Monitoring Runoff from Pacifica: a Low Impact Development Subdivision

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Abstract

Storm rainfall on and runoff from a 3.35-ha low impact development (LID) residential subdivision in the Piedmont region of North Carolina were monitored for 6+ years, which included pre-, during-, and post-development periods. Runoff was monitored and sampled at two stations using automated samplers. Along with residences, the drainage area to one of the stations (PC1) included an undisturbed wooded riparian buffer with level spreaders to distribute runoff, while the area to the other station (PC2) included four bioretention areas, permeable pavement, a roof runoff collection system, a detention pond, and other LID measures. Monitoring results documented that the post-development, runoff to rainfall ratio and pollutant export at both stations were significantly greater than those of the pre-development period, during which time land use on the site was mature woods. However, runoff to rainfall ratio, TN, TP, and TSS export at PC1 were significantly less than a nearby, similar watershed with cropland and woods as the land use. The TKN, TN, TP, and TSS export at both LID monitoring stations was 23 to 92% less than those from a nearby traditional subdivision monitored previously. These data indicate that LID subdivisions constructed in the Piedmont region cannot maintain the runoff to rainfall ratio and TN, TP, and TSS export if the pre-development land use is mature woods; however, if the pre-development land use is cropland mixed with woods, then it may be possible to maintain predevelopment runoff to rainfall ratio and TN, TP and TSS export. Further, the extensive use of LID techniques/measures in residential subdivisions can result in less TN, TP, and TSS export compared to similar conventional subdivisions.

Introduction

Residential development is occurring throughout many areas of the United States including central North Carolina. Stormwater runoff from development can be damaging to downstream surface water resources by increasing the peak and volume of discharge as well as sometimes carrying high levels of various pollutants (Line and White 2007; Makepeace et al. 1995). Much of the negative impact of development has been attributed to the increase in the associated impervious surfaces (Ferguson and Suckling, 1990; Carle et al. 2005; Wang et al. 2001). To lessen the negative impact of development, municipalities have begun placing a greater emphasis on permeable pavement and minimizing and/or treating stormwater on-site using principles and techniques generally referred to as Low Impact Development (LID). A guiding principle of LID is to maintain the pre-development hydrology of the site following development (Perrin et al. 2009). To meet this goal, designers of LID sites attempt to minimize impervious surfaces, retain and infiltrate runoff on-site, store and reuse roof runoff, maintain and utilize natural features to reduce runoff, and install various other management practices to control and treat stormwater runoff on-site.

Research on individual LID practices such as bioretention areas, grass filter strips, permeable pavement, and has shown that they can reduce runoff volume and peak flow rates along with reducing pollutants in runoff (Davis et al., 2001; Dietz and Clausen, 2005; Line and Hunt, 2009). However, there are few published studies which assess the effectiveness of LID on a site or watershed scale using water quality monitoring (Dietz and Clausen, 2008). Although some studies have documented increases in runoff volume as an area was developed, much of the recent research relates to the comparison of different watersheds with different land uses (Line and White, 2007). Monitoring runoff from a developing site before construction to completion is particularly difficult for several reasons including the researcher must know the site will be developed long before construction begins, development often changes runoff drainage patterns, cooperation from developers is scarce, and construction sites tend to be magnets for theft and vandalism.

This project was designed to conduct runoff monitoring from an LID development beginning before construction and continuing to after completion to document changes in runoff and pollutant export. Runoff from a nearby, topographically-similar conventionally-developed site was also monitored to provide a comparison drainage area for use in statistical analyses.

Methods

The 3.35-ha residential development site was located in the Piedmont physiographic region of North Carolina (35.923N;79.077W). There were a combination of condominiums, townhouses, and detached houses built on the site for a total of 46 dwelling units. Most of the units were two-story in order to minimize the impervious area of the site. A 6.1-m wide and 290-m long private drive provided vehicular access to houses in the development, although the drive was basically along the periphery of two-thirds of the site (figure 1). A 2.44-m wide asphalt walking path with grass paver reinforced shoulders provided emergency vehicle access to the inner units of the development. Access to individual units from both the drive and path was by 1.52-m wide walkways composed of permeable concrete or pavers. The narrow access road, permeable walkways, and reduced footprints houses were designed to minimize the impervious area of the site.

