Journal of Environmental Management 187 (2017) 470–481

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Urbanization impacts on surface runoff of the contiguous United States

Jingqiu Chen [a], Lawrence Theller [a], Margaret W. Gitau [a], Bernard A. Engel [a, *], Jonathan M. Harbor [b]

[a] Department of Agricultural and Biological Engineering, Purdue University, 225 S. University Street, West Lafayette, IN 47907, USA
[b] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form
2 November 2016
Accepted 7 November 2016
Available online 13 November 2016

Keywords:
Hydrology
Urbanization
Runoff
Hydrologic impact
Hydrologic modeling
Population

1. Introduction

Urbanization is one of the most important anthropogenic modifications of the global environment (Antrop, 2004; DeFries and Eshleman, 2004; Eshleman, 2004; Foley et al., 2005; Weng, 2002; Wu, 2014). Every urban region in the United States has expanded substantially in area in recent decades (USEPA, 2013). Urbanization presents humans with a dilemma (Foley et al., 2005). On one hand, urban development is essential because it provides convenience of infrastructure, goods and services needed by people, government, economic development, industry, and trade (Foley et al., 2005; Lowry, 1990); on the other hand, land surface modifications occur during the process of urbanization including vegetation reduction, soil compaction, and change from pervious surfaces to impervious surfaces such as roofs, roads, and parking lots (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Schueler, 1994). The consequences of these land surface modifications include but are not limited to: changes in water supply from altered hydrologic processes of infiltration, groundwater recharge, and runoff; water quality degradation from urban runoff and combined sewer overflows (CSOs); and changes in water demand (Burns et al., 2012; DeFries and Eshleman, 2004; Gitau et al., 2016; Passerat et al., 2011; Semadeni-Davies et al., 2008; Tong and Chen, 2002; Vietz et al., 2016).

In general, surface runoff and river discharge increase when natural vegetation, especially forests, decrease (Costa et al., 2003; Foley et al., 2005; Sahin and Hall, 1996). Impervious surfaces developed during urbanization contribute more surface runoff due to decreased infiltration (Arnold and Gibbons, 1996; Schueler, 1994; Schueler et al., 2009). Reduced infiltration leads to higher peak flows, even for short duration low intensity rainfall, and increases the risk of flooding (Bhaduri et al., 2001; Suriya and Mudgal, 2012). Urban runoff also carries non-point source pollutants, such as oil, grease, metals, and pesticides, into streams and rivers during rainfall events (Arnold and Gibbons, 1996; Blair et al., 2014; Schueler, 1994). Even if urban runoff is captured by a sewer system and can be conveyed to wastewater treatment plants, Combined Sewer Overflows (CSOs) in some highly urbanized areas continue to cause serious water pollution problems (Bhaduri et al., 2001; Passerat et al., 2011; Semadeni-Davies et al., 2008).

Computer-based hydrological models can save time and money because of their ability to perform temporal and spatial simulation of the effects of hydrologic processes and management activities on water quantity and water quality (Moriasi et al., 2007). The United States Department of Agriculture (USDA) Soil Conservation Services (SCS) Curve Number (CN) (Natural Resources Conservation Services (NRCS), 1986) approach is widely used in several hydrological models that are used to assess the impact of land use change on surface hydrology, including sophisticated models such as Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Srinivasan et al., 1998), as well as models adopting the philosophy of simplicity such as the Long-Term Hydrologic Impact Assessment (L-THIA) (Bhaduri et al., 2000; Harbor, 1994). Sophisticated models usually require more parameters to set up the model before simulation, which may create limitations due to lack of data or time (Bhaduri et al., 2001). L-THIA is an easy, quick, and user friendly

* Corresponding author. 225 South University Street, West Lafayette, IN 47907-2093, USA.
E-mail addresses: chen1415@purdue.edu (J. Chen), theller@purdue.edu (L. Theller), mgitau@purdue.edu (M.W. Gitau), engelb@purdue.edu (B.A. Engel), jharbor@purdue.edu (J.M. Harbor).

http://dx.doi.org/10.1016/j.jenvman.2016.11.017
0301-4797/

tool, which only requires readily available data including hydrologic soil group (HSG), land use, and long-term rainfall data to assess surface runoff influenced by past, present, as well as future land management decisions for specific locations (Bhaduri et al., 2001; Grove et al., 2001; Tang et al., 2005). The L-THIA model has been successfully used in numerous studies to assess the impact of land use change on surface hydrology and water quality (e.g., Bhaduri et al., 2000; Choi, 2007; Davis et al., 2010; Grove et al., 2001; Gunn et al., 2012; Kim et al., 2002; Lim et al., 2006a, 2006b, 2010; Muthukrishnan et al., 2006; Pandey et al., 2000; Tang et al., 2005; Wilson and Weng, 2010). The L-THIA model has also been incorporated and integrated into Web-based and GIS-based decision support systems (Choi et al., 2003, 2005a, 2005b; Choi and Engel, 2003; Engel, 2001; Engel et al., 2003; Engel and Hunter, 2009; Pandey et al., 2000; Shi et al., 2004; Tang et al., 2004), as well as a low impact development model (Ahiablame et al., 2012a, 2012b, 2013; Engel and Ahiablame, 2011; Hunter et al., 2010; Liu et al., 2015a, 2015b, 2016a, 2016b; Martin et al., 2015; Wright et al., 2016).

Research evaluating urbanization impacts on surface runoff using L-THIA has focused primarily on watershed-scale analysis, and quantitative assessment of urbanization impacts on surface runoff at a national scale is limited. The release of National Land Cover Database (NLCD) 2011 edition datasets for 2001, 2006, and 2011 across the nation makes the assessment of urban land use change impacts on surface hydrology at the national level feasible (Homer et al., 2015). The NLCD extends land use/land cover coverage over larger areas at more frequent time intervals allowing large scale investigations to be conducted (DeFries and Eshleman, 2004). Explicit understanding of urbanization impacts on surface runoff will provide information for decision makers who need to balance trade-offs between the advantages and possible unintended consequences of urbanization. This study assessed urbanization impacts on surface runoff for 2001, 2006, and 2011 in the contiguous United States using the L-THIA Tabular Tool, a derivative of the L-THIA model. We first present the assessment of the normalized average annual runoff depth (NAARD) for 2001, 2006, and 2011 by contiguous U.S. counties and evaluate whether population change is a consistent indicator for urban development; then we present an assessment of NAARD for 2001, 2006 and 2011 by U.S. states; finally, we present the assessment of the national average annual runoff volume increase due to urbanization.

2. Methods and materials

2.1. L-THIA Tabular Tool

The L-THIA Tabular Tool, which shares the same philosophy as the original L-THIA model (Harbor, 1994), uses the SCS CN method (Natural Resources Conservation Services (NRCS), 1986) to calculate average annual runoff for land use and soil combinations based on long-term climate data for that area (Bhaduri et al., 2001). The runoff depth is estimated when rainfall exceeds initial abstraction based on (Natural Resources Conservation Services (NRCS), 1986):

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \text{ for } P > I_a = 0.2S \qquad Q = 0 \text{ for } P \le I_a = 0.2S \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

$$I_a = 0.2S \tag{3}$$

where Q represents direct runoff depth in mm; P represents rainfall depth in mm; S represents potential maximum retention after runoff begins in mm; CN represents curve number; and I_a represents initial abstraction in mm.

The L-THIA Tabular Tool was developed using the Python programming language and is run as a toolbox in ArcGIS version 10.2.2. It is designed to expedite tabulating calculations over diverse geographical areas. An external component (a Java program) calculates daily runoff for all curve numbers using the equations above. The calculations are performed for each precipitation gauge in a region using daily rainfall and all curve numbers. The calculations are made for each year in the database (typically between 30 and 100 years). The user selects how many of the available years of annual runoff to average in order to create average annual runoff, and the same number of years is used from every gauge.

The ArcGIS implementation (a Python script tool) of L-THIA Tabular consists of three main components. The first component aims to generate a CN raster using land use and HSG combination. A six-digit combination raster layer including HSG (first digit), land use (second to third digits), and corresponding CN (fourth to sixth digits) was created for each pixel in the NLCD data, as shown in Table 1. The second component prepares the study area boundary for the runoff calculation. This operation determines which Thiessen polygons (Thiessen, 1911) representing rain gauges intersect the study area. The tool determines how many pixels of each of CN raster is within each Thiessen polygon. The third component is used to tabulate the selected years of average annual runoff, under antecedent moisture condition (AMC) II condition (normal antecedent soil moisture), using the CN raster information generated from the first component inside the study outline generated from the second component, as well as rainfall data. The tabulation consists of accumulating the area of each CN present in each precipitation polygon in the region, and fetching the appropriate runoff total for each CN from the web-based results of the runoff calculator, and averaging the requested number of years to obtain average annual runoff for each CN used in the study area. Runoff depth is converted to volume through multiplying by pixel area for each CN. The final outputs of L-THIA Tabular Tool include average annual runoff volume and depth within a given boundary. The units of the output average annual runoff volume and depth can be represented using both U.S. and metric units. The third component also computes non-point source pollution estimates using the runoff volume and the CN-land use pairs to choose the appropriate pollution coefficient (event mean concentration, EMC) if desired.

