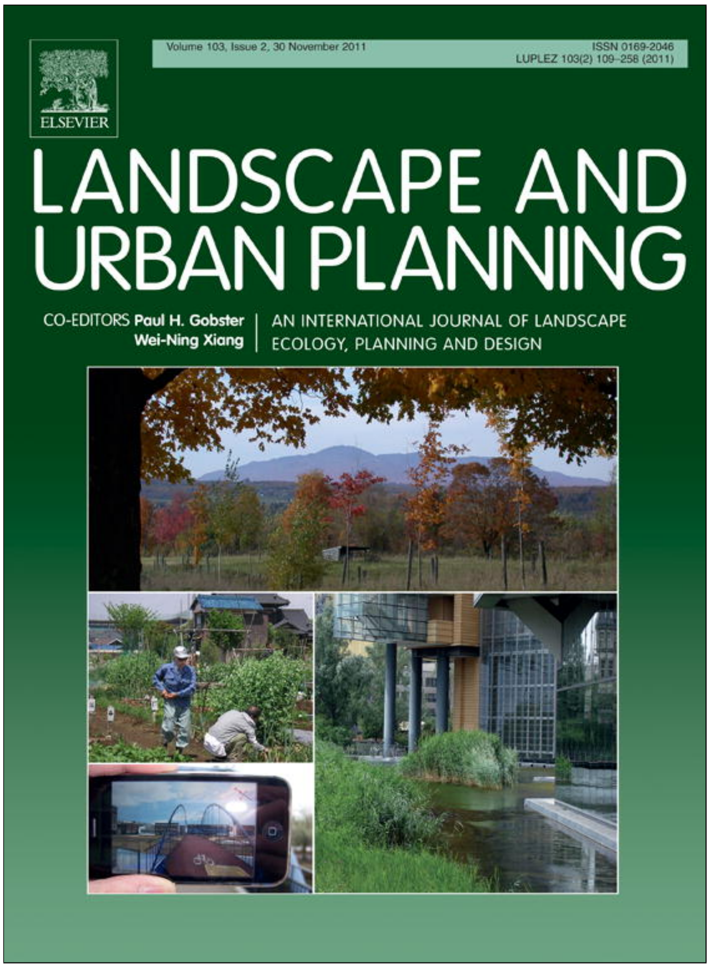
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Assessment of low impact development for managing stormwater with changing precipitation due to climate change

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ABSTRACT

Evidence suggests that built environments will need to function under climatic conditions different from the recent past. Observed warming temperatures and changes in precipitation already suggest that historical observations and personal experience may not be reliable guides to future conditions. Yet, uncertainties remain about future climatic conditions, particularly at local and regional scales where land use planning decisions are made. Faced with this uncertainty, responding to climate change will require identifying key vulnerabilities of the built environment and developing adaptive strategies for reducing the risk of harmful impacts. One area of potential vulnerability is stormwater management. Increased precipitation due to climate change could exacerbate the impairment of surface waters due to increases in stormwater runoff. This study considers the potential effectiveness of low impact development, specifically compact development with decreased impervious cover, for reducing stormwater impacts on surface water under changing precipitation patterns. The study location is a redevelopment project south of Boston, MA, USA. A simple stormwater model, SGWATER, is used to assess the sensitivity of stormwater runoff and pollutant loads to changes in impervious cover, precipitation volume, and event intensity. Simulation results suggest that when expressed on a constant percent basis, stormwater runoff is most sensitive to changes in site impervious cover, followed by changes in precipitation volume and event intensity. The study illustrates, in a simple but quantitative way, the potential benefits of a common low impact development practice for increasing the resilience of communities to changing precipitation patterns.

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1. Introduction

Stormwater runoff from roads, rooftops, parking lots, and other impervious cover in urban and suburban environments is a well known cause of stream degradation, commonly referred to as urban stream syndrome. Common impacts of stormwater runoff include increased flooding, channel instability, water quality impairment, and disruption of aquatic habitats (NRC, 2008; Paul & Meyer, 2001; Roy et al., 2005; Walsh et al., 2005). Stream degradation has made the protection and restoration of aquatic habitats through comprehensive stormwater management an important sustainability goal of communities. Typically, stormwater management practices are designed to meet performance standards based on historical climate conditions. In the coming decades, however, the built environment, including stormwater management systems, may need to meet performance expectations under climatic conditions different from those in recent history (IPCC, 2007; Karl, Melillo, & Peterson, 2009; Milly et al., 2008; USGCRP, 2009).

During the past century much of the U.S. has experienced warming temperatures and changes in the amount, intensity, and form of precipitation (Douglas & Fairbank, 2011; Groisman et al., 2005; IPCC, 2007; USGCRP, 2009). Climate modeling experiments suggest

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these trends are likely to continue or accelerate throughout the 21st century, although uncertainty remains regarding future precipitation, particularly at spatial scales important to local and regional planning (IPCC, 2007; USGCRP, 2009). The implications of projected climate change for communities will be determined, in large part, by the design, operation, and maintenance of the built environment. Adapting the built environment, including stormwater management infrastructure, will involve assessing vulnerabilities and implementing strategies to offset or reduce negative social, economic, and ecological effects associated with climate change (Smit & Wandel, 2006). Given the inherent uncertainty of the problem, successful adaptation strategies will likely need to encompass practices and decisions to reduce vulnerabilities across a wide range of plausible future climatic conditions (LaGro, 2008).

