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RESEARCH ARTICLE

Impact of urbanization on estimated surface runoff and resulting issuance of flash flood warnings in Jackson, Tennessee

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ABSTRACT

Land-use and land cover (LULC) changes for the Jackson, TN area from 1992–2011 were evaluated based on data from the National Landcover Database. During the time of study, this area underwent noted changes in LULC with an increase in the area defined as urban and decreases in forested and agricultural areas. This study also makes note of the increase in the number of days flash flood warnings were issued during the 1990's as compared to the 2000's. During the same time period, high intensity rainfall events during 1990's (n=198) did not appreciably increase when compared to the 2000's (n=208); therefore, increases in flash flood warnings were not influenced by changes in rainfall events. The purpose of this work was to determine if changes in LULC and increases in flash flood warnings were statistically significance. Overall, an increase in runoff of 25% for the study area between 1990-2011 was determined. The majority of correlation analyses between runoff/urban and runoff/agriculture were also found to be significant.

KEYWORDS

Land use-land cover, SCS Curve number, Rainfall runoff, CN Number, Flash flood warnings

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INTRODUCTION

Flash flood warnings are issued by the National Weather Service when flash flooding is observed or is imminent (National Weather Service, 2024). An increase in the number of flash flood warnings over Jackson, Tennessee, was observed from the 1990s into the 2000s. In fact, from 1990 to 1999, there were nine different days in which flash flood warnings were issued; contrasted with forty-four days of warnings issued from 2000–2009 (Iowa State University, 2024). These small-scale frequent flood events are of prime concern to Madison County and the city of Jackson, Tennessee (Whetstone, 2016). Whetstone reports that flooding in the area is such a concern that Madison County was awarded funds to develop flood control projects benefiting the county as well as the city of Jackson. Part of the funds will focus on infrastructure improvements to storm water sewer systems. Other monies are earmarked for the construction of artificial wetland areas that will offer recreation as well as flood control for the northern portion of the city and county (Tennessee.gov, 2017; Thomas, 2016).

Causes of Flood Events

Noticeable changes in the land-use and land cover (LULC) have occurred in Jackson, Tennessee from 1992–2011 (Figure 1). For example, areas recognized as urban have increased, while areas identified as agriculture and forest

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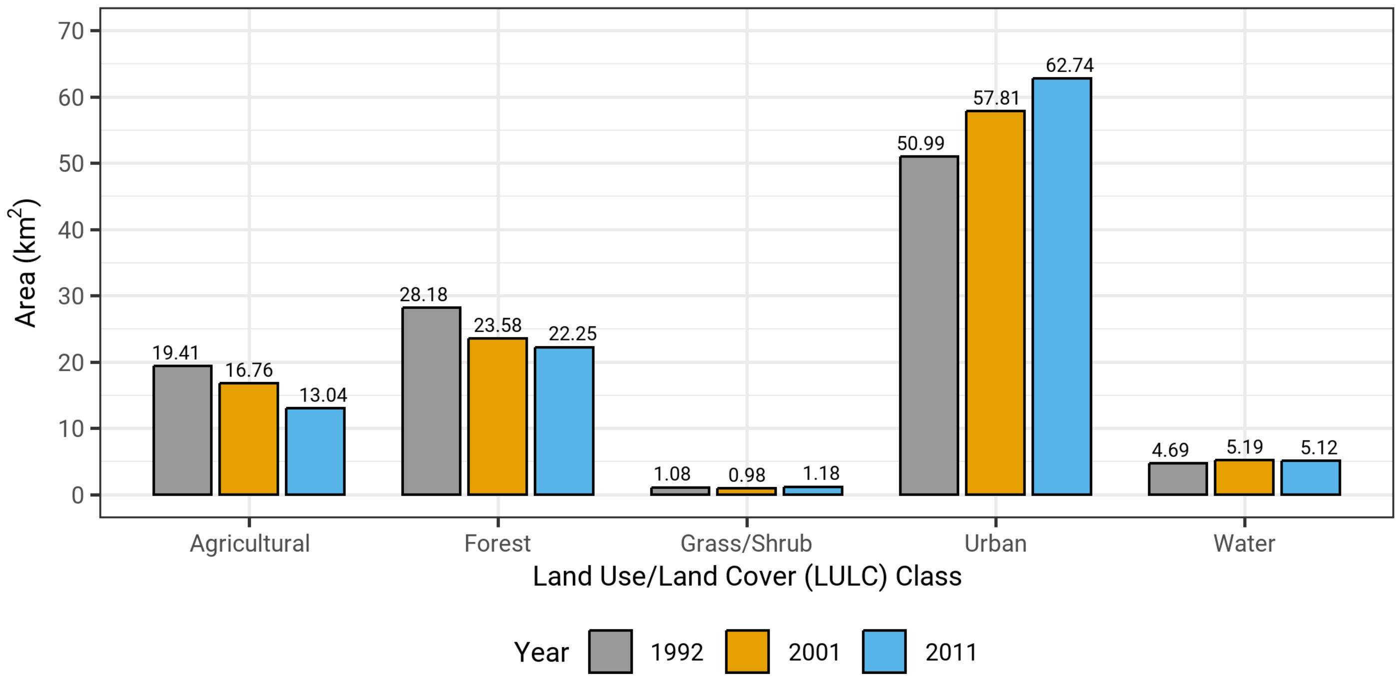

FIGURE 1: Extent of LULC of the study area in square kilometers from 1992, 2001, and 2011. Data for LULC is from the National Landcover Database (Multi-Resolution Land Characteristics Consortium, 2016).