The study area is the contiguous United States, which includes 48 adjoining states and the District of Columbia (DC). The L-THIA Tabular Tool was set up to create analyses based on U.S. county boundaries. A total of 3109 counties were modeled. Calibration and validation would be challenging for a national analysis due to the scarcity of observed surface runoff data from county based urban areas. However, the SCS CN method is a well-known and widely used runoff estimation approach, and a substantial number of studies have reported its usefulness and credibility; for example, many L-THIA studies have validated the SCS CN method with little or no calibration (Ahiablame et al., 2013; Bhaduri et al., 2001; Grove et al., 2001; Kim et al., 2002; Liu et al., 2015b; You et al., 2012). Thus, this approach can be applied to assess surface runoff at a national scale.

2.2. Input data

In the L-THIA Tabular Tool, the basic input data include daily

Table 1
Six-digit combination raster layer for urban land in the national land cover database (NLCD).

Land use index in NLCD	Urban land types in NLCD	Six-digit combinations			
21	Developed Open Space	121,039	221,061	321,074	421,080
22	Developed Low Intensity	122,056	222,071	322,081	422,086
23	Developed Medium Intensity	123,069	223,081	323,087	423,090
24	Developed High Intensity	124,089	224,092	324,094	424,095

Note: For six-digit combination raster layer, the first digit represents hydrologic soil group, A = 1, B = 2, C = 3, and D = 4; the second to third digits represent the urban land index in NLCD, 21 = Developed open space, 22 = Developed low intensity, 23 = Developed Medium Intensity, and 24 = Developed high intensity; the last three digits represent SCS CN value, those values are based on USDA NRCS (Natural Resources Conservation Services (NRCS), 1986).

precipitation, land use/land cover data, and HSG data. In this study, CLIGEN (Climate Generator, version 5.3) - a stochastic weather generator employing quality control techniques for improved reproducibility of climatic parameters - was used to produce daily precipitation based on monthly statistical values derived from historic measurements at each particular site (Meyer et al., 2002, 2008; Zhang and Garbrecht, 2003). Quality control techniques in CLIGEN involve computing the probability that the mean and standard deviation of the random numbers driving CLIGEN were standard normal as assumed and reject those that were not. For the contiguous United States, 50-year daily precipitation was generated for a total of 2600 CLIGEN stations nationwide using station specific parameter files. The Thiessen method (Thiessen, 1911) was applied to generate Thiessen polygons covering the contiguous United States based on CLIGEN station points. Areas within the same polygon shared the same daily precipitation dataset.

With the recent release of the NLCD 2011 product, a decade of consistently produced land cover datasets became available (Homer et al., 2015). Homer et al. (2015) suggested that NLCD 2001 (2011 Edition) and NLCD 2006 (2011 Edition) must be used if conducting direct change comparison. In this study, NLCD 2001 (2011 version), NLCD 2006 (2011 version), and NLCD 2011 (Fry et al., 2011; Homer et al., 2007, 2015), which were created by the Multi-Resolution Land Characteristics (MRLC) Consortium (Wickham et al., 2014), were used as sources of land use data. The three NLCD datasets adopted the same 16 class land cover classification scheme based on a decision-tree classification of Landsat satellite data circa that year at a spatial resolution of 30 m (Fry et al., 2011; Homer et al., 2007, 2015).

The State Soil Geographic (STATSGO) dataset (Wolock, 1997) was applied as a source of HSG. In this study, any complex HSG such as A/D, B/D, and C/D, was assumed to be D soil for urban areas due to construction impacts (Lim et al., 2006a); other single type HSG were assumed to be the same as the original HSG.

2.3. *Preliminary assessment of land use/land cover change impacts on surface runoff*

The initial motivation of this study was to estimate the land use/land cover change impacts on surface runoff nationally including all 16 land use types from the NLCDs. Precipitation and HSG data were applied uniformly to the three NLCDs within a ten-year time period. L-THIA Tabular Tool was set up based on U.S. county boundaries, and the 50-year average annual runoff depth (AARD) was calculated for each pixel with land use and HSG combination within each specific U.S. county. The final output was AARD and volume for each U.S. county. The percentage change (from 2001 to 2006, from 2006 to 2011, and from 2001 to 2011) in AARD was calculated for each U.S. county. Counties classified as mild outliers (between 1.5 interquartile range (IQR) and 3.0 IQR) and extreme outliers (greater than 3.0 IQR) for both increasing and decreasing percent change AARD were mapped.

As shown in Fig. 1, outliers with respect to percentage change in AARD showed no pattern, and some were reversed between the two five-year periods. For example, numerous counties in the western U.S. showed an increasing trend in AARD from 2001 to 2006, while from 2006 to 2011 they had decreasing AARD, which is counterintuitive. Land use/land cover changes were examined further for counties that had outliers of both increasing and decreasing AARD since the land use/land cover served as the only variable. As shown in Fig. 2 a through d, some land use/land cover types such as wetlands, cultivated crops, forests, herbaceous, barren land, and open water, changed inconsistently between two five-year periods, which indicates likely misclassification issues. For example, in sub-figure a, classified barren land in counties belonging to outliers with increasing AARD increased in area by 1915 km^2 from 2001 to 2006, but then decreased in area by 670 km^2 from 2006 to 2011; classified open water in counties belonging to outliers with increasing AARD decreased in area by 2384 km^2 from 2001 to 2006, while it increased in area by 1348 km^2 from 2006 to 2011. Homer et al. (2015) stated that even though extensive efforts had been put into image pre-processing, spectral change detection, and change labeling work during NLCD creation, some misclassifications occurred. Our results of this preliminary modeling trial also indicate that apparent misclassification issues in some land use/land cover types in NLCDs may limit the analysis at a national scale. However, according to Homer et al. (2015), during the classification processes, urban class pixels in the NLCDs had top priority, with any change related to newly developed lands always being included in the final land cover change map. Since urban land classification has more accuracy than other categories, only urban land was considered in further analysis to assess the urbanization impact on surface runoff at a national scale for 2001, 2006, and 2011.

The urban classes in NLCDs include developed open space, developed low intensity, developed medium intensity, and developed high intensity lands (Fry et al., 2011; Homer et al., 2007, 2015). Fig. 3 illustrates changes in urban land between 2001, 2006 and 2011. Within the ten-year time period from 2001 to 2011, urban development occurred and increased in area by 20,296 km^2. Developed medium intensity ranked at the top of net gain in area (9049 km^2), developed low intensity ranked second with an increased area of 4437 km^2, and developed high intensity and open space ranked third and fourth with similar net area gains (3427 km^2 and 3383 km^2, respectively). In the first five-year time period from 2001 to 2006, the ranks of net gain in area were: developed medium intensity (5441 km^2) > developed low intensity (2689 km^2) > developed open space (2563 km^2) > developed high intensity (1975 km^2). In the latter five-year period from 2006 to 2011, the ranks of net gain in area were: developed medium intensity (3609 km^2) > developed low intensity (1748 km^2) > developed high intensity (1453 km^2) > developed open space (821 km^2). Comparing urban land change between the two five-year time periods, all four urban land types have higher