Faced with uncertainty about future climate change, and given constraints on available resources, communities may choose to pursue *no-regrets* strategies – actions that are beneficial in addressing current stormwater management needs regardless of whether or how climate may change in the future (Means, Laugier, Daw, Kaatz, & Waage, 2010). Many communities across the U.S. are now implementing smart growth and low impact development (LID) practices to meet stormwater management goals (e.g., see Benedict and McMahon, 2006; NRC, 2008; USEPA, 2011a). A general aim of LID is increased onsite retention and infiltration of stormwater runoff. Common practices include higher density development, installation of green infrastructure such as pervious pavement and grass swales, preservation of natural lands, re-use of already developed lands (e.g., see LeFevre, Watkins, Gierka, & Brophy-Prince, 2010; USEPA, 2011b), and other approaches for reducing impervious cover (Arnold & Gibbons, 1996; Brabec, 2009; Schueler, 1994; Sutherland, 1995). LID may also provide for assimilating stormwater pollutants and increasing infiltration are well documented (e.g., see Bedan & Clausen, 2009; NRC, 2008; USEPA, 2011b).

LID may also provide increased resilience to future climate change, but little is known about LID performance in this context. Studies have explored the potential implications of climate change for stormwater management infrastructure, including LID. Gill, Handley, Ennos, and Pauleit (2007) found LID to be effective in moderating potential climate change impacts such as extreme temperatures and increased surface runoff.

Rosenberg et al. (2009) assessed stormwater sensitivity to climate change in the Puget Sound region of Washington State using the Hydrologic Simulation Program-Fortran (HSPF) model (Bicknell, Imhoff, Kittle, Thomas, and Donigian, 2005).

Results were inconclusive, but suggest that increased runoff volumes may require modification to current stormwater management. Stormwater Management Model (SWMM) (Rossman, 2010) simulations of an urban site in British Columbia, Canada, using modified Intensity-Duration-Frequency (IDF) curves extrapolated to represent projected future storm event intensities for 2020 and 2050, suggested that site infrastructure would need minimal upgrades to account for the larger runoff volumes, but that future increases in stormwater runoff could still result in impaired stream health (Denault, Millar, & Lence, 2006). Waters, Watt, Marsalek, and Anderson (2003) completed SWMM simulations to identify the vulnerabilities of a stormwater management system in Ontario, Canada by increasing the design event intensity by 15%. The study found the system pipe size inadequate in some areas, but peak discharge could potentially be offset with disconnected downspouts and increased storage (Waters et al., 2003).

An improved understanding of LID in the context of climate change adaptation can help inform stormwater management decisions to reduce the risk of harmful future impacts. In this paper we assess the potential effectiveness of one common element of LID, compact development with reduced impervious cover, for decreasing stormwater runoff and pollutant loads under conditions of changing precipitation. A simple stormwater model, SG WATER (Smart Growth Water Assessment Tool for Estimating Runoff), is used to evaluate runoff and pollutants under a range of hypothetical climate change and land use scenarios for a redevelopment project in Massachusetts (USEPA, 2002a, 2002b). The goal is to illustrate, in a simple but quantitative way, the sensitivity of stormwater runoff and pollutant loads from alternative land use scenarios across a range of potential future changes in precipitation. This knowledge can help build our understanding of how to adapt stormwater management practices and build climate resilient communities.

2. Methods

Scenario analysis using computer simulation models is a useful and common approach for assessing the potential outcomes across a range of alternative climate conditions, land use patterns, and management decisions on watersheds (IPCC-TGICA, 2007). Given the uncertainty of climate change, analyzing an ensemble of scenarios allows for the exploration of multiple futures to identify potential vulnerabilities and management responses that will be robust across a range of plausible conditions (Lempert & Groves, 2010; Lempert, Groves, Popper, & Bankes, 2006; Volkery & Ribeiro, 2009). Scenarios can be developed in a number of ways to assess watershed sensitivity including extrapolation of historical trends (Denault et al., 2006), using model projections (Rosenberg et al., 2010), synthetically adjusting specific parameters (Waters et al., 2003), or any combination of the above (IPCC-TGICA, 2007).

In this study, the SG WATER model was used to simulate the quantity and quality of stormwater runoff that would occur under a range of hypothetical precipitation change scenarios and three land use scenarios for the South Weymouth Naval Air Station (SWNAS), a 567-hectare former military base south of Boston, Massachusetts. SWNAS was closed in 1997 as a result of the Defense Base Closure and Realignment Act of 1990. Several alternate redevelopment site designs were proposed with varying degrees of density and amenities, including transit accessibility. This study focused on two of the proposed site designs, hereafter referred to as the *conventional site* and *low impact site* designs.

Precipitation in this region, as determined by data from National Climatic Data Center's Hingham, Massachusetts weather station (located approximately 9 km from the site) for 1960–2010, is relatively uniform throughout the year, averaging about 125 cm/yr. Average monthly temperature ranges from −2 °C to 22.3 °C with an annual average of about 10.1 °C.