have decreased. When previously rural areas experience changes in land-use due to urbanization, these man-made changes to the natural drainage systems can have dramatic effects on a basins ability to move and/or store water (Booth, 1991). In areas where overland flow is the dominant path for storm water runoff, the addition of impervious surfaces causes the overland flow velocity to increase. In general, the process of rainfall runoff has not changed (Booth, 1991); however, the speed and therefore, amount of water that enters a stream channel can change or increase. With the addition of an established storm water sewer system, an urban area can effectively drain a region of storm water at a much faster rate (Hollis, 1988). This may be due to a shorter distance as well as a smoother and/or straighter path water travels to the stream channel. The problem with this scenario is the possibility of continued rainfall and the effect additional storm drainage may have on the stream channel. Changes due to additional storm water runoff may include increased stream velocity, higher rates of erosion, and more frequent flood events.

The main objective of this case study was to determine if changes in LULC may be a contributing to the increase in flash flood warnings issued from 1990–2009. First, the increase in flash flood warnings were assessed relative to the number of heavy rainfall episodes defined as an event breaching the 95^{th} percentile. Second, runoff was estimated and assessed for statistical significance during the time of study. Finally, the estimated runoff was compared to changes in LULC and assessed for statistical significance.

STUDY AREA

Jackson, Tennessee, is situated about halfway in between Memphis and Nashville, Tennessee, (FIGURE 2) within the West Tennessee Coastal Plain physiographic province (Bailey, 1993). This area is located in the Southeastern Plains and Hills Ecoregion (Tennessee Department of Environment and Conservation (TDEC), 2002) and is underlain by several different geologic and sedimentary units; some of the geologic units include Porters Creek Clay, Memphis Sand, and Fort Pillow Sand (Bailey, 1993) and sediments include clays, silts, silty-clays, and fine-grained sands, to name a few (TDEC, 2002). The 2010 census estimated Jackson's population at 67,685 (United States Census Bureau, 2024). Interstate 40 also provides a rough division of precipitation runoff between North Jackson with the Middle Fork of the Forked Deer River and South Jackson with the South Fork of the Forked Deer River. Jackson has an average elevation of ~125 meters (410 feet) above sea-level. One of the area's highest elevation points is just over ~198 meters (650 feet), with a low elevation of ~97 meters (320 feet), the area relief of just over 100.6 meters (330 feet) (TDEC, 2002). Precipitation for the area has an average of nearly 127 centimeters (50 inches) per year (Bailey, 1993).

DATA AND METHODS

95th Percentile Rainfall Events

Precipitation data for 95TH percentile rainfall events was supplied by local weather stations; specifically, Jackson McKellar-Sipes Airport and the Jackson Experimental Station. These daily data were retrieved from the Global Historical Climatology Network (Menne et al., 2012). Extreme precipitation events were found by ranking all available days of precipitation totals for each month during the study period (1992–2011) and computing the 95th percentile. The 95th percentile for each month was then treated as a threshold for an extreme precipitation day. Frequencies of extreme precipitation were then computed monthly.

Surface Runoff Model

Runoff estimations were based on the United States Soil Conservation Service's procedure known as the SCS curve number method (Cronshey, 1986). This method was chosen since it is a well-established procedure employed by engineers and hydrologists (Ponce and Hawkins, 1996). A simplified variation of the SCS equation can be expressed as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{1}$$

where: Q is the runoff; P is the precipitation; and S is the potential maximum storage represented as $(1000/CN) - 10$; with CN representing the curve number. The CN is derived from a combination of land-use, land cover and hydrologic soil group information. Therefore, the two input variables needed to solve this equation are rainfall value(s) and a derived curve number.

Rainfall Amount for SCS CN Method

With an understanding that long-term impacts of land-use change on surface water runoff is more than likely influenced by the collective results of typical precipitation events rather than infrequent large-scale storms (Li and Wang, 2009; McClintock et al., 1995), a representative storm amount for the study area was sought. The NOAA's Precipitation Frequency Atlas was, therefore, employed (Bonnin et al., 2006). Rainfall frequency estimates for the different geographic regions of the United States are provided by NOAA. Atlas 14 Volume 2 Version 3 represents the most current rainfall estimates for the Ohio River basin,

