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Low Impact Development Applications in Urban Watersheds: Efficacy Evaluation by Imperviousness Connectivity Estimations

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Abstract: This is the abstract section. Although recent studies have emphasized the benefits of Low Impact Development (LID), the influence of LID on impervious surface connectivity to downstream drainage has not yet been fully investigated by using quantitative measurements. Some previous studies have attempted to measure correlates between discharged stormwater volume and the directly connected impervious areas (DCIA), a fraction of the impervious area that is hydraulically connected to downstream drainage by a piped route. They found that DCIA could be a more accurate predictor of urban development impacts on stream ecosystems than is the total impervious area. This study measured the DCIA of urban watersheds in the Energy Corridor District, Houston, Texas, where rapid urbanization and increasing impervious surfaces have caused urban stream degradation during the past decades. This study primarily prioritized land use into four types based on the contribution of hypothetically implemented LID facilities to DCIA reduction for each land use. Stormwater infrastructure and impervious cover data were analyzed using Geographic Information Systems. Sutherland's equations taken from Sutherland, R.C. (1995) were utilized to compute DCIA at the parcel level. The results were 1) a greater value of current DCIA in commercial areas than in residential areas, especially for big box retail stores; 2) a significant reduction of DCIA for both land uses after hypothetically implementing LID techniques; 3) but varying effectiveness of LID techniques depending on land use types; and 4) more reliable assessment of LID performance when applying DCIA than TIA. The results will contribute to determining which land use type is of higher priority in implementing source-control stormwater infrastructure and providing local governments with a promising indicator to calculate drainage fees which are currently imposed on property owners based on total impervious area.

Keywords: impervious surface connectivity, stormwater management, land use, directly connected impervious area (DCIA), low impact development (LID) technique

1. Introduction

Groundwater deficiency is one of the most critical water challenges faced by Texas in recent decades. With an increased frequency and intensity of extreme drought, Texas has experienced a severe reduction in groundwater recharge and surface water supplementation [1]. Projections indicate that by 2040 the population will double in Montgomery County, Texas, causing groundwater use by human activities to exceed the capacity of the Gulf Coast aquifer recharge [2]. Excessive withdrawals of groundwater for human use have consequently caused deficit-pumping, land subsidence, and increased vulnerability to flood events [3].

Houston is one of the fastest growing cities in Texas and the nation. Its metropolitan population exceeded two million in 2002 [4]. There was an approximate 40% increase in urban surface in the Houston Metropolitan Area between 1978 and 2000 [5]. This rapid urban growth has increased urban stormwater runoff drained by Buffalo Bayou and organic and nutrient loading in major tributaries [6, 7]. To reduce the impacts of urban surfaces and collect additional revenue for city drainage system improvement, the City Council of Houston has imposed drainage fees on property owners, charged according to the area of impervious surface in each parcel [8]. However, as the Houston-Galveston Area Council has forecast, another 300 square miles of undeveloped lands will be urbanized by 2035 [9], and stream impairment in the Houston area will be unavoidable.

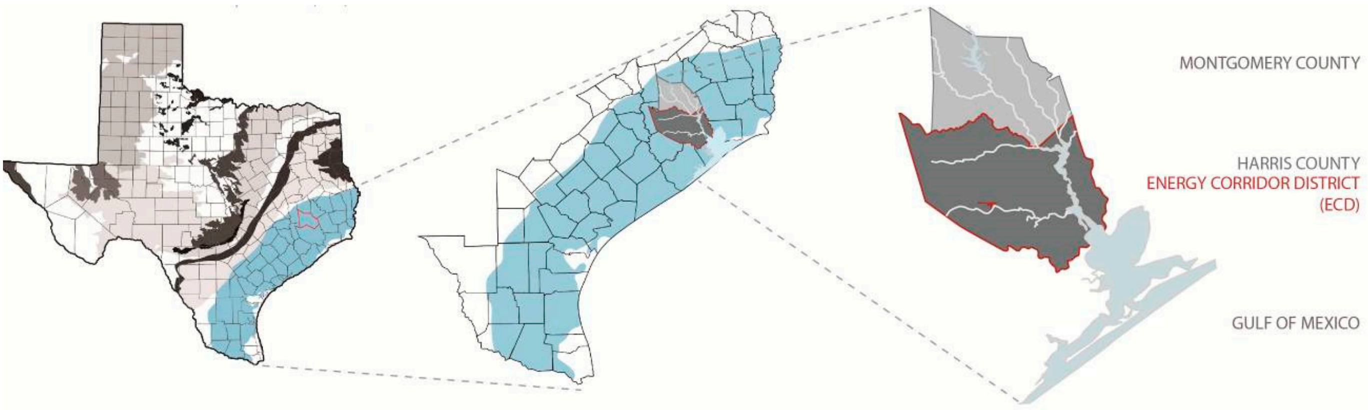
In response to this challenge, a low impact development (LID) approach appears to be a promising alternative to promote on-site infiltration and reduce direct runoff discharge to the stormwater pipelines [10]. In an effort to minimize the impact of impervious land cover, LID technology emphasizes stormwater runoff management by integrating hard and soft engineering [11]. It is an approach to land development that simulates natural processes as a way of on-site stormwater management - that is, treatment at or near the source.