Slopes on the entire site ranged from 2 to 25%; however, slopes of the developed area, excluding the wooded riparian buffer, ranged from 2-5% and they changed relatively little during construction grading. Soils were mapped predominantly as Appling with some Wilkes and Enon also occurring. The pre-construction land use was 100% wooded composed of mature hardwood and pine trees. All of the trees except the wooded riparian buffer along the north side of the site were removed during construction in the spring of 2005. The timeline for monitoring and construction on the site is shown in Table 1. While the timeline included a single date to mark the beginning and end of each phase, the reality was that there were transition periods of 1 to 3 months between phases. For example, the Developed monitoring period for PC1 began on 4/25/07, but finishing construction on 1 or 2 houses in the drainage area was ongoing and landscaping and other minor construction-related activities were continuing. However, the storm drain system was in use and other major construction activities were completed.

The monitoring was not continuous due to gaps in funding and transition periods between construction stages when major changes in the drainage were occurring. Drainage areas to monitoring stations changed with the installation of a diversion at the beginning of construction and stormdrains near the end of it. The diversion transported runoff out of the PC1 area to the PC3 area during the construction phase and was removed after construction. The PC3 monitoring station (figure 1) was located at the outlet of the sediment basin, but was moved to the outlet of the detention pond (PC2) at the end of the construction period when the basin was removed and the stormdrain system to the detention pond was completed.

There were many LID management measures implemented by the developer on the site including permeable sidewalks (270 m) and parking spaces (900 m^2), grass pavers, vegetated swales, bioretention areas (5), level spreaders (3), and minimizing impervious surfaces through reduced length and width parking spaces (38% of spaces subcompact size), smaller footprint homes, and narrow roads. In addition, rainwater runoff from the roof of the large common house (145 m^2 of roof) was collected and stored in a cistern and used for washing clothes and flushing toilets, while stormwater was stored near the outlet of the site in a detention pond and pumped to a storage tank to be used to irrigate the community garden. The measures were designed to minimize runoff at the source, infiltrate runoff in transport, treat runoff and then retain and reuse runoff.

Monitoring stations: The PC1 monitoring station (figure 1) was installed in March, 2003 and maintained during three different periods as funding was obtained (Table 1). A 20 to 46 cm high plywood diversion wall buried at least 10 cm in the ground was installed to direct runoff from the wooded riparian buffer to the station for monitoring purposes. This diversion was necessary because runoff often meandered through the buffer using several different flow paths. The station, which consisted of a 61-cm rectangular weir and an automated sampler with an integrated flowmeter, was maintained at the same location during the entire duration of monitoring. The flowmeter continuously measured the stage of water over the weir crest and used the standard weir equation to compute discharge, which then facilitated the collection of flow-proportional samples by the automated sampler.

The PC3 monitoring station, consisting of a 120 degree v-notch weir and automated sampler with flowmeter, was installed at the outlet of the sediment basin in May, 2005. The station monitored discharge from the basin and collected flow-proportional samples until the sediment basin was removed in December, 2006. A tipping-bucket raingage was installed which recorded rainfall accumulation at 15-minute intervals. In April 2008, when construction was completed, the monitoring station was moved to the outlet of the stormwater detention/irrigation pond where a 91.4-mm rectangular weir was installed and the site renamed PC2. By the time this station was installed, the stormdrain system was functioning transporting most of the runoff from the development to the pond (fig. 1). Like PC1, the flowmeter was used to monitor water height over the weir crest and the standard weir equation was used to convert the measured height to discharge.