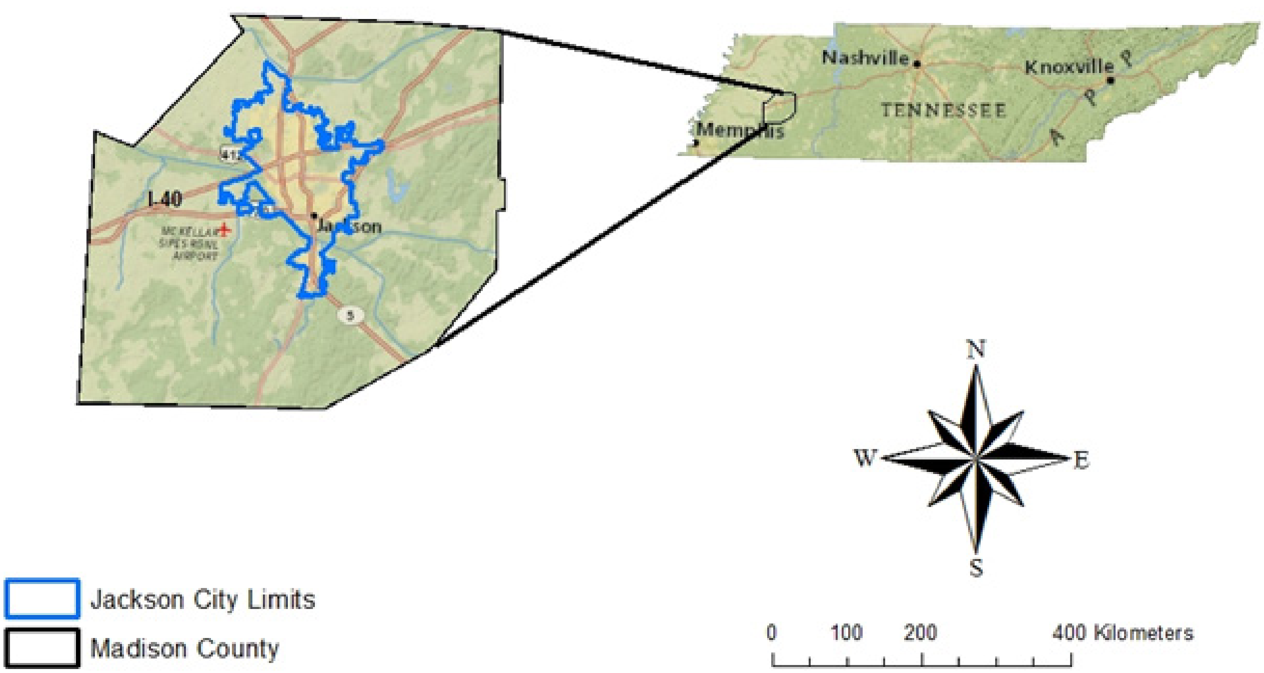

FIGURE 2: Basemap showing the location of Jackson, Tennessee, in Madison County, and the location of major roads. GIS data is derived from ESRI, Inc.

which includes Tennessee. The NOAA employs an interactive webpage that allows one to select an area of interest. Once selected, a range of frequency estimates for storms with recurrence intervals ranging from 1 year to 1000 years and storm durations from five minutes to 60 days are displayed (National Weather Service, 2017). Cronshey (1986) states when consistent rainfall amounts are applied in successive sub-basins, it is sometimes desirable to employ synthetic storms of which 24-hour rainfall durations are commonly used. According to Atlas 14 values found on NOAA's webpage, a one-year recurrence interval rainfall event of a 24-hour duration is 8.18 centimeters (3.22 inches) for the study area.

Curve Number Grid

The relationship between precipitation and runoff, when employing the SCS curve number method, is greatly influenced by potential maximum storage (Weng, 2001). Since the CN is an integral part of potential maximum storage, it is important to obtain the correct value for the CN. Calculation of a curve number grid is the first step in generating a representative CN for a watershed, basin, or sub-basin (Merwade, 2012a). Merwade's (2012a) procedures for the derivation of a curve number grid employing ArcGIS and the HEC-GeoHMS extension were followed. Requirements for curve number grids are a digital elevation model (DEM), soils data, and LULC data. The digital elevation model was retrieved from the United States Geological Survey (USGS) (USGS, 2017), soil data was retrieved from the National Resource Conservation Service (NRCS) (NRCS, 2017b), and land-use data was retrieved from the National Landcover Database (NLCD) (Multi-Resolution Land Characteristics Consortium (MRLC), 2016). Once obtained, DEM, soils data, and LULC data all exhibited 30x30-meter resolution and were clipped to the city limits of Jackson.

Specific land-use data downloaded from the NLCD included 1992, 2001, and 2011 maps of conterminous United States; 1992 data was the land cover change retrofit data. By using 1992–2001 retrofit data, one is able to make more accurate comparisons of land-use change compared to the original 1992 NLCD data (Fry et al., 2009). Land cover classes were reclassified into five classes; these included water (open water and wetland areas), urban, forest, grassland/shrubland, and agriculture (combined with barren lands). One issue with combining classes, such as open water and wetland areas into a single class, is the possibility of exaggerating the CN value. In the instance of the merged water class, initial runoff estimates could be inflated because CN values of "water" are treated as nearly impermeable. 2001 and 2011 NLCD maps were reclassified using the same classification scheme as 1992 retrofit. Classes for 2001 and 2011 were combined as follows: water (open water and all wetland areas), urban (all types of urban areas), forest (all types of forest areas), grassland/shrubland (shrub and grassland/herbaceous areas), and agriculture (hay/pasture and cultivated crop lands). The National Engineering Handbook of Hydrology was referenced in order to assign hydrologic soil values for soil groups A, B, C, and D to the various land covers (Natural Resource Conservation Service, 2017a). Within ArcGIS, the HEC-GeoHMS extension was then used to combine soil and land-use data in order to create a curve number grid of the study area (Shahid et al., 2017). These procedures were then repeated to produce a separate curve number grid for each of the NLCD maps.

Delineation of the Study Area and CN

The next step in deriving a CN was the development of a stream network for the study area. This was accomplished by following accepted procedures employed through HEC-GeoHMS called terrain preprocessing (Knebl et al., 2005; Merwade, 2012c). Merwade's (2012c) tutorial for terrain preprocessing includes completion of a RawDEM, HydroDEM, flow direction grid, flow accumulation grid, stream grid, stream link grid, catchment grid, catchment polygons, drainage line polygons, and adjoint catchment polygons. Following completion of these procedures the study area was divided into 20 sub-basins representing 81% of Jackson's city limits (Figure 3). The number of sub-basins derived through the implementation of these procedures is reliant upon the overall size of the watershed (Kingston III, 2012). A simple default for stream network size determination, i.e. basin size, is 1% of the watershed area. The final steps needed to produce representative CN values for the study area's time periods were to define a project point and a project area (Merwade, 2012b).

