

Article

Green Infrastructure Design for Stormwater Runoff and Water Quality: Empirical Evidence from Large Watershed-Scale Community Developments

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Abstract: Green infrastructure (GI) design is advocated as a new paradigm for stormwater management, whereas current knowledge of GI design is mostly based on isolated design strategies used at small-scale sites. This study presents empirical findings from two watershed-scale community projects (89.4 km² and 55.7 km²) in suburban Houston, Texas. The GI development integrates a suite of on-site, infiltration-based stormwater management designs, and an adjacent community development follows conventional drainage design. Parcel data were used to estimate the site impervious cover area. Observed streamflow and water quality data (*i.e.*, NO₃-N, NH₃-N, and TP) were correlated with the site imperviousness. Results show that, as of 2009, the impervious cover percentage in the GI site (32.3%) is more than twice that of the conventional site (13.7%). However, the GI site's precipitation-streamflow ratio maintains a steady, low range, whereas this ratio fluctuates substantially in the conventional site, suggesting a “flashy” stream condition. Furthermore, in the conventional site, annual nutrient loadings are significantly correlated with its impervious cover percentage ($p < 0.01$), whereas in the GI site there is little correlation. The study concludes that integrated GI design can be effective in stormwater runoff reduction and water quality enhancement at watershed-scale community development.

Keywords: drainage design; community planning; ecological planning; Ian McHarg; multifunctional landscapes; landscape performance; GIS

1. Introduction

Mitigating the development impact on stream hydrology and stormwater quality has been extensively discussed [1–6]. Excessive runoff leads to costly flooding events and the export of nitrogen and phosphorous to streams, which become concerns of environmental protection agencies and health agencies [7,8]. The main culprit behind these events is the elevated level of impervious cover as a result of community development. Impervious covers such as rooftops, streets, and parking lots alter the natural hydrological cycle and increase the pollutant loadings [9–11]. During the past three decades, imperviousness continues to be the single most important variable to define the amount of urban development, and a considerable number of studies have suggested a definite relationship between impervious areas and watershed stream health [12–14]. Watershed degradation generally is a result of a gradual process when impervious cover increases. However, many studies suggest that when impervious cover exceeds a range from 10% to 20%–25%, negative impacts are more prominent, including severe erosion, high nutrient flux, diminished stream species diversity, alteration of stream morphology, and an overall degradation of the aquatic system health [9,15–17].

In community development, the conventional drainage solution (curb-and-gutter, drop inlet, and underground piping) transfers stormwater faster than the natural hydrological cycle and may contribute to downstream flooding [18–20]. Common mitigation measures such as detention basins focus on peak discharge reduction and present limited success in runoff volume reduction or water quality improvement [2,21]. Moreover, if the basin is located inappropriately, it may aggravate flooding [22–24]. The U.S. Environmental Protection Agency (USEPA) advocates retrofitting the conventional stormwater system toward using low-impact development (LID) and green infrastructure (GI) design [7,25,26]. GI design typically encompasses open space, parks, green roofs, bioretention and constructed wetlands, decentralized water management (e.g., rainwater harvesting), protection of riparian areas, and various hybrids of pervious surfacing options [26,27]. GI design is based on ecological engineering principles [28,29], and a number of studies have suggested that integrated GI designs can be more effective than single-design strategies [30–32]. While the main focus of conventional drainage solution is peak discharge reduction, GI design aims at restoring the predevelopment flow regimes, such as reduction of runoff volume, enhancement of stormwater quality, and maintenance of base flows [33–35].

To achieve the above performance benefits, GI design treats runoff close to where it is generated. For instance, runoff is detained or infiltrated onto permeable surfaces on-site. As a result, the amount of effective impervious area (EIA) that directly contributes to runoff is reduced. EIA is a subset of the commonly used term “total impervious area” (TIA), which is often used to define the extent of community development. TIA is the sum of all noninfiltrating surfaces. EIA, or directly connected impervious area, includes only those impervious areas that drain into a piped storm sewer and further discharge into a surface-water body (e.g., parking lot runoff goes directly to a stormwater drain) [36,37]. Recent studies suggest that EIA increases when the connectivity of TIA increases and that development patterns can be better indicators than TIA alone in estimating stormwater runoff and pollutant exports [38,39].

Although community development inevitably increases the TIA, GI design can be effective in reducing the EIA and runoff volume [35,40–42]. However, most current knowledge of GI design is

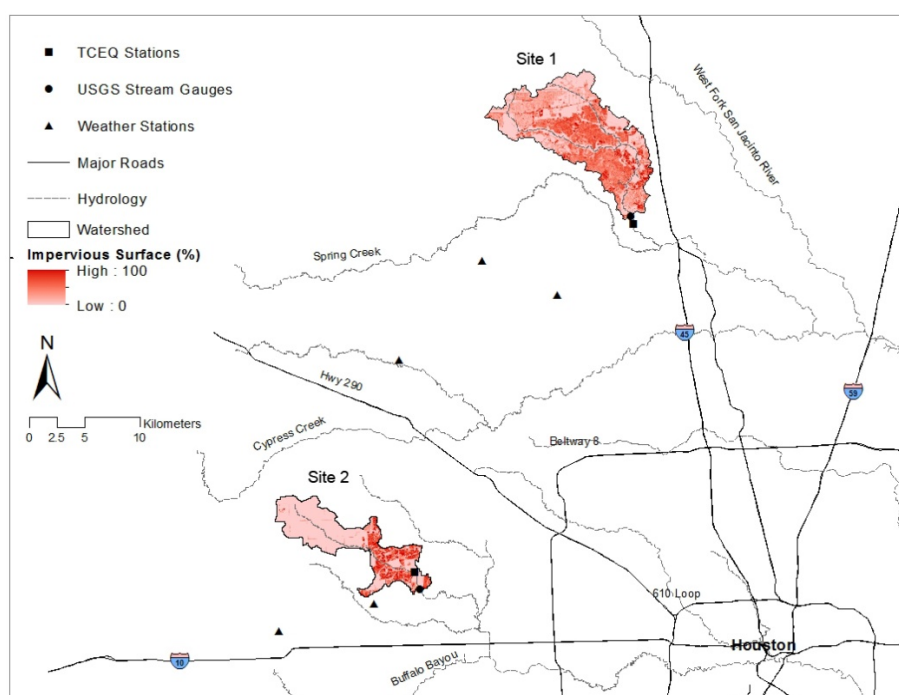
based on isolated design strategies used at small-scale sites. Few studies have fully measured the effectiveness of integrated GI design that encompasses entire watersheds [43,44]. This current study presents empirical findings from two watershed-scale community projects in suburban Houston, Texas. One of the projects, The Woodlands, is a renowned large-scale community development. It is a precursor of the USEPA's GI design initiative: a series of integrated GI design strategies were used to meet flood control and stormwater quality goals [44–47]. Several recent studies have demonstrated the effectiveness of The Woodlands GI design on flood mitigation [31,32,46]. In addition to stormwater quantity, this current study further assessed water quality performance of The Woodlands' GI design with built communities that use the conventional drainage design.