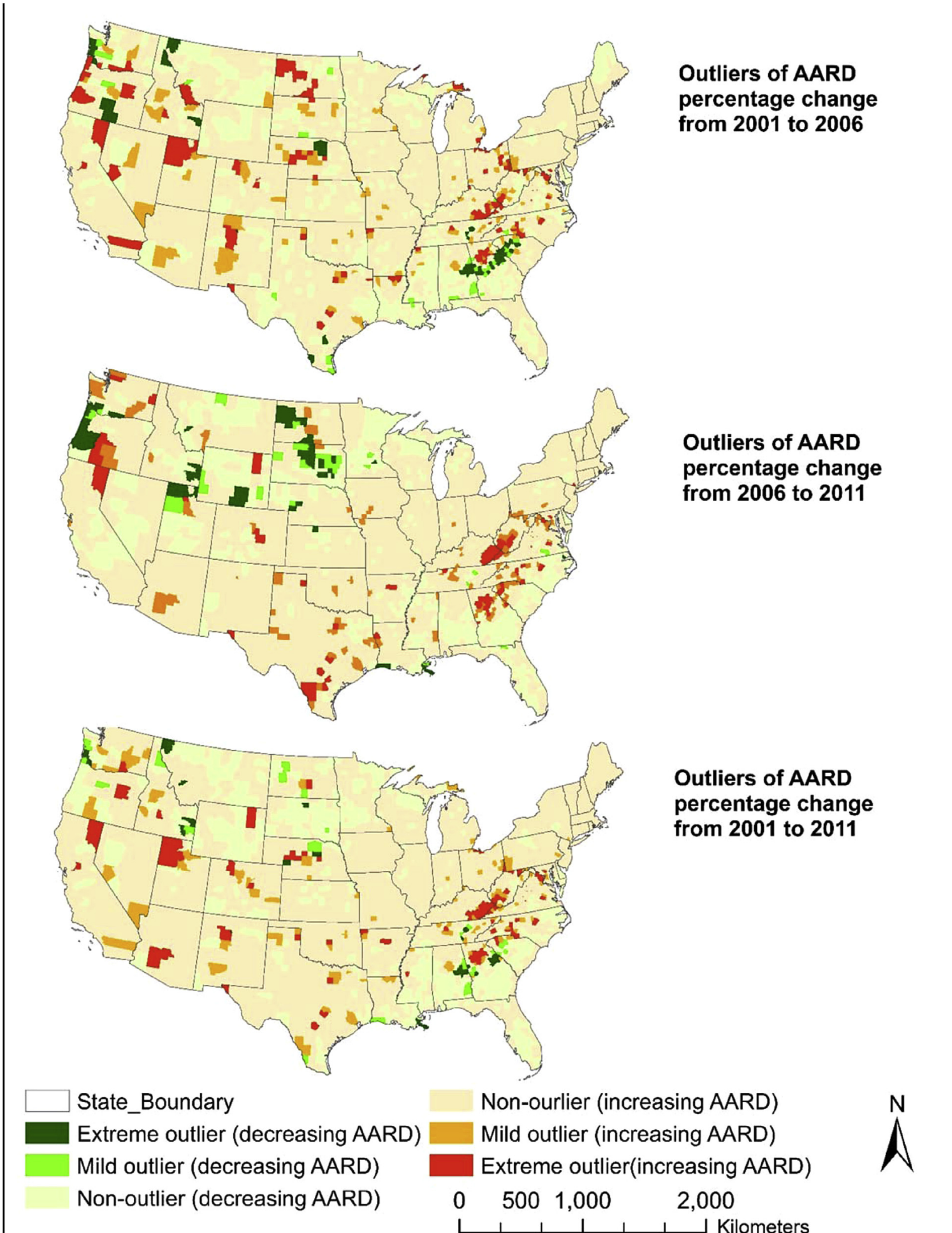


Fig. 1. County based outlier of AARD change percentage.

net gain in area during the first five-year time period from 2001 to 2006 than in the latter five-year period from 2006 to 2011. One possible reason for this trend might be slower economic development in the latter five years due to the financial crisis beginning in 2008 (Erkens et al., 2012; Ivashina and Scharfstein, 2010; Peters et al., 2012; Reinhart and Rogoff, 2008).

2.4. Simulation of urban land impact on surface runoff

The L-THIA Tabular Tool was set up based on U.S. county boundaries, and the AARD was calculated only from pixels belonging to developed land as indicated by categories 21, 22, 23, and 24. The final output was AARD and volume from urban land for each U.S. county. In order to conduct direct comparison between different U.S. counties, normalized average annual runoff depth (NAARD) was calculated using the following equation:

$$NAARD_{County} = \frac{RV_{Urban}}{A_{County}} \quad 1000 \tag{4}$$

where $NAARD_{county}$ represents NAARD for each U.S. county in mm, RV_{urban} represents the average annual runoff volume from urban land within each U.S. county in m^3, A_{county} represents the U.S. county area in m^2, and multiplying by 1000 represents the unit conversion from meters to millimeters.

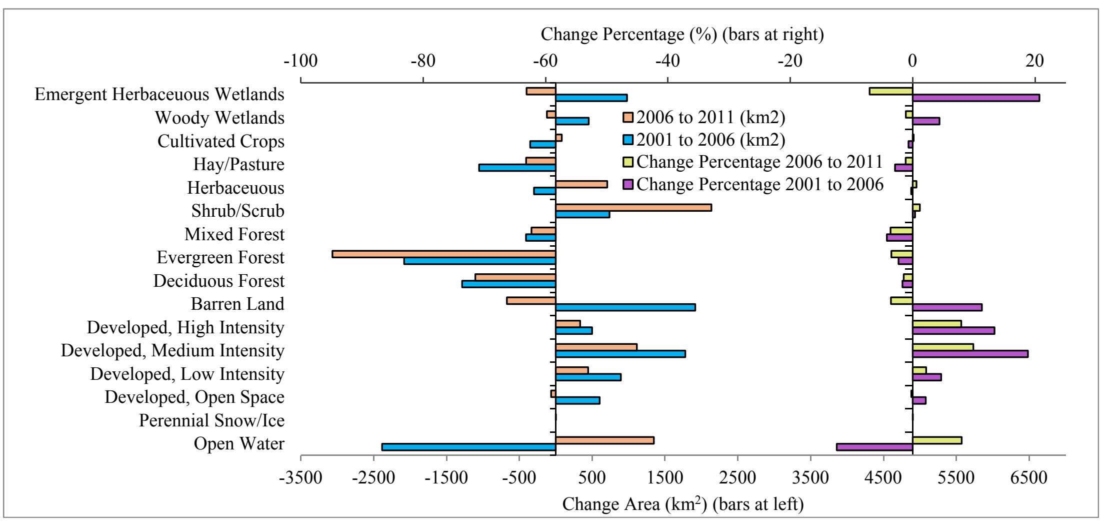
The NAARD of each U.S. state was also calculated using the following equation:

$$NAARD_{State} = \frac{\sum_{i=1}^{n} RV_{County\_i}}{\sum_{i=1}^{n} A_{County\_i}} \quad 1000 \tag{5}$$

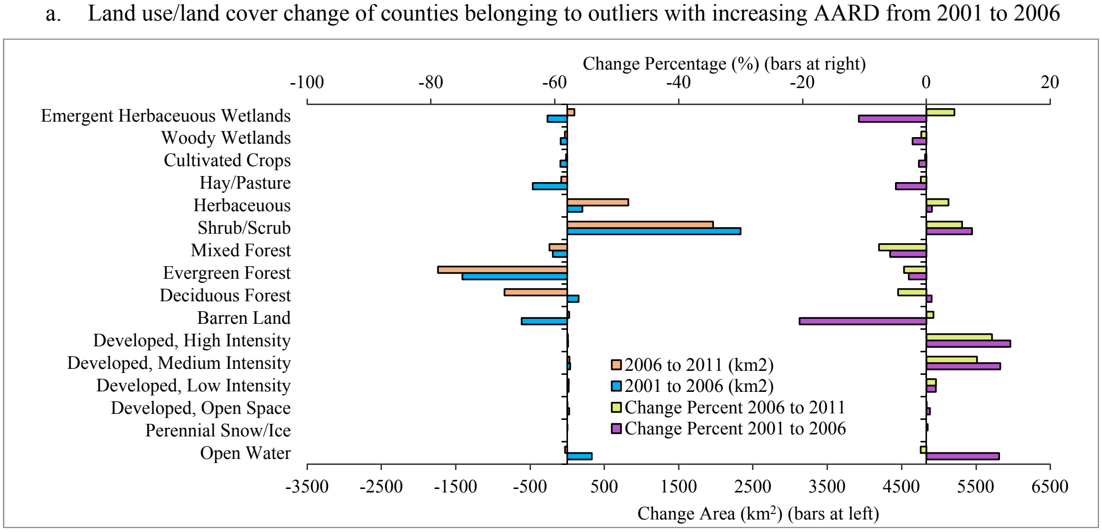
where $NAARD_{State}$ represents the NAARD of each U.S. State in mm, n represents the total number of counties within a U.S. state, RV_{County_i} represents the average annual runoff volume from the ith U.S. county within a U.S. state in m^3, A_{County_i} represents the area of the ith U.S. county in m^2, and multiplying by 1000 represents the unit conversion from meters to millimeters.