2.1. Stormwater modeling

The SG WATER model was used to simulate annual stormwater runoff, total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS) loads for all land use and precipitation change scenarios. SG WATER was developed by the USEPA to provide decision makers with preliminary, screening-level information on potential water quality and quantity impacts resulting from urban/suburban development (USEPA, 2002a, 2002b). The model can be used to simulate annual stormwater runoff, TN, TP, and TSS. Users can assess runoff sensitivity to different development patterns, location (soil) characteristics, growth projections, and stormwater best management practices.

SG WATER uses the curve number (CN) method developed by the Natural Resources Conservation Service to simulate stormwater runoff volume as a function of rainfall and land use (USEPA, 2002a, 2002b). Curve numbers reflect the runoff generated from different land use categories based on conditions including soil hydrologic group, antecedent soil moisture, and percentage of impervious

Table 1
Attributes of SWNAS conventional and low impact site designs.

Design attributes	Conventional	Low impact	Open space
Total site area (ha)	567	567	567
Open space (% of total site)	64	71	100
Impervious cover (% of total site)	25	16	0
Estimated resident population	1540	5958	0
Development footprint (ha)	206	166	0
Impervious cover (% of footprint)			
Total	71	57	0
Roofs	34	20	0
Parking	23	10	0
Right-of-way	14	27	0

Table 2
Summary of historical weather observations in Hingham, MA.

Mean total monthly precipitation for 1/1/1996 to 12/31/2005 (cm)	
January	12.1
February	9.6
March	14.5
April	12.4
May	11.4
June	9.4
July	10.2
August	11.4
September	10.9
October	14.8
November	10.3
December	11.3
Mean total annual precipitation (cm)	138.2
95th percentile event magnitude (cm)	3.9
99th percentile event magnitude (cm)	7.7
99.9th percentile event magnitude (cm)	13.9
Average annual number of events	122

cover (USDA, 1986; USDA-SCS, 1985). Model users have the option to override default CNs by assigning the percent impervious cover to a land use. This functionality allows users to assess the effects of different site design characteristics such as changes to street width and green rooftops on stormwater. The model accounts for differences in antecedent soil moisture based on the season of the year and antecedent rainfall as defined by the CN method (USEPA, 2002a, 2002b). SG WATER does not simulate peak flow rates. It can only be used to simulate total annual runoff volume (USEPA, 2002a, 2002b). Air temperature is not directly considered, but evapotranspiration is indirectly determined by factors used to calculate the CNs (USEPA, 2002a, 2002b).

SG WATER calculates stormwater pollutant loads as the product of stormwater runoff volume and event mean concentrations (EMCs). EMCs are available in SG WATER for TN, TP, and TSS as a function of different land use categories. EMCs were developed using data from National Urban Runoff Program (NURP) and the Corpus Christi Bay National Estuary Program (CCBNEP) (USEPA, 2002a, 2002b). Users have the option of overriding national default EMC values to use local data and to evaluate the application of user-selected best management practices (BMPs) for reducing pollutant loads (USEPA, 2002a, 2002b).

It should be noted that SG WATER is not calibrated or validated against observed stormwater runoff values. It is therefore appropriate only for evaluating relative changes resulting from different scenarios, and not for providing absolute, quantitative predictions or comparing to simulations from other hydrologic models.

2.2. Land use scenarios

The conventional site design is automobile-oriented with extensive parking lots and low walkability (i.e., amenities and transit are distant from housing) (Fig. 1). Impervious cover is 25% of the total site (Table 1), a level general associated with low-intensity suburban development (e.g., National Land Cover Database, http://www.mrlc.gov/). The low impact site design, a revision of the conventional site design, incorporates transit-oriented features and a more compact, mixed-use configuration with habitat preservation. Impervious cover is 16% of the total site. An *open space* land use scenario was also included in the analysis to provide a baseline representing conditions of an undeveloped site. The open space scenario was defined to have 75% or more grass cover and 0% impervious cover. SG WATER requires information about soil hydrologic properties to simulate runoff using the CN method. Soil hydrologic properties were determined based on information in the SSURGO and STATSGO databases. All land use scenarios assumed soils at the SWNAS site were 33% soil hydrologic group A, 10% group B, 28% group C, and 29% group D.

The conventional and low impact site designs considered in this study were selected to illustrate different site planning paradigms that result in substantially different landscape attributes. More specifically, the principal difference between the sites is the density of development and amount of impervious cover. Additional BMPs or LID practices were not considered in this study. It is important to note that the conventional design in this case is not a worst case development scenario. In fact, both the conventional and low impact site plans were proposed by developers and approved by local authorities. Consequently, both plans represent viable land use alternatives that leave more than 60% of the site in undeveloped open space. Neither was designed with any explicit consideration of their performance under changing climatic conditions.

2.3. Precipitation scenarios

Precipitation is the only aspect of climate change considered in this study. This simplification was necessary given the use of the SG WATER model which uses only precipitation as an input in stormwater simulations. Precipitation is arguably the principal driver of stormwater runoff from urban areas. Evaluation of the effects of precipitation change on stormwater is thus considered reasonable as a first order approximation of broader climate change impacts.

