00	1,770	47	--
8	07/20/1999	13:07	07/21/1999	20:07	84	69	--
9	08/23/1999	08:35	08/24/1999	14:45	82	52	0.08
12	04/19/2000	07:45	04/19/2000	12:40	n/a	n/a	n/a
13, 14[a]	04/20/2000	00:18	04/21/2000	10:00	n/a	n/a	n/a
13a	05/17/2000	12:47	05/21/2000	15:15	278	256	.37
14a	05/26/2000	22:14	06/01/2000	18:13	376	312	.32
15	06/12/2000	05:50	06/15/2000	22:15	n/a	n/a	n/a
16	07/02/2000	19:36	07/04/2000	21:07	168	128	.16
17	07/10/2000	03:41	07/11/2000	16:00	46	17	.06
18	08/05/2000	11:10	08/07/2000	17:00	98	79	.14
19	08/17/2000	02:23	08/19/2000	06:00	42	25	.07
20	09/11/2000	07:38	09/13/2000	17:00	106	71	.25
21	09/22/2000	09:36	09/24/2000	00:30	38	14	.09
22	01/29/2001	11:08	01/31/2001	03:00	10,000	49	.20
23	02/08/2001	14:47	02/10/2001	16:00	1,410	51	.16
24	02/24/2001	09:21	02/25/2001	11:50	646	60	.21
25	04/10/2001	22:49	04/14/2001	00:20	366	193	.25
26	04/21/2001	00:10	04/22/2001	15:00	396	300	.30
27	05/10/2001	19:40	05/12/2001	21:50	152	113	.22
28	05/20/2001	23:58	05/23/2001	01:27	118	59	.13
29	05/23/2001	01:28	05/24/2001	22:00	206	18	.09
30	06/05/2001	01:29	06/07/2001	12:00	320	21	.05
31	06/11/2001	22:04	06/13/2001	21:10	298	148	.25
32	07/18/2001	07:21	07/20/2001	13:00	132	42	.10
33	08/01/2001	18:00	08/04/2001	23:00	n/a	n/a	n/a
34	08/24/2001	19:05	08/27/2001	04:00	122	59	.06
35	09/07/2001	12:19	09/11/2001	20:00	98	59	--
36	09/18/2001	23:44	09/22/2001	17:00	78	17	.07
37	09/22/2001	22:34	09/25/2001	06:00	74	32	.08
38	10/22/2001	14:38	10/24/2001	08:09	94	44	.13
39	11/23/2001	22:17	11/25/2001	19:00	82	60	.10
40	02/18/2002	22:13	02/23/2002	21:00	3,050	28	.12
41	03/08/2002	16:53	03/12/2002	19:00	1,050	234	.29
42	04/07/2002	03:39	04/07/2002	06:48	180	26	.08
43	08/04/2002	02:25	08/04/2002	10:33	112	55	.11
44	08/11/2002	16:34	08/11/2002	17:44	104	56	.12