However, although various benefits of LID have been emphasized in recent studies [11-14], the impact of LID on impervious surface connectivity to downstream drainage has not yet been fully investigated. This study will quantitatively evaluate the impact of urban development on direct stormwater discharge into streams and identify how effectively LID techniques would contribute to managing stormwater runoff on different land use types. This study measured directly connected impervious areas (DCIA) to assess development impact. Unlike the total impervious area (TIA), DCIA is a fraction of the impervious area that is hydraulically connected to downstream drainage by a buried piped route. Recent studies have documented that DCIA is a more accurate predictor of urban development impact on stream ecosystems than is the total impervious area [15, 16]. By estimating the DCIA of conventionally developed watersheds with different land use, this study first identified the most influential land use type in increasing impervious surface connectivity in the existing condition. Second, contributions of hypothetical LID applications for mitigating DCIA were evaluated on different land use types. Finally, it was verified that DCIA served as a more effective measure in assessing LID performance than TIA.

2. Methods

2.1. Study Area

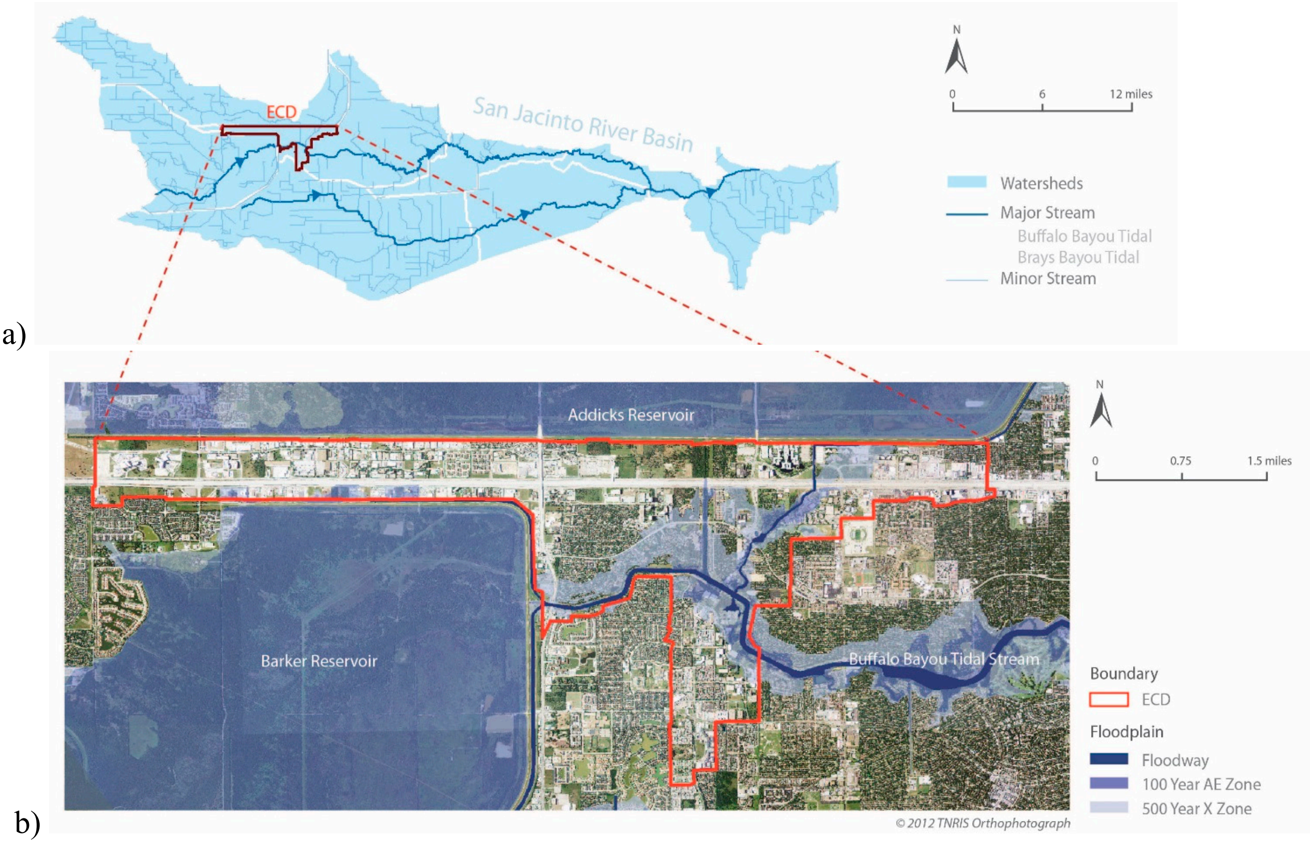
Figure 1. Study area.



