



COMPARISON OF STORMWATER LAG TIMES FOR LOW IMPACT AND TRADITIONAL RESIDENTIAL DEVELOPMENT¹

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ABSTRACT: This study compared lag time characteristics of low impact residential development with traditional residential development. Also compared were runoff volume, peak discharge, hydrograph kurtosis, runoff coefficient, and runoff threshold. Low impact development (LID) had a significantly greater centroid lag-to-peak, centroid lag, lag-to-peak, and peak lag-to-peak times than traditional development. Traditional development had a significantly greater depth of discharge and runoff coefficient than LID. The peak discharge in runoff from the traditional development was 1,100% greater than from the LID. The runoff threshold of the LID (6.0 mm) was 100% greater than the traditional development (3.0 mm). The hydrograph shape for the LID watershed had a negative value of kurtosis indicating a leptokurtic distribution, while traditional development had a positive value of kurtosis indicating a platykurtic distribution. The lag times of the LID were significantly greater than the traditional watershed for small (<25.4 mm) but not large (≥ 25.4 mm) storms; short duration (<4 h) but not long duration (≥ 4 h) storms; and low antecedent moisture condition (AMC; <25.4 mm) storms but not high AMC (≥ 25.4 mm) storms. This study indicates that LID resulted in lowered peak discharge depth, runoff coefficient, and discharge volume and increased lag times and runoff threshold compared with traditional residential development.

(KEY TERMS: hydrograph analysis; stormwater runoff; urban hydrology; stormwater management; low impact development; watershed management.)

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INTRODUCTION

Low impact development (LID) is being widely promoted to control runoff and prevent downstream floods (ASCE, 1992); yet, little is known about the hydrologic impacts of LID compared with traditional development. Common LID stormwater techniques include: disconnected impervious areas, swales and

filter strips, porous pavement (ASCE, 1992), bio-retention (USEPA, 2000), and cluster development (Schueler, 1994). Generally, LID utilizes on-site detention and infiltration of runoff to control the water quantity and quality impacts of urbanization (Ferguson, 1994; Coffman, 2000). The LID approach to stormwater management has been cited by several researchers (Klein, 1979; ASCE, 1992; Ellis, 2000; Ferguson, 2005) as the most effective way to mitigate

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the impact of urban land use. The lack of research pertaining to LID creates a need to link specific development types with hydrologic impacts (Bledsoe and Watson, 2001).

Urbanization has been shown to increase the runoff volume and peak discharge (Leopold, 1968; Waananen, 1969; Hammer, 1972; Hollis, 1975, 1977; Ferguson, 1994) and decrease the lag time (James, 1965; Leopold, 1968, 1991; Anderson, 1970; Pawlow, 1977; Kang *et al.*, 1998; Booth *et al.*, 2002) for a watershed. The modified hydrology caused by urbanization is primarily a result of increased impervious area (Leopold, 1968), compaction of soils (Booth and Jackson, 1997), and channelization of storm flow (James, 1965; Leopold, 1968). Increased imperviousness and compaction of soils reduces infiltration and increases the volume of stormwater runoff. The installation of stormwater sewer pipes and exchange of subsurface flow for overland flow allows water to be transported away from a catchment at a greater velocity than under natural conditions (Loukas and Quick, 1996; Elsenbeer and Vertesy, 2000; Booth *et al.*, 2002). The increased volume of water being transported at a greater velocity results in an abbreviated hydrograph that peaks sooner than in a basin under natural conditions. The lag time of an urbanized watershed is thus shorter than an unaltered watershed.

Lag time is a theoretically useful value that acts like a fingerprint of a watershed because it incorporates many aspects of runoff generation (Leopold, 1991). The characteristics which affect lag time include watershed size, soils, geology, slope, and land use (Dingman, 2002), precipitation amount and duration (Pawlow, 1977), timing of peak rainfall intensity (Askew, 1968), and antecedent precipitation (Kang *et al.*, 1998). Most studies that address lag time have focused on the development of a predictive model for flood planning (Snyder, 1938; Watt and Chow, 1985; Loukas and Quick, 1996) or have compared natural areas to urban development (Pawlow, 1977; Kang *et al.*, 1998). For example, Pawlow (1977) and Kang *et al.* (1998) studied watershed development over time and found centroid lag-to-peak time to decrease with increased urbanization. There have been no reports that compare the lag time of a traditional residential development with that of a LID.

Phillips *et al.* (2003) previously found in the Jordan Cove Urban Watershed Project in Connecticut that, during construction, LID reduced runoff volume and peak discharge compared with traditional development by examining weekly data. The purpose of this study was to compare the lag time, runoff volume, peak discharge, runoff coefficient, and runoff threshold characteristics of LID with traditional residential development. This study also compared the

effects of storms of various size, duration, and antecedent moisture condition (AMC) on discharge characteristics.

METHODS

Site Description

The study was located in the town of Waterford in Southeastern Connecticut (Figure 1). Three relatively small watersheds, that ultimately drain into Jordan Cove and Long Island Sound, were included in the project (Table 1). Two watersheds (traditional and control) represented traditional development (Figure 1a and c). Residential developments, which incorporated standard stormwater management practices, were built within the traditional and control watershed in 2003 and 1988, respectively. The control watershed was originally utilized in the calibration of the paired watersheds (Clausen and Spooner, 1993) used by the Jordan Cove Urban Watershed Project (Phillips *et al.*, 2003). Despite its earlier construction, the control watershed was used as a second example of traditional development in this study. Standard curb and gutter stormwater collection practices were used in the control and traditional watersheds. This included installation of 8.5 m-wide asphalt roads and roadside curbs. Roof runoff was directed onto asphalt driveways, which conveyed runoff to the roads. Road and driveway runoff was transported along roadside curbs into catchbasins where it was carried from the site through stormwater drainage pipes.