Upon completion of these steps only the addition of the previously generated curve number grids was needed for an average CN for each individual sub-basin representing 1992, 2001, and 2011. Once determined, we were able to insert the CN value for each sub-basin with the previously retrieved synthetic rainfall amount into the surface runoff model and generate an estimated runoff amount for each sub-basin over the time of study (Table 1). There are many other steps that

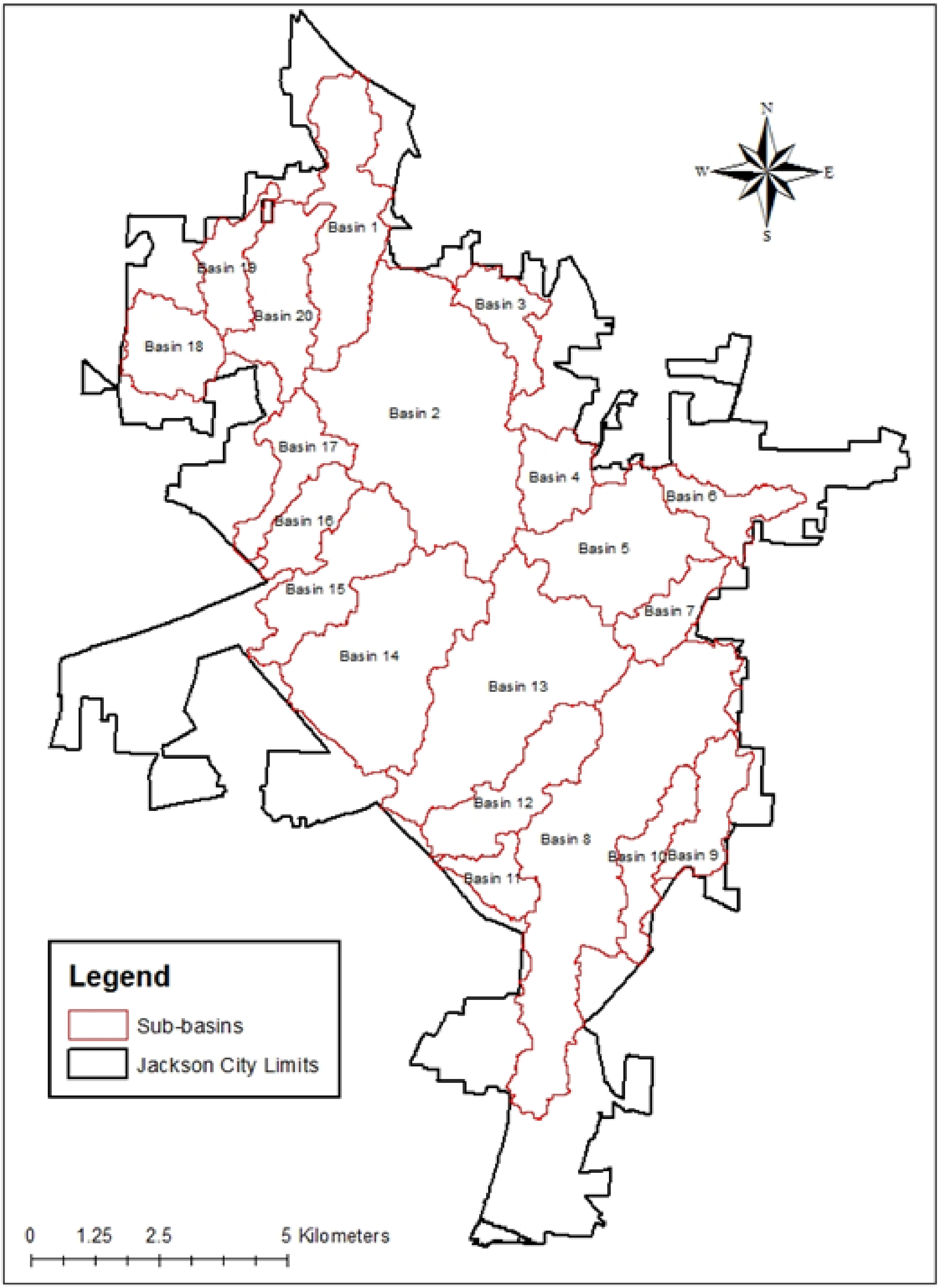

Figure 3: Details the shape and location of the 20 sub-basins derived using procedures established by Merwade (2012a; 2012b; 2012c) and their location within Jackson's city limits.

both precede and follow the inclusion of curve number grids when following Merwade's (2012b) instructions. However, these steps are implemented when the purpose is to develop a model that can be downloaded directly into the U.S. Army Corps of Engineers hydrology program (HEC-HMS), but this was not the case in this study. Only the derivation of a representative CN for each sub-basin originating from the different NLCD maps was sought.

TABLE 1: Derived CN#'s and resulting estimated runff for 1992, 2001, and 2011.