Appendix table 2-4. Event mean concentrations for sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; mg/L, milligram per liter; --, not computed; n/a, data not available; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (mg/L)	Total suspended solids (mg/L)	Total phosphorus (mg/L)
45	08/21/2002	18:01	08/22/2002	13:00	54	35	0.08
46	09/02/2002	03:46	09/02/2002	11:01	64	42	.08
47	09/28/2002	21:44	09/29/2002	05:29	112	71	--
48	03/04/2004	17:40	03/05/2004	11:28	138	54	.20
49	03/25/2004	20:09	03/26/2004	03:17	188	132	.13
50	05/08/2004	06:31	05/09/2004	00:53	270	179	.24
51	05/10/2004	02:24	05/10/2004	15:05	92	47	.18
52	05/17/2004	20:01	05/18/2004	03:01	164	105	.19
53	05/21/2004	07:16	05/21/2004	08:28	96	56	.14
54	05/29/2004	06:54	05/29/2004	12:05	<50	16	.07
55	05/30/2004	07:58	05/30/2004	10:42	88	54	.07
56	05/31/2004	06:54	05/31/2004	21:00	98	66	.12
57	06/09/2004	21:42	06/10/2004	12:15	<50	26	.10
58	06/10/2004	14:15	06/11/2004	05:00	78	30	.06
59	06/12/2004	00:06	06/12/2004	02:04	<50	19	.07
60	06/16/2004	20:26	06/17/2004	03:46	<50	21	.11
61	06/24/2004	06:04	06/24/2004	11:21	60	24	.10
62	07/03/2004	15:06	07/04/2004	00:04	78	47	.15
63	07/09/2004	11:33	07/09/2004	12:43	100	43	.15
64	07/16/2004	10:01	07/16/2004	16:41	192	117	.22
65	07/21/2004	07:49	07/21/2004	10:36	94	32	.20
66	07/29/2004	13:07	07/29/2004	17:31	104	51	.30
67	08/01/2004	05:59	08/01/2004	07:08	76	51	.11
68	08/02/2004	10:00	08/02/2004	11:43	60	27	.08
69	08/03/2004	17:51	08/04/2004	01:25	134	87	.19
70	08/18/2004	17:14	08/18/2004	18:40	154	105	.22
71	09/01/2004	03:48	09/01/2004	05:39	78	43	.15
72	09/15/2004	09:29	09/15/2004	15:32	120	64	.24
73	10/07/2004	23:24	10/08/2004	06:29	66	16	.11
74	10/22/2004	17:14	10/23/2004	09:23	52	14	.13
75	10/29/2004	22:38	10/29/2004	23:07	214	108	--
76	11/26/2004	22:08	11/27/2004	16:24	<50	11	.07
77	12/05/2004	21:12	12/06/2004	07:29	74	19	.09
78	12/07/2004	00:44	12/07/2004	11:18	<50	17	.07
79	01/01/2005	19:30	01/02/2005	18:00	456	10	.30
80	01/12/2005	06:46	01/13/2005	02:00	690	33	.36
81	03/22/2005	12:00	03/23/2005	19:00	222	32	.43
82	03/24/2005	12:00	03/24/2005	19:00	--	29	.50
83	03/30/2005	13:31	03/30/2005	18:18	530	364	.52
84	04/06/2005	18:54	04/06/2005	20:38	210	143	.18

Appendix table 2-4. Event mean concentrations for sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; mg/L, milligram per liter; --, not computed; n/a, data not available; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (mg/L)	Total suspended solids (mg/L)	Total phosphorus (mg/L)
85	05/11/2005	03:50	05/11/2005	10:04	--	--	.14
86	05/13/2005	00:49	05/13/2005	06:34	110	73	0.13
87	05/18/2005	21:36	05/19/2005	03:14	82	39	.13
88	06/05/2005	01:06	06/05/2005	03:44	176	123	.39
89	06/24/2005	18:38	06/25/2005	04:44	174	74	.27
90	06/30/2005	01:41	06/30/2005	01:45	--	--	--
91	07/21/2005	08:45	07/21/2005	13:28	350	167	.19
92	07/25/2005	00:47	07/26/2005	02:20	90	56	.09
93	08/11/2005	07:12	08/11/2005	23:41	104	57	.13
94	08/26/2005	19:29	08/26/2005	20:30	136	88	.22
95	09/13/2005	16:17	09/13/2005	16:35	--	--	.39
96	09/19/2005	05:07	09/19/2005	07:18	--	--	.17
97	09/22/2005	02:49	09/22/2005	12:29	150	100	.20
98	09/25/2005	09:46	09/25/2005	21:08	80	49	.10

[a] Single discharge event separated into three sampled periods.

