Runoff Impacts of Land-Use Change in Indian River Lagoon Watershed

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Abstract: Changes in land use can have significant impacts on hydrology and the environment. The Long-Term Hydrologic Impact Analysis model and a geographic information system-based Soil Conservation Service curve number method were used to estimate average annual runoff and runoff for rainfall events with varying return periods, respectively, for NASA's John F. Kennedy Space Center (KSC) within the Indian River Lagoon watershed (IRL), Florida, for 1920, 1943, and 1990 land uses. Changes in estimated runoff depths due to land-use alteration between 1920 and 1990—for design rainfall events ranging from a 24 h/1 year to a 24 h/100 year return period—ranged from 7–17% for KSC to 22–55% for the IRL watershed. The percentage changes in average annual runoff due to land-use changes were much greater. Between 1920 and 1990, estimated average annual runoff for the KSC increased about 49%, and the IRL runoff increased nearly 113%. For the KSC and IRL, most of the increase in runoff between 1920 and 1990, both for single events and annually, came from landscape urbanization, although increased agricultural land uses in the IRL also contributed to increased runoff. Large differences in estimated runoff between the KSC and IRL are due to differences in the amount of urban land use within the respective areas (1990 urban land uses for the IRL are 34.8 versus 20.5% for KSC). Land-use change can have a dramatic impact on annual runoff volume, as demonstrated in this study; thus the effects of land-use change on annual or long-term runoff should be considered in land-use planning.

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Introduction

Land-use change, especially urbanization, has significant impacts on hydrology, in terms of both water quality and quantity, over a range of temporal and spatial scales. The nature and scale of the impacts depend on the form of the land-use change and its climatic context. Hydrologic impacts affect many aspects of the environment, such as river channel erosion and widening, riparian and wetland habitat loss, wetland and aquatic community population declines, and reduced ecological diversity. In addition, considerable economic costs are associated with attempts to manage and reduce the negative impacts of land-use change over a range of spatial scales.

The traditional focus in urban surface water management has been the control of peak discharges from individual high-magnitude storm events that cause flooding. Models such as those developed by the U.S. Army Corps of Engineers (USACE 1985) and the U.S. Dept. of Agriculture (USDA 1983, 1986) are often used for such purposes. The U.S. Environmental Protection Agency storm water management model (Huber et al. 1985) is routinely used for assessing the impact that proposed land-use changes will have on design event runoff quantity. The results are the basis for designing storm-water facilities to prevent flooding problems. Although this is an appropriate approach for local-scale flood prevention, its value is limited for understanding long-term hydrologic impact of land use change and hydrologic changes at watershed scales.

The Soil Conservation Service (SCS) curve number (CN) method was developed by the USDA (1986) to compute CN values for land use, hydrologic soil group, and land-management practices. Empirical approaches were used to establish predictive relationships between precipitation depth, CN values, and runoff. This method is widely accepted and has been applied to situations ranging from runoff calculations from small watersheds to comprehensive hydrologic/water quality models, such as the Soil and Water Assessment Tool (SWAT) (Adamus and Bergman 1993; Srinivasan and Arnold 1994; Arnold et al. 1995). The CN method has also been applied using a geographic information system (GIS) (Engel 1997).

When calculating runoff volume, traditional hydrologic methods (Julien 1996; Burges et al. 1998) rarely focus on assessing the long-term hydrologic impact of land-use change, but instead typically focus on "design" events. However, for effective surface-water management, it is necessary to perform long-term simulations because much of the runoff from urbanized watersheds originates from smaller-intensity, high-frequency storms.