Sample collection was basically the same at all monitoring stations, in that flow-proportional samples were collected and stored in individual bottles within the machine. For the PC1 and PC2 stations, duplicate samples were collected during discharge, with one of the samples being placed in a pre-acidified bottle and the duplicate in a nonacidified bottle. The acidified (H_2SO_4 to pH<2) samples were used for nitrogen and phosphorus analysis, while the nonacidified samples were used for sediment and turbidity analysis (Table 2). For the PC3 station, duplicate flow-proportional samples were not collected as only TSS analysis was conducted. Once every 2 weeks (more frequent depending on rainfall) the sampler was visited and the individual flow proportional samples were combined into one acidified (for PC1 and PC2) and one nonacidified composite sample (for PC1, PC3, and PC2) for laboratory analysis by withdrawing representative equal-volume aliquots from each sampler bottle. The 2-week holding time for TSS exceeded that recommended for TSS (Eaton et al., 1995); however, since the TSS was likely composed of almost exclusively inert soil particles, the concentration should not vary in this relatively short period of time. In fact, 13 samples of runoff were collected and analyzed within 5 hours, while the remainder of each sample was stored outdoors in a shelter similar to the sampler shelter. After 2 weeks, the TSS concentrations of these samples were not significantly different (level=0.1) from those analyzed within 3 hours according to a paired t-test.

Analysis methods and method detection limits (MDLs) for TSS, nitrogen forms, and total phosphorus are shown in Table 1. During construction, some samples (<10%) were analyzed using method 2540B for total solids (Eaton et al. 1995) and used as TSS, because the concentration of solids in the sample was too high to filter a sufficient volume of sample to be considered representative of the whole sample. Standard methods and a state-certified laboratory were used for each analysis to provide accurate, reliable, and repeatable results (Eaton et al., 1995).

Basically two statistical analyses were used to compare monitoring data from sites. Paired t-tests were used to compare data collected from the two stations during the same monitoring period at the Pacifica site. Because data from more than 50 storms were used in the analysis, test for normality were not conducted. Analysis of covariance was used to compare the relationship between storm rainfall and runoff and pollutant loading when monitoring did not occur at the same time. While this analysis was conducted using storm event rainfall and loads, it was assumed the results would apply to annual pollutant export rates as these are simply the sum of the storm event loads for a given area. The 0.05 level was used to determine significance.

Results and Discussion

Monitoring results were divided into pre- (Pre-dev.) and during-construction (Construct) and the developed (Developed) phases for each monitoring station as shown in Table 3. Because of changes in drainage and the difficulty of isolating runoff, there was no pre-development or during-construction runoff monitoring for the PC2 station. Rainfall characteristics for the various stages of construction are shown in Table 3. Because large (> 25.4 mm) storms can have a disproportionately greater impact on runoff and pollutant export (Line and White, 2007), the number of these storms was counted. Results showed that the number of large storms was not dramatically different between periods. The average of rainfall depth/accumulation and overall intensity for storms occurring during the pre-development phase at PC1 were not significantly different from those occurring during the post-development period of PC1 or PC2. However, the average of the peak 30-minute intensities for storms occurring during the Pre-dev period at PC1 was significantly less than those for the Developed periods at PC1 and PC2. In contrast to rainfall depths for storms, runoff depth was significantly greater for the Developed period at PC1 and PC2 compared to the

Pre-dev period of PC1 thereby suggesting that the development caused a significant increase in runoff. In addition, mean peak runoff also increased considerably from Pre-dev period to Developed period at PC1 and PC2.

<u>During Construction Monitoring Data</u>: Cumulative rainfall and pollutant export rates for the PC1 and PC3 stations during construction are shown in Table 4, while data from individual storms are shown in the Appendix. For PC1, pollutant export for all six constituents increased considerably during construction as compared to pre-construction. One of the reasons for this was that the runoff to rainfall ration increased 2.6 times resulting in more runoff to transport pollutants. This was expected given the site was in mature woods prior to construction. However, the increase in export was not solely the result of increased runoff as the pollutant export rates increased from 10 to 924 times the pre-construction rates. Increased pollutant export, although to a lesser extent, during construction was also the case for a similar study conducted in the region as shown near the bottom of Table 4 under ‘Other studies’. Both the pre-development and construction total nitrogen, phosphorus, and TSS export from this study was less than the previous study, which was likely due to the small area of clearing, the preservation of the riparian buffer, and the fact that area was previously unmanaged mature forest. The pre-development land use for the site in the paper by Line and White (2007) was farmland converted to woods and in fact a small portion of the drainage area was still in cropland; hence, the export from the Pacifica site was expected to be less.