Appendix table 2-5. Constituent loads computed for sampled discharge events in the low-impact-development (LID) basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; --, no data]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (pounds)	Total suspended solids (pounds)	Total phosphorus (pounds)
2	10/05/1998	17:19	10/05/1998	20:07	4	2	--
3	02/11/1999	13:27	02/11/1999	16:30	289	237	--
4	04/22/1999	19:21	04/23/1999	09:52	487	288	0.94
5	05/16/1999	21:56	05/17/1999	19:31	54	17	.10
6	06/30/1999	23:38	07/01/1999	09:52	110	9	--
7	07/17/1999	02:46	07/17/1999	15:10	27	29	--
8	07/20/1999	13:48	07/24/1999	18:40	1,096	787	--
9	08/23/1999	08:36	08/25/1999	10:35	390	160	.41
10	02/23/2000	09:00	02/24/2000	22:00	430	86	.77
11	02/25/2000	18:14	02/26/2000	12:49	363	131	.43
13, 14, 15[a]	04/20/2000	00:16	04/22/2000	07:42	436	102	.49
16	05/17/2000	12:49	05/19/2000	21:53	10,495	5,892	54.13
17	05/30/2000	06:23	06/01/2000	15:00	5,870	1,501	8.66
18	06/13/2000	15:36	06/15/2000	02:54	4,895	1,489	6.69
19	07/02/2000	19:34	07/03/2000	17:07	141	85	.23
20	07/10/2000	03:40	07/11/2000	02:25	56	22	.07
21	08/05/2000	11:09	08/06/2000	03:54	1,103	823	1.41
22	08/17/2000	02:23	08/18/2000	01:50	44	14	.09
23	09/11/2000	07:37	09/12/2000	14:03	194	140	.39
24	09/22/2000	09:16	09/24/2000	03:07	67	18	.23
25	04/09/2001	23:18	04/10/2001	03:10	137	21	.18
26	04/11/2001	06:01	04/12/2001	13:48	588	186	.81
27	04/21/2001	00:11	04/21/2001	23:55	94	21	.14
28	05/20/2001	23:50	05/22/2001	05:59	355	173	.60
29	05/23/2001	01:34	05/23/2001	21:03	15	2	.02
30	06/05/2001	01:29	06/06/2001	06:40	116	24	.17
31	08/01/2001	18:00	08/03/2001	13:30	23,260	20,670	31.56
32	09/07/2001	19:05	09/09/2001	00:02	254	79	--
33	09/18/2001	23:28	09/20/2001	10:48	184	13	.47
34	09/22/2001	22:34	09/24/2001	15:23	971	298	2.15
35	10/22/2001	14:36	10/23/2001	22:14	48	7	.23
36	11/23/2001	22:17	11/25/2001	13:20	70	8	.21
37	02/18/2002	22:10	02/21/2002	20:19	732	69	.80
38	04/07/2002	15:14	04/09/2002	16:25	168	13	.20
39	03/04/2004	18:04	03/06/2004	12:24	1,241	379	1.52
40	03/25/2004	14:20	03/27/2004	05:25	631	180	.96
41	05/21/2004	07:16	05/24/2004	10:00	13,720	8,003	19.76
42	05/29/2004	06:41	06/01/2004	00:00	360	140	.56
43	07/03/2004	15:03	07/04/2004	12:00	46	13	.11
44	07/16/2004	10:01	07/17/2004	10:00	1,417	831	2.45
45	08/03/2004	17:51	08/04/2004	14:00	788	396	1.90
46	01/12/2005	13:04	01/13/2005	15:38	1,098	37	.64
47	03/21/2005	14:00	03/24/2005	19:10	186	31	.60
48	03/24/2005	10:00	03/25/2005	21:45	55	5	.10
49	03/30/2005	13:33	03/31/2005	17:14	40	6	.06

[a] Single discharge event separated into three sampled periods.