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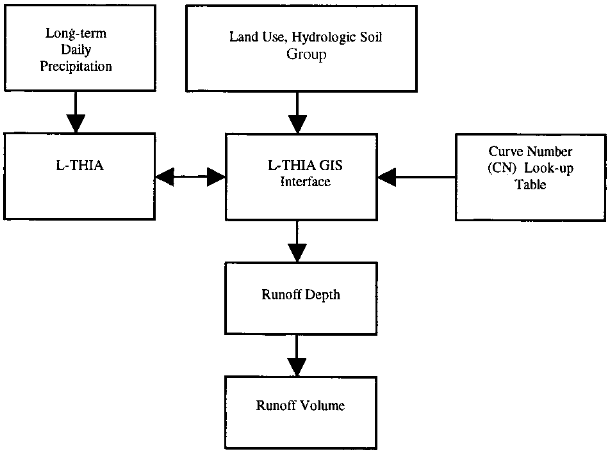

Fig. 1. Long-Term Hydrologic Impact Analysis (L-THIA) geographic information system overview

Harbor (1994) proposed using a runoff calculation technique to generate a measure of the long-term potential hydrologic impact of land-use change. This approach, called Long-Term Hydrologic Impact Analysis (L-THIA), uses the CN method for calculating runoff and only requires readily available data, such as hydrologic soil group, land use, and a long-term climate record (typically 30 years). From these data, average annual runoff for each CN is determined. L-THIA was recently integrated with GIS to facilitate its use (Bhaduri 1998; Grove et al. 1998). More recently, L-THIA GIS was modified to use a raster data format for fast and easy manipulation of spatial data (Lim et al. 1999; L-THIA 2001). L-THIA GIS estimates of runoff have been validated for watersheds with varying land uses (Bhaduri et al. 1997; Grove et al. 1998; Bhaduri et al. 2000). The L-THIA GIS method (Fig. 1) used in this study is a user-friendly runoff simulation technique that could overcome many of the limitations of existing hydrologic models and provide a simple initial assessment of the long-term hydrologic impacts of land-use change.

Objectives

The focus of this study is to evaluate the effects of land-use change on runoff volume in the Indian River Lagoon (IRL) watershed and the Kennedy Space Center (KSC), Florida. The effect of historical land-use changes on runoff for ''design'' events and annually will be quantified. Land use for 1920, 1943, and 1990 was used to assess the long-term changes in runoff volumes from historical to present development.

Methodology

Study Area

The KSC is located within the IRL watershed along the east coast of central Florida on northern Merritt Island, a barrier island complex adjacent to Cape Canaveral (Fig. 2). Scrub and pine flatwoods are the dominant upland communities on the KSC (Provancha et al. 1986; Larson 1992). Fresh water and salt water marshes occur adjacent to the estuary and in low areas interspersed among scrub and pine flatwoods (Schmalzer and Hinkle 1990). Few forests occurred historically; the current distribution of forests is the result of fire suppression or land disturbance (Breininger et al. 1991). The 248 km IRL system, as it exists today, is a product of long-term natural landscape development and short-term anthropogenic impacts, and the climate is warm and humid. Holocene sea-level rise has been the most significant influence on the evolution of the physical and biological aspects of this barrier island complex. The north section of the IRL watershed contains ridge and swale topography (elevations of about 10 m) associated with Cape Canaveral that is geographically relatively stable. Elevations in the south portions of the watershed are less than 3 m, resulting in greater variability and influence of marine processes in the lagoon region. The entire barrier island and lagoonal system took 240,000 years to form, but most human development has occurred within the past 8,000 years (History 2001). The IRL watershed boundaries differ over time due to changes in drainage (Fig. 2.).