2. Materials and Methods

2.1. Study Site

The test-bed watersheds are Panther Creek watershed (The Woodlands, GI design) and Bear Creek watershed (west Houston, conventional drainage design). These two watersheds have different stormwater infrastructures, development densities and patterns, and levels of impervious surface cover (Figure 1, Table 1). Both watersheds belong to the northern humid gulf coastal prairies of Texas and present similar land use land cover conditions before development.

Figure 1. Study sites Panther Creek watershed (Site 1 The Woodlands green infrastructure development) and Bear Creek watershed (Site 2 conventional development) in Texas. USGS, US Geological Survey. TCEQ, Texas Commission on Environmental Quality.



Notes: (1) At both sites the USGS and TCEQ gauge stations are on the main stream channel; (2) At Site 1, the TCEQ gauge station (No. 16628) is 55 m downstream of the USGS gauge station (No. 08068450). For graphic presentation purposes, the distance between these two stations is shown as larger than 55 m. There is a 1.01 km² (250-acre) recreation lake (built in 1985) 2332 m upstream of the TCEQ gauge station; (3) At Site 2, the TCEQ gauge station (No. 17484) is 1,656 m upstream of the USGS gauge station (No. 08072730).

Table 1. Study sites and respective watersheds.

Watershed	Drainage area (km ²)	Development start date	Population	Household number	% Impervious cover (2009)
1. Panther Creek (Woodlands, GI)	89.4	1974	66,143	24,655	32.3
2. Bear Creek (comparative)	55.7	1976	33,763	9,559	13.7

Notes: Watersheds are defined by the U.S. Geological Survey gauging stations: No. 08068450 (Panther) and No. 08072730 (Bear). Slopes in these two watersheds are less than 1%. Population and household information is based on 2010 U.S. Census Block data.

Development started around the same period in these two watersheds in the 1970s, whereas stormwater management methods differ. The Woodlands has been well-managed as a planned community from its inception [45,47]. Ecological planner Ian McHarg laid out a suite of decentralized, infiltration-based drainage designs to reduce runoff volume and improve water quality [48–51]. McHarg's GI design was ahead of his time in that most Houston subdivision communities have been adopting the conventional drainage practices. One of McHarg's important land planning strategies was to determine building densities and land use based on soil permeability. This is achieved by preserving land with high soil permeability as open space and land with low soil permeability for development. Hence, runoff is infiltrated in close proximity to where it is generated [48]. In addition to the extensive infiltration-based drainage designs, other development strategies also help minimize the TIA and the EIA. Typical streets in The Woodlands are 5 to 8 ft (on average 10%) narrower than Houston subdivision standards for road width [49]. Open surface drainage channels were used to detain runoff, and curb-and-gutter drainage was avoided (Figure 2) ([48], p. 10).

Figure 2. (a) A typical view in The Woodlands: preserving the original vegetation, minimizing turfgrass areas, and using open surface drainage; (b) A typical collector street in The Woodlands: stormwater drains to the vegetated medium for treatment.



In collector streets, runoff is detained and treated in the vegetated street medium for better water quality (see Figure 2). Check dams were used to retard runoff and further soak it (Figure 3). Porous pavements were used in the commercial district of the first subdivision village and other locales [52].

Wetlands are protected for water quality treatment and to facilitate ecosystem services [53–55]. Modeling analyses projected the after-built runoff scenarios and ascertained that runoff is detained as close as possible to where it is generated (Figure 4).

Figure 3. (a) Open drainage design guideline which promotes impoundment on permeable soils. Check dams retard runoff and increase infiltration. LEH: medium to well-drained soil; SPH (Splendora): poorly drained soil ([50], p. 31) (Image courtesy: WRT); (b) Open surface drainage along collector streets in The Woodlands.