The study area is the 4,060-acre Energy Corridor District (ECD) located in west Houston, Harris County, Texas. Established in 2001, the district is the third largest employment center in Houston [17]. It has become highly urbanized since 1990 and the impervious surfaces have increased by 12.5% for the past decade [18, 19]. Due to the significant decrease in groundwater recharge followed by rapid population growth, the Trinity River currently serves as a major alternative water resource [20].

The average annual precipitation in the ECD is 49.8 inches, which is far higher than the average annual precipitation of Texas of 35 inches [21]. Over 5.5 billion gallons of rainwater fell on the 4,060-acre site which is enough to fill 8,270 Olympic-sized swimming pools. However, the ECD mostly consists of soils with a low infiltration capacity; the soil infiltration rate of 42.5% at the site is only 0-0.06 inch/hour [22]. This implies a high potential for stormwater runoff. The current condition reveals that runoff from the most impervious areas is directly discharged into the Buffalo Bayou Tidal Stream through underground drainage pipelines. The site has a high vulnerability to flooding; however, two large natural reservoirs surrounding the ECD help control flooding in the urban area (see Figure 2).

Figure 2. a) San Jacinto River basin and b) flood plain in the ECD.



To measure the impervious surface connectivity of different land use within or near the district, nine subcatchments have been selected for analysis. Each subcatchment represents a different land use, density, and development pattern (undeveloped, single family residential, multi-family residential, big box retail, and scattered small-scale retail) (see Table 1). Five subcatchments are within or on the boundary of the ECD; four are within 7.5 miles from the ECD boundary. The number of parcels in each subcatchment varies from 30 to 1,050. Because in many cases it is hard to find a watershed with only a particular land use type, subcatchments with similar land development patterns were selected in proximity to the ECD. Moreover, to control varying sizes of subcatchments, all measurements were shown by percentage.

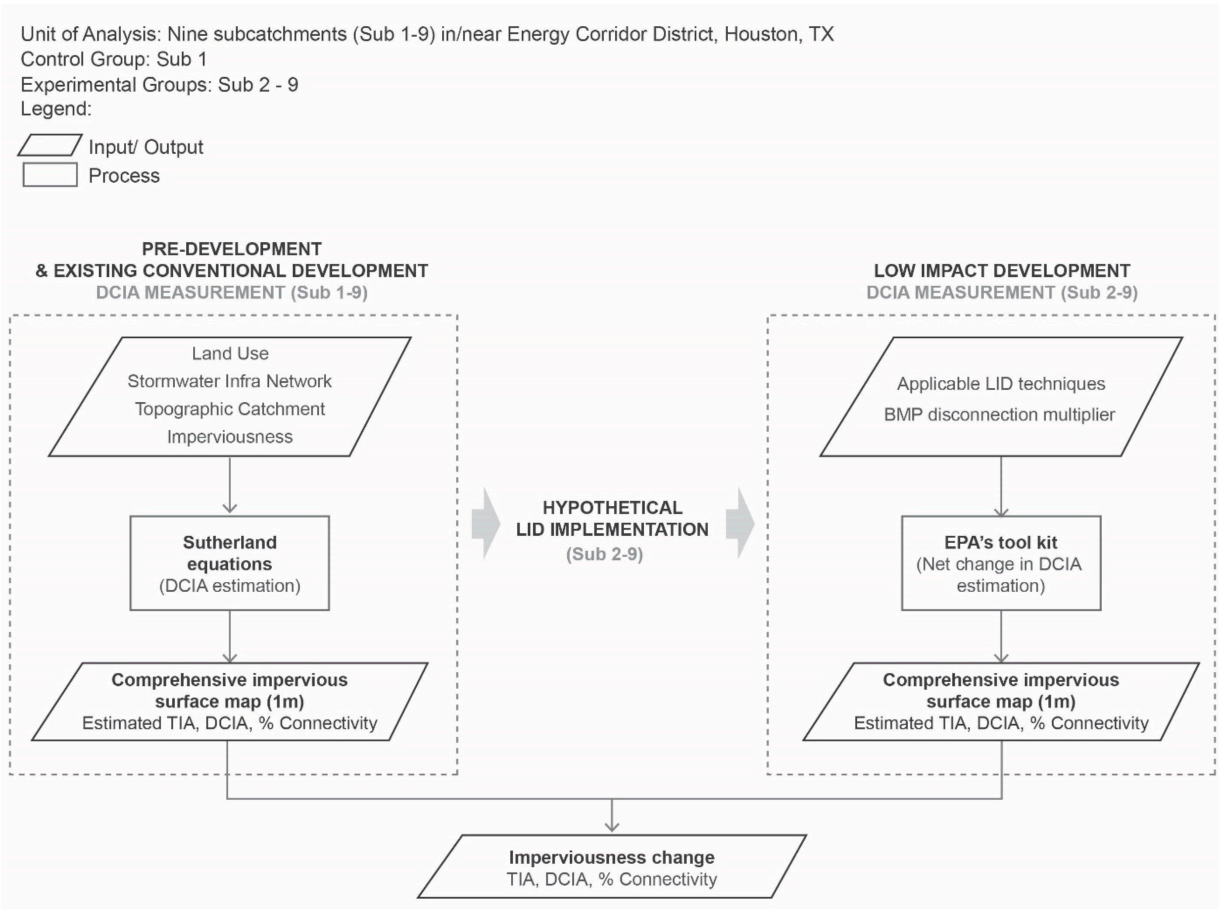
Table 1. Unit of analysis.