2.5. Comparison of population change and urban land change

After obtaining NAARD values for U.S. counties and states, population data for 2001, 2006, and 2011 were obtained from U.S. Census Bureau (http://www.census.gov/) (U.S. Census Bureau, Population

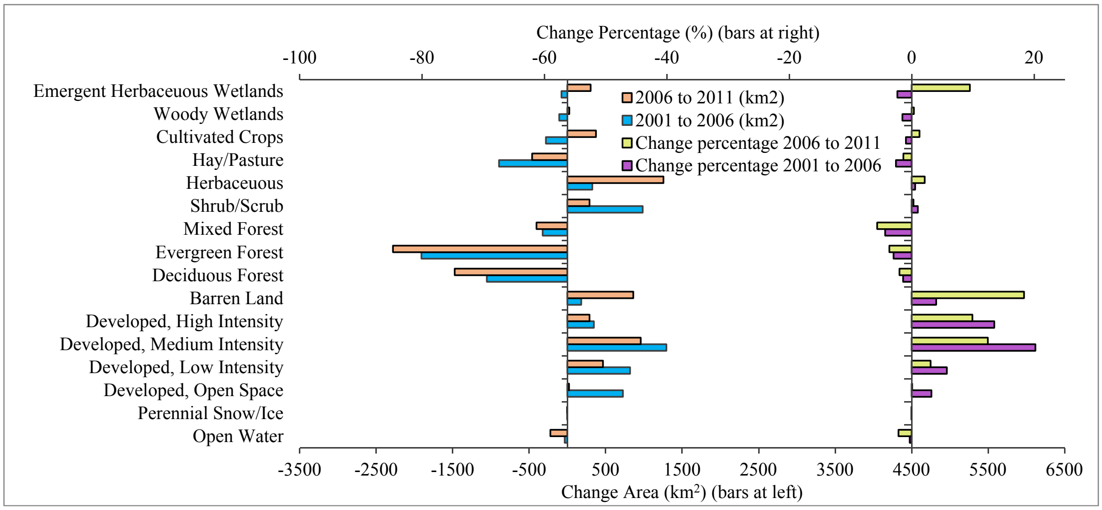


a. Land use/land cover change of counties belonging to outliers with increasing AARD from 2001 to 2006

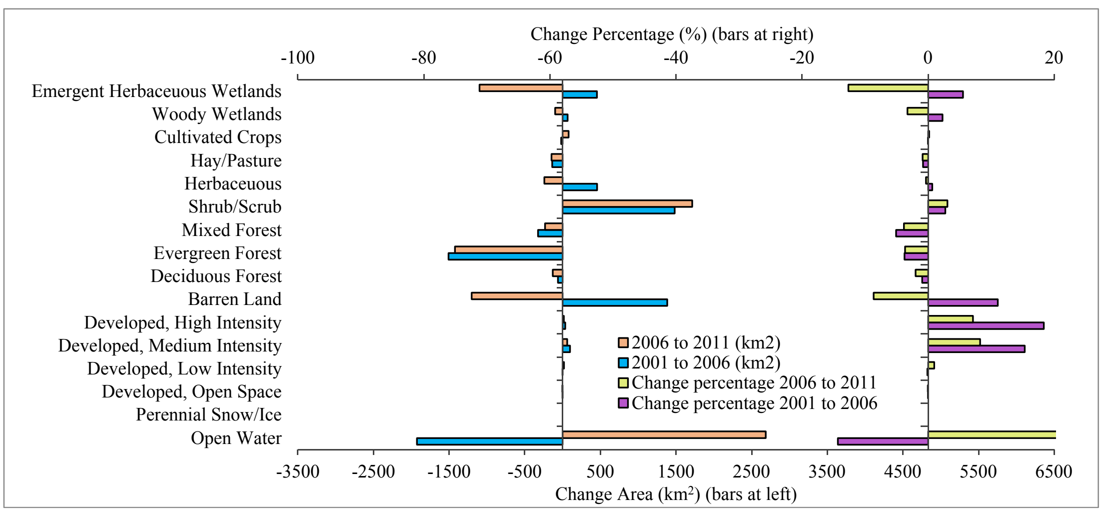


b. Land use/land cover change of counties belonging to outliers with decreasing AARD from 2001 to 2006

Fig. 2. Land use/land cover change of outlier counties. a. Land use/land cover change of counties belonging to outliers with increasing AARD from 2001 to 2006. b. Land use/land cover change of counties belonging to outliers with decreasing AARD from 2001 to 2006. c. Land use/land cover change of counties belonging to outliers with increasing AARD from 2006 to 2011. d. Land use/land cover change of counties belonging to outliers with decreasing AARD from 2006 to 2011.



c. Land use/land cover change of counties belonging to outliers with increasing AARD from 2006 to 2011



d. Land use/land cover change of counties belonging to outliers with decreasing AARD from 2006 to 2011

Fig. 2. (*continued*).

Division, 2006, 2011) and considered in the analysis (Note: the population data for year 2001 are included in U.S. Census Bureau, Population Division, 2006 dataset). Population change was compared with urban land change in order to evaluate whether population change was a consistent indicator for urban development.

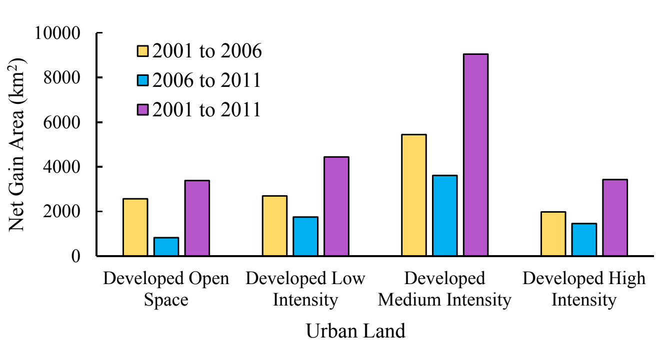


Fig. 3. Urban land change between 2001, 2006, and 2011 for the contiguous U.S. Data source: Homer et al., 2015.

3. Results and discussion

3.1. Assessment of NAARD by counties in the contiguous U.S.

During the processes of urbanization, many other types of land, such as forest, shrub land, and herbaceous land, are converted to urban land; while some urban land can also be changed to other types of land, those changes are far less than urbanization as evidenced by the expansion in urban areas. Increased urban land over time can significantly increase runoff volume due to increased impervious surfaces. The spatial variability of urban development impacts spatial variation of runoff (Tang et al., 2005). The NAARD was used to assess urbanization impacts on surface runoff, which allows direct comparison of runoff among different regions regardless of area differences. The NAARD calculated for each county in the contiguous U.S. was represented using the standard

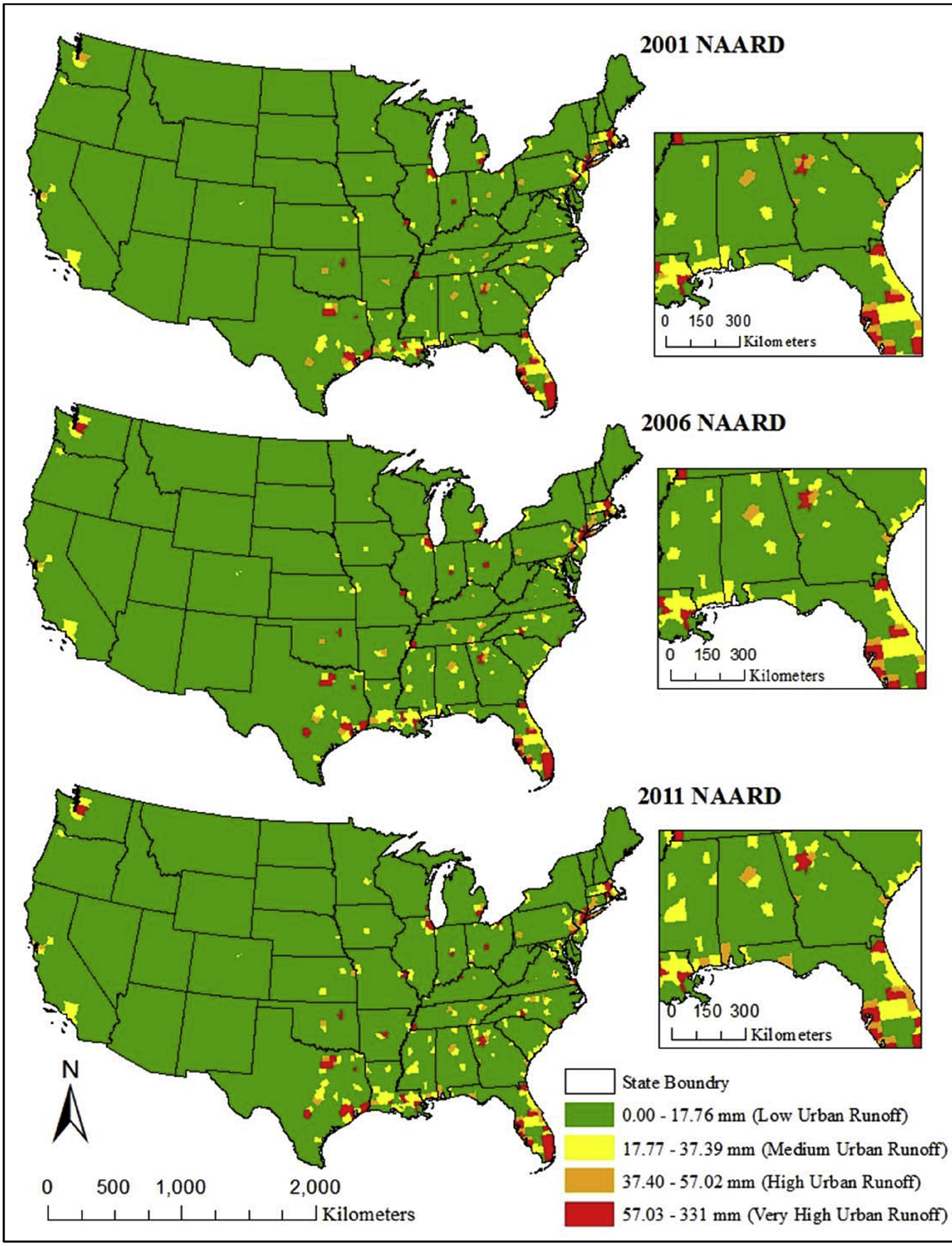


Fig. 4. County-based long-term (50 years) normalized average annual urban runoff depth maps of contiguous U.S. in 2001, 2006, and 2011.

deviation classification method that shows how spread out the values are and their spatial distribution. As shown in Fig. 4, green represents low runoff, which means that NAARD values are less than 0.5 standard deviation of NAARD value in 2001 (0–17.8 mm); yellow represents medium runoff, which means that NAARD values range between 0.5 and 1.5 standard deviation of NAARD value in

2001 (17.8 mm–37.4 mm); orange represents high runoff, which means that NAARD values range between 1.5 and 2.5 standard deviation of NAARD value in 2001 (37.4 mm–57.0 mm); red represents very high runoff, which means that NAARD values are greater than 2.5 standard deviation of NAARD value in 2001 (57.0 mm–331 mm).