The third watershed (LID) refers to the drainage area in which a low impact residential subdivision was built in 2002 (Figure 1b). The storm-flow reduction measures incorporated into this development included shared driveways for 10 of 12 lots and a large bioretention area located in the middle of the cul de sac in place of a paved area. Each house lot incorporated a bioretention rain garden, which retained roof and lot runoff. These bioretention areas allow for retention and infiltration of runoff (Dietz and Clausen, 2005). A 6.1 m-wide infiltrating concrete paver road and grassed bioretention swales were used in place of a curb and gutter stormwater collection system. The absence of a roadside curb allowed road and driveway runoff to be directed into the grassed swales, which conveyed storm runoff from the site. Driveway materials varied with two made of crushed stone, two of concrete pavers, and three of asphalt (Gilbert and Clausen, 2006). Cluster development within the LID watershed allowed for

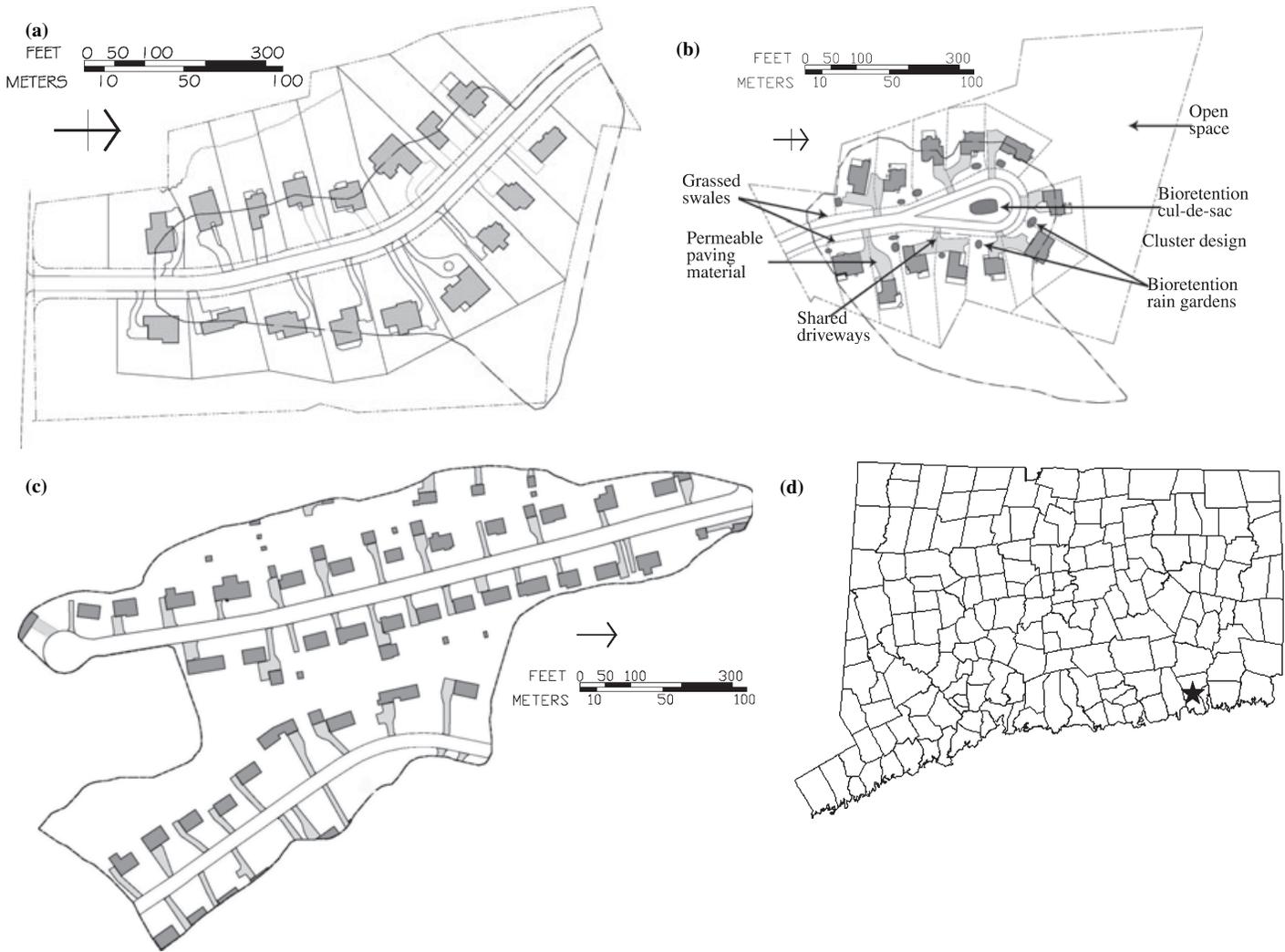


FIGURE 1 (a) Traditional Subdivision Area and Location of Monitoring Station. Dark dashed line indicates watershed area. (b) Low impact development subdivision area, location of monitoring station, and selected BMPs. Dark dashed line indicates watershed area. (c) Control subdivision watershed area and location of monitoring station. (d) Location of project within the state of Connecticut.