Model simulations were conducted for each SWNAS redevelopment plan using six precipitation scenarios: historical precipitation plus five hypothetical scenarios of future precipitation change. The scenarios are based on historical daily precipitation data from the National Climatic Data Center's Hingham, Massachusetts weather station for the period January 1, 1996 to December 31, 2005. Precipitation events for all scenarios were defined as days with at least 0.05 cm of recorded precipitation. Average annual precipitation during this period was 138 cm/yr, and was distributed uniformly throughout the year. Monthly averages and summary information on event magnitudes for historical precipitation are provided in Table 2.

The six precipitation scenarios evaluated in this study are: Precipitation change scenarios were developed using the change factor method (Anandhi et al., 2011), whereby one or more multipliers were applied to historical precipitation events during an arbitrary baseline period to create a modified daily precipitation time series for input to SG WATER. The *historical* precipitation scenario served as the baseline. Precipitation change scenarios were created to represent two types of potential climate change: changes in the annual precipitation volume (hereafter referred to as volume scenarios) and changes in the proportion of annual precipitation occurring in large magnitude events (hereafter referred to as intensity scenarios).

1. *Historical*: Observed precipitation events (as defined above).

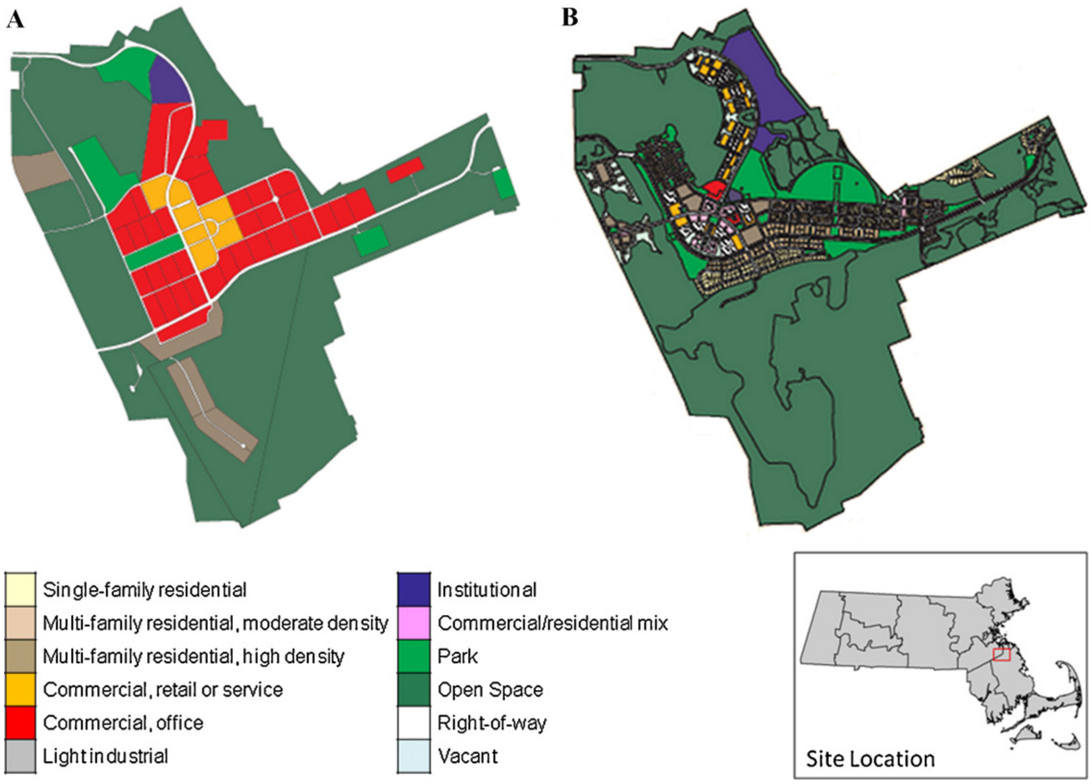

Fig. 1. South Weymouth Naval Air Station study site. Panel (A): conventional site design. Panel (B): low impact site design.

2. *V*(−20): Volume decrease of all events by 20%.
3. *V*(+*20*): Volume increase of all events by 20%.
4. *I*(10): Low range intensity increase in large magnitude events. Approximately 10% increase in the proportion of annual precipitation occurring in the largest 5% of events. Intensity was decreased in small events to achieve no net change in annual volume.
5. *I*(45): High range intensity increase in large magnitude events. Approximately 45% increase in the proportion of annual precipitation occurring in largest 5% of events. Intensity was decreased in small events to achieve no net change in annual volume.
6. *I*(10) + *V*(3): Low range intensity increase in large magnitude events plus a net increase in annual volume. Approximately 10% increase in the proportion of annual precipitation occurring in largest 5% of events. Intensity was not decreased in small events resulting in a 3% net increase in annual volume.

The two *volume scenarios* were created by applying a constant multiplier to decrease all daily precipitation events in the historical precipitation record by 20% (*V*(−20)), and increase all daily precipitation in the historical precipitation record by 20% (*V*(+20)).