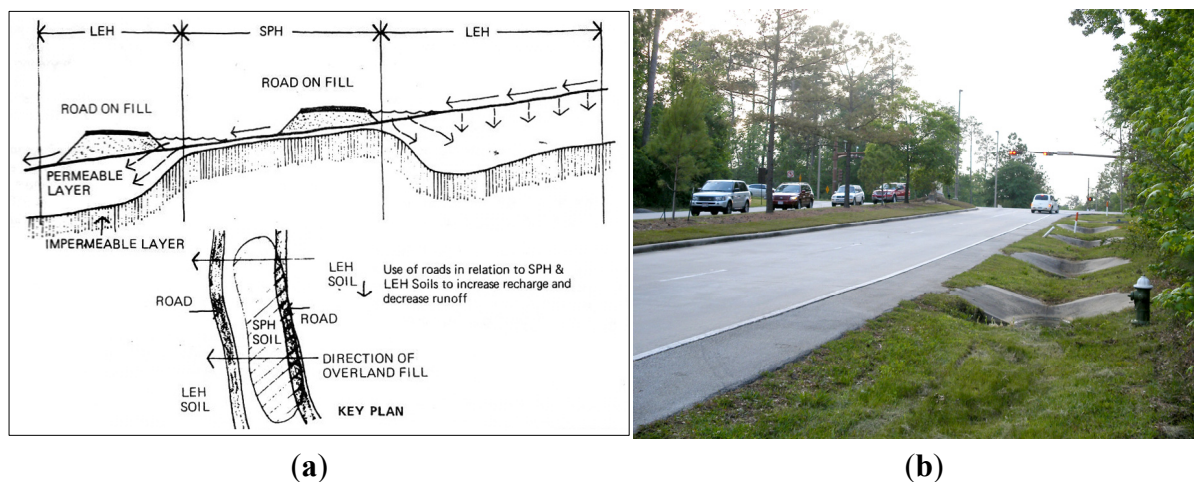
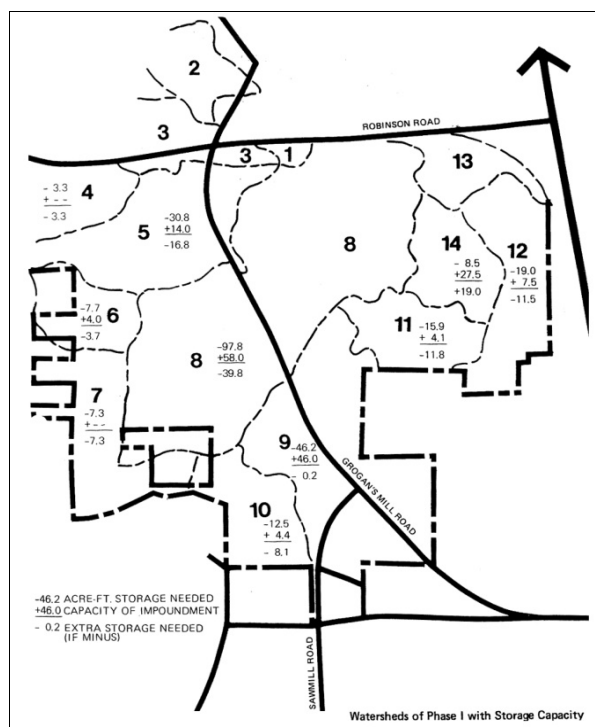


Figure 4. Modeling analysis on runoff storage in Phase I development (8 km²), with no excessive runoff allowed ([50], p. 9) (Image courtesy: WRT).



Historical extreme storm events attested to the success of McHarg's integrated GI design. The Woodlands survived 100-year storms in 1979 and 1994 with little property damage, while several adjacent communities and Houston (50 km to the south) were severely flooded [56,57]. In addition, the

first phase development alone would save \$14 million in construction costs compared with the conventional drainage method [45]. However, residents did not appreciate the aesthetics of the GI design. Market studies showed that most residents preferred visually appealing conventional drainage design (e.g., curb-and-gutter street). The rustic appearance of natural vegetation and unmaintained understory are contrary to average American's preference for a manicured lawn (see Figure 2a) [54,58]. As a result, starting around 1985, a hybrid approach was used in the later phases of development—conventional underground pipe drainage was introduced in subdivisions [59]. After 1997, McHarg's approach was largely abandoned when The Woodlands was sold to a different developer [46,58].

Bear Creek watershed is located in the fast growing west Houston region. Population in this region has surpassed 1 million since 1999 [60]. Over 34% of the residential community development in Greater Houston is projected to occur here, given the fact that Houston is currently one of the most rapidly expanding regions in the nation [61]. Bear Creek watershed presents typical subdivision developments: cookie-cutter lot layout, turfgrass-dominated landscaping, and curb-and-gutter and underground pipe drainage (Figure 5). Bear Creek watershed is part of residential development areas, designated by the West Houston Association (WHA) [60] and City of Houston General Plan [62]. There are significant flooding and water quality concerns in this region [63].

Figure 5. Typical neighborhood views in comparative Houston communities in the Bear Creek watershed (less consideration of preserving vegetation and curb-and-gutter conventional drainage).



2.2. Data

2.2.1. Development Data

In land use planning, three data sources and methods are generally used to capture the impervious cover area: (1) use parcel data to quantify the impervious area [36,64]; (2) classify Landsat remote sensing imagery to extract the impervious area [3,65,66]; and (3) digitize high-resolution aerial photographs to delineate the impervious area [66,67]. This study used the first data source to quantify

impervious cover area. Parcel data provide the parcel boundary and location, parcel area, building type, year built, and building square footage. Road information was obtained from the Texas Transportation Institute [68].

2.2.2. Soil Data

Soil infiltration capacity can be assessed through examining the area of hydrologic soil groups in the two watersheds. The soil dataset used was the 1:24,000 scale Soil Survey Geographic (SSURGO) database developed by the Natural Resources Conservation Service (NRCS) [69]. The U.S. Department of Agriculture (USDA) [70] defines four hydrological soil groups (A, B, C, and D) based on soil infiltration rates. A soils are sandy and loamy sand soils; B soils are sandy loam and loam soils; C soils are silt loam and sandy clay loam soils; and D soils are clay loam, silty clay loam, and clay soils. A soils have the highest infiltration rate, B and C soils have moderate infiltration rates, and D soils have the lowest infiltration rate.

2.2.3. Precipitation Data

Historical precipitation data were obtained from the National Climatic Data Center (NCDC) [71]. The Thiessen polygon method [72] was used to estimate precipitation for each watershed. Three weather stations (COOPID No. 411956, No. 419076, and No. 414300) were identified for Panther Creek watershed, and three other stations (COOPID No. 412206, No. 414704, and No. 414313) are used for Bear Creek watershed (see Figure 1). The area weighted percentage of each station was used to calculate the composite precipitation value.

2.2.4. Streamflow and Water Quality Data

Streamflow and water quality data of 2002–2009 were used for comparison. Streamflow data were collected from the U.S. Geological Survey (USGS) gauge stations No. 08068450 and No. 08072730 [73], at the watershed outlets (see Figure 1). Water quality data were obtained from the Texas Commission on Environmental Quality (TCEQ) [74] stations No. 16628 and No. 17484. The TCEQ also collects streamflow data when water quality data are collected but with some data gaps. Because the TCEQ monitoring stations are placed close to the USGS gauge stations (see Figure 1), the USGS streamflow data were used for consistency. Since 2000, the TCEQ has been collecting 5 to 12 water quality samples each year for each station. Water-quality samples were consistently obtained on the same day at these two stations. The date of sampling during a particular month was irregular, and the samples may not necessarily have been taken after a rainfall event. Nutrient-related parameters that show consistent records from these two stations were analyzed, including nitrate-nitrogen ($\text{NO}_3\text{-N}$), ammonia nitrogen ($\text{NH}_3\text{-N}$), and total phosphorous (TP). If in either site there were fewer than six samples for a year, that year was excluded from the analysis.