Fig. 4 reveals an uneven spatial pattern of urban growth, which confirms that urbanization occurred non-uniformly across the contiguous U.S. from 2001 to 2011; the majority of counties in the contiguous U.S. belong to the category of low runoff with a NAARD value of less than 17.8 mm. The brighter colors including yellow, orange and red, representing medium, high, and very high runoff, occur mainly in large metropolitan areas, where a high proportion of impervious surfaces occur, such as Miami (FL), Orlando (FL), Tampa (FL), Jacksonville (FL), and Atlanta (GA) (see three insets in Fig. 4), as well as Chicago (IL), Houston (TX), Dallas (TX), San Antonio (TX), Seattle (WA), New York (NY), Memphis (TN), Charlotte (NC), and Boston (MA). From 2001 to 2011, the color change patterns included: green was turned to yellow, yellow was turned to orange or red, orange was turned to red, and more yellow or orange emerged around the red. Those color change patterns over time indicate the occurrence of urban expansion and intensification.

Table 2 lists the number of counties belonging to four categories of runoff. Low runoff counties are the dominant category among 2001 (91.9%), 2006 (91.2%), and 2011 (90.5%). Total number of counties with low runoff decreases from 2001 to 2011, total number of counties with high runoff remains stable during the ten-year time period, while total number of counties with medium runoff and very high runoff increases from 2001 to 2011 with an increasing percentage of 21.8% and 23.3%, respectively. The increasing percentage of medium and very high runoff counties from 2001 to 2006 (12.1% and 16.4%, respectively) was greater than that from 2006 to 2011 (8.6% and 5.9%, respectively), which corresponds to the increasing trend in urban land during the two five-year time periods. Urban sprawl and urban intensification resulted in higher NAARD and more medium and very high runoff counties.

3.2. NAARD, urban land, and population of counties with very high runoff

For 90 counties with very high runoff in 2011, analysis of urban land change and population change were conducted. The top ten counties with increased percentage of NAARD from 2001 to 2011 and their associated urban land change as well as population change are shown in Fig. 5. The percentage increase of NAARD from 2001 to 2011 for the top ten counties with very high runoff ranges from 18.0% to 44.8%, and their high percentage increase of NAARD are associated with increased population (11.3%–60.9%) as well as large increase of urban land (10.9%–34.6%). Typically, large urbanization rates are driven by large population growth rates rather than by economic growth (Buhaug and Urdal, 2013; Cincotta et al., 2003). For the top ten counties with very high runoff, large

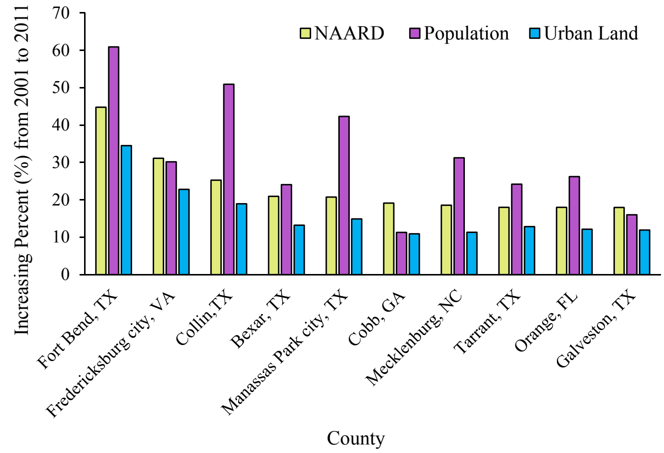


Fig. 5. Change percentage of NAARD, population, and urban land from 2001 to 2011 of top ten counties with very high runoff.

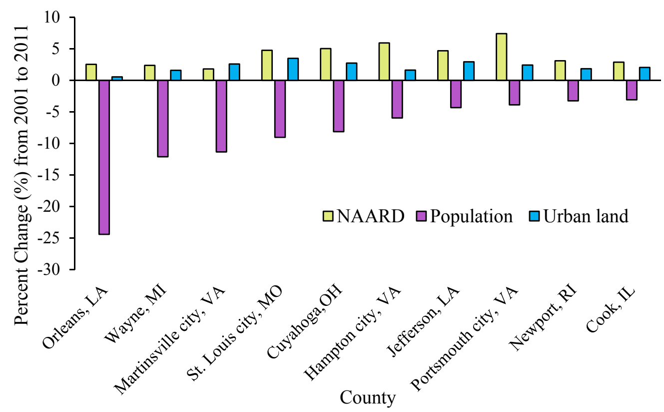


Fig. 6. Change percentage of NAARD, population, and urban land from 2001 to 2011 of some counties with very high runoff.

population increases likely stimulated urban development in order to fulfill people's life needs. Population could be considered a driving force for increasing the extent of developed land. However, as depicted in Fig. 6, many exceptions existed; some counties with very high runoff experienced an increase in NAARD and developed land from 2001 to 2011, but the population decreased during the same ten-year time period. This result is consistent with UN statistics (United Nations, 2010; United Nation - Habitat, 2010), which show that the global urban population increased more than four times during the 20th century. Further, the statistics show that urban growth remained persistent even while overall population growth is slowing. Thus, population growth is not a consistent factor stimulating urban development.

Table 2
Number of counties in the contiguous U.S. in low (green), medium (yellow), high (orange), and very high (red) urban runoff categories for 2001, 2006, and 2011.

Categories	NAARD range (mm)	2001		2006		2011		Change percentage (%)		
		Amount	Percentage (%)	Amount	Percentage (%)	Amount	Percentage (%)	01 to 06	06 to 11	01 to 11
Green	0–17.76	2858	91.93	2835	91.19	2815	90.54	0.80	0.71	1.50
Yellow	17.77–37.39	124	3.99	139	4.47	151	4.86	12.10	8.63	21.77
Orange	37.40–57.02	54	1.74	50	1.61	53	1.70	7.41	6.00	1.85
Red	57.03–331.00	73	2.35	85	2.73	90	2.89	16.44	5.88	23.29