The three *intensity scenarios* were created by modifying historical daily precipitation values to increase the proportion of annual precipitation occurring in the largest magnitude events (hereafter referred to as event intensity). Groisman et al. (2005) presented historical precipitation data for the U.S. between 1970 and 1999 indicating statistically significant nationwide increases in the magnitude of the largest precipitation events on a per decade basis. This analysis showed a 4.6% increase in magnitude for the 95th percentile events per decade, a 7.2% increase in magnitude for the 99th percentile events per decade, and a 14.1% increase in magnitude for the 99.9th percentile events per decade. The intensity scenarios were created to represent the extrapolation of these trends 20 and 90 years into the future. The *I*(10) and *I*(10) + *V*(3) scenarios represent the 20-year extrapolation, and the *I*(45) scenario the 90-year extrapolation.

To develop intensity scenarios, daily precipitation events were first ranked and grouped into four percentile range bins: 0–95th percentile, 95–99th percentile, 99–99.9th percentile, and events greater than the 99.9th percentile. Multipliers were then developed to approximate extrapolations of the trends in event intensity reported by Groisman et al. (2005) 20 and 90- years into the future (Table 3). All precipitation events within the top three bins – 95–99th percentile, 99–99.9th percentile, and events greater than the 99.9th percentile – were adjusted by the 20-year or 90-year multipliers. We modified the fourth bin – events in the 0–95th percentile – in two different ways. For the *I*(10) and *I*(45) intensity scenarios, a multiplier was applied to all events in the 0–95th percentile bin to decrease the precipitation volume by an amount equal to the increase in precipitation volume resulting from the adjustments to event magnitude in the other three bins, i.e., total annual precipitation was held constant. Thus, the *I*(10) and *I*(45) scenarios represent a 10 and 45% increase, respectively, in the proportion of annual precipitation occurring in large magnitude events with no change in average annual precipitation volume. For the *I*(10) + *V*(3) scenario, no adjustment was made to events in the 0–95th percentile bin. Thus, the *I*(10) + *V*(3) scenario represents a 10% increase in the proportion of annual precipitation occurring in large magnitude events together with an approximate increase of 3% in average annual precipitation volume.

It should be noted that the multipliers used to create these scenarios (Table 3) differ slightly from those presented by Groisman et al. (2005) due to differences in how bin boundaries were calculated. The numbers presented by Groisman et al. (2005) group events into bins greater than the 95th, 99th, and 99.9th percentiles. In this study, an algebraic adjustment was used to approximate trend values for non-overlapping bins representing the 95–99th percentile, 99–99.9th percentile, and events greater than the 99.9th percentile.

Table 3
Summary of percent changes applied to events within each percentile range bin for the intensity scenarios. The average percent increase in the upper three bins is reflected parenthetically in each scenario name.

Event bin boundaries	Percent change in event intensity *I*(10)	Percent change in event intensity *I*(45)	Percent change in event intensity *I*(10) + *V*(3)
>99.9 percentile	28.2%	126.9%	28.2%
99–99.9 percentile	12.8%	57.6%	12.8%
95–99 percentile	8.0%	36.0%	8.0%
>95 percentile	−3.8%	−17.1%	0%

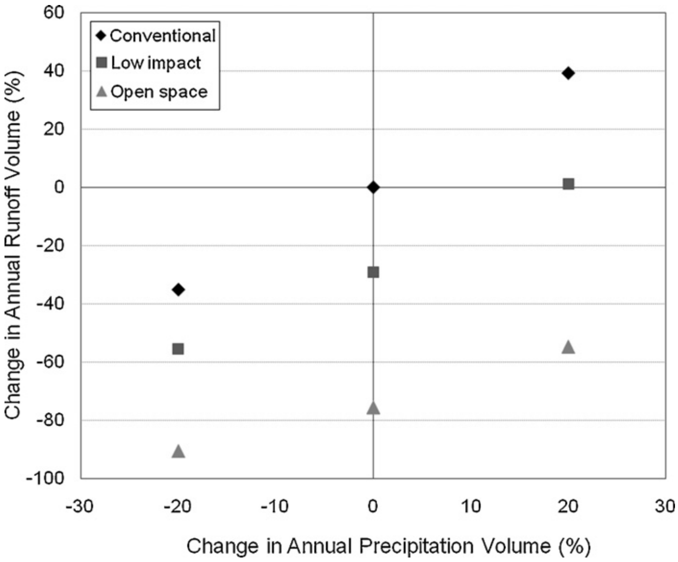

Fig. 2. Changes in annual stormwater runoff volume for the *V*(−20) and *V*(+20) scenarios. Percent change expressed relative to the conventional site under the historical precipitation scenario which is represented by point (0,0).