2.3. Analysis

Three sets of analyses were conducted to compare the impacts of different drainage methods on flow regime and water quality. The first set of analyses assessed development extent and soil

conditions to provide background conditions of stormwater quantity and quality comparisons. Geographic Information System (GIS) was used to analyze the parcel data. Building footprint and other impervious cover areas were calculated and sorted by year built, which provides the state of development in the watershed each year. Road surface area was estimated by multiplying the road length by the average width of the roads in the watershed [64]. A majority of the developments in this study have sidewalks on both sides of the road. Hence, the road length was doubled for the sidewalk length. Estimation was also made of the driveway impervious area. Previous studies have used the number of garage stalls multiplied by the average width (3 m) of the driveway [75,76]. However, parcel data do not provide driveway information. The Woodlands Residential Development Standards specified the front yard setback distance: “a garage or garage addition must be set back at least 16 feet (4.88 m) from the side property line” ([77], Section 2.1, p. 14). This setback distance was multiplied by the width of a two-stall garage (6 m) to approximate the driveway impervious area in The Woodlands, calculated by Equation (1):

$$\text{Driveway area (m}^2\text{)} = \text{Front yard setback (m)} \times 3 \text{ m} \times \text{Number of garage stalls} \quad (1)$$

Then, this driveway area was multiplied by the total number of parcels in the watershed to estimate the total driveway areas. Likewise, estimation of driveway area was made for Site 2 (Bear Creek watershed), based on the 20-ft (6.1-m) garage setback distance for local streets [78]. GIS was also used to analyze the percentages of different hydrologic soil groups, which will provide insights into the overall stormwater infiltration capacities of the study sites. Soil condition is of particular importance to The Woodlands because McHarg’s unique development concept is to preserve high-infiltration soils for stormwater management.

The second set of analyses examined the relationships of watershed streamflow volume and streamflow-precipitation ratio with impervious cover percentage. Streamflow depths and streamflow-precipitation ratios were examined for water years 2002–2009 for each watershed. A water year, according to the USGS definition, is from October of the preceding year to September of the current year (*i.e.*, water year 2002 = 1 October 2001 to 30 September 2002).

Streamflow-precipitation ratio (as %) for each year were calculated by dividing annual streamflow (m) by annual precipitation (m), and multiplying by 100. Annual streamflow depth (m) is calculated by dividing the total streamflow volume (m³) by the watershed area (m²), using Equation (2) below:

$$H = \frac{Q_i \times t}{A} \quad (2)$$

where H is the watershed annual streamflow depth (m); Q_i is the annual mean flow at year i (m³·s^{−1}); t is a constant, 31,536,000 s, the total number of seconds in a year; and A (m²) is the watershed area. This method assumes a uniform depth of precipitation falling onto the watershed; therefore, flow volume is standardized and becomes comparable.

The third set of analyses examined annual nutrient export. This study used the annual flow-weighted method developed by Littlewood [79,80] to calculate nutrient loadings for NO₃-N, NH₃-N, and TP, according to Equation (3):

$$Flux = KV \frac{\sum_{i=1}^n C_i Q_i}{\sum_{i=1}^n Q_i} \quad (3)$$

where K is the conversion factor to adjust for units and intervals of sampling; V is the annual accumulative flow (calculated from continuous data) ($\text{m}^3 \cdot \text{s}^{-1}$); C_i is the concentration measured at the day and time of the i th sample ($\text{mg} \cdot \text{L}^{-1}$); and Q_i is the flow rate measured at the day and time of the i th sample ($\text{mg} \cdot \text{L}^{-1}$).

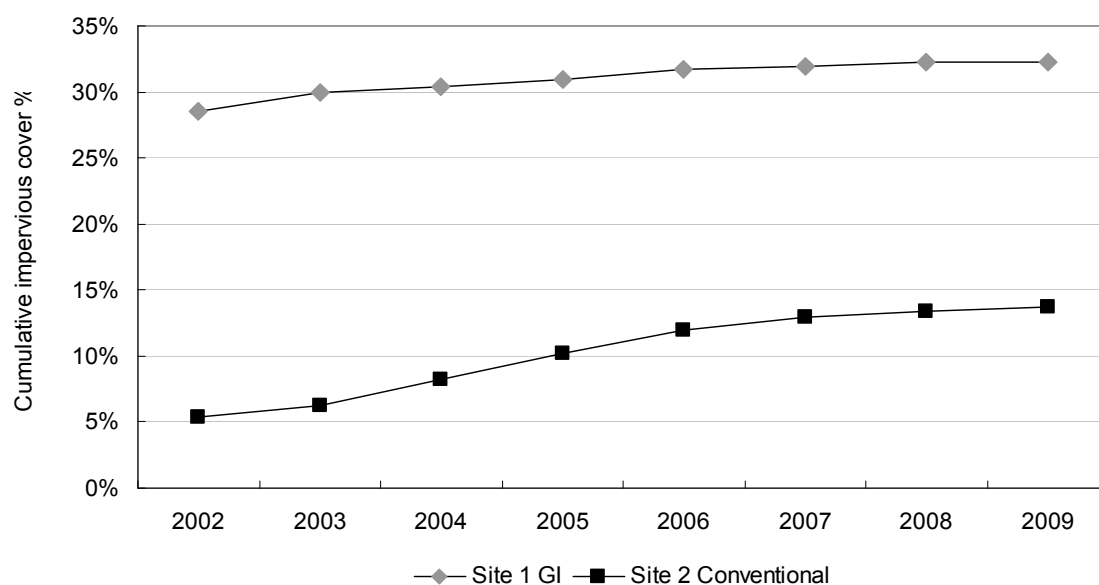
Regression analysis was conducted for each watershed, with the independent variable being watershed impervious coverage (%), and pollutant loading being the dependent variables. Each point on the graphs therefore represents a year. Regression significance testing, R^2 calculations, and parameter estimates were performed with the SPSS statistical package.