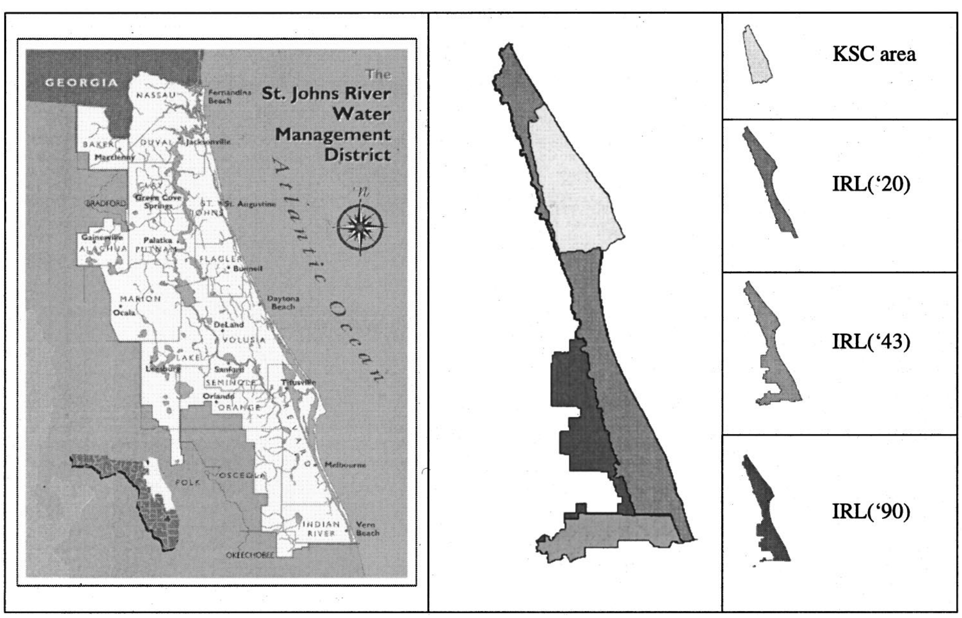

Fig. 2. Location of Indian River Lagoon (IRL) watershed and Kennedy Space Center (KSC) (IRL watersheds differ due to changes in drainage)

Table 1. Summary of Land-Use Distribution for Kennedy Space Center (KSC) and Indian River Lagoon (IRL)

Land use for L-THIA model		Area (10^6 m^2,%) 1920		1943		1990	
	Agricultural	20.95	*0.8*	182.38	*6.8*	198.97	*7.0*
KSC	Commercial					4.38	*0.2*
	Forest	1,658.01	*62.1*	1,466.05	*54.3*	1,653.37	*58.2*
	Grass/pasture	939.30	*35.2*	918.94	*34.1*	405.72	*14.3*
	HD residential					139.88	*4.9*
	Industrial					173.82	*6.1*
	LD residential	50.86	*1.9*	130.49	*4.8*	265.40	*9.3*
	Non-water area	2,669.12	*100.0*	2,697.86	*100.0*	2,841.54	*100.0*
	(Water)	6,672.01		6,646.33		6,311.98	
	Total area	9,341.13		9,344.19		9,153.52	
IRL	Agricultural	78.78	*0.6*	2,812.64	*16.3*	5,497.88	*28.0*
	Commercial			16.83	*0.1*	413.99	*2.0*
	Forest	9,038.44	*72.4*	8,185.13	*47.8*	5,452.87	*26.9*
	Grass/pasture	2,919.43	*23.3*	5,048.12	*29.2*	2,089.26	*10.3*
	HD residential					738.40	*3.7*
	Industrial					903.41	*4.4*
	LD residential	456.63	*3.7*	1,117.54	*6.6*	5,005.97	*24.7*
	Non-water area	12,493.28	*100.0*	17,180.26	*100.0*	20,101.78	*100.0*
	(Water)	14,617.56		17,003.35		13,829.57	
	Total area	27,110.84		34,183.61		33,931.35	

The KSC is the largest public land area along Florida's Atlantic coast. After the Civil War, railroad establishment led to permanent towns associated with the citrus industry. Logging of virgin pine became prevalent; from 1900 to 1962, there was repeated logging of pine, burning for free-ranging cattle, and draining and diking of wetlands for mosquito control. Since the late 1950s, much of the KSC area has been returned to more natural land uses as the Merritt Island National Wildlife Refuge and home to NASA space operations.