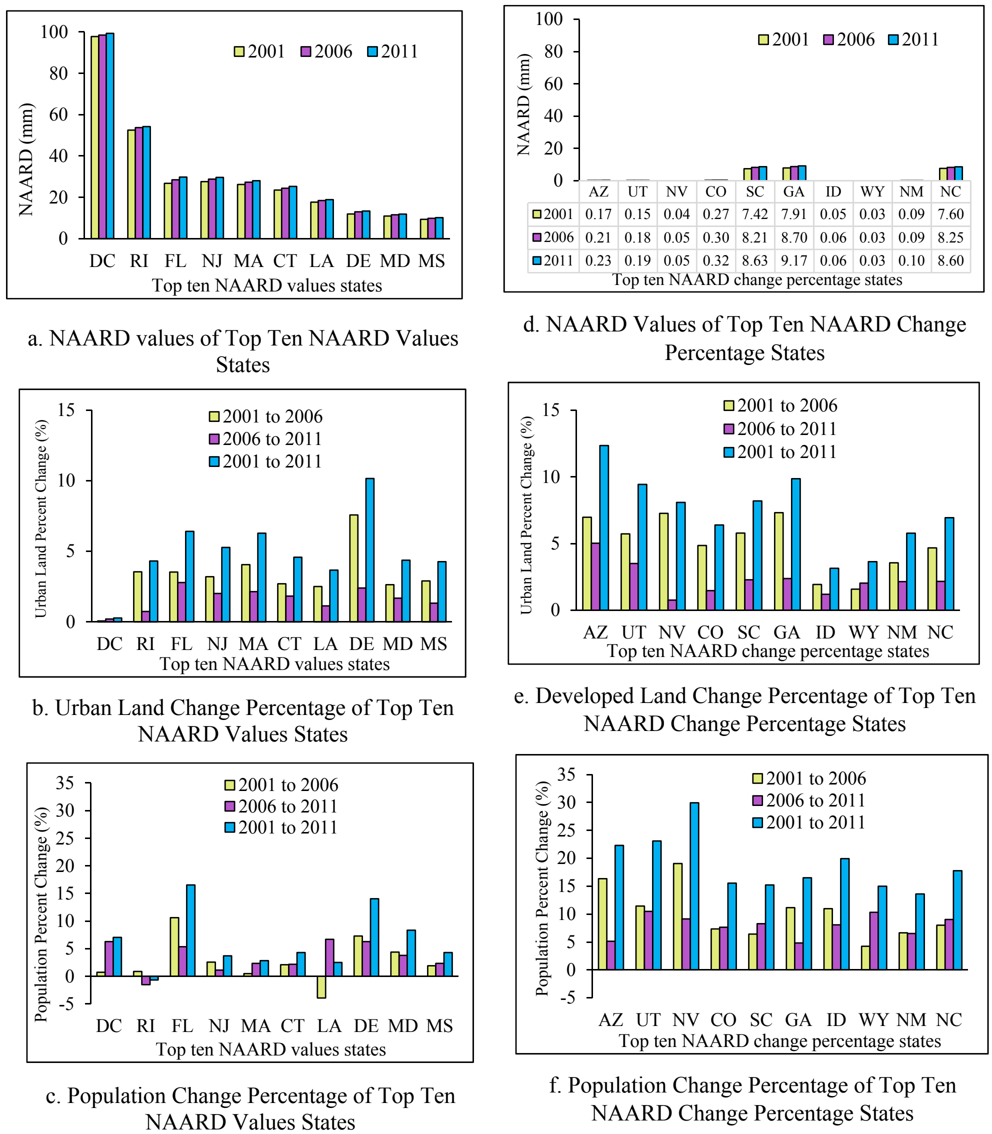


Fig. 7. Comparison of top ten NAARD values states in 2011 (group 1, left side a, b and c) with top ten NAARD change percentage states in 2011 (group 2, right side d, e and f). a. NAARD values of Top Ten NAARD Values States. b. Urban Land Change Percentage of Top Ten NAARD Values States. c. Population Change Percentage of Top Ten NAARD Values States. d. NAARD Values of Top Ten NAARD Change Percentage States. e. Developed Land Change Percentage of Top Ten NAARD Change Percentage States. f. Population Change Percentage of Top Ten NAARD Change Percentage States. Note: population data were from U.S. Census Bureau population (U.S. Census Bureau, Population Division, 2006, 2011).

3.3. Assessment of NAARD by states in the contiguous U.S.

The NAARD value of each state in the contiguous U.S. was calculated in order to conduct direct comparison of runoff among different states regardless of area differences. The top ten NAARD values states in 2011 (group 1) as well as the top ten NAARD change percentage states (group 2) in 2011 were selected for the state level analysis. For each group, the NAARD values, urban land change percentage among 2001, 2006, and 2011, as well as population change among 2001, 2006, and 2011, are depicted in Fig. 7. Sub-figures a through c represent group 1 and sub-figures d through f represent group 2. There are similarities between the two groups: NAARD values increased from 2001 to 2011; urban land had increasing percentages in both five-year periods, and the percentage increase from 2001 to 2006 was higher than that from 2006 to 2011, except in DC and Wyoming (WY).

The NAARD values of the top ten NAARD value states, as shown in sub-figure a of Fig. 7, range from 10.2 mm to 99.4 mm in 2011. Those ten states are mainly located in the northeast, east, southeast, and southern United States. One reason for their high NAARD values is that higher precipitation often occurs in those areas relative to other US locations. A large percentage of urban land also contributes to high NAARD values as depicted in sub-figure b of Fig. 7. Population change within the decade from 2001 to 2011 varied in different states, as shown in sub-figure c of Fig. 7. Rhode Island (RI) experienced a population increase from 2001 to 2006, but saw a population decrease from 2006 to 2011 which was of a higher magnitude than prior increase, resulting in an overall population decrease from 2001 to 2011. Louisiana (LA) experienced a population decrease from 2001 to 2006 attributable to natural disasters such as Hurricane Katrina in 2005 (Burby, 2006; Hartman and Squires, 2006; Kates et al., 2006), while population increased from 2006 to 2011 with higher magnitude, which led to an overall increased population from 2001 to 2011. Seven other states and DC have undergone population increases in both five-year time periods, among them, population percentage increases from 2001 to

2006 in four states including FL, New Jersey (NJ), Delaware (DE), and Maryland (MD) were higher than that from 2006 to 2011; the population increase of Massachusetts (MA), Connecticut (CT), Mississippi (MS) and DC from 2001 to 2006 was lower than that from 2006 to 2011.

For group 2, as shown in sub-figure d of Fig. 7, seven out of the top ten NAARD change percentage states are distributed in the western U.S. except South Carolina, Georgia, and North Carolina. The NAARD values of those western states are low due to low precipitation in those areas. Their high percentage increases in NAARD values were greatly influenced by large urban land increases within the decade from 2001 to 2011 (ranging from 3.1% to 12.3% in 2011), as shown in sub-figure e of Fig. 7, which indicated that areas that experienced more urban growth had a larger potential for increased average annual surface runoff. Similar studies also found that rapid urban expansion increased annual runoff, daily peak flow, and flood volume (Barron et al., 2013; Du et al., 2012; Weng, 2001; White and Greer, 2006). Population increased consecutively in the two five-year time periods from 2001 to 2011 with different magnitudes, as depicted in sub-figure f of Fig. 7. The increasing percentage ranges from 13.6% to 29.9% from 2001 to 2011, which could stimulate urban development. By comparing groups 1 and 2, urban growth had a higher magnitude in areas with larger population increase, while urban growth continues to occur even if population decreases. This indicates that population should only be considered as one of the possible factors stimulating the growth of urban land, and that only considering population growth is not a good way to analyze the increase in urban development, consistent with Hasse's (Hasse and Lathrop, 2003) study on land resource impact indicators of urban sprawl.

3.4. Assessment of runoff volume increase due to urbanization

The national average annual runoff volume was calculated by summing runoff volume from each county. As depicted in Fig. 8, for the contiguous U.S., about 1.9 billion cubic meters of average annual runoff were generated due to urbanization from 2001 to 2006 and about 1.4 billion cubic meters of average annual runoff were gained from urbanization from 2006 to 2011, totaling 3.3 billion cubic meters of average annual runoff gained due to urbanization for the decade from 2001 to 2011, which is about 10% of the total amount of urban runoff in 2001. This increased runoff can have substantial impacts on many issues, such as flooding, reduced groundwater recharge, and water quality degradation.

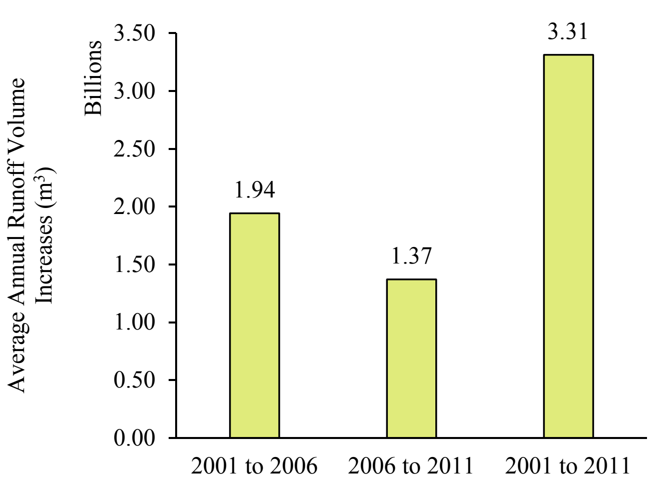


Fig. 8. National average annual runoff volume increase due to urbanization.

The scale of the national average annual runoff volume increase due to urbanization from this study can be used to strengthen decision maker's awareness of potential long-term impacts of urban expansion and intensification. It also implies that future urban planning or urban re-development should consider mitigation approaches, such as low impact development to reduce the impacts of urbanization.

4. Conclusions

This study quantified urbanization impacts on surface runoff at a national scale. The contiguous United States underwent urbanization in the decade from 2001 to 2011. Urbanization occurred non-uniformly across the nation, and urban expansion and intensification served as driving forces altering surface runoff. The runoff change analysis revealed that: (i) the majority of counties in the contiguous Unites States were low runoff counties during the period 2001 to 2011 and had long-term normalized average annual runoff depth from urban land less than 17.8 mm. However, spread of urban sprawl to suburban areas around metropolitan as well as newly urbanized areas within metropolitan areas resulted in more medium and very high runoff counties; (ii) For the top ten NAARD states in 2011, NAARD values were jointly influenced by high precipitation and increasing urban land, while the top ten NAARD change percentage states in 2011 were mainly in the western U.S. in areas with low precipitation, and their NAARD values were mainly influenced by high increases in urban land; (iii) Nationally, about 3.3 billion cubic meters of average annual runoff were gained due to urbanization from 2001 to 2011; and (iv) Population increases are a factor in urban development, however population is not a good predictor of urbanization levels because some areas have undergone decreasing population but increasing urban land area. Therefore, population change alone is not a sufficient proxy with which to analyze the increase in urban development.