Assuming that all of the TSS originated from 0.15 ha of cleared land in the 0.6 ha drainage area the TSS export from the cleared area was approximately 17,650 kg/ha-yr. This sediment export occurred in spite of silt fences, sediment traps, and diversions. Sediment export from PC3 during construction (17,870 kg/ha-yr) was similar to that estimated from the cleared area of PC1 even though the PC3 drainage area contained various erosion control practices, sediment traps, and a large sediment basin with a floating drain pipe designed to empty the basin from the top of the water column. A chemical flocculent was added to the water in the basin manually at various times, but this usually occurred after the majority of the rain event was over. These data highlight the difficulty in controlling sediment loss from construction sites on highly erodible soils with a significant percentage of fines (>33% silt and clay). The difference in the sizes of the drainage areas prevents a direct comparison between PC1 and PC3; however, the data suggest that the large sediment basin with floating drain and occasional flocculent application was not significantly more effective than the standard sediment trap (stone dam) at reducing overall sediment loss from this site over the period of monitoring. Observation of the sediment basin revealed that fine sediment remained in suspension for days and removing water from the top of the water column appeared to make little difference. In fact, the relatively long drawdown time associate with the floating drain pipe may have hurt the efficiency of the basin for storms occurring in close succession. One practice that appeared to be effective, although it was not monitored, was a temporary level spreader installed by the developer in the wooded buffer which received the effluent from the sediment basin and spread it out on the contour in the riparian wooded buffer.

<u>Developed Monitoring Data</u>: As shown in Table 4, the runoff to rainfall ratio, TKN, NO_x-N, TN, and TP export rates at PC1 increased considerably from the construction period, while the NH_3-N and TSS export rates decreased. The nearly ten-fold reduction in TSS was expected given that almost all exposed soil surfaces had been stabilized with vegetation or impervious surfaces. The reason for the drop in NH_3-N export rate was unknown but may be related to fertilization to

establish vegetation in the construction phase. The runoff to rainfall ratio and all of the pollutant export rates were much greater during the Developed compared to the Pre-dev period, even though the average annual rainfall was less. In fact, the pollutant export rates were 12 to 83 times greater for the Developed period compared to those of the Pre-dev period. Analysis of covariance using storm loads suggested that all of these increases were statistically significant, except NO_x-N for which the number of data points limited the analysis as only one storm during the Pre-dev period had any NO_x-N load. Increases were expected given that the cleared and impervious surface areas increased; however, they were much greater than those in the study reported by Line and White (2007) which compared pre-development runoff and pollutant export to those following conventional development (Table 4). The reason for the large increase may be that the pre-development land use of this site was mature woods, which had a very low runoff and pollutant export rate, whereas pre-development land use in the Line and White (2007) study was cropland and historic cropland converted to woods, which had much greater runoff and export. Obviously, the data show that LID on sites such as this one where the pre-development land use was mature woods, the hydrology cannot be maintained following clearing and development.

More commonly in many regions, areas with mixtures of cropland and less mature woods are developed into residential subdivisions; hence, a more appropriate comparison is between the pre-developed runoff and pollutant export of Line and White (2007) and those of the developed period for PC1. Analysis of covariance was conducted using storm loads for these sites documented that export of TKN, NO_x-N, TN, and TP from PC1 post-development was significantly less than from a pre-developed area of woods and cropland, while runoff, NH_3-N and TSS export were not significantly different. Hence, these data indicate that LID in areas where the pre-development land use is cropland and woods converted from cropland, the runoff and pollutant export may not increase following residential development. At this point it is important to note that only 42% of the drainage area to PC1 was cleared and developed, while the rest remained as a wooded riparian buffer. Further, the mitigating effect of the buffer was maximized via the installation of level spreaders that distributed the incoming runoff from the developed area over a large area of the buffer.

As shown in Table 4, the runoff to rainfall ratio and pollutant export rates for the developed period were much greater at PC2 compared to PC1. During most of the developed period (4/5/08 to 5/8/12) monitoring occurred at both PC1 and PC2 so these data were paired. Paired t-tests of storm event data suggested that runoff and all pollutant loads were significantly greater for PC2 compared to PC1. This was expected given that the PC2 area was 100% developed with nearly twice the percentage of impervious surfaces, whereas PC1 was only 42% developed.