Subject	Land Use	Subcatchment
Control group	Undeveloped	Sub 1
Experimental group	Residential area I: Single family housing	Sub 2; sub 3
	Residential area II: Multi-family housing	Sub 4; sub 5
	Commercial/Industrial area I: Big box retails	Sub 6; sub 7
	Commercial/Industrial area: Scattered small-scale retails	Sub 8; sub 9

2.2. Research Framework

Figure 3 presents the conceptual research framework for assessing the impervious surface connectivity in the nine selected subcatchments. Comparisons of DCIAs were first made between undeveloped and conventionally developed subcatchments in the existing condition. Second, after employing hypothetical LID techniques, DCIAs of these subcatchments were estimated again. Last, DCIAs between conventional development and LID approaches were compared at a subcatchment scale by different land use types. Meanwhile, impervious surface connectivity, which is the ratio of DCIA to TIA in each subcatchment, was calculated.

Figure 3. Conceptual research framework.



2.3. Data

The dependent variables of this research are the total impervious area (TIA), the directly connected impervious areas (DCIA), and the impervious surface connectivity. Independent variables include land use, stormwater infrastructure networks, BMP disconnection multiplier, topographic catchment, and impervious cover data (see Table 2). Most data were collected from the City of Houston (COH) and the Houston-Galveston Area Council (HGAC).

2.3. Data Analysis

This study includes four major tasks: total impervious area (TIA) estimation, directly connected impervious area (DCIA) estimation, hypothetical LID implementation, and reduced TIA and DCIA estimation. First, land use and impervious surface data at one-meter resolution of the National Agriculture Imagery Program (NAIP) satellite imagery were integrated in Geographic Information Systems (GIS) to calculate the TIA in each parcel of selected subcatchment. Second, a comprehensive impervious surface map was created based on stormwater infrastructure networks and topographic data to estimate current DCIAs. Sutherland's equations were utilized to calculate DCIAs at the parcel level. Third, the hypothetical scheme of LID implementation was established based on the Harris County LID design criteria for stormwater management. Last, net changes in TIA and DCIA after LID applications were estimated using the Environmental Protection Agency's BMP disconnection factors.

Table 2. Research construct and variables.

Construct	Variables	Unit	Sources
Dependent Variables			
Imperviousness connectivity	Total impervious area (TIA)	sf, ac	Sutherland equations (Sutherland, 1995), EPA[1]' tool kit
	Directly connected impervious area (DCIA)	sf, ac	
	% Connectivity	%	
Independent Variables			
Land use (Parcel level)	Parcel / land use	-	HCAD[2], HGAC[3]
	Population density	#/ac	COH[4]
	Road	-	HGAC
	Percent imperviousness	%	MRLC[5]
	Satellite image	-	TNRIS[6]
	Building footprint	sf, ac	COH
Stormwater infrastructure network	Stormwater gravity lines	-	H-GIMS[7]
	Stormwater inlets / manholes	-	H-GIMS
BMP disconnection multiplier	BMP's runoff reduction rate	%	EPA
Topographic catchment	Overland drainage area	-	COH
	Overland flow path	-	COH
	Contours	Ft	H-GIMS
Imperviousness	Impervious surface area	sf, ac	COH