This study also demonstrated that the L-THIA Tabular Tool is capable of generating useful information about urbanization impacts on surface runoff using the stochastic weather generator, CLIGEN, together with the NLCD datasets and STATSGO soil dataset. Potential future research directions include exploring urbanization impacts on water quality, for instance, computing non-point source pollution estimates using the runoff volume and the CN-land use pairs to choose the appropriate EMC; comparing the results from this study to results obtained by applying nationwide spatial-distributed observed daily precipitation; comparing the results from this study to results by applying Soil Survey (SSURGO) geographic data; or simulating future land use change scenarios and their hydrological and environmental impacts, among others. The results of this study can be used to strengthen a decision maker's awareness of potential long-term impacts of urbanization. The tool can also be used for analyzing trade-offs between the advantages and possible unintended consequences of urbanization in future urban planning or urban re-development.

Acknowledgements

Special thanks to Dr. Younghyun Cho for helping with part of the modeling work in our preliminary modeling trial.

References

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012a. Effectiveness of low impact development practices: literature review and suggestions for future research. Water Air Soil Pollut. 223 (7), 4253–4273.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012b. Representation and evaluation of low impact development practices with L-THIA-LID: an example for site planning. Environ. Pollut. 1 (2), 1.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2013. Effectiveness of low impact development practices in two urbanized watersheds: retrofitting with rain barrel/cistern and porous pavement. J. Environ. Manag. 119, 151–161.
Antrop, M., 2004. Landscape change and the urbanization process in Europe. Landsc. Urban Plan. 67 (1–4), 9–26. http://dx.doi.org/10.1016/S0169-2046(03)00026-4.
Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. Am. Plan. Assoc. 62 (2), 243–258.
Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. J. Am. Water Resour. Assoc. 34, 73–89. http://dx.doi.org/10.1111/j.1752-1688. 1998.tb05961.x.
Barron, O.V., Barr, A.D., Donn, M.J., 2013. Effect of urbanisation on the water balance of a catchment with shallow groundwater. J. Hydrol. 485, 162–176.
Bhaduri, B., Harbor, J., Engel, B., Grove, M., 2000. Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model. Environ. Manag. 26 (6), 643–658.
Bhaduri, B., Minner, M., Tatalovich, S., Harbor, J., 2001. Long-term hydrologic impact of urbanization: a tale of two models. J. Water Resour. Plan. Manag. 127 (1), 13–19.
Blair, A., Lovelace, S., Sanger, D., Holland, A.F., Vandiver, L., White, S., 2014. Exploring impacts of development and climate change on stormwater runoff. Hydrol. Process. 28 (5), 2844–2854.
Booth, D.B., Jackson, C.R., 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. J. Am. Water Resour. Assoc. 33 (5), 1077–1090.
Buhaug, H., Urdal, H., 2013. An urbanization bomb? Population growth and social disorder in cities. Glob. Environ. Change 23 (1), 1–10.
Burby, R.J., 2006. Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. Ann. Am. Acad. Polit. Soc. Sci. 604 (1), 171–191.
Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Hatt, B.E., 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landsc. Urban Plan. 105 (3), 230–240. http://dx.doi.org/10.1016/j.landurbplan.2011.12.012.
Choi, W., 2007. Estimating land-use change impacts on direct runoff and non-point source pollutant loads in the Richland Creek basin (Illinois, USA) by applying the L-THIA model. J. Spat. Hydrol. 7 (1).
Choi, J.Y., Engel, B.A., 2003. Real-time watershed delineation system using Web-GIS. J. Comput. Civ. Eng. 17 (3), 189–196.
Choi, J.Y., Engel, B.A., Muthukrishnan, S., Harbor, J., 2003. GIS Based long term hydrologic impact evaluation for watershed urbanization. J. Am. Water Resour. Assoc. 39, 623–635. http://dx.doi.org/10.1111/j.1752-1688. 2003.tb03680.x.
Choi, J.Y., Engel, B., Farnsworth, R., 2005a. Web-based GIS and spatial decision support system for watershed management. J. Hydroinform. 7, 165–174.
Choi, J.Y., Engel, B.A., Theller, L., Harbor, J., 2005b. Utilizing web-based GIS and SDSS for hydrological land use change impact assessment. Trans. ASAE 48 (2), 815–822.
Cincotta, R.P., Engelman, R., Anastasion, D., 2003. The Security Demographic: Population and Civil Conflict after the Cold War. Population Action International Security Demographic, Washington DC.
Costa, M.H., Botta, A., Cardille, J.A., 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J. Hydrol. 283 (1), 206–217.
Davis, A.Y., Pijanowski, B.C., Robinson, K., Engel, B., 2010. The environmental and economic costs of sprawling parking lots in the United States. Land Use Policy 27 (2), 255–261.
DeFries, R., Eshleman, K.N., 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrol. Process. 18 (11), 2183–2186.
Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y., Xu, C.Y., 2012. Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. J. Hydrol. 464, 127–139.
Engel, B., 2001. L-THIA NPS Long-Term Hydrologic Impact Assessment and Non-Point Source Pollutant Model, Version 2.1. Purdue University and US Environmental Protection Agency.
Engel, B., Ahiablame, L.M., 2011. L-THIA-LID Long-Term Hydrologic Impact Assessment-Low Impact Development Model, sv_version1.1. Purdue University.
Engel, B., Hunter, J., 2009. L-THIA LID Long-term Hydrologic Impact Assessment Low Impact Development Model. Spreadsheet Version. Purdue University.
Engel, B.A., Choi, J.Y., Harbor, J., Pandey, S., 2003. Web-based DSS for hydrologic impact evaluation of small watershed land use changes. Comput. Electron. Agric. 39 (3), 241–249.
Erkens, D.H., Hung, M., Matos, P., 2012. Corporate governance in the 2007–2008 financial crisis: evidence from financial institutions worldwide. J. Corp. Finance 18 (2), 389–411.
Eshleman, K.N., 2004. Hydrological consequences of land use change: a review of the state-of-science. Ecosyst. Land Use Change 13–29.
Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., et al., 2005. Global consequences of land use. Science 309 (5734), 570–574.
Fry, J.A., Xian, G., Jin, S., Dewitz, J.A., Homer, C.G., Limin, Y., Wickham, J.D., 2011. Completion of the 2006 national land cover database for the conterminous United States. Photogramm. Eng. Remote Sens. 77 (9), 858–864.
Gitau, M.W., Chen, J., Ma, Z., 2016. Water quality indices as tools for decision making and management. Water Resour. Manag. 30 (8), 2591–2610.
Grove, M., Harbor, J., Engel, B., Muthukrishnan, S., 2001. Impacts of urbanization on surface hydrology, Little Eagle Creek, Indiana, and analysis of LTHIA model sensitivity to data resolution. Phys. Geogr. 22 (2), 135–153.
Gunn, R., Martin, A., Engel, B., Ahiablame, L., 2012. Development of two indices for determining hydrologic implications of land use changes in urban areas. Urban Water J. 9 (4), 239–248.
Harbor, J.M., 1994. A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. J. Am. Plan. Assoc. 60 (1), 95–108.
Hartman, C.W., Squires, G.D., 2006. There Is No Such Thing as a Natural Disaster: Race, Class, and Hurricane Katrina. Taylor & Francis.
Hasse, J.E., Lathrop, R.G., 2003. Land resource impact indicators of urban sprawl. Appl. Geogr. 23 (2), 159–175.
Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Wickham, J., 2007. Completion of the 2001 national land cover database for the counterminous United States. Photogramm. Eng. Remote Sens. 73 (4), 337.
Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., Megown, K., 2015. Completion of the 2011 national land cover database for the conterminous United States–Representing a decade of land cover change information. Photogramm. Eng. Remote Sens. 81 (5), 345–354.
Hunter, J.G., Engel, B.A., Quansah, J.E., 2010. Web-based low impact development decision support tool for watershed planning. Proc. Low Impact Dev. 11–14.
Ivashina, V., Scharfstein, D., 2010. Bank lending during the financial crisis of 2008. J. Financ. Econ. 97 (3), 319–338.
Kates, R.W., Colten, C.E., Laska, S., Leatherman, S.P., 2006. Reconstruction of New Orleans after Hurricane Katrina: a research perspective. Proc. Natl. Acad. Sci. 103 (40), 14653–14660.
Kim, Y., Engel, B.A., Lim, K.J., Larson, V., Duncan, B., 2002. Runoff impacts of land-use change in Indian River Lagoon watershed. J. Hydrol. Eng. 7 (3), 245–251.
Lim, K.J., Engel, B.A., Muthukrishnan, S., Harbor, J., 2006a. Effects of initial abstraction and urbanization on estimated runoff using CN technology. J. Am. Water Resour. Assoc. 42, 629–643. http://dx.doi.org/10.1111/j.1752-1688.2006.tb04481.x.
Lim, K.J., Engel, B.A., Tang, Z., Muthukrishnan, S., Choi, J., Kim, K., 2006b. Effects of calibration on L-THIA GIS runoff and pollutant estimation. J. Environ. Manag. 78 (1), 35–43.
Lim, K.J., Park, Y.S., Kim, J., Shin, Y.-C., Kim, N.W., Kim, S.J., et al., 2010. Development of genetic algorithm-based optimization module in WHAT system for hydrograph analysis and model application. Comput. Geosci. 36 (7), 936–944.
Liu, Y., Ahiablame, L.M., Bralts, V.F., Engel, B.A., 2015a. Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff. J. Environ. Manag. 147, 12–23.
Liu, Y., Bralts, V.F., Engel, B.A., 2015b. Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. Sci. Total Environ. 511, 298–308.
Liu, Y., Cibin, R., Bralts, V.F., Chaubey, I., Bowling, L.C., Engel, B.A., 2016a. Optimal selection and placement of BMPs and LID practices with a rainfall-runoff model. Environ. Model. Softw. 80, 281–296.
Liu, Y., Theller, L.O., Pijanowski, B.C., Engel, B.A., 2016b. Optimal selection and placement of green infrastructure to reduce impacts of land use change and climate change on hydrology and water quality: an application to the Trail Creek Watershed, Indiana. Sci. Total Environ. 553, 149–163.
Lowry, I.S., 1990. World urbanization in perspective. Popul. Dev. Rev. 148–176.
Martin, A.R., Ahiablame, L.M., Engel, B.A., 2015. Modeling low impact development in two Chicago communities. Environ. Sci. Water Res. Technol. 1 (6), 855–864.
Meyer, C.R., Renschler, C., Vining, R.C., 2002. Implementing quality control techniques for random number generators to improve stochastic weather generators: the CLIGEN experience. In: 13th Conference on Applied Climatology, Session 5.
Meyer, C.R., Renschler, C.S., Vining, R.C., 2008. Implementing quality control on a random number stream to improve a stochastic weather generator. Hydrol. Process. 22 (8), 1069–1079.
Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50 (3), 885–900.
Muthukrishnan, S., Harbor, J., Lim, K.J., Engel, B.A., 2006. Calibration of a simple rainfall-runoff model for long-term hydrological impact evaluation. URISA Wash. D.C. 18 (2), 35.
Natural Resources Conservation Services (NRCS), 1986. Urban Hydrology for Small Watersheds. Technical Release 55. United States Department of Agricultural (USDA) NRCS. http://www.cpesc.org/reference/tr55.pdf.
Pandey, S., Gunn, R., Lim, K.J., Engel, B., Harbor, J., 2000. Developing a web-enabled tool to assess long-term hydrologic impacts of landuse change: information technology issues and a case study. URISA Wash. D.C. 12 (4), 5–22.
Passerat, J., Ouattara, N.K., Mouchel, J.-M., Rocher, V., Servais, P., 2011. Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. Water Res. 45 (2), 893–903.
Peters, G.P., Marland, G., Le Quéré, C., Boden, T., Canadell, J.G., Raupach, M.R., 2012. Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. Nat. Clim. Change 2 (1), 2–4.
Reinhart, C.M., Rogoff, K.S., 2008. Is the 2007 US sub-prime financial crisis so different? An international historical comparison (No. w13761). National Bureau of Economic Research.
Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. J. Hydrol. 178 (1), 293–309.
Schueler, T.R., 1994. The importance of imperviousness. Watershed Prot. Tech. 1 (3), 100–111.