Sub-basin	1992 CN#	1992 Runoff (in)	2001 CN#	2001 Runoff (in)	2011 CN#	2011 Runoff (in)	Area (km^2)
1	72.17	0.95	77.82	1.28	77.81	1.28	6.32
2	71.66	0.92	74.40	1.07	75.19	1.12	15.74
3	70.97	0.89	74.27	1.07	75.05	1.11	2.26
4	61.29	0.46	65.67	0.64	66.88	0.69	2.44
5	60.76	0.44	62.36	0.50	63.04	0.53	6.37
6	62.27	0.50	65.79	0.64	66.20	0.66	2.21
7	68.31	0.76	71.32	0.91	71.81	0.93	2.14
8	72.05	0.94	74.50	1.08	75.20	1.12	15.56
9	67.29	0.71	70.28	0.85	70.90	0.89	2.55
10	75.53	1.14	77.55	1.26	78.18	1.30	2.33
11	91.82	2.35	94.37	2.60	94.48	2.61	1.56
12	71.02	0.89	73.16	1.00	73.52	1.02	4.24
13	65.16	0.62	67.26	0.71	67.91	0.74	11.55
14	68.69	0.78	72.06	0.95	72.51	0.97	10.12
15	68.68	0.78	73.28	1.01	73.90	1.05	4.63
16	64.86	0.60	68.89	0.79	69.52	0.82	2.26
17	62.09	0.49	64.76	0.60	65.27	0.62	2.68
18	70.55	0.87	77.58	1.26	77.24	1.24	3.06
19	69.14	0.80	75.41	1.13	75.39	1.13	2.13
20	70.34	0.86	75.83	1.16	75.92	1.16	4.24

Statistical Procedures

Runoff data derived from the SCS curve number method was entered into the Statistical Package for the Social Sciences (SPSS) version 24. Through SPSS, it was determined that runoff data was not normally distributed and would require the implementation of nonparametric statistical procedures (Helsel, 1987). For the purpose of this paper, p values <0.05 were considered to be statistically significant. In order to determine if the amount of rainfall runoff in the study area had changed significantly over the study time (1992, 2001, and 2011), Friedman's ANOVA (the nonparametric equivalent to repeated measures ANOVA) was employed. In instances where Friedman results were significant, the post-hoc Wilcoxon signed-rank test was utilized to determine significance between years of study (1992, etc.). In addition, several Spearman's correlations were performed to test for relationships between percent change in precipitation runoff (1992–2011) and percent changes in urban growth, forest, and agriculture (1992–2011).

RESULTS

No appreciable change in the number of heavy rainfall events from the 1990s (n=198) into the 2000s (n=208) was detected. Thus, the large increase in the number of flash flood warnings does not seem to be entirely related to changes in the number of heavy rainfall events. Next, relationships between estimated runoff and changes in LULC were assessed.

Estimated Runoff

FIGURES 4A and 4B show changes in estimated runoff over time. The null hypothesis for Freidman's ANOVA was that the mean rank of estimated runoff was consistent over the study period. Results from statistical procedures indicated there was a significant difference in estimated runoff over time, χ^2 (2) = 37.013, $p < 0.05$. The Wilcoxon signed-rank test was then employed to determine if statistical significance was for the entire study period or if significance only occurred between certain years of the study. All post-hoc comparisons were found to be significant; specifically, 1992–2001 $p < 0.05$, 2001–2011 $p = 0.001$, and 1992–2011 $p < 0.05$. Therefore, we reject the null hypothesis of no difference and can state that