Land Cover and Soil Maps for Study Area

For computing runoff volume (depth) with the CN and L-THIA GIS methods, the land-cover map is an important data source. Land-cover classification of the KSC and IRL in 1920, 1943, and 1990 was obtained from the SJRWMD (St. Johns River Water Management District) GIS library. The 1943 and 1990 data were created through photo interpretation of 1:15,840 and 1:24,000 black-and-white aerial photography, respectively (Larson 1992; Schmalzer et al. 1996). The 1920 land cover was modeled using 1943 data, historical maps, and soil/natural community associations (Duncan and Larson 1997). Over 150 cover types were consolidated into nine land-use categories for use in the L-THIA GIS model. Land-cover classes were grouped by similarity of land use. Low- and high-density residential land use did not actually occur on the KSC; however, some NASA facilities were more similar in land use to residential than to industrial or commercial categories.

The KSC has undergone some urbanization in the last 70 years (Table 1). Most of the KSC has wetland land uses that were reclassified as water. In 1920, 71% of the land area consisted of water. Forest and grass/pasture made up 62% and 35% of the nonwater area, respectively, and the remaining 3% of the nonwater area consisted of agricultural and low-density residential areas. Agricultural and low-density residential areas increased to 3 and 9% of the nonwater area, respectively, between 1920 and 1990. In 1990, three additional urban land-use categories were added: commercial, high-density residential, and industrial. These three new categories made up 11% of the total nonwater area in 1990.

For the IRL, historical land-use distribution trends are very similar to those for the KSC. The largest land area in the IRL in 1920 was forest that covered 72% of the nonwater area. However, the portion of forest decreased to 48% in 1943 and to 27% in 1990. In 1990, the percentage of the three new land-use categories (commercial, high-density residential, and industrial) in the IRL was about 10% of the total nonwater area, which was similar to that of KSC. The percentage of agricultural and low-density residential areas in the IRL in 1990 was much higher than in the KSC.

The SCS (USDA 1986) has classified over 8,500 soil series into four hydrologic groups according to their infiltration charac-

Table 2. Summary of Hydrologic Soil Groups on Kennedy Space Center (KSC) and in Indian River Lagoon (IRL)

Hydrologic soil group	KSC (%)	IRL (%)	Remarks
A	*12.2*	*11.8*	Low runoff potential (sand, gravel)
B	*47.7*	*57.7*	Moderate infiltration rate when thoroughly wetted (moderately fine to moderately coarse texture)
C	*23.9*	*15.3*	Slow infiltration rates when thoroughly wetted (moderately fine to fine texture)
D	*16.3*	*15.2*	High potential for runoff, since they have very slow infiltration rates when thoroughly wetted (clay soils with high swelling potential)
Total	*100.0*	*100.0*	Excludes water

teristics. Soil maps were obtained from the Natural Resources Conservation Service (NRCS) (USDA 1986) for the study area. The hydrologic soil group and characteristics within KSC and the IRL are summarized in Table 2.

Runoff Estimation

Land-use maps, hydrologic soil group maps, event rainfall data, and long-term daily precipitation data were prepared to run L-THIA GIS for estimating runoff volume. Land-cover maps for the study area for 1920, 1943, and 1990 were edited so they contained the land use classifications required for L-THIA GIS. The land-use classes considered by L-THIA are agricultural, commercial, forest, grass/pasture, high-density (HD) residential, low-density (LD) residential, and industrial (Table 1). The hydrologic soil group map was reclassified into four groups: A, B, C, and D (Table 2). The land-use management practice was assumed good for the entire study area. The land-use maps of IRL and KSC for 1920, 1942, and 1990 and the hydrologic soil group maps were used to create CN maps of the study areas for each year using L-THIA GIS.

Rainfall events of 1-, 5-, 10-, 50-, and 100-year return periods for 24 h were selected for analysis, in addition to the long-term L-THIA analysis. Rainfall depths for these events were obtained from U.S. Weather Bureau (1961) precipitation data. Long-term daily precipitation data for the past 30 years were obtained from ''Summary of the Day'' CD-ROMs (EarthInfo 1996). Precipitation data from the Melbourne, Florida, weather station were used for the entire study area.