In order to assess LID in the PC2 drainage area, runoff and pollutant export must be compared to a conventional residential subdivision with nearly 100% development such as was monitored during the Line and White (2007) study. While these developed areas were not monitored at the same time, they were both in the Piedmont region, had similar soils, and were each monitored for at least 2.5 years, which is usually a sufficient duration to include a wide variety of storm events. As shown in Table 4, the runoff to rainfall ratio was nearly the same between the sites indicating that the LID measures such as permeable pavement made little difference in reducing runoff. This was not unexpected as the soils at Pacifica were relatively impermeable and the site had been almost totally stripped of topsoil and compacted during construction just like the conventional subdivision. The implication is that the permeable pavement and other LID measures were not effective at reducing runoff from this site, at least for the first 2.5 years following grading and compaction. These results included all storms even though the focus of LID measures is on controlling runoff from smaller storms. When storms of greater than 17 mm were deleted, results were similar to those with all storms in that the runoff to rainfall ratio for the conventional site was 0.50 and PC2 was 0.47. This finding differs from that of Dietz and Clausen (2008) who reported that runoff from an LID subdivision along the coast of Connecticut was much less than that of a nearby traditional subdivision. However, their LID subdivision was built on a closed gravel pit for which the fill soil, imported to construct the subdivision, had a higher infiltration capacity than the native soil and which had an earthen berm diversion near the outlet that likely reduced runoff by enhancing infiltration (Clausen, 2007). These results highlight the critical importance of maintaining/enhancing soil permeability to the effectiveness in LID. Further, if the construction employs traditional techniques such as clearing and grading the entire site thereby also compacting the soil, then some LID measures such as permeable pavement will have limited effectiveness, at least in the short term. Over longer periods of time soil structure and permeability may recover which will improve the effectiveness of the LID measures.

The TKN, TN, TP, and TSS export at PC2 were less than those at the conventional development as reported by Line and White (2007) in Table 4. An analysis of covariance using rainfall and storm loads to evaluate the differences between export rates suggested that all of the export rates were significantly different except TN. The reason for the higher NH_3-N and NO_x-N export rates at PC2 was not known. The fact that both PC1 and PC2 had higher NH_3-N than expected may be the result of excess application of fertilizer, although fertilizer application rates on the site were not known. The higher NO_x-N export rates may be attributed to nitrogen conversion in and export from the bioretention areas due to groundwater intrusion. Past studies have documented increased export of NO_x-N from bioretention areas (Line and Hunt, 2009). The TP and TSS export from PC2 was much less than those of the conventional development. The low TSS export was likely because most of the runoff passed through bioretention areas, which tend to be excellent sediment filters.

Summary and Conclusions

Storm rainfall and runoff were monitored at two stations during a 6+ year period encompassing before, during, and after development of a 3.35-ha LID residential subdivision in the Piedmont region of North Carolina. Flow-proportional samples of runoff were collected by automated samplers and analyzed for nitrogen, phosphorus, and sediment. In addition to the residences, the drainage area to one of the stations (PC1) included an undisturbed wooded riparian buffer with level spreaders, while the area to the other station (PC2) included four bioretention areas, permeable pavement, a roof runoff collection system, a detention pond, and other LID measures. Monitoring results documented that post-development runoff to rainfall ratio and pollutant export was much less at PC1 compared to PC2, which was expected given that 58% of drainage area to PC1 remained as an undisturbed wooded buffer. The runoff to rainfall ratio and pollutant export from PC1 were significantly greater than those of the pre-development period, during which time land use on the site was mature woods. However, runoff to rainfall ratio, TN, TP, and TSS export at PC1 was significantly less than a nearby, similar watershed with cropland and woods as the land use. The TKN, TN, TP, and TSS export at both LID monitoring stations was less than those from a nearby traditional subdivision monitored previously. Thus, these data indicate that LID subdivisions constructed in the Piedmont region cannot maintain the runoff to rainfall ratio and TN, TP, and TSS export if the pre-development land use is mature woods; however, if the pre-development land use is cropland mixed with woods, then it is possible to maintain predevelopment runoff to rainfall ratio and TN, TP and TSS export. Further, the use of LID techniques/measures can result in less TN, TP, and TSS export compared to similar conventional subdivisions. Of the LID measures, the undisturbed wooded buffer with level spreaders was more effective at minimizing runoff and pollutant export from this site than the other LID measures.