TABLE 1. Characteristics of Study Watersheds.

	LID	Control	Traditional
Watershed area (ha)	1.7	5.5	2.0
Number of lots	12	43	17
Imperviousness (%)	22	29	32
Slope	0.059	0.012	0.015
Length (m)	207	335	219
Time of concentration (min)	44.3	11.2	22.8

Note: LID = low impact development.

1.8 ha (26%) of developable land be dedicated for open space. Open space is defined by town regulations as space not occupied by a building or other roofed structure. The control and traditional watersheds contain no land dedicated as open space.

Using Technical Release 55 (USDA, 1986), the time of concentration for the LID watershed was two times greater than for the traditional watershed and four times greater than for the control watershed (Table 1). The presence of forest with dense underbrush and the lack of a curb and gutter stormwater collection system contributed to the LID watershed's increased time of concentration. The LID watershed also had less impervious area than the control and traditional watersheds (Table 1).

The project was located in a climate that is influenced by both continental polar and maritime tropical air masses (Brunbach, 1965). Normal annual precipitation was 1,265 mm and distributed uniformly throughout the year. Large storms may occur as nor'easters (winter/spring) local convective

(summer) or tropical storms/hurricanes (late summer/fall).

Soils on the site were originally mapped as Canton and Charlton but Udorthents soils associated with development are now found extensively throughout the watersheds. Before construction, the LID watershed was a closed-out gravel pit, which had most topsoil removed. Prior to construction, the traditional watershed contained poultry buildings, a house, and a parking lot. During construction, soil was brought in to assist with road construction, grading, and landscaping. Soils in the control watershed were classified as Udorthents.

Monitoring Methods

Precipitation was recorded at the LID watershed at 15 min intervals using a heated, tipping-bucket rain gauge. Air temperature was continuously monitored to allow for exclusion of runoff events caused by snowmelt.

Stormwater flow was monitored continuously from the three watersheds using ISCO 4230 bubbler flowmeters. These meters are accurate to 0.003 m. Levels were compared weekly to permanent staff gages and adjusted if ≥ 6.1 mm differences occurred. At the control watershed, a combination rectangular/V-notch weir installed in a 760 mm stormwater sewer pipe was used to measure flow. The traditional watershed used a 381 mm Palmer-Bowlus flume attached to a stormwater pipe located in a monitoring manhole. A 457 mm H-flume embedded in a concrete wall was used at the end of a grassed swale in the LID watershed. Accuracy of these devices are generally 2-5% depending on accuracy of level measurement (USDIBOR, 1997).

Storms selected for this study were those that had: (1) a minimum of 1.27 mm of precipitation, (2) a minimum of 30 min of no rainfall preceding and following the event, (3) a minimum of 30 min of no runoff for each watershed preceding and following the event, (4) runoff data available for at least two of the three watersheds, and (5) and no snowmelt. The 104 storms used in analysis do not represent a random sample of all rainfall events between the May 2002 and December 2004 study period, but rather storms for which complete data were available.

Microsoft Excel (Microsoft Corporation Inc., 2000) was used to plot a hydrograph and hyetograph for each storm event (Figure 2). Four measures of lag time were calculated for each watershed: centroid lag-to-peak, centroid lag, lag-to-peak, and peak lag-to-peak (Figure 3). Centroid lag-to-peak was the time from the centroid of precipitation to the peak discharge. Centroid lag was the time from the centroid

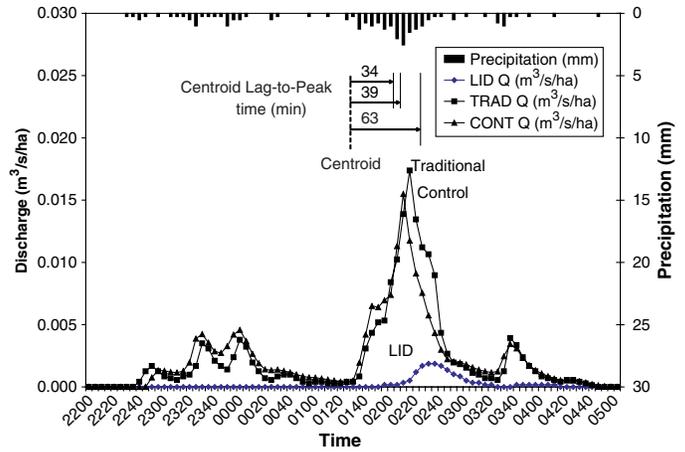


FIGURE 2. Stormwater Hydrograph and Precipitation Hyetograph for a September 1, 2003, 28.7 mm Rainfall.

of precipitation to the centroid of discharge. Lag-to-peak was the time from the beginning of precipitation to the peak discharge. Peak lag-to-peak was the time from the peak rainfall intensity to the peak discharge. The centroid of precipitation was determined from Dingman (2002),

$$t_{wc} \equiv \frac{\sum_{i=1}^n W_i \times t_i}{\sum_{i=1}^n W_i}, \tag{1}$$

where t_{wc} = centroid of precipitation, W_i = precipitation for period i , and t_i = time for period i . The centroid of runoff was determined from (Dingman, 2002):

$$t_{qc} \equiv \frac{\sum_{i=1}^n Q_i \times t_i}{\sum_{i=1}^n Q_i}, \tag{2}$$

where t_{qc} = centroid of runoff, Q_i = runoff for period i , and t_i = time for period i .