Appendix table 2-6. Constituent loads computed for sampled discharge events in the conventional-development basin.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; --, no data; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (pounds)	Total suspended solids (pounds)	Total phosphorus (pounds)
1	10/05/1998	18:01	10/05/1998	19:55	305	276	--
3	04/21/1999	20:58	04/26/1999	03:50	399	126	0.40
4	05/16/1999	16:25	05/17/1999	22:45	919	728	.77
5	06/06/1999	14:24	06/07/1999	04:24	249	169	--
7	07/16/1999	20:34	07/18/1999	02:00	7,681	204	--
8	07/20/1999	13:07	07/21/1999	20:07	332	273	--
9	08/23/1999	08:35	08/24/1999	14:45	229	145	.24
12	04/19/2000	07:45	04/19/2000	12:40	90	30	.07
12[a]	04/20/2000	00:18	04/21/2000	10:00	880	270	.38
13	05/17/2000	12:47	05/21/2000	15:15	4,028	3,710	5.36
14	05/26/2000	22:14	06/01/2000	18:13	4,910	4,074	4.13
15	06/12/2000	05:50	06/15/2000	22:15	3,000	1,858	2.98
16	07/02/2000	19:36	07/04/2000	21:07	559	426	.53
17	07/10/2000	03:41	07/11/2000	16:00	134	49	.16
18	08/05/2000	11:10	08/07/2000	17:00	492	397	.71
19	08/17/2000	02:23	08/19/2000	06:00	116	69	.20
20	09/11/2000	07:38	09/13/2000	17:00	348	233	.80
21	09/22/2000	09:36	09/24/2000	00:30	67	25	.15
22	01/29/2001	11:08	01/31/2001	03:00	41,704	204	.84
23	02/08/2001	14:47	02/10/2001	16:00	7,231	262	.79
24	02/24/2001	09:21	02/25/2001	11:50	1,260	117	.41
25	04/10/2001	22:49	04/14/2001	00:20	671	354	.46
26	04/21/2001	00:10	04/22/2001	15:00	505	382	.38
27	05/10/2001	19:40	05/12/2001	21:50	392	292	.58
28	05/20/2001	23:58	05/23/2001	01:27	516	258	.58
29	05/23/2001	01:28	05/24/2001	22:00	297	26	.13
30	06/05/2001	01:29	06/07/2001	12:00	1,277	84	.22
31	06/11/2001	22:04	06/13/2001	21:10	3,212	1,595	2.73
32	07/18/2001	07:21	07/20/2001	13:00	321	102	.23
33	08/01/2001	18:00	08/04/2001	23:00	3,954	3,068	6.25
34	08/24/2001	19:05	08/27/2001	04:00	378	183	.19
35	09/07/2001	12:19	09/11/2001	20:00	711	428	--
36	09/18/2001	23:44	09/22/2001	17:00	445	97	.37
37	09/22/2001	22:34	09/25/2001	06:00	296	128	.31
38	10/22/2001	14:38	10/24/2001	08:09	203	95	.28
39	11/23/2001	22:17	11/25/2001	19:00	168	123	.20
40	02/18/2002	22:13	02/23/2002	21:00	17,782	163	.72
41	03/08/2002	16:53	03/12/2002	19:00	1,430	319	.40
42	04/07/2002	03:39	04/07/2002	06:48	225	32	.10
43	08/04/2002	02:25	08/04/2002	10:33	162	80	.16