[1] Environmental Protection Agency [2] Harris County Appraisal District

[3] Houston-Galveston Area Council [4] City of Houston

[5] Multi-Resolution Land Characteristics Consortium

[6] Texas Natural Resources Information System

[7] Houston Geographic Information & Management System

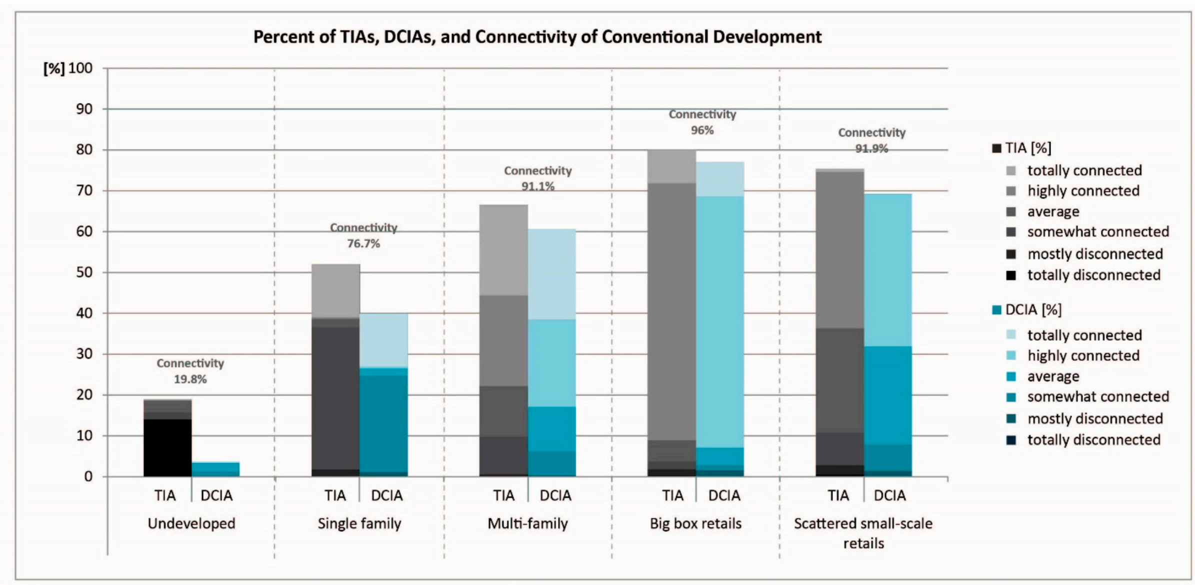
3. Results

3.1. Imperviousness Connectivity of Conventional Development

Current development conditions in/near the Energy Corridor District (ECD) revealed varying imperviousness connectivity depending on land use types. As illustrated in Figure 4, the big box retails had the highest percent of TIA, DCIA, and connectivity (80% TIA, 77% DCIA, 96% connectivity), while the single family residential area had the lowest values (52% TIA, 40% DCIA, 77% connectivity). Large parking lots with few infiltration areas, direct connections of building rooftops to stormwater pipelines, and highways in the proximity significantly contributed to increasing the values of TIA and DCIA in the big box retail areas. In contrast, several front/back yards in single family housing helped drain stormwater into the soil before it reached underground storm sewerlines and therefore reduced the values of DCIA. The value of imperviousness connectivity of scattered small-scale retails was similar to that of multi-family housing (91.1% for multi-family housing and 91.9% for scattered small-scale retails). This was due to their similar development patterns and drainage systems; both land use types had analogous building-to-land ratios and mostly directed rooftop runoff to street gutters or small pockets of lawn area.

As expected, developed subcatchments (subs 2-9) revealed higher DCIAs and TIAs than undeveloped subcatchment (sub 1). The undeveloped subcatchment had the greatest discrepancy between TIA and DCIA.

Figure 4. Percentage of TIAs, DCIAs, and connectivity of conventional developments.



3.2. Comparison of TIA and DCIA Changes after LID applications

Except for vegetated swales, TIAs in both residential and commercial/industrial areas remained almost unchanged after LID applications. In contrast, the reduction rates of DCIAs were significant but varied by land use types and LID facilities implemented. As seen in Table 3, application of vegetated swales resulted in the greatest reduction of DCIAs in all land use types. Yet, there were contrasting contributions from rainwater harvesting systems and pervious pavement in residential and commercial/industrial areas. Rainwater harvesting systems in residential areas significantly reduced DCIA as much as vegetated swales; the percent of imperviousness connectivity even became lowest in multi-family housing with the use of rain barrels. On the contrary, pervious pavement was less effective in residential areas. In commercial/industrial areas, pervious pavement outperformed rainwater harvesting systems. To illustrate, pervious pavement in big box retails mitigated DCIA by 43% while rainwater harvesting reduced 21% of DCIA.