The number of storm events used in the analysis varied depending on the type of hydrologic information being investigated and ranged from 18 to 104. All analyses used at least 65 events, except for kurtosis where 18 events were used. Peak discharge was determined using 1-min flow data from the report of the ISCO 4230 flowmeters. If more than one storm occurred within a 24-h period, the peak of the smaller storm was determined using ISCO Flowlink 4 software (ISCO Inc., 2002). Flowlink 4 software determines runoff rate as the mean discharge of each 15-min time interval.

Hydrograph characteristics were statistically analyzed using JMP version 4.0 software (SAS Institute

Inc., 2000). The Shapiro-Wilk statistic was used to test precipitation and runoff data for normality. Variables were log transformed if the transformation increased the Shapiro-Wilk W statistic by 0.05 or greater. Runoff depth, peak discharge, precipitation depth, precipitation maximum intensity, precipitation duration, average precipitation, and antecedent moisture were log transformed and geometric means (Zar, 1996) are presented. A constant was added to runoff depth (0.01 mm) and peak discharge ($1.0 \times 10^{-10} \text{ m}^3/\text{s}/\text{m}^2$) prior to log transformation in order to compensate for zero values (Kilmartin and Peterson, 1972). The constant was subsequently subtracted from the geometric mean for presentation. Analysis of variance was performed to test for differences in geometric means (SAS Institute Inc., 2000). Tukey-Kramer honestly significant difference was used for means separation (SAS Institute Inc., 2000).

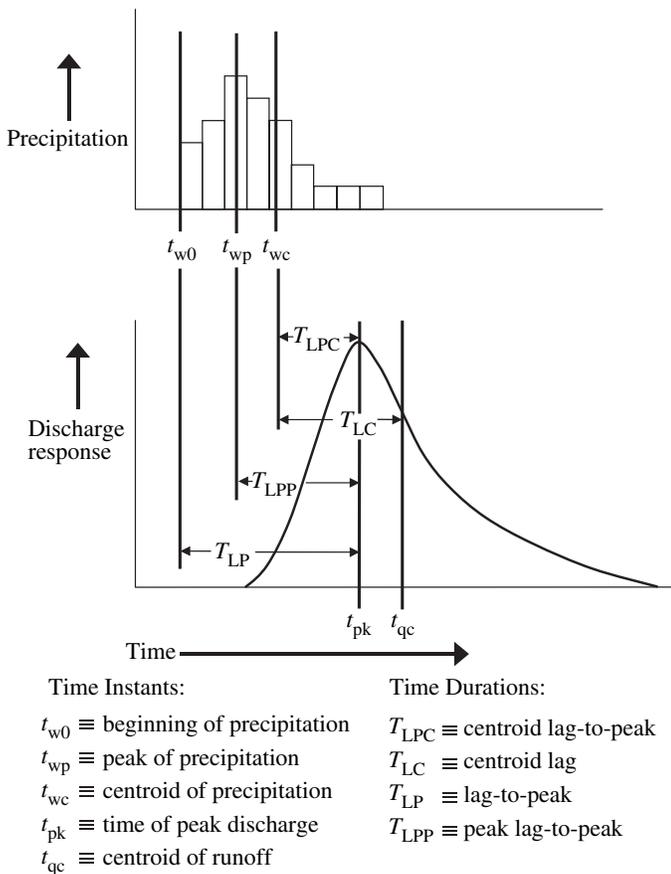


FIGURE 3. Definitions of Terms Used to Describe Hyetographs and Response Hydrographs Based on Dingman (2002) and Hall (1984).

The hydrographs of the 104 storms selected for event analysis were visually examined and 18 single-peak storms were selected for kurtosis analysis. The storm selection criteria for kurtosis analysis included: (1) single peaked hydrographs from all sites and (2)

1 h of uninterrupted flow from each watershed. The threshold rainfall of each watershed was determined as the x -intercept of a linear regression of precipitation and runoff depth (Li and Gong, 2002; Rezaur *et al.*, 2003). All storms, which met the criteria for lag time analysis, were included in threshold analysis.

Temporary storage and infiltration of stormwater enable LID to mimic predevelopment site hydrology (Ferguson, 1994; PGC 1999a). During storm events, storage and infiltration capacity is reduced as detention areas are filled and soils become saturated. This study examined the effectiveness of LID under reduced storage and infiltration conditions by separating storms in three ways: (1) storm size (25.4 mm), (2) storm duration (4 h), and (3) AMC (25.4 mm). LID is often designed to use on-site storage and retention techniques to treat at least the first 12.7 mm (0.5 in.) of runoff (PGC 1999b). The runoff coefficient of typical single-family residential areas is 0.30-0.50 (Dunne and Leopold, 1978). A residential area with a 0.50 runoff coefficient would generate 12.7 mm (0.5 in.) of runoff from a 25.4 mm (1.0 in.) storm event. In order to test the ability of LID to treat the first 12.7 mm (0.5 in.) of runoff, 25.4 mm (1.0 in.) was selected as the amount of precipitation for separation of small (<25.4 mm) from large (>25.4 mm) storm events.