Appendix table 2-6. Constituent loads computed for sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; --, no data; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (pounds)	Total suspended solids (pounds)	Total phosphorus (pounds)
44	08/11/2002	16:34	08/11/2002	17:44	247	133	0.29
45	08/21/2002	18:01	08/22/2002	13:00	103	66	.14
46	09/02/2002	03:46	09/02/2002	11:01	172	113	.23
47	09/28/2002	21:44	09/29/2002	05:29	179	113	--
48	03/04/2004	17:40	03/05/2004	11:28	646	253	.92
49	03/25/2004	20:09	03/26/2004	03:17	571	401	.39
50	05/08/2004	06:31	05/09/2004	00:53	377	250	.34
51	05/10/2004	02:24	05/10/2004	15:05	103	53	.21
52	05/17/2004	20:01	05/18/2004	03:01	244	156	.29
53	05/21/2004	07:16	05/21/2004	08:28	196	114	.28
54	05/29/2004	06:54	05/29/2004	12:05	<82	26	.12
55	05/30/2004	07:58	05/30/2004	10:42	149	91	.11
56	05/31/2004	06:54	05/31/2004	21:00	94	63	.12
57	06/09/2004	21:42	06/10/2004	12:15	<50	26	.10
58	06/10/2004	14:15	06/11/2004	05:00	128	49	.10
59	06/12/2004	00:06	06/12/2004	02:04	<50	19	.07
60	06/16/2004	20:26	06/17/2004	03:46	<64	27	.14
61	06/24/2004	06:04	06/24/2004	11:21	54	22	.09
62	07/03/2004	15:06	07/04/2004	00:04	258	156	.49
63	07/09/2004	11:33	07/09/2004	12:43	70	30	.11
64	07/16/2004	10:01	07/16/2004	16:41	1,004	612	1.16
65	07/21/2004	07:49	07/21/2004	10:36	90	31	.19
66	07/29/2004	13:07	07/29/2004	17:31	54	27	.15
67	08/01/2004	05:59	08/01/2004	07:08	61	41	.09
68	08/02/2004	10:00	08/02/2004	11:43	63	28	.09
69	08/03/2004	17:51	08/04/2004	01:25	384	249	.56
70	08/18/2004	17:14	08/18/2004	18:40	169	115	.24
71	09/01/2004	03:48	09/01/2004	05:39	95	52	.18
72	09/15/2004	09:29	09/15/2004	15:32	162	86	.33
73	10/07/2004	23:24	10/08/2004	06:29	163	40	.27
74	10/22/2004	17:14	10/23/2004	09:23	110	30	.27
75	10/29/2004	22:38	10/29/2004	23:07	234	118	--
76	11/26/2004	22:08	11/27/2004	16:24	<28	6	.04
77	12/05/2004	21:12	12/06/2004	07:29	51	13	.06
78	12/07/2004	00:44	12/07/2004	11:18	<82	28	.11
79	01/01/2005	19:30	01/02/2005	18:00	1,562	34	1.02
80	01/12/2005	06:46	01/13/2005	02:00	2,049	98	1.08
81	03/22/2005	12:00	03/23/2005	19:00	661	95	1.29
82	03/24/2005	12:00	03/24/2005	19:00	--	42	.73

Appendix table 2-6. Constituent loads computed for sampled discharge events in the conventional-development basin—Continued.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; --, no data; <, less than]

Sample number	Start date (mm/dd/yyyy)	Start time (hh:mm)	End date (mm/dd/yyyy)	End time (hh:mm)	Total solids (pounds)	Total suspended solids (pounds)	Total phosphorus (pounds)
83	03/30/2005	13:31	03/30/2005	18:18	550	378	.53
84	04/06/2005	18:54	04/06/2005	20:38	205	140	0.18
85	05/11/2005	03:50	05/11/2005	10:04	--	--	.36
86	05/13/2005	00:49	05/13/2005	06:34	130	86	.15
87	05/18/2005	21:36	05/19/2005	03:14	80	38	.13
88	06/05/2005	01:06	06/05/2005	03:44	4	3	.01
89	06/24/2005	18:38	06/25/2005	04:44	15	6	.02
90	06/30/2005	01:41	06/30/2005	01:45	--	--	--
91	07/21/2005	08:45	07/21/2005	13:28	823	393	.45
92	07/25/2005	00:47	07/26/2005	02:20	278	173	.29
93	08/11/2005	07:12	08/11/2005	23:41	72	40	.09
94	08/26/2005	19:29	08/26/2005	20:30	85	55	.14
95	09/13/2005	16:17	09/13/2005	16:35	--	--	.19
96	09/19/2005	05:07	09/19/2005	07:18	--	--	.17
97	09/22/2005	02:49	09/22/2005	12:29	144	96	.19
98	09/25/2005	09:46	09/25/2005	21:08	186	114	.24

[a] Single discharge event separated into three sampled periods.

Prepared by the Wisconsin Water Science Center:

U.S. Geological Survey
Wisconsin Water Science Center
8505 Research Way
Middleton, WI 53562
tel: (608) 828-9901
fax: (608) 821-3817

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