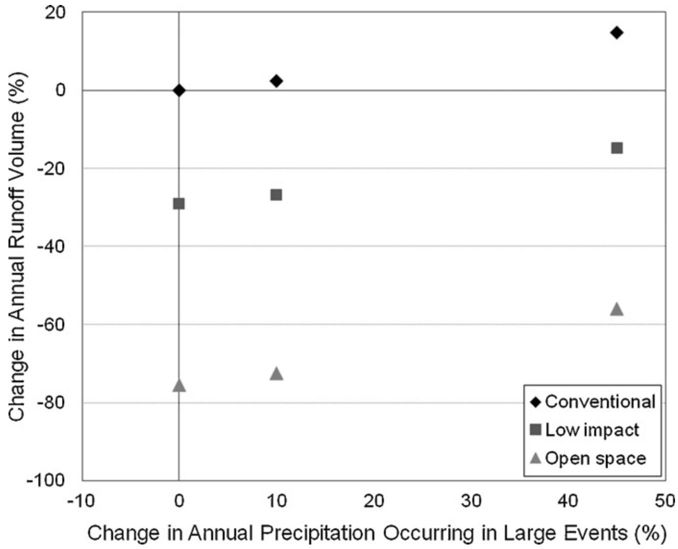

Fig. 3. Changes in annual stormwater runoff volume for the *I*(10) and *I*(45) scenarios. Percent change expressed relative to conventional site under the historical precipitation scenario which is represented by point (0,0).

It should also be noted that all precipitation change scenarios evaluated in this study are hypothetical, and are intended only to illustrate the general sensitivity of stormwater response to potential changes in precipitation. They are not intended as forecasts of future climate change in this region. The precipitation change scenarios are also relatively simple and do not represent changes in precipitation seasonality, frequency, or other factors that may influence stormwater runoff. Scenarios are, however, intended to lie within a plausible range of future change for this region (e.g., see Climate Wizard, http://www.climatewizard.org; Groisman et al., 2005; IPCC, 2007; USGCRP, 2009).

3. Results

3.1. Simulated runoff from low impact versus conventional site

The low impact site was uniformly superior to the conventional site for managing stormwater runoff and pollutant loads from all precipitation scenarios. Under the historical scenario, simulated runoff from the low impact site was 29% less than the conventional site (Table 4). Annual pollutant loads were 24, 33, and 26% less for the low impact versus conventional site for TN, TP, and TSS, respectively. Under the *V*(−20) scenario, annual stormwater runoff from the low impact and conventional sites was 55 and 35% less, respectively, than the conventional site under the historical scenario; a 20% difference in runoff (Fig. 2). Under the *V*(+20) scenario the low impact and conventional sites produced one and 39% more runoff, respectively; a 38% difference in runoff. Annual TN, TP, and TSS loads under the *V*(−20) scenario for the low impact site were 52, 57, and 54% less, respectively, than the conventional site under the historical scenario, while the TN, TP, and TSS loads for the conventional site were 35, 33, and 36% less, respectively. Similar pollutant load trends resulted under the *V*(+20) scenario.

The *I*(10) and *I*(45) scenarios assume increases of 10 and 45% in the proportion of annual precipitation occurring in large magnitude events. For the *I*(10) and *I*(45) scenarios, the low impact site produced 27 and 15% less runoff, respectively, while the conventional site produced two and 15% more runoff, respectively, than the conventional site under the historical scenario (Fig. 3). Annual TN, TP, and TSS loads from the low impact site under the *I*(10) scenario were 22, 33, and 23% less, respectively, than the conventional site under the historical scenario, while the conventional site under the *I*(10) scenario generated 2, 1, and 3% more, respectively. The *I*(45) scenario yielded similar results for both site designs.

The *I*(10) + *V*(3) scenario represents combined changes in precipitation volume and event intensity. Under this scenario, the low impact site generated 23% less runoff and the conventional site generated seven percent more runoff than the conventional site under the historical scenario. Pollutants responded similarly with TN, TP, and TSS loads from the low impact site 11, 27, and 10% less, respectively, than the conventional site under the historical scenario, while the conventional site generated 14, seven, and 16% more, respectively.

3.2. Stormwater sensitivity to changes in precipitation

Fig. 4 shows the percent changes in runoff resulting from each of the precipitation-land use scenario combinations in comparison to the conventional site under the historical scenario. Precipitation scenarios are presented from left to right in order of increasing annual precipitation volume and/or intensity (i.e., generally drier to wetter). These results illustrate the relative influence of changes in precipitation volume and intensity on stormwater runoff. For

Table 4
Stormwater runoff volumes and pollutant loads under all precipitation change scenarios.

Land use scenario	Indicator	Historical	*I*(10)	*I*(45)	*V*(−20)	*V*(+20)	*I*(10) + *V*(3)
Conventional	TSS (kg/ha/yr)	164	169	191	106	230	177
	Phosphorus (kg/ha/yr)	0.73	0.74	0.80	0.50	0.99	0.78
	Nitrogen (kg/ha/yr)	4.19	4.29	4.79	2.74	5.81	4.50
	Stormwater (m^3/ha/yr)	2634	2697	3025	1709	3666	2829
Low impact	TSS (kg/ha/yr)	122	126	147	76	175	133
	Phosphorus (kg/ha/yr)	0.49	0.50	0.55	0.33	0.67	0.52
	Nitrogen (kg/ha/yr)	3.18	3.27	3.75	2.03	4.49	3.44
	Stormwater (m^3/ha/yr)	1869	1928	2242	1173	2665	2028
Open space	TSS (kg/ha/yr)	45	51	81	18	83	55
	Phosphorus (kg/ha/yr)	0.08	0.09	0.14	0.03	0.14	0.09
	Nitrogen (kg/ha/yr)	0.97	1.09	1.74	0.38	1.78	1.18
	Stormwater (m^3/ha/yr)	644	724	1162	252	1189	785