The mean and median duration for the 104 storms selected for analysis was 4.58 and 3.50 h, respectively. In order to test the ability of LID to treat brief and lengthy rainfall events 4 h was selected for the separation of short (<4 h) from long (>4 h) storms.

Antecedent moisture condition was defined using the USDA-SCS (1963) definition as the total precipitation depth in the 5-day period preceding a storm event. The LID watershed rain gauge was used to determine the 5-day sum of rainfall preceding each storm event.

Average AMC II is defined as 12.7-27.9 mm (0.5-1.1 in.) during the dormant season and 35.6-53.3 mm (1.4-2.1 in.) during the growing season (USDA-SCS, 1963). Storms used in the analysis occurred during both the growing and dormant seasons. In order to test LID effectiveness under dry and wet soil conditions, 25.4 mm (1.0 in.) was selected as an intermediate value between dormant and growing season AMC for separation of storms occurring during low (<25.4 mm) and high (≥ 25.4 mm) AMC.

RESULTS AND DISCUSSION

Lag Time

The centroid lag-to-peak time for the LID watershed was significantly greater than the centroid

TABLE 2. Geometric Means of Hydrologic Variables by Watershed.

Variable	n	Watershed		
		LID*	Control	Traditional
Centroid lag-to-peak time (min)	83	40 a	-4 b	5 b
Centroid lag time (min)	66	61 a	14 b	21 b
Lag-to-peak (min)	77	153 a	111 b	111 b
Peak lag-to-peak (min)	76	41 a	11 b	14 b
Runoff (mm)	97	0.2 a	1.2 b	1.7 b
Peak discharge (m ³ /s/m ²)	82	1.0 × 10 ⁻⁷ a	4.9 × 10 ⁻⁷ b	1.1 × 10 ⁻⁶ c
Runoff coefficient**	77	0.067 a	0.193 b	0.239 c
Kurtosis	18	-0.458 a	1.526 b	1.731 b
Runoff threshold (mm)	97	6.0	0.9	3.0

Notes: Means followed by the same letter for a variable are not significantly different at α = 0.05.

*LID = low impact development. **Runoff coefficient = runoff depth/rainfall depth.

lag-to-peak time for the traditional and control watersheds (Table 2). The mean centroid lag-to-peak time of the LID watershed was 8.7 times greater than the traditional watershed and 10.3 times greater than the control watershed (Table 2). By example, the precipitation hyetograph and runoff hydrographs for the three watersheds for two September 2003 storms show that the LID watershed has a greater centroid lag-to-peak time than the control and traditional watersheds (Figures 2 and 4). For one storm, the control watershed had a negative centroid lag-to-peak time for the storm (Figure 4). Negative lag is the result of an advanced precipitation distribution in which peak rainfall intensity occurs soon after the start of the storm and is followed by an extended

period of lower rainfall intensity (Chow, 1964). The peak discharge occurs soon after the peak rainfall, while the center of mass of rainfall is skewed right by the lower intensity rainfall following the peak. Negative values were found for centroid lag-to-peak, centroid lag, and peak lag-to-peak times. Lag-to-peak time produced only positive values. Elsenbeer and Vertesy (2000) also found negative peak and centroid lag times for forested watersheds in eastern Peru as a result of storm events with high initial rainfall intensities.

The centroid lag time for the LID watershed was also significantly greater than the centroid lag time for the control and traditional watersheds (Table 2). The mean centroid lag time of the LID watershed was three times greater than the traditional watershed and 4.5 times greater than the control watershed (Table 2). Most other research has also found centroid lag times reduced by urbanization. Anderson (1970) used data from 53 watersheds to determine that the centroid lag time of a completely urbanization watershed was about 1/8th that of an undisturbed watershed. Leopold (1991) used the unit hydrograph method to determine that the centroid lag time of a 17.6 ha watershed was cut in half by a 20% increase in impervious surface area due to urbanization. Surprisingly, Laenen (1983) found centroid lag time not to be correlated with urban development. Laenen (1983) developed a series of regression equations from 41 Pacific Northwest watersheds to determine the effect of urbanization on stormwater runoff characteristics. When basin lag time was plotted as a function of stream length and slope, some highly developed urban basins had a similar response to natural basins. Laenen (1983) attributes the inconsistency with previous research (Anderson, 1970) to difficulties in estimating accurate values of effective impervious area, soil permeability, and channelization used in regression analysis.

The lag-to-peak for the LID watershed was also significantly greater than the lag-to-peak for the control and traditional watersheds (Table 2). The mean lag-to-peak of the LID watershed was 1.4 times greater than the traditional and control watersheds (Table 2). The lag-to-peak for the LID watershed was more variable than the control and traditional watersheds (Figure 5b). Lag-to-peak time was positively correlated with precipitation duration (r = 0.62-0.65) and precipitation depth (r = 0.43-0.49) for the three watersheds. No relation (r < 0.35) was found among centroid lag-to-peak, centroid lag, or lag-to-peak lag times and precipitation depth (r = 0.11-0.35), discharge depth (r = 0.10-0.31), and AMC (r = 0.03-0.13).