Overall, vegetated swales generated the lowest post-DCIAs of all land use types. Rainwater harvesting and pervious pavement contributed as much as vegetated swales only in selected land use types.

3.3. Multiple LID applications and Changes in Imperviousness Connectivity

When three types of LID facilities including rainwater harvesting systems, pervious pavement, and vegetated swales were applied altogether, post-imperviousness connectivity (ratios of DCIAs to TIAs) in each land use were undoubtedly lower than a single technique applied alone. However, the level of differences in connectivity between single and multiple LID applications varied by land use types (Figure 5). In single family and scattered small-scale retail areas, only a small reduction of connectivity occurred between implementation of vegetated swale-only and all-three LID techniques combined. In contrast, multiple LID applications in big box retail areas resulted in reducing the largest amount of imperviousness connectivity compared not only to the conventional development but also to the application of single LID technique.

Figure 5. Comparisons of percent imperviousness connectivity by land use types. (* CIP = conventional impervious pavement, RH = rainwater harvesting, PP = pervious pavement, VS = vegetated swale).

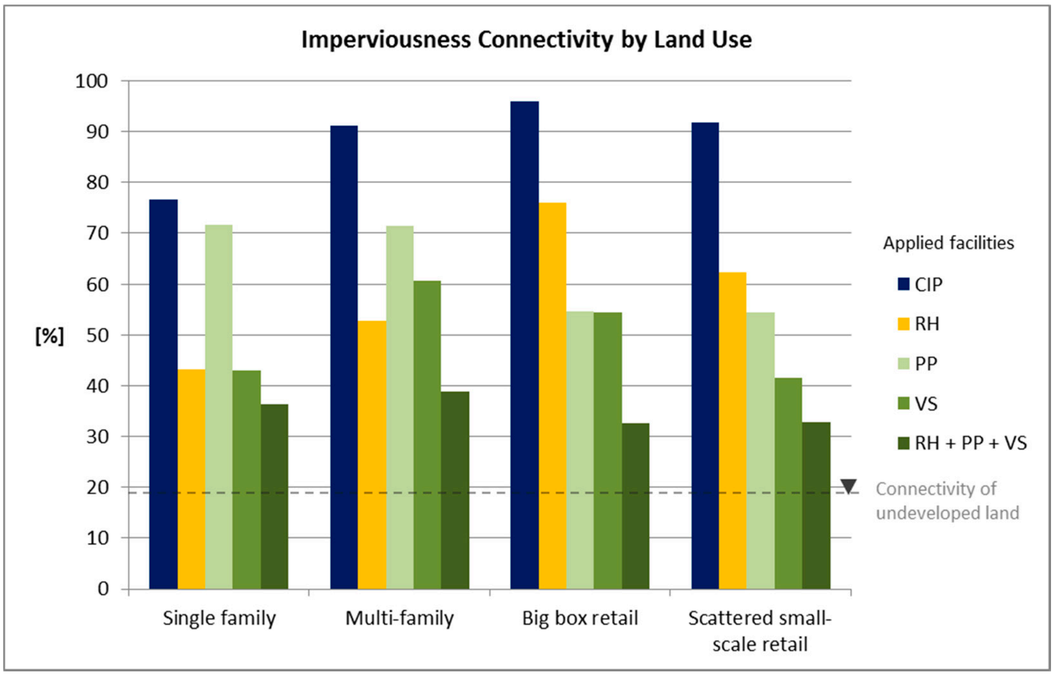


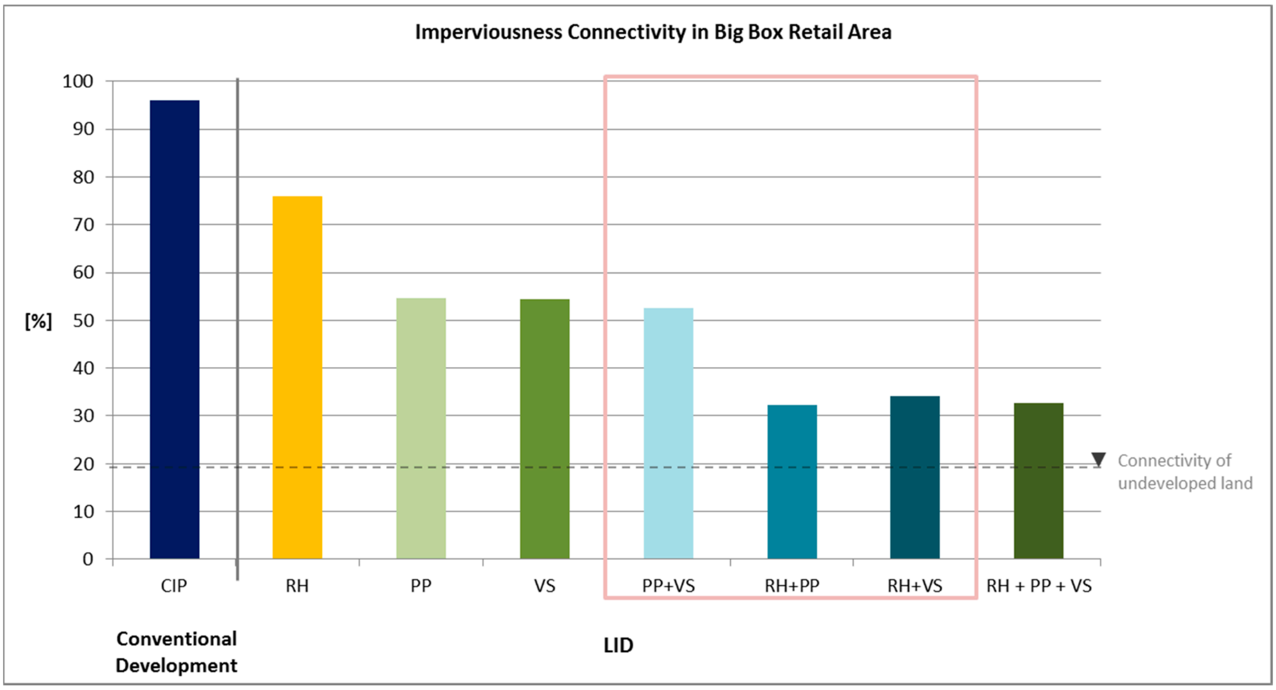
Table 3. Estimated percentage of watershed's TIA, DCIA, and imperviousness connectivity for conventional and LID development types.

Land Use	Watershed	Development Type	Facility	TIA [%]	DCIA [%]	TIA reduction rate [%][1]	DCIA reduction rate [%][2]	Connectivity [%][3]
Undeveloped	Sub 1	No development	Non-pervious pavement	19.0	3.7	-	-	19.8
Single family	Sub 2-3	Conventional development	Connected impervious pavement	52.0	39.9	-	-	76.7
		Low Impact Development (LID)	Rainwater harvesting	52.0	22.5	0.0	43.7	43.2
			Pervious pavement	52.0	37.3	0.0	6.5	71.7
			Vegetated swale	52.0	22.4	0.0	43.8	43.1