The L-THIA GIS system was used to compute runoff depth maps for the group of events as well as the long-term average annual runoff. The same 30 years of daily rainfall data were used to obtain L-THIA GIS estimated runoff for each land-use map, so differences in runoff are due only to land-use changes. From the runoff maps, the L-THIA GIS system was used to estimate runoff volumes.

Table 3. Simulated Runoff Depth for Kennedy Space Center (KSC) and Indian River Lagoon (IRL) using Curve Number Method

	Rainfall return period duration	Rainfall (cm)	Land-use map	Average runoff depth (cm)
			1920	3.26
KSC	1 year/24 h	10	1943	3.45
			1990	3.81
			1920	5.76
	5 year/24 h	14	1943	6.04
			1990	6.48
			1920	9.55
	10 year/24 h	19	1943	9.93
			1990	10.45
			1920	13.66
	50 year/24 h	24	1943	14.13
			1990	14.71
			1920	16.89
	100 year/24 h	28	1943	17.41
			1990	18.02
			1920	2.52
IRL	1 year/24 h	10	1943	3.05
			1990	3.91
			1920	4.72
	5 year/24 h	14	1943	5.51
			1990	6.65
			1920	8.17
	10 year/24 h	19	1943	9.27
			1990	10.74
			1920	12.02
	50 year/24 h	24	1943	13.37
			1990	15.08
			1920	15.07
	100 year/24 h	28	1943	16.59
			1990	18.46

Results and Discussion

Runoff from Single Rainfall Events

Runoff estimates from five rainfall events (1 year/24 h, 5 year/24 h, 10 year/24 h, 50 year/24 h, and 100 year/24 h), as simulated for the KSC and IRL nonwater areas using the CN method for historical land uses, are listed in Table 3. The hydrologic impact of land-use change is typically assessed based on high intensity, periodic storms such as 1-, 5-, 10-, 50-, and 100-year recurrence intervals for flood-control purposes. Comparing the 1 year/24 h and 100 year/24 h return period events, expected rainfall increased 2.75 times and estimated runoff depth increased approximately 4.7 to 6 times for the study areas.

For the 1 year/24 h event, the rainfall depth was 10 cm and the average runoff for the KSC area calculated by the CN method was 3.26, 3.45, and 3.81 cm for 1920, 1943, and 1990 land uses, respectively. Runoff for the KSC from this rainfall event due to land-use change increased by approximately 6% between 1920 and 1943 and by about 17% between 1920 and 1990. Estimated runoff depths from the IRL for this event were 2.52, 3.05, and 3.91 cm for 1920, 1943, and 1990 land uses, respectively. This represents a change in runoff of approximately 21% between 1920 and 1943 and 55% between 1920 and 1990. The differences in percentage increase in estimated runoff between the KSC and the IRL result from differences in urbanization and agricultural development of these watersheds. The IRL experienced greater urbanization and agricultural development than KSC between 1920 and 1990, and thus the increases in estimated runoff for the IRL are greater.

For the 100 year/24 h event, rainfall was 28 cm and the calculated average runoff for the KSC was 16.89, 17.41, and 18.02 cm for 1920, 1943, and 1990 land uses, respectively. Runoff for the KSC from this rainfall event due to land-use change increased by approximately 3% between 1920 and 1943 and by approximately 7% between 1920 and 1990. Runoff depths for the IRL for this event are 15.07, 16.59, and 18.46 cm for 1920, 1943, and 1990 land uses, respectively. The changes in runoff depths for the IRL area are approximately 10% between 1920 and 1943 and approximately 22% between 1920 and 1990. The differences in percentage changes between KSC and IRL runoff are the result of differences in land-use changes. As expected, percentage increases in runoff are smaller for the 100-year return period than for other events analyzed, since land use has less effect on the portion of rainfall that becomes runoff as the depth of rainfall increases.