The peak lag-to-peak for the LID watershed was significantly greater than the peak lag-to-peak for the

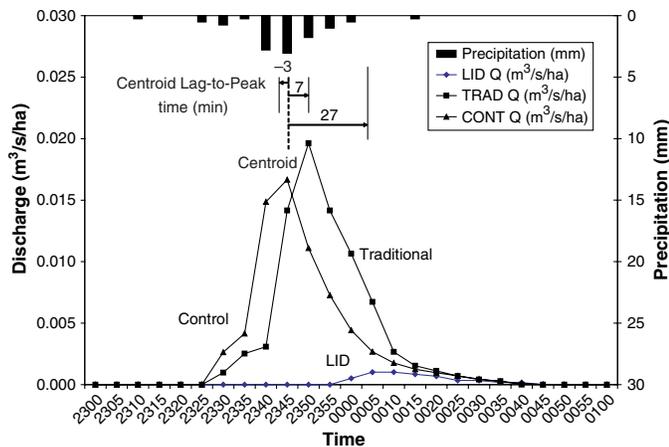


FIGURE 4. Stormwater Hydrograph and Precipitation Hyetograph for a September 15, 2003, 11.2 mm Rainfall.

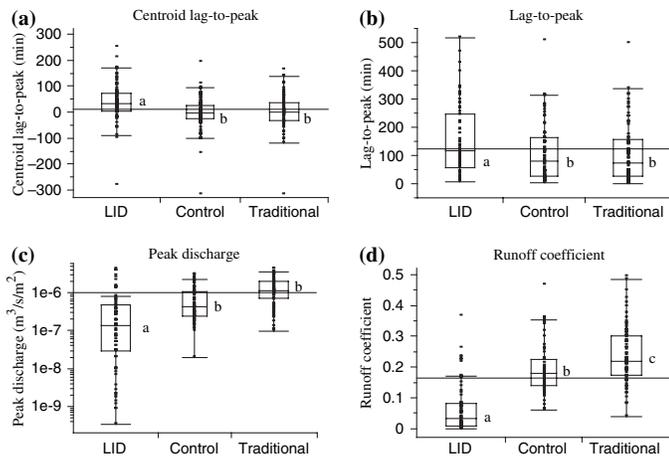


FIGURE 5. Box Plots of (a) Centroid Lag-to-Peak Time, (b) Lag-to-Peak, (c) Peak Discharge, and (d) Runoff Coefficient by Watershed. The horizontal line through each graph represents the mean of all values. Within each variable, means followed by the same letter are not significantly different at $\alpha = 0.05$.

control and traditional watersheds (Table 2). The mean peak lag-to-peak of the LID watershed was 2.9 times greater than the traditional watershed and 3.7 times greater than the control watershed (Table 2).

Lag time has been shown to increase with drainage area size (Dunne and Leopold, 1978). Most of the early lag time research focused on watersheds with a lower limit of about 10 ha (Yu *et al.*, 2000). There are few reports available, which focus on drainage areas comparable in size to the small ones used in this study. One exception was a study by Leopold (1991). The 20% impervious Cerrio Creek watershed (17.6 ha) was observed to have a centroid lag time of 13 min. This value is consistent with the centroid lag time of the control and traditional watersheds. Leopold (1991) used a synthetic hydrograph to hypothesize, that under natural conditions, the Cerrio Creek watershed would have a centroid lag time of 28 min.

The differences in the lag times found are due to the LID practices used in this study. Previous analysis of data from this study determined, using the paired watershed approach, that the runoff volume and peak discharge from the LID watershed were lower than from the traditional watershed due to the effects of best management practices (BMPs) and not differences in watershed slope, size, location, vegetation, or soil type (Clausen, 2004, unpublished data). These BMPs include grassed swales, bioretention areas, and the elimination of a curb and gutter stormwater collection system. Swales reduce flow velocities and increase times of concentration compared with storm sewers and curbs (Coffman, 2000; USEPA, 2000). Bioretention can further increase the time of concentration by retaining overland flow and rooftop runoff (Coffman, 2000).

Runoff Depth

The depth of runoff from the LID watershed was significantly less than the depth of runoff from the traditional and control watersheds (Table 2). The mean runoff depth from the traditional watershed was 8.5 times greater than from the LID watershed. The mean runoff depth from the control watershed was 6.0 times greater than from the LID watershed (Table 2). Runoff depth for the LID watershed was more variable than for the control and traditional watersheds (data not shown).

The differences in the amount of runoff rate per unit area is attributed to the effects of best management practices implemented within the LID watershed and differences in percentage imperviousness (Table 1). The use of permeable pavement in place of asphalt pavement reduces runoff volume by allowing for infiltration of stormwater (USEPA, 2000). Bioretention has also been shown to reduce the volume of runoff (Davis *et al.*, 2003; Dietz, 2005). The infiltration in grassed swales contributed further to decreased runoff volumes (USEPA, 2000).

Peak Discharge

The areal peak discharge from the LID watershed was significantly less than from the traditional watershed, which was also significantly less than from the control watershed (Table 2). The traditional watershed had an average 11.0 times greater peak discharge compared with the LID watershed. The control watershed had a 4.9 times greater peak discharge compared with the LID watershed. The peak discharge for the LID watershed was more variable than the control and transitional watersheds (Figure 5c).

The difference in peak discharge between the LID watershed and the control and traditional watersheds is the result of the best management practices within the LID watershed. Modeling studies have suggested that the peak discharge for LID could be 60% that for traditional development (Holman-Dodds *et al.*, 2003). The infiltration capabilities of bioretention areas (Davis *et al.*, 2003), grassed swales, and permeable paving surfaces (USEPA, 2000; Ferguson, 2005) have been shown to reduce the peak discharge compared with traditional stormwater conveyance systems (Ferguson, 1995).