			All three LID techniques	52.0	18.9	0.0	52.7	36.3
Multi-family	Sub 4-5	Conventional development	Connected impervious pavement	66.5	60.6	-	-	91.1
		Low Impact Development (LID)	Rainwater harvesting	66.5	35.1	0.0	42.1	52.7
			Pervious pavement	66.5	47.5	0.0	21.6	71.5
			Vegetated swale	55.4	33.6	16.7	44.6	60.6
			All three LID techniques	55.4	21.6	16.7	64.4	38.9
Big box retail	Sub 6-7	Conventional development	Connected impervious pavement	80.1	76.9	-	-	96.0
		Low Impact Development (LID)	Rainwater harvesting	80.1	60.8	0.0	20.9	75.9
			Pervious pavement	80.1	43.8	0.0	43.0	54.7
			Vegetated swale	74.0	40.3	7.6	47.7	54.4
			All three LID techniques	74.0	24.2	7.6	68.6	32.7
Scattered small-scale retail	Sub 8-9	Conventional development	Connected impervious pavement	75.3	69.2	-	-	91.9
		Low Impact Development (LID)	Rainwater harvesting	75.3	47.0	0.0	32.1	62.4
			Pervious pavement	75.3	41.1	0.0	40.7	54.5
			Vegetated swale	69.7	28.9	7.5	58.2	41.5
			All three LID techniques	69.7	22.8	7.5	67.0	32.8

1) TIA reduction rate = [reduced TIA after LID applications]/[TIA in conventional development] x 100%
2) DCIA reduction rate = [reduced DCIA after LID applications]/[DCIA in conventional development] x 100%3) Connectivity = [DCIA%]/[TIA%] x 100%

Since *highly connected* parcels were dominant in big box retail areas, most watersheds were storm sewered with curbs and gutters, little infiltration existed, and rooftops were directly connected to sewerlines. In this context, multiple LID techniques could effectively redirect stormwater runoff from parking lots and rooftops. As presented in Figure 6, different combinations of LID applications contributed to lessening the level of imperviousness connectivity in big box retails. Interestingly, application of a rainwater harvesting system alone was less effective, while its application with pervious pavement or vegetated swales would generate about the same amount of connectivity mitigation as three LID techniques combined.