The runoff depths from the KSC for events from 1920 and 1943 land uses are larger than those for the IRL, largely due to the greater percentage of C hydrologic group soils on the KSC compared to the IRL. The influence of the hydrologic group soil dif-

Table 4. Simulated Annual Runoff Depth and Runoff Volume % for Kennedy Space Center (KSC) and Indian River Lagoon (IRL) using Long-Term Hydrologic Impact Analysis Geographic Information System (GIS) when Curve Number Values were Adjusted for Antecedent Moisture Condition I

		1920		1943		1990	
	Land use	Depth (cm)	%	Depth (cm)	%	Depth (cm)	%
KSC	Agricultural	6.8	*1.5*	6.2	*11.0*	6.6	*8.8*
	Commercial					45.4	*1.3*
	Forest	2.8	*49.5*	2.9	*41.3*	3.0	*33.2*
	Grass/pasture	4.7	*46.9*	4.7	*42.0*	4.0	*10.9*
	HD residential					16.3	*15.4*
	Industrial					18.0	*21.0*
	LD residential	3.8	*2.1*	4.5	*5.7*	5.3	*9.4*
	Total	3.5	*100.0*	3.8	*100.0*	5.2	*100.0*
IRL	Agricultural	6.3	*1.3*	6.8	*28.3*	7.0	*29.2*
	Commercial			47.2	*1.2*	46.2	*14.5*
	Forest	2.6	*60.9*	2.6	*31.6*	2.8	*11.8*
	Grass/pasture	4.4	*33.4*	4.3	*32.1*	4.2	*6.7*
	HD residential					15.9	*8.9*
	Industrial					17.2	*11.8*
	LD residential	3.7	*4.5*	4.1	*6.8*	4.5	*17.1*
	Total	3.1	*100.0*	3.9	*100.0*	6.6	*100.0*

ferences is less important as land uses become more urban and agricultural, as demonstrated by the results for 1990 land uses. The estimated percentage changes in runoff between 1920 and 1990 due to land use changes are smaller for the KSC than those for the IRL. The larger percentage changes in estimated runoff in the IRL are a result of more urban land uses within the IRL than in KSC between 1920 and 1990.

Average Annual Runoff

The L-THIA GIS model was used to estimate effects of land-use change on annual average runoff volume for the KSC and IRL based on historical land use maps for 1920, 1943, and 1990. Table 4 and Figs. 3 and 4 show the L-THIA GIS simulation results for average annual runoff volume during these three time spans when CN values are adjusted for antecedent moisture condition (AMC). Table 5 presents simulated average annual runoff volume; when CN values are not adjusted for AMC, an AMC II condition is assumed.

Forest and grass/pasture land uses were the largest portion of the nonwater KSC land uses in 1920 and were the primary source of runoff. Contributions from agriculture and low-density residential areas were less than 4% of the total volume in 1920. In 1943 (beginning of the development stage), total runoff volume increased slightly (less than 10%), with agricultural runoff responsible for the majority of the increase and low-density residential runoff accounting for the remaining increase. Agricultural and low-density residential areas increased almost eight and two times, respectively, between 1943 and 1920. However, these land uses remained a very small portion of the KSC area. For 1990 land uses (more-developed stage), the total runoff volume increased by 49% (48% when CN values were not adjusted for AMC) compared to 1920 runoff. Agricultural runoff volume was