Schueler, T.R., Fraley-McNeal, L., Cappiella, K., 2009. Is impervious cover still important? Review of recent research. J. Hydrol. Eng. 14 (4), 309–315.
Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.-G., 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: combined sewer system. J. Hydrol. 350 (1), 100–113.
Shi, Y., Asher, J., Bartholic, J., Choi, J., Engel, B., Farnsworth, R., 2004. An online webGIS-based hierarchical watershed decision support system for United States. Environ. Inf. Arch. 2, 838–845.
Srinivasan, R., Ramanarayanan, T.S., Arnold, J.G., Bednarz, S.T., 1998. Large area hydrologic modeling and assessment part II: model application. J. Am. Water Resour. Assoc. 34, 91–101. http://dx.doi.org/10.1111/j.1752-1688.1998.tb05962.x.
Suriya, S., Mudgal, B.V., 2012. Impact of urbanization on flooding: the Thirusoolam sub watershed—a case study. J. Hydrol. 412, 210–219.
Tang, Z., Engel, B.A., Choi, J., Sullivan, K., Sharif, M., Lim, K.J., 2004. A Web-based DSS for erosion control structure planning. Appl. Eng. Agric. 20 (5), 707–714.
Tang, Z., Engel, B.A., Pijanowski, B.C., Lim, K.J., 2005. Forecasting land use change and its environmental impact at a watershed scale. J. Environ. Manag. 76 (1), 35–45.
Thiessen, A.H., 1911. Precipitation averages for large areas. Mon. Weather Rev. 39 (7), 1082–1089.
Tong, S.T., Chen, W., 2002. Modeling the relationship between land use and surface water quality. J. Environ. Manag. 66 (4), 377–393.
United Nations, 2010. World Urbanization Prospects: The 2009 Revision. Highlights. United Nations Population Division, New York.
United Nation - Habitat, 2010. State of the World's Cities 2010/2011- Cities for All: Bridging the Urban Divide. UN-Habitat.
U.S. Census Bureau, Population Division, 2006. Annual Estimates of the Population for the United States, Regions, and States and for Puerto Rico: April 1, 2000 to July 1, 2006 (NST-EST2006–01). Web. Access Date: June 02, 2015.
U.S. Census Bureau Population, Division, 2011. Annual Estimates of the Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2011 (NST-EST2011–01). Web. Access Date: June 02, 2015.
USEPA, 2013. Our Built and Natural Environments: a Technical Review of the Interactions Among Land Use, Transportation, and Environmental Quality, second ed. EPA 231K13001. http://www.epa.gov/sites/production/files/2014-03/documents/our-built-and-natural-environments.pdf.
Vietz, G.J., Rutherfurd, I.D., Fletcher, T.D., Walsh, C.J., 2016. Thinking outside the channel: challenges and opportunities for protection and restoration of stream morphology in urbanizing catchments. Landsc. Urban Plan. 145, 34–44. http://dx.doi.org/10.1016/j. landurbplan.2015.09.004.
Weng, Q., 2001. Modeling urban growth effects on surface runoff with the integration of remote sensing and GIS. Environ. Manag. 28 (6), 737–748.
Weng, Q., 2002. Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. J. Environ. Manag. 64 (3), 273–284.
White, M.D., Greer, K.A., 2006. The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California. Landsc. Urban Plan. 74 (2), 125–138.
Wickham, J., Homer, C., Vogelmann, J., McKerrow, A., Mueller, R., Herold, N., Coulston, J., 2014. The Multi-Resolution Land Characteristics (MRLC) Consortium-20 years of development and integration of USA national land cover data. Remote Sens. 6 (8), 7424–7441.
Wilson, C., Weng, Q., 2010. Assessing surface water quality and its relation with urban land cover changes in the Lake Calumet Area, Greater Chicago. Environ. Manag. 45 (5), 1096–1111.
Wolock, D.M., 1997. STATSGO Soil Characteristics for the Conterminous United States (97-656). Retrieved from Lawrence, KS. http://pubs.er.usgs.gov/publication/ofr97656.
Wright, T.J., Liu, Y., Carroll, N.J., Ahiablame, L.M., Engel, B.A., 2016. Retrofitting LID practices into existing neighborhoods: is it worth it? Environ. Manag. 57 (4), 856–867. http://dx.doi.org/10.1007/s00267-015-0651-5.
Wu, J., 2014. Urban ecology and sustainability: the state-of-the-science and future directions. Landsc. Urban Plan. 125, 209–221. http://dx.doi.org/10.1016/j.landurbplan.2014.01.018.
You, Y.Y., Jin, W.B., Xiong, Q.X., Xue, L., Ai, T.C., Li, B.L., 2012. Simulation and validation of non-point source nitrogen and phosphorus loads under different land uses in Sihu Basin, Hubei Province, China. Procedia Environ. Sci. 13, 1781–1797.
Zhang, X.C., Garbrecht, J.D., 2003. Evaluation of CLIGEN precipitation parameters and their implication on WEPP runoff and erosion prediction. Trans. ASAE 46 (2), 311–320.