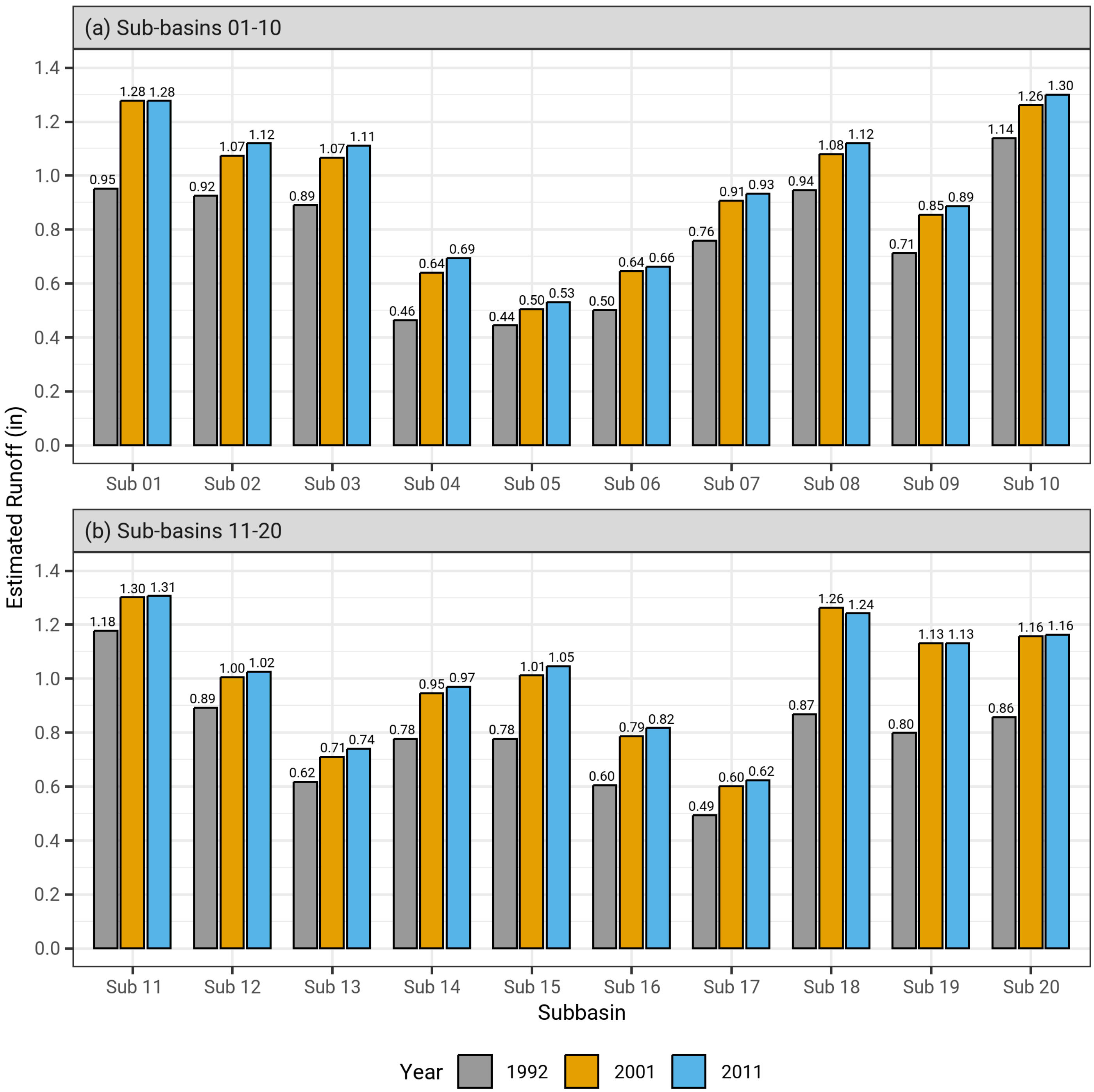

FIGURE 4: (a; top) Details of estimated runoff values for sub-basins 1-10; (b; bottom) Details of estimated runoff values for sub-basins 11-20. The estimated runoff values for sub-basin 11 were normalized.

statistically significant differences between estimated runoff occurred throughout the time of study.

Land-use and Land Cover

Changes in LULC included little to no variations in water and grassland/shrub areas, however, a steady decrease in forested and agricultural areas and a steady increase in urban areas was noted (FIGURE 1). Correlation analysis was performed based on percent changes in estimated rainfall runoff and percent change in LULC that occurred between 1992–2011, 1992–2001, and 2001–2011. Results from correlation analysis indicated that a very strong, positive correlation (r = 0.808) existed between percent change in runoff (PCR) and percent change in urban areas (PCU) from 1992–2011. A moderate, positive correlation (r = 0.399) existed between PCR and percent change in agricultural areas (PCA) during the same span of time. Statistical analysis for PCR and PCU correlation was significant at $p < 0.05$ while PCR and PCA correlation was weakly significant at $p = 0.04$ (one tailed). No significant relationship between PCR and percent change in forest areas (PCF) was observed between 1992–2011. A strong, positive relationship (r = 0.704) existed between PCR and PCU and a moderate, positive correlation between PCR and PCA (r = 0.544) was noted for 1992–2001. Significance between PCR and PCU was $p = 0.001$ and significance between PCR and PCA was $p = 0.013$. Again, no significant relationship was indicated between PCR and PCF between 1992–2001. A weak, negative, relationship that was weakly significant was noted between PCR and PCU ($r = -0.385$, $p = 0.04$, one tailed), while a moderate, positive, and significant correlation between PCR and PCA ($r = 0.507$, $p = 0.023$) was noted for 2001–2011. However, no significant relationship between PCR and PCF existed during the same span of time.

DISCUSSION

Changes in Estimated Runoff

Statistical analyses demonstrated runoff changes were significant for the study interval (1992–2011; Figures 4a and 4b). However, estimated runoff in some sub-basins, between 2001 and 2011, exhibited little to no change or even a decrease in estimated runoff. For example, sub-basins one and 20 revealed no appreciable change in runoff estimates, while sub-basins 18 and 19 displayed a decrease in estimated runoff. These outcomes may be attributed to the type of urbanization taking place in these sub-basins. It is possible that the little to no change in estimated runoff and decrease in runoff estimates reflects a change between agriculture and urbanization. A case has been made where a decrease in estimated runoff was explained by conversion of agricultural lands to suburban lands (Grove et al., 2001). The authors explained that in some instances a low-density or suburban area may have a lower CN value when compared to certain types of agricultural areas, thereby impacting runoff estimates. Comparisons of derived CN values (Table 1) offer possible confirmation of outcomes alluded to by Grove and others (2001). For example, differences in CN values between 2001–2011 in sub-basins 1 and 20 were minimal, while slight decreases in CN values in sub-basins 18 and 19 between the same years were also noted.

Changes in Land-use and Land Cover

As previously stated, changes in LULC included an increase in urban areas and decreases in agricultural and forested areas. With the noted increases in estimated runoff, correlations between percent changes in runoff and percent changes in urban and agricultural areas were, for the most part, expected. Statistical outcomes from 1992–2001 and 1992–2011 describe positive relationships indicative of areas experiencing urban growth with noted decreases in agricultural areas (Li and Wang, 2009). As previously mentioned, the amount of land classified as agriculture decreased over the study period; this is indicated by negative increases in percent change. Therefore, the positive relationship between PCR and PCA signifies an increase in runoff as the amount of agricultural area decreases. Graphs illustrating the percent of land that was urban (Figures 5a and 5b) and the percent of land that was agriculture (Figures 6a and 6b) illustrate changes experienced in each sub-basin. However, the one exception was the negative correlation between PCR and PCU, which is contrary to outcomes of similar studies (Li and Wang, 2009; Weng, 2001). Again, this might be explained by the conversion of agricultural lands to low-density urban lands, lowering the CN value and reducing estimated runoff (Grove et al., 2001). A reduction in the estimated runoff and an increase in percent of land that was categorized as urban might produce the negative correlation observed in this study between PCR and PCU.