3. Results

3.1. Impervious Cover

Figure 6 shows the accumulative impervious cover percentage of the two sites with development from 2002 to 2009. It is evident that Site 1 (GI) shows a higher impervious cover percentage than Site 2 (conventional) across the study period. As of 2009, the percentage of impervious cover in Site 1 (GI, 32.3%) is more than twice that of the Site 2 (conventional, 13.7%).

Figure 6. Accumulative percentages of impervious cover area of Site 1 (Panther Creek watershed, The Woodlands green infrastructure development) and Site 2 (Bear Creek watershed, conventional development), 2002–2009.



3.2. Hydrologic Soil Group Distribution

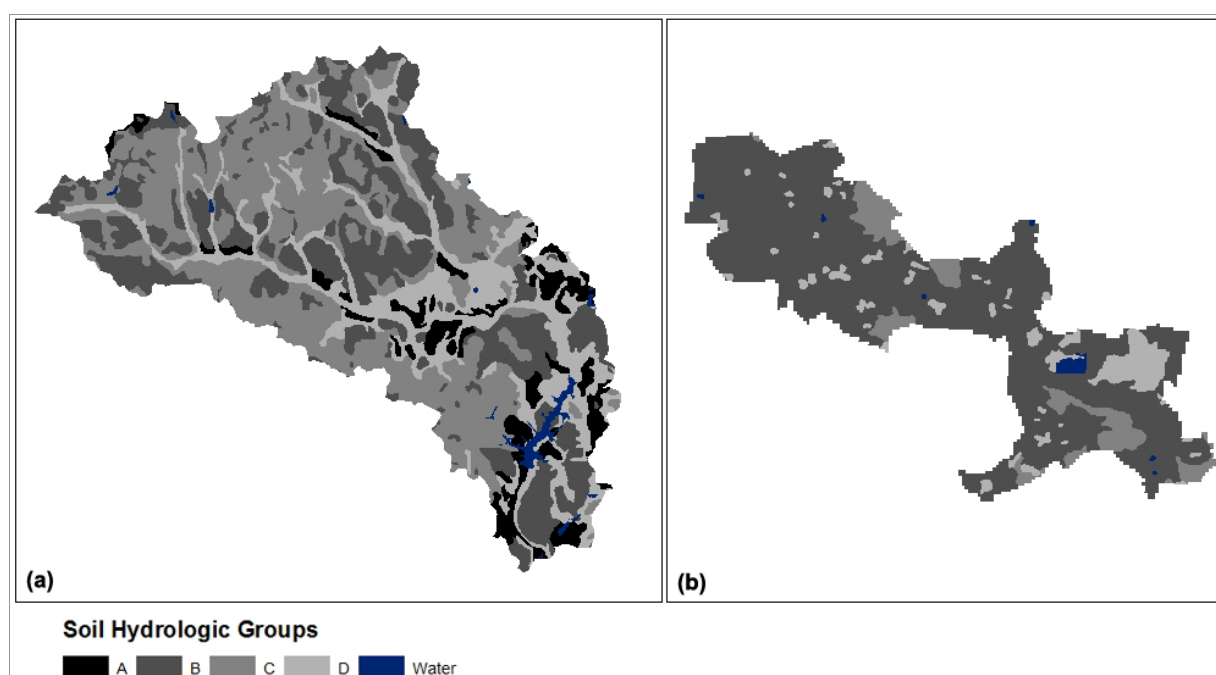
Table 2 and Figure 7 show the area distribution of four hydrologic soil groups in Sites 1 and 2. These four soil groups were further divided into two groups: A & B (sandy and loam), and C & D (silt

and clay), in order to show the overall stormwater infiltration capacity (e.g., good *versus* poor). It is evident that stormwater infiltration capacity of Site 1 (GI) is lower than that of Site 2 (conventional), because Site 1 has a much lower percentage of A & B soils (38.7% *versus* 80.2% in Site 2).

Table 2. Hydrologic soil groups in Site 1 (Panther Creek watershed, The Woodlands green infrastructure development) and Site 2 (Bear Creek watershed, conventional development).

Hydrologic soil groups	Site 1 (GI)	Site 2 (conventional)
A	8.3%	0
B	30.4%	80.2%
C	40.1%	9.8%
D	19.9%	9.0%
Water	1.2%	0.9%

Figure 7. Area distribution of four hydrologic soil groups and water surface in Site 1 (Panther Creek watershed, The Woodlands green infrastructure development) and Site 2 (Bear Creek watershed, conventional development).



3.3. Precipitation and Streamflow

Figure 8 shows the annual precipitation in Sites 1 and 2 (approximately 45 km from each other). Figures 9 and 10 show the annual precipitation depths (m) and the annual streamflow-precipitation ratios (%) at Sites 1 and 2, respectively. The average precipitation of 2002–2009 at Site 1 (GI, 1.48 m) is 15.3% higher than that at Site 2 (conventional, 1.28 m). Despite this, Site 1's streamflow volume is 6% lower than that of Site 2. More importantly, Site 1 (GI)'s precipitation-streamflow ratio is kept within a steady, lower range (32%–49%) than that of Site 2 (conventional, 30%–66%). Site 2's more fluctuating ratio suggests a “flashy” stream condition.

Figure 8. Annual precipitation in Site 1 (Panther Creek watershed, The Woodlands green infrastructure development) and Site 2 (Bear Creek watershed, conventional development), 2002–2009.