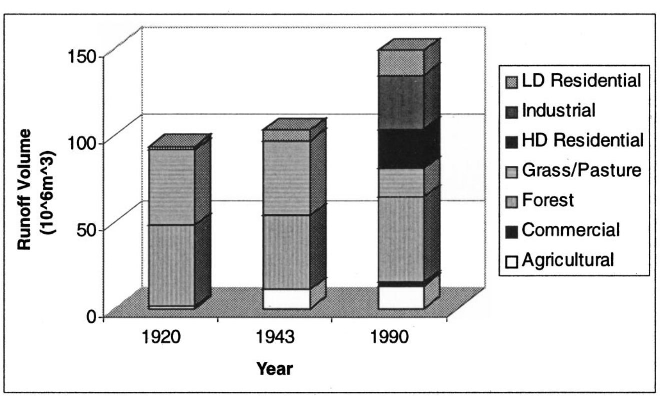

Fig. 3. Changes in estimated runoff volume for Kennedy Space Center when curve number values were adjusted for antecedent moisture condition

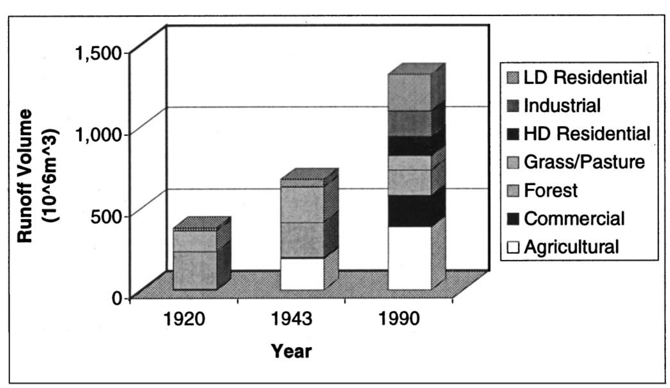

Fig. 4. Changes in estimated runoff volume for Indian River Lagoon when curve number values were adjusted for antecedent moisture condition

Table 5. Simulated Annual Runoff Depth and Runoff Volume % for Kennedy Space Center (KSC) and Indian River Lagoon (IRL) using Long-Term Hyrdologic Impact Analysis Geographic Information System for Curve Number Antecedent Moisture Condition II

		1920		1943		1990	
	Land use	Depth (cm)	%	Depth (cm)	%	Depth (cm)	%
KSC	Agricultural	15.2	*1.6*	13.6	*11.4*	14.6	*9.5*
	Commercial					70.1	*1.0*
	Forest	5.7	*48.1*	5.9	*40.0*	6.2	*33.2*
	Grass/pasture	10.0	*48.1*	10.1	*42.8*	8.4	*11.0*
	HD residential					32.8	*14.9*
	Industrial					36.1	*20.4*
	LD residential	8.0	*2.1*	9.6	*5.8*	11.6	*10.0*
	Total	7.3	*100.0*	8.1	*100.0*	10.8	*100.0*
IRL	Agricultural	14.0	*1.4*	15.1	*29.8*	15.6	*29.2*
	Commercial			70.9	*0.8*	70.4	*14.5*
	Forest	5.1	*59.1*	5.3	*30.2*	5.8	*11.8*
	Grass/pasture	9.4	*34.9*	9.1	*32.3*	8.9	*6.7*
	HD residential					31.8	*8.9*
	Industrial					34.5	*11.8*
	LD residential	7.9	4.6	8.7	6.8	9.7	*17.1*
	Total	6.3	*100.0*	8.3	*100.0*	13.4	*100.0*

similar to that in 1943, forest and grass/pasture runoff volume decreased due to conversion of these land use types to urban land uses, and runoff from urban land uses was responsible for 47% of the total estimated 1990 runoff. Two notable changes occurred between 1943 and 1990. Total runoff volume increased 37%, with most of the increase in simulated runoff volume from the high-density residential and industrial areas. Even though the combined area of these two categories comprised 11% of the total land area in 1990, they contributed 36% of the total estimated runoff volume. This shows that land-use change, dominated by an increase in urban areas, has a significant impact on expected annual runoff volume for KSC.