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Figure 1. Aerial view of development.

Table 1. Monitoring Timeline and Drainage Areas.

Start Date	End Date	Stage	Drainage Area	Cleared Area	Impervious[1]
			ha	ha	%
PC1					
3/15/03	3/31/04	Pre-construction	0.92	0	0
5/12/05	4/11/07	During construction	0.60	0.15	0
4/25/07	9/25/08	Developed	0.81	0.34	12.4
5/15/10	5/8/12	Developed	0.81	0.34	12.4
PC3					
5/12/05	11/30/06	During construction	1.48	1.48	0
PC2					
4/5/08	9/25/08	Developed	1.57	1.57	24.1
5/15/10	5/8/12	Developed	1.57	1.57	24.1

[1] Excludes permeable pavement and roofs with rainwater collection system.

Table 2. Methods of Sample Analysis.

Parameter	Method	MDL
TSS	2540D[1]	1 mg/L

TP	4500-P E[1]	0.01 mg/L
TKN	EPA 351.1	0.14 mg/L
NH_3-N	4500 NH_3 H[1]	0.007 mg/L
NO_3+NO_2 (NO_x-N)	4500-NO_3-F[1]	0.006 mg/L
Turbidity	HACH 2100P	0.1 NTU

[1] Eaton et al., 1995.

Table 3. Rainfall and Runoff Characteristics for Storms During Monitoring Periods.

Site	Large[1] Storms no./yr	Mean Rain Depth mm	Median Rain Depth mm	Peak 30-Minute Intensity mm/hr	Mean Intensity mm/hr	Mean Runoff Depth mm	Mean Peak Runoff L/s
PC1							
Pre-dev	12	24.9a	18.3	4.60b	6.45e	1.8f	1.3
Developed	10	21.9a	15.2	7.95c	6.45e	5.6g	5.9
PC2							
Developed	9	20.1a	14.5	7.62d	5.84e	11.2h	25.9

[1] Defined as storm of greater than 25.4 mm accumulation.

Note: numbers with the different letter as Pre-dev are significantly different (0.05 level).

Table 4. Summary of Monitoring Results

Site	Dur.	Rain	Run/rain	TKN	NH_3-N	NO_x-N	TN	TP	TSS
	yr	mm/yr		-----------------------	kg/ha-yr		--------------------		
PC1									
Pre-dev.	1.04	1231	0.07	0.20a	0.05a	0.02a	0.22a	0.03a	3.6a
Construct	1.92	988	0.18	1.90	1.08	0.22	2.11	0.53	3,327
Developed	3.46	861	0.24	2.77b	0.47b	0.83a	3.59b	0.37b	160b
PC3									
Construct	1.56	935	0.38	na	na	na	na	na	17,870
PC2									
Developed	2.46	1043	0.56	10.47	2.45	3.39	13.86	0.89	166
Other Studies									
Pre-dev.[1]	5.6	800	0.22	5.3	0.2	1.0	6.3	0.5	349
Construct[1]	0.7	1428	0.50	8.4	0.7	2.0	10.4	2.8	29,250
Developed[1]	3.5	706	0.55	16.2	1.7	1.8	18.0	1.7	1,958
LID[2]	2.9			0.90	0.02	0.25	2.0	0.4	8

Note: Pollutant export rates with different letters are significantly different at the 0.05 level.

[1] Results from nearby conventional development from Line and White (2007).

[2] From Clausen (2007).

Table 5. Export Differences Between LID and Conventional Developments.

	Run/rain %	TKN %	NH_3-N %	NO_x-N %	TN %	TP %	TSS %
PC1 vs Conventional							
arithmetic	56	83	72	54	80	78	92
LS means	59	93	91	82	91	91	97
PC2 vs Conventional							
arithmetic	-2	35	-44	-88	23	48	92
LS means	-19	58	-48	-154	0	56	79