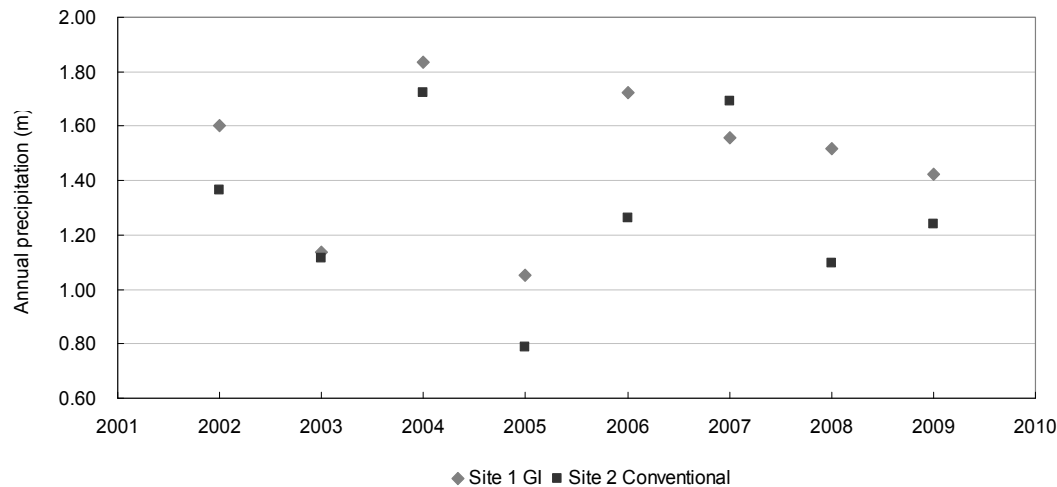


Figure 9. Annual streamflow-precipitation ratio and precipitation depth of Site 1 (Panther Creek watershed, The Woodlands green infrastructure development), 2002–2009.

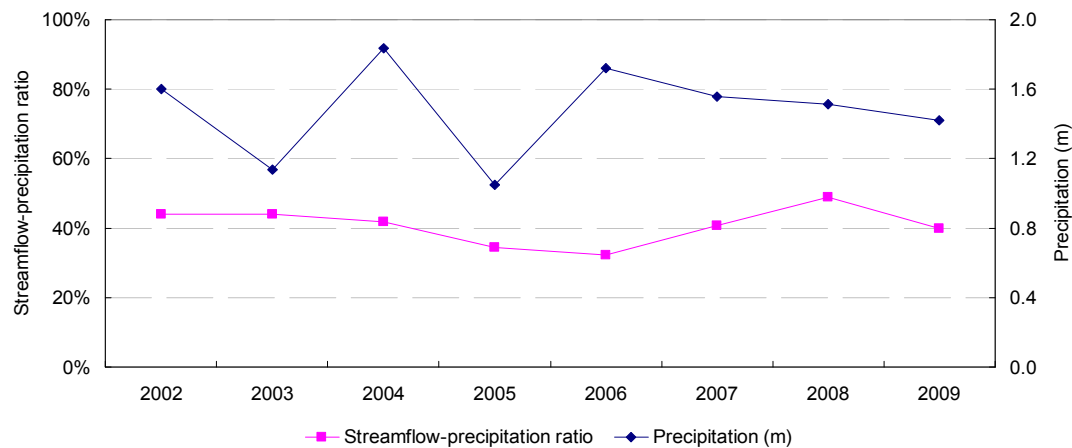
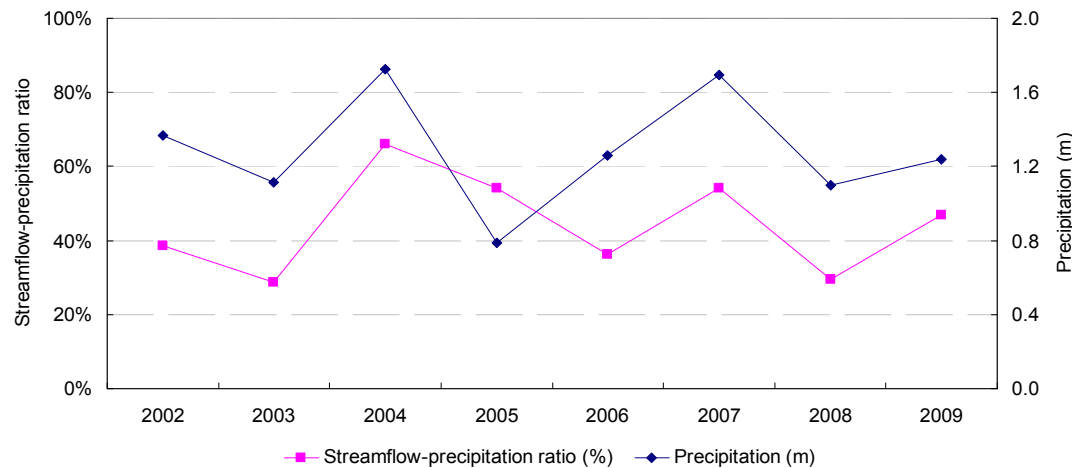


Figure 10. Annual streamflow-precipitation ratio and precipitation depth of Site 2 (Bear Creek watershed, conventional development), 2002–2009.



3.4. Nutrient Export Loading

Figure 11, Tables 3 and 4 show the regression analysis between nutrient loading and impervious cover percentage. The results reveal that nutrient loadings are tightly correlated with impervious cover in Site 2 (conventional). In contrast, in Site 1 (GI), there is little correlation between nutrient loadings and the extent of impervious ground cover. These analyses further suggest that GI design can create a robust system that is tolerant to development impacts. Thus, nutrient loadings show a similar response to streamflow volume analyses. $\text{NO}_3\text{-N}$ export increased in Site 2 (conventional) after development; however, little change was found in Site 2 (GI). $\text{NH}_3\text{-N}$ export showed a similar trend as $\text{NO}_3\text{-N}$ export from Site 2 (conventional). Likewise, TP export presented a significant ($p < 0.01$) trend in Site 2 (conventional), whereas no trend was found for Site 1 (GI).

Figure 11. Annual loadings of nutrient exports from Site 1 (Panther Creek watershed, The Woodlands green infrastructure development) and Site 2 (Bear Creek watershed, conventional development), 2002–2009: (a) $\text{NO}_3\text{-N}$, (b) $\text{NH}_3\text{-N}$, and (c) TP.