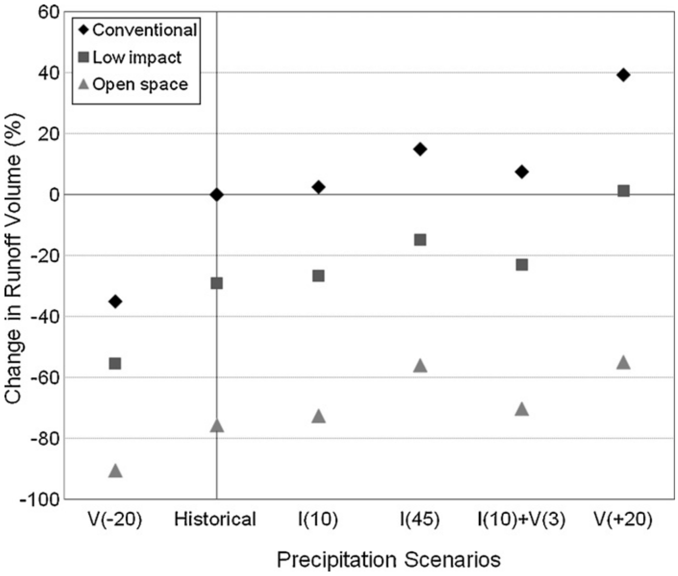

Fig. 4. Changes in runoff volume resulting from each land use and precipitation change scenario combination expressed relative to runoff from the conventional site under the historical precipitation scenario.

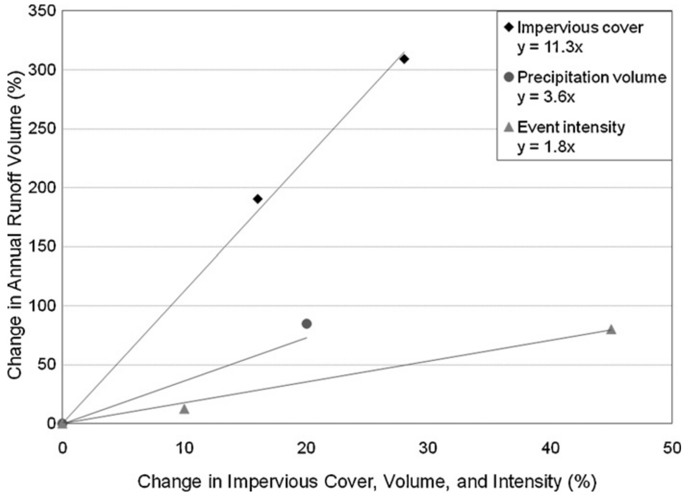

Fig. 5. Simulated sensitivity of runoff to changes in impervious cover, precipitation volume, and event intensity. *X*-axis has been truncated at 0 and does not show one data point representing a −20% change in precipitation volume.

example, the historical, *I*(10), and *I*(45) scenarios all have the same annual precipitation volume, yet the *I*(45) scenario creates the largest amount of runoff among these three scenarios indicating the general sensitivity of stormwater runoff to increases in event intensity. Conversely, runoff volumes in the *I*(10) + *V*(3) scenario are greater than the *I*(10) scenario indicating a synergistic relationship between increases in precipitation volume and intensity on stormwater runoff.

3.3. *Stormwater sensitivity to precipitation versus land use change*

The simulations conducted in this study illustrate the general sensitivity of stormwater runoff to three drivers: amount of impervious cover, precipitation volume, and event intensity. Fig. 5 shows the changes in stormwater runoff associated with changes in impervious cover (holding precipitation volume and event intensity constant), precipitation volume (holding impervious cover and event intensity constant), and event intensity (holding impervious cover and precipitation volume constant). These results suggest that when expressed on a constant percent basis, stormwater runoff is most sensitive to changes in impervious cover, followed by changes in precipitation volume and event intensity.

4. Discussion

The model simulations, while simple and limited in scope, provide insight into the relationship between land use, changes in precipitation, and stormwater runoff volume and pollutant loads. As climate changes, locations exposed to increased precipitation volume and/or event intensity are likely to experience increased stormwater runoff and pollutant loads. If current stormwater management infrastructure is not robust enough to cope with these changes, impairment of local streams and water bodies could result.

Land use management, including LID, will be an important component of strategies for adaptation. Research has shown that the effects of land use and climate change on watersheds can vary, yet the two factors can operate synergistically, increasing the magnitude of stormwater runoff and overall water quality impacts (Chang, 2004; Tu & Xia, 2008). Simulations conducted in this study suggest that, when expressed on a constant percent change basis, stormwater runoff is most sensitive to changes in impervious cover, followed by changes in precipitation volume and event intensity (Fig. 5). If we assume the effects of these three factors on stormwater are additive, these relationships provide a simple, heuristic understanding of how reductions in impervious cover could be used to compensate for increased stormwater runoff associated with climate change. For example, using the data in Fig. 5, a 45% increase in stormwater runoff would result from a 10% increase in precipitation volume and 5% increase in event intensity (10% × 3.6 + 5% × 1.8 = 45%). This could be offset by a decrease in impervious cover of 4% (45%/11.3 = 4%). The true relationships are clearly far more complex than depicted in this simple model.