Table 4 and Fig. 4 show the estimated average annual runoff from the IRL for 1920, 1943, and 1990 land uses when CN values were adjusted for AMC. Table 5 shows estimated average annual runoff from the IRL for the same land uses when AMC II CN values were used. Runoff volume increases for the 1920–1990 land uses for the IRL were much greater than runoff increases at the KSC for the same period. From 1920 to 1943, runoff volume in the IRL increased by approximately 26%, when volumes are adjusted for changes in area. From 1943 to 1990, estimated annual runoff volume increased by 69% when adjusted for changes in area. The overall increase in runoff volume from 1920 to 1990 was almost 113% (also 113% when CN values were not adjusted for AMC), compared to an estimated 49% (48% when CN values were not adjusted for AMC) increase in runoff volume for the KSC for the same period.

The greater increase in estimated runoff volume in the IRL was due to a greater portion of the IRL's land uses being converted to urban and agricultural uses than at the KSC. In the IRL, 34.8% of the land use in 1990 was urban, while land uses for the KSC remained more natural, with 20.5% in urban land uses in 1990. A further land-use difference contributing to changes in runoff is the larger proportion of agricultural land uses in the IRL compared to the KSC (28 versus 7% in 1990). As with the KSC area, the commercial, high-density residential, and industrial areas comprised a small portion of the total land area, but they contributed the most to the overall increase in runoff volume in the IRL between 1920 and 1990. Estimated runoff from these land uses was responsible for nearly 80% of the estimated total runoff volume in 1990.

The percent change in annual runoff associated with land-use change (Tables 4 and 5) was much greater than the runoff for single rainfall events between 1920 and 1990 (Table 3). Estimated change in runoff for the single events ranged from 7 to 17% for the KSC and from 22 to 55% for the IRL between 1920 and 1990. Changes in average annual runoff for this same period were approximately 49 and 113% for the KSC and the IRL, respectively. Changes in land uses had a much greater impact on annual runoff than runoff from single events. This occurs because as land uses become more urban, runoff is produced from events with smaller rainfall depths. For locations such as the study area, which receives numerous rainfall events within a year, the runoff from the many smaller rainfall events becomes a significant portion of the annual runoff.

Summary and Conclusions

A GIS-based SCS CN method and the L-THIA GIS model were used to estimate rainfall event runoff and average annual runoff for the KSC and the IRL watershed in Florida for 1920, 1943, and 1990 land uses. Changes in estimated runoff depths due to land-use alteration between 1920 and 1990 for design rainfall events (ranging from a 24 h/1 year to a 24 h/100 year return period) ranged from about 7–17% for the KSC to 22–55% for the IRL. The changes in average annual runoff due to land use changes were much greater for both study areas. Between 1920 and 1943, estimated average annual runoff for the KSC increased less than 10%, while average annual runoff for IRL increased nearly 26%. Between 1943 and 1990, estimated average annual runoff for the KSC increased 37%, while runoff for the IRL increased 69%. Between 1920 and 1990, estimated average annual runoff for the KSC increased about 49%, while runoff for the IRL increased nearly 113%. For both the KSC and IRL, most of the increase came from the urbanization of the landscape. Urbanized land uses on the KSC made up only 20.5% of the total land area, but contributed 47% of the estimated average annual runoff volume for 1990 land uses. The striking differences in runoff changes between the KSC and the IRL from 1920 to 1990 are due to differences in rates of land-use change. The IRL has experienced far greater urbanization than the KSC (urban land uses for 1990 in the IRL were 34.8 versus 20.5% on the KSC). The IRL has also experienced greater agricultural development than the KSC, which results in greater runoff (agricultural land uses for 1990 in the IRL were 28.0 versus 7.0% on the KSC).

Land-use change can have a dramatic impact on annual runoff volume, as demonstrated in this study. Changes in runoff resulting from land-use alteration, which are estimated based on design rainfall events, can underestimate the overall impacts of land use on hydrology. The effects of land-use alteration on annual or long-term runoff should be considered in land-use planning. The L-THIA GIS approach provides a simple way to obtain quantitative estimates of changes in average annual runoff using readily available data.

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