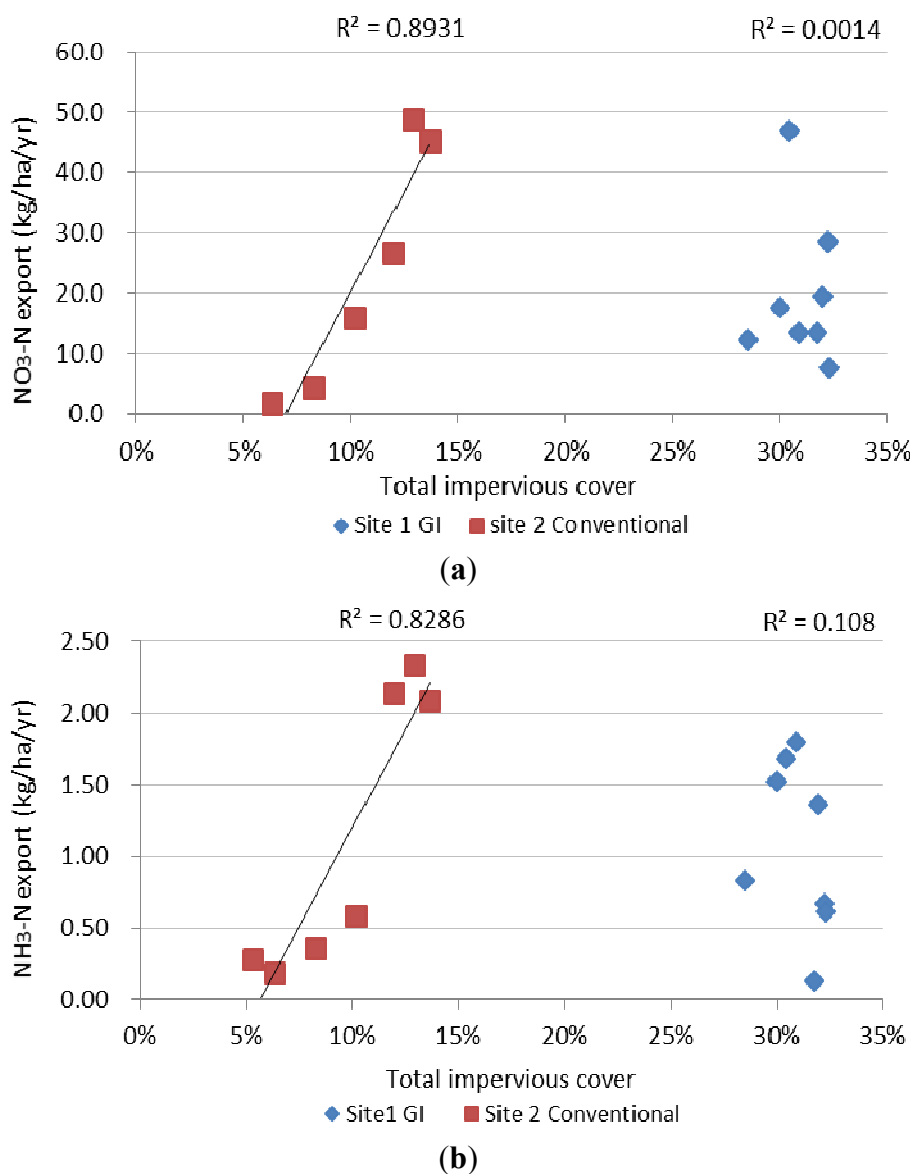


Figure 11. Cont.

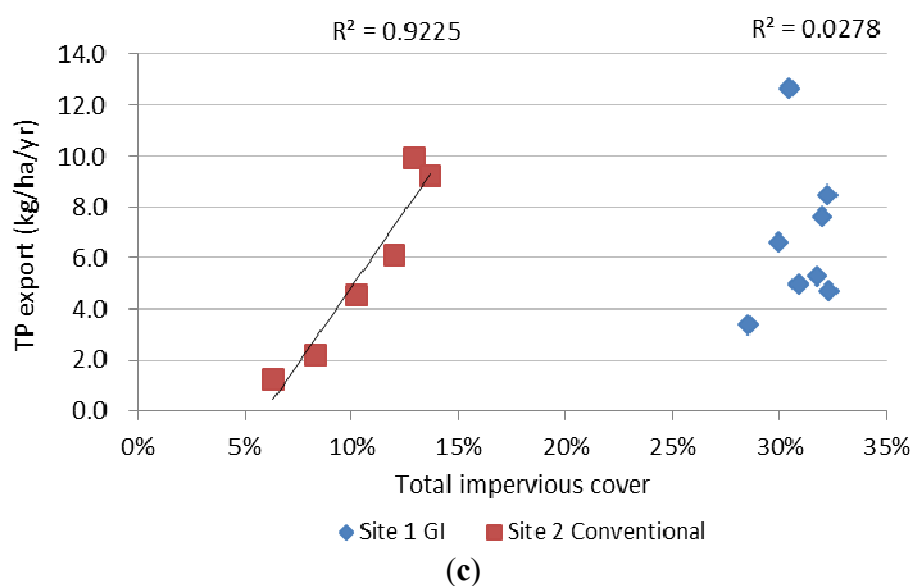


Table 3. Relationship between watershed impervious cover percentage and nutrient loading in Site 1 (Panther Creek watershed, The Woodlands green infrastructure development).

Nutrient	R ²	Equation	P-value	Sample size (2002–2009)
NH ₃ -N	0.108	NA	0.427	58
NO ₃ -N	0.001	NA	0.930	33
TP	0.028	NA	0.693	33

Table 4. Relationship between watershed impervious cover percentage and nutrient loading in Site 2 (Bear Creek watershed, conventional development).

Nutrient	R ²	Equation	P-value	Sample size (2002–2009)
NH ₃ -N	0.829	$y = 0.028x - 0.002$	0.004	78
NO ₃ -N	0.894	$y = 0.666x - 0.046$	0.004	57
TP	0.923	$y = 0.12x - 0.007$	0.002	56

Note: x is watershed impervious cover percentage; and y is nutrient loading.