Runoff Coefficient

The runoff coefficient for the LID watershed was significantly less than for the control watershed,

which was significantly less than for the traditional watershed (Table 2). The traditional watershed runoff coefficient was 3.6 times greater than for the LID watershed. The runoff coefficient for the control watershed was 2.9 times greater than that for the LID watershed (Table 2). The runoff coefficient for the LID watershed was less variable than the control and traditional watersheds (Figure 5d). Pawlow (1977) and Leopold (1991) found that runoff coefficients, like runoff volumes, increase with the degree of urbanization within a watershed. Pawlow (1977) reported the runoff coefficient of a 311 ha New Jersey watershed increased from 0.397 to 0.517 as impervious surface area increased from 3.0% to 7.9%.

Kurtosis

The mean kurtosis of LID watershed hydrographs was negative and significantly less than the kurtosis of the traditional and control watersheds (Table 2). A negative value of kurtosis indicates a platykurtic distribution, which is somewhat flattened and has more values in the tails than in normal distributions. The traditional and control watersheds had a positive value of kurtosis indicating leptokurtic distributions, which has more values around the mean than a normal distribution. The kurtosis of the LID watershed was less variable than the control and traditional watersheds (data not shown). Urban runoff has been characterized as being flashy (Leopold, 1968) and a flattened hydrograph would be desirable.

Runoff Threshold

The runoff threshold for the control, traditional, and LID watersheds was 0.9, 3.0, and 6.0 mm, respectively (Figure 6). Of the 104 storms included in this study, 20 storms (19%) failed to produce runoff in the LID watershed but produced runoff in the traditional watershed. The LID watershed’s higher runoff threshold is attributed to the various BMPs utilized which allowed for additional infiltration through on-site stormwater retention. The low runoff threshold for the control watershed is attributed to a large amount of directly connected impervious area within the watershed.

Storm Characteristics and Lag Times

Storm size did influence the lag times. The lag times for the LID watershed were significantly greater than the lag times for the traditional watershed for small storms (<25.4 mm) but not for large

storms (>25.4 mm), except for centroid lag times (Table 3). Thus, the benefits of LID on lag times diminished with increasing storm size. But runoff depth and peak discharge for the LID watershed were significantly less than the traditional watershed for all storm events (Table 4). However, only three storms greater than 45.0 mm were included in analysis. Due to the small number of storms greater than 45.0 mm, it is not possible to extrapolate the results to larger storms than those observed.

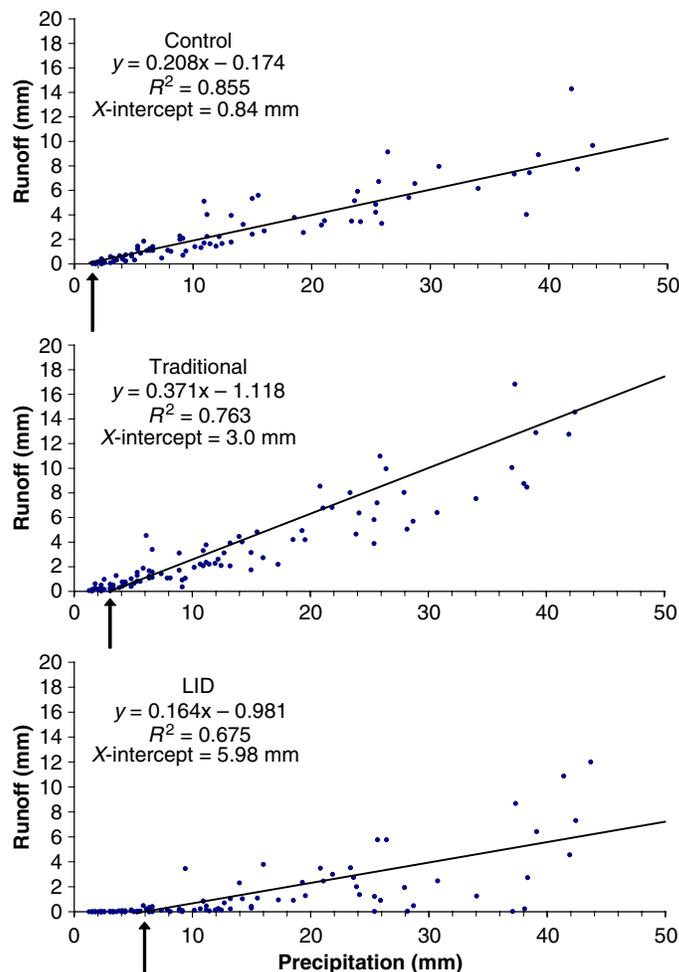


FIGURE 6. Runoff and Threshold of Runoff Response (as indicated by arrow) by Watershed.

Storm duration influenced lag times. The lag times for the LID watershed were significantly greater than the lag times for the traditional watershed for short duration storms (<4 h) but not for long duration storms (>4 h), except for centroid lag time (Table 4). Runoff depth and peak discharge for the LID watershed were significantly less than the runoff depth and peak discharge for the traditional watershed for both short and long duration storms (Table 4).