CONCLUSIONS

This study investigated whether increased urbanization may impact surface runoff measured by issued flash flood warnings in Jackson, Tennessee. We utilized the SCS curve number method in order to produce estimated runoff over a 20-year period for the Jackson, Tennessee, area. Derivation of a CN is an important component of the surface runoff model. Therefore, based on procedures established by Merwade (2012a; 2012b; 2012c) and beginning with LULC data from 1992, representative CNs for each sub-basin were determined. These procedures were then repeated with the inclusion of LULC data representing 2001 and 2011. The SCS curve number method was then employed in order to produce estimated runoff amounts for each sub-basin during the time of study. Once obtained, statistical procedures were

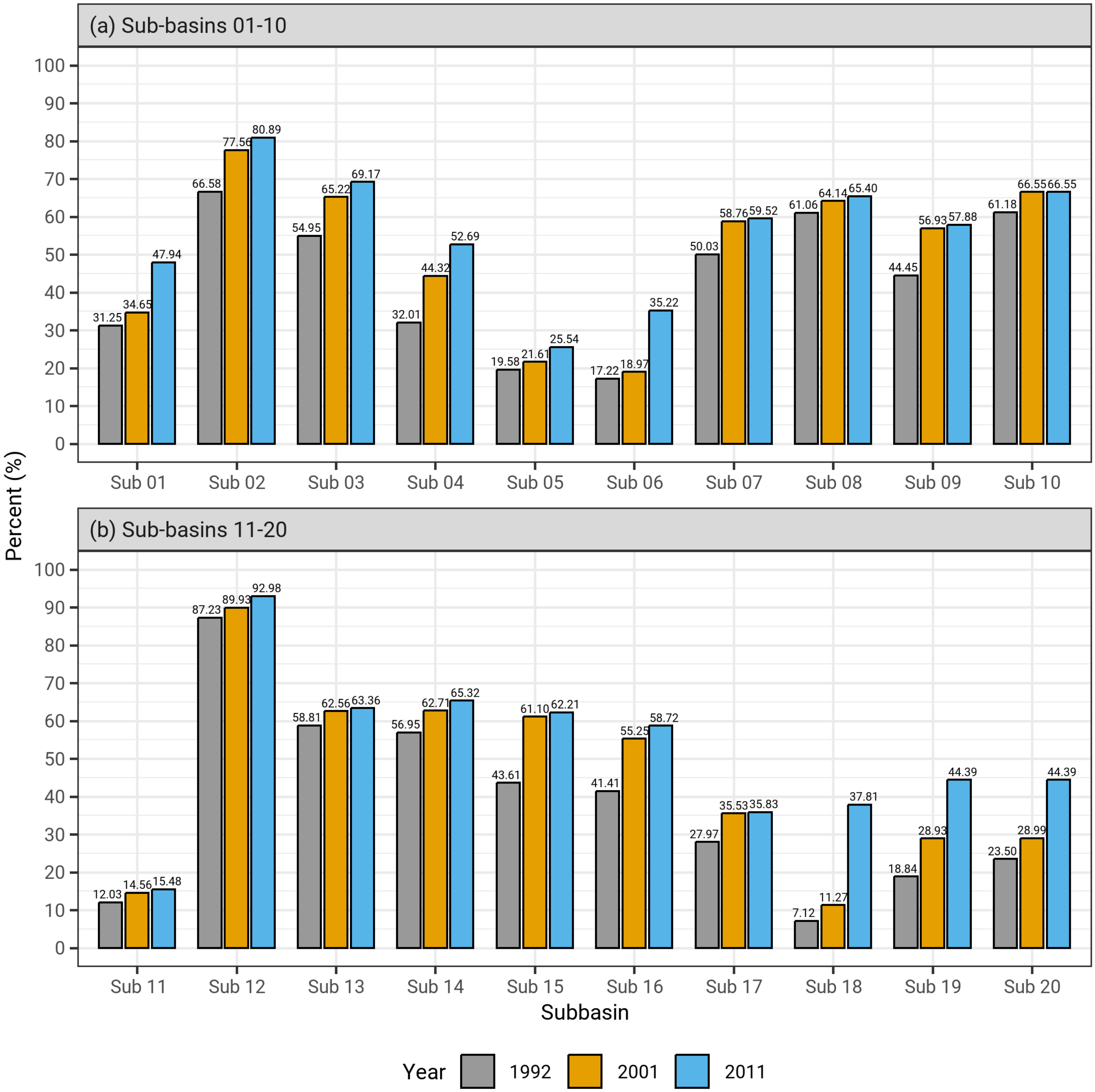

Figure 5: (a; top) Details of the percent of land categorized as urban in sub-basins 1-10 for 1992, 2001, and 2011; (b; bottom): Details of the percent of land categorized as urban in sub-basins 11-20 for 1992, 2001, and 2011.

applied to determine if estimated runoff amounts might be a factor in the increased number of flash flood warnings issued in the study area.