4. Discussion

The eight years of empirical data yield consistent results showing that GI design produces less development impact on the flow regime and better stormwater quality than the conventional drainage design. As of 2009, the percentage of impervious cover in Site 1 (GI, 32.3%) is more than twice that of the Site 2 (conventional, 13.7%). In addition, Site 1 (GI)'s total precipitation is 15.3% higher than that of Site 2 (conventional). Further, Site 1 (GI) has a much lower runoff infiltration capacity than Site 2 (conventional) (e.g., 38.7% *versus* 80.2% of A & B soils). The opposite is true, however, when comparing watershed outputs—the Site 1 (GI) streamflow volume and streamflow-precipitation ratio are lower than those of Site 2 (conventional). Therefore, the differences in streamflow response can be largely attributed to the different drainage designs.

Figures 9 and 10 show that Site 2 (conventional) streamflow is more sensitive to precipitation and that it has a lower runoff storage capacity than Site 1 (GI). Large variability of streamflow-precipitation ratio suggests “flashy” stream conditions. In wet years such as 2004 and 2007, streamflow-precipitation ratios in Site 2 (conventional) increased dramatically. In contrast, Site 1 (GI) maintained a stable flow regime, which can be interpreted as low disturbance on the riparian habitat and riverine ecology. Likewise, water quality analyses showed consistency with the findings in streamflow. Nutrient exports from Site 1 (GI) are in general lower than that of Site 2 (conventional) (see Figure 11).

This study also demonstrates that GI design can be applied across different scales. The study shows that large-scale GI performance (e.g., a few thousand acres) can be as effective as in site-level scales (e.g., 10–50 acres). GI design was implemented across various scales in The Woodlands. At the regional scale, lands with large patches of sandy soils were preserved as open space to infiltrate runoff [45]. Road alignment considered sandy soil locations where check dams were built to slow runoff velocity (see Figure 3) [31,50]. At the site level, a Landscape Clearance Index was developed to ensure the minimum clearance of vegetation. This index specified guidelines to preserve vegetation under different soil conditions in order to achieve the objective of zero runoff from individual parcels ([51], p. 46).

Moreover, this study confirms with previous studies that *integrated* GI design strategies are better than a single strategy [30,31,44]. This is because Site 1’s GI design mimics the natural hydrological cycle by keeping the portion of runoff that originally infiltrates underground. Soil and vegetation medium further improve water quality. In other words, the decentralized, on-site runoff treatment reduced the EIA after The Woodlands development.

The effectiveness of single GI designs is often reported in the literature, such as pollutant removals of rain gardens, green roofs, and porous pavements [81–85], and the USEPA’s current guidelines are also focusing on performance measures of individual GI designs [7]. This study contributes to the USEPA’s guidelines by demonstrating that integrated GI design strategies are effective in reducing the EIA and improving water quality. Site 1 (GI) presents a much higher TIA than Site 2 (conventional) (*ca.* 2.4–5.4 times). However, its streamflow volume is 6% less than that of Site 2 (conventional). This means that the EIA of Site 1 (GI)—the direct contributor to runoff volume and quality impairment—is considerably lower than Site 1’s TIA (32.3%). Site 1’s EIA can be even lower than Site 2 (conventional)’s TIA (13.7%), because the impervious surface areas in Site 2 (conventional) are considered to be well connected for efficient drainage design.

However, the efficacy of McHarg’s GI design may not be fully revealed because of the research design of this study. McHarg’s GI design innovations were primarily used in the early phases of community development, during which McHarg presided the design [45]. Unfortunately, residents do not appreciate some of the GI designs (e.g., bioswale) [52]. As a result, a hybrid approach which combined McHarg’s design and conventional drainage design were used in the later phases of development [58,59]. About one third of The Woodlands’ early phases (*i.e.*, followed McHarg’s design) do not lie in the Panther Creek watershed. Hence, performance of GI design may be underestimated due to these study limitations. Also, the study cannot completely tease out the performance of The Woodlands early and later development phases in respect to their stormwater performance, because they were treated together as one study site (*i.e.*, Site 1).

Another study limitation is that the small water-quality sample size may decrease the precision of nutrient loading estimations. The TCEQ uses a sampling frequency of one month to meet the

monitoring objectives in western Houston areas. Littlewood's method used in this current study is based on these discrete water-quality data to estimate annual mass loads [79,80]. The precision range and confidence level of estimation decrease when the sampling frequency (e.g., monthly) and the length of the estimation period (e.g., five years) decrease. A sampling frequency that is too low (e.g., less than six samples per year) is not recommended—a principle followed in this study. In addition, estimates for dry years exhibit higher precision than those for wet years. This study used the best available data and the study period contains normal variations of dry *versus* wet years.

Finally, the 1.01 km² (250-acre) lake in Site 1 (GI, The Woodlands) upstream of the TCEQ gauge station is likely to dilute the concentration of pollutants contributed by the upstream areas of the lake. This study cannot tease out this lake dilution effect and the effect presents some limitations. However, according to the original design [86], the lake is intended to serve as a recreation amenity and as a flood control device in The Woodlands comprehensive stormwater management plan. Therefore, this integrated design strategy showed success in flood control and water quality improvement. Nonetheless, future studies are called for to evaluate the performance of each individual strategy and to compare it with the overall efficacy of the integrated strategy, as shown in this current study.

5. Conclusions

This study compares the stormwater management performance of GI design and conventional design at large-scale community developments (89.4 km² and 55.7 km²). Empirical evidence strongly suggests that integrated GI application can be effective in stormwater runoff reduction and water quality improvement. Despite a much higher TIA, GI design results in a much lower runoff volume, compared with conventional design. Further, nutrient outputs are significantly correlated with the extent of development in the conventional site, whereas there is little correlation in the GI site.

In the United States and many parts of the world, community development continues to be a major development project and covers a large territory of land. The status quo of stormwater management practices increasingly draws criticism for causing environmental quality problems. This study shows that integrated GI design can help achieve multiple stormwater management goals and may provide a cost-effective solution. In addition to the enormous construction cost savings, the potential flooding costs and potential pollution treatment costs can be avoided. Future studies need to directly assess the EIA and GI performance during peak events. Further studies are also needed to test GI performance in different climatic conditions and to improve the aesthetics of GI design based on public input.

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Conflicts of Interest

The authors declare no conflict of interest.

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