TABLE 3. Geometric Means of Hydrologic Variables of Small (<25.4 mm) and Large (≥25.4 mm) Storm Events by Watershed.

Variable	Storm Depth					
	<25.4 mm (Small)			≥25.4 mm (Large)		
	Watershed			Watershed		
	n	LID	Traditional	n	LID	Traditional
Centroid lag-to-peak time (min)	62	39 a	6 b	21	42 a	24 a
Centroid lag time (min)	47	54 a	15 b	19	81 a	34 b
Lag-to-peak (min)	62	129 a	92 b	15	249 a	192 a
Peak lag-to-peak (min)	57	36 a	7 b	19	58 a	36 a
Runoff (mm)	76	0.10 a	1.06 b	21	1.68 a	10.01 b
Peak discharge (m ³ /s/m ²)	60	6.6 × 10 ⁻⁸ a	9.2 × 10 ⁻⁷ b	21	3.5 × 10 ⁻⁷ a	1.8 × 10 ⁻⁶ b

Notes: Means followed by the same letter for a variable are not significantly different at α = 0.05. LID = low impact development.

TABLE 4. Geometric Means of Hydrologic Variables of Short (<4 h) and Long (≥4 h) Duration Storm Events by Watershed.

Variable	Storm Duration					
	<4 h (Short)			≥4 h (Long)		
	Watershed			Watershed		
	n	LID	Traditional	n	LID	Traditional
Centroid lag-to-peak time (min)	37	29 a	-7 b	46	47 a	12 a
Centroid lag time (min)	24	33 a	9 b	42	77 a	27 b
Lag-to-peak (min)	34	70 a	40 b	43	252 a	204 a
Peak lag-to-peak (min)	36	31 a	3 b	40	48 a	21 a
Runoff (mm)	52	0.05 a	0.84 b	45	0.86 a	4.00 b
Peak discharge (m ³ /s/m ²)	36	3.7 × 10 ⁻⁸ a	1.2 × 10 ⁻⁶ b	46	2.3 × 10 ⁻⁷ a	1.1 × 10 ⁻⁶ b

Notes: Within each variable and storm duration, means followed by the same letter are not significantly different at α = 0.05. LID = low impact development.

TABLE 5. Geometric Means of Hydrologic Variables of Storm Events Occurring During Low (<25.4 mm) and High (≥25.4 mm) Antecedent Moisture Conditions by Watershed.

Variable	Antecedent Moisture Collection					
	<25.4 mm (Low)			≥25.4 mm (High)		
	Watershed			Watershed		
	n	LID	Traditional	n	LID	Traditional
Centroid lag-to-peak time (min)	64	38 a	4 b	19	49 a	6 a
Centroid lag time (min)	52	59 a	20 b	14	68 a	24 b
Lag-to-peak (min)	59	166 a	131 a	18	179 a	129 a
Peak lag-to-peak (min)	60	43 a	16 b	16	45 a	15 a
Runoff (mm)	77	0.16 a	1.63 b	20	0.31 a	2.18 b
Peak discharge (m ³ /s/m ²)	63	1.1 × 10 ⁻⁷ a	1.2 × 10 ⁻⁶ b	19	1.1 × 10 ⁻⁷ a	8.2 × 10 ⁻⁷ b

Notes: Within each variable and storm depth, means followed by the same letter are not significantly different at α = 0.05. LID = low impact development.

Antecedent moisture conditions also influenced lag times. The lag times for the LID watershed were significantly greater than the lag times for the traditional watershed for storms occurring during low

(<25.4 mm) AMCs but not for storms occurring during high (>25.4 mm) AMCs (Table 5). There was no significant difference in lag-to-peak time for the traditional and LID watersheds for storms occurring during low

or high AMCs (Table 5). Thus, LID practices used worked better during dryer conditions. Runoff depth and peak discharge for the LID watershed were significantly less than the runoff depth and peak discharge for the traditional watershed for storm events occurring during all AMCs (Table 5).

CONCLUSIONS

Low impact development lowered peak discharge, the runoff coefficient, and runoff volume and increased centroid lag, centroid lag-to-peak, lag-to-peak, and peak lag-to-peak times and the runoff threshold as compared with traditional residential development. These effects apply better to small, short-duration storms, and lower AMC conditions than for larger, longer storms with wet conditions. However, LID reduced the runoff depth and peak discharge for all storms.

Over the past several years, there has been an increasing amount of interest in LID as an alternative to centralized stormwater control strategies of traditional residential development. Until recently, the lack of scientific data has been an obstacle to the large-scale implementation of LID (Coffman, 2001). This study indicates that the decentralized, micro-scale treatment of stormwater can be used to promote predevelopment site hydrology.

Due to the site-specific nature of LID performance, these results cannot be used directly in current hydrologic models. However, these findings and other paired watershed results conclusively indicate that the LID practices used in this study had clear stormwater benefits. Based on these observations, LID practices should be implemented in future residential developments, and given credit for their effects on stormwater runoff.

The goal of LID is to reduce urban stormwater pollution by mimicking predevelopment site hydrology. Data presented in this study are focused on the hydrologic impact of LID on precipitation-induced surface runoff. Further exploration should include the study of LID on water pollution control, evapotranspiration, groundwater, and stream base flow. Future studies should also consider the effect of snowmelt and rain-on-snow events as well as the comparison of a LID watershed to an undeveloped forested watershed.

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