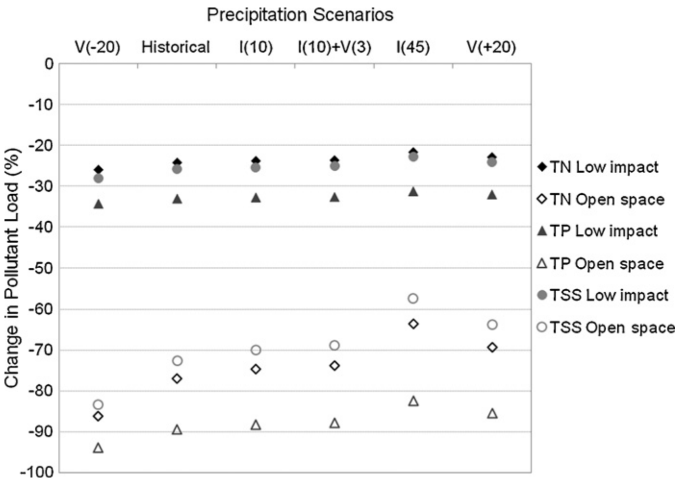

Fig. 6. Changes in average annual pollutant loads from the low impact and open space site designs. Percent change expressed relative to runoff from the conventional site design represented by zero on the *X*-axis.

A simple heuristic model of this type developed for local conditions may, however, could provide improved understanding of the relationships between land use and changes in precipitation.

The results of this study also demonstrate the effectiveness of site redevelopment, including increased density and reduced impervious cover as a no-regrets adaptation strategy for reducing pollutant loads associated with stormwater runoff. It is not surprising that the open space site resulted in the smallest annual pollutant loads (Fig. 6). It is interesting to note, however, that the increase in pollutant loads is much greater between the open space and low impact sites than between the low impact and conventional sites for all precipitation scenarios (see Table 4). For example, under the *I*(10) scenario, the annual TTS load from the low impact site is 75 kg/ha/yr greater than the open space site, but 44 kg/ha/yr less than the conventional site. Similar trends in this region have been discussed in Tu and Xia (2008) and Tu (2009), where findings indicate water quality is impacted by land use changes much more dramatically in watersheds that are less developed as compared to those with extensive existing development.

Conversely if you consider the total residential population supported by the three land use scenarios, the increase in pollutant loads between the low impact and conventional sites is likely much greater than what is indicated in our findings, and potentially greater than the increase between the open space and low impact sites. The low impact and conventional sites have an approximately 4400 person difference in anticipated residential population: 1540 residents for the conventional site versus 5958 residents for the low impact site. If the conventional site was constructed and the additional 4400 residents desired a similar residential site design, approximately three additional conventional sites would have to be constructed, potentially increasing the annual stormwater volume and pollutant loads by 300 percent. The benefits of LID on stormwater pollutant loads can also be considered on a per capita basis. Jacob and Lopez (2009) found that as development density increases in terms of housing units per acre, the per capita contribution to stormwater runoff and pollutants decrease. Applying this same principle to the SWNAS site under the historical precipitation scenario, for example, the per capita TSS load for the conventional site is approximately 60 kg/yr versus 12 kg/yr for the low impact site.

5. Conclusions

Climate change during the next century will add greater uncertainty to the design, operation, and maintenance of stormwater management infrastructure, a challenge that many practitioners and decision makers are just beginning to consider (Blanco, Alberti, Forsyth, et al., 2009; Blanco, Alberti, Olshansky, et al., 2009). Responding to climate change will be complicated by the scale, complexity, and inherent uncertainty of the problem, therefore it is unlikely that this challenge can be solved using any single strategy. The scenario analyses conducted in this study illustrate the potential effectiveness of one common element of LID, reducing impervious cover, in the context of climate adaptation. While only providing a first-order approximation, results suggest that even a modest reduction in impervious cover (here reducing impervious cover from 25 to 16 percent) has the potential to significantly reduce increases in stormwater runoff volume and pollutant loads associated with increases in precipitation. Given the uncertainty concerning the specific patterns and magnitude of future precipitation, LID is particularly appealing as a no-regrets strategy for climate change adaptation.

The model simulations in this study were made with a relatively simple stormwater model that only provides results on an annual basis, and involved a number of simplifying assumptions. Results should thus not be considered absolute. Rather, results are best considered illustrative of the general sensitivity of stormwater at this location to potential changes in precipitation, and in particular how changes in land use could be used as an effective hedging strategy to offset impacts.

The implications of climate change on stormwater are complex and will vary in different locations due differences in the type of change that occurs, attributes of local watersheds and sewer systems, and interaction with existing management practices. This study is only one small step in what is likely to be a long learning process. More detailed studies are needed to better understand the specific implications of climate change and develop adaptation strategies to ensure long-term stainability of stormwater management.

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