Statistical analysis of estimated runoff and LULC changes were, statistically significant. Changes in runoff estimates were significant between 1992–2001, 2001–2011, and 1992–2011. The majority of correlation analyses between PCR and PCU and PCR and PCA, during the study interval, were also significant. Outcomes of correlation analyses included an increase in estimated runoff as urban areas increased and agricultural areas decreased. Calculated runoff, in the study area, increased by 25% from 1992–2011. The majority of the

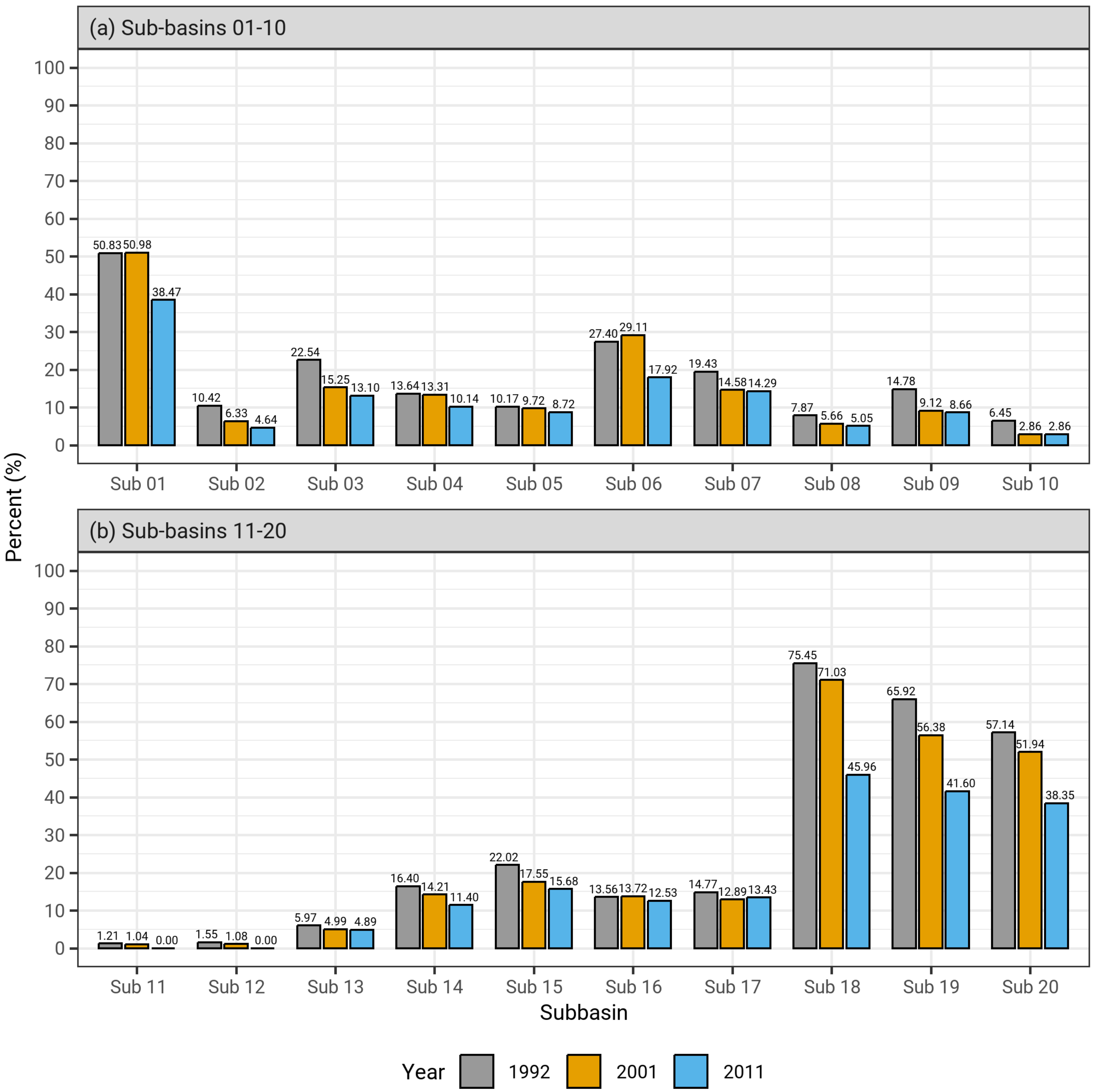

FIGURE 6: (a; top) Details of the percent of land categorized as agriculture in sub-basins 1-10 for 1992, 2001, and 2011; (b; bottom) Details of the percent of land categorized as agriculture in sub-basins 11-20 for 1992, 2001, and 2011.

stated increase in estimated runoff occurred from 1992–2001 (22%), while estimated changes in runoff from 2001–2011 were only about 3%. Therefore, changes in LULC might be a factor in the increase in flash flood warnings issued from the 1990s to the 2000s.

However, there are limitations that must be considered. First, the more detailed a LULC change map is the more representative a CN value can be produced. This study employed NLCD maps that are primarily used for regional studies instead of comparisons made at a smaller than regional scale (Crowther, 2015). In addition, the use of the 1992 retrofit data may have limited the number of land-use classes available for comparison. Use of more detailed classes, such as specific types of agricultural lands or distinctions between low, medium, and high intensity urban development, might have a significant impact on the derivation of CN's. For example, because the water land-use class and wetlands land-use class were combined and labeled as water, initial runoff estimates in sub-basin 11 were likely exaggerated. This is because standing water has a high CN value and treats runoff water similar to that of impervious surfaces. If more detailed land-use classes had been used when deriving CN values, normalization of estimated runoff results for sub-basin 11 would have been unnecessary. Second, the inclusion of satellite imagery for the purpose of completing a LULC study of the area would allow for more detailed classes, while covering a significantly longer period of time. A LULC change study and a longer time period might produce estimated runoff outcomes that differ from these results.

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