Figure 6. Comparisons of percent imperviousness connectivity in big box retails by different combinations of three LID facilities applied. (* CIP = conventional impervious pavement, RH = rainwater harvesting, PP = pervious pavement, VS = vegetated swale).



4. Discussion and Conclusions

4.1. DCIA as an Accurate Predictor of Urban Development Impacts and its Further Applications

DCIA refers to a subset of the TIA which is directly connected to downstream drainage by underground stormwater pipelines. Some studies accentuated the significance of DCIA in assessing urban development impacts on stream ecosystems [15, 16]. For DCIA estimation, field assessment guarantees the highest accuracy but requires significant work to obtain the data [23]. In this study, TIA and DCIA were calculated with measurements validated in previous research [24]. Comparing TIA and DCIA changes after hypothetical LID installations, the results revealed that TIA remained almost the same while values of DCIA were reduced based on land use types and the LID facilities proposed. Especially in big box retail areas, approximately 200 acres out of a 380-acre impervious area became disconnected after applying three LID techniques thus creating the biggest discrepancy between TIA and

DCIA values. This indicated that the DCIA conveyed more accurate information about the hydrological relationships between impervious surface and stormwater runoff discharge than TIA.

Furthermore, parcel-scale TIA and DCIA data could enable municipalities to calculate drainage fees. While stormwater facilities located on public properties and within the public right-of-ways are inspected and maintained by local governments, private property owners are not required to disconnect impervious surfaces and minimize stormwater discharges to the public sewer system. Fair drainage fees based on DCIA measurement may encourage property owners to take individual action to reduce stormwater runoff and simultaneously increase awareness about LID.

Similarly, stormwater incentives for DCIA mitigation could promote individual efforts to control stormwater runoff at/near the source and minimize its impacts. To accelerate this process, further studies on improving validation and precision of DCIA measurements at the parcel level are needed. The assessment of imperviousness connectivity in parcels will allow effective stormwater management at site-specific levels and foster future implementation of stormwater management policies.

4.2. Priority of Land Use Types for LID Implementation

The Energy Corridor District represents highly urbanized watersheds with diverse land uses. The measurement of imperviousness connectivity in this study indicates the significance of establishing efficient stormwater management policies in association with land use plans. Previous studies evidenced that commercial areas had a higher ratio of DCIA/TIA than residential areas, and public properties such as streets had a higher percentage of connectivity than private properties [15, 23]. Similarly in this study the results revealed the greatest imperviousness connectivity in commercial/industrial areas especially in big box retails. In contrast, single family housing had the lowest value of connectivity. This would imply the need for optimized stormwater management action and specified regulations in accordance with diverse land use types.

After EPA established stormwater permit regulations in 1990 for municipal separate storm sewer systems (MS4) serving a population of 100,000 or more, the City of Houston, Harris County/Harris County Flood Control District and Texas Department of Transportation prepared the permit applications. After receiving a National Pollutant Discharge Elimination System (NPDES) permit from EPA in 1998, Harris County initiated stormwater control policies at the county-level and adopted the Regulations of Harris County Texas for Storm Water Quality Management. This regulation requires a stormwater quality management plan for any new development or redevelopment disturbing five acres or a larger land tract in Harris County [25, 26]. Currently the Texas Commission on Environmental Quality (TCEQ), a permitting authority since 2003, has intensified regulations, extended permit coverage to even small construction sites greater than one acre, and required engineers to include best management practices in stormwater pollution prevention plans (SWP3) [27].

However, current local regulations for stormwater control do not acknowledge the impact of land use on runoff discharge; municipalities identically allow general LID applications for any new development or redevelopment regardless of current/proposed land use types. As evidenced in this study, DCIA measurement implies a strong relationship between the spatial characteristics of land use and stormwater discharge into downstream drainage. Particular land use types with high imperviousness connectivity shall require more immediate stormwater impact minimization measures and specified management plans. With precise understanding of stormwater mechanisms in terms of imperviousness connectivity, water resource strategies need to be interdependent with land use plans. Then the current stormwater burden of municipalities will be assuaged.

Conflict of Interest

The authors declare no conflict of interest.

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