Nat Hazards
DOI 10.1007/s11069-017-2806-6

ORIGINAL PAPER

Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area

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Received: 31 October 2016 / Accepted: 10 March 2017

Abstract This research examines changes in residential built-environment flood exposure within the current boundaries of the Atlanta, Georgia metropolitan statistical area, by estimating the number of housing units that are located within the floodplains of the region. Housing unit data at the block level from the 1990 to 2010 decennial censuses are used to estimate housing unit exposure to floods using a binary dasymetric and proportional allocation method. Three different representations of the 100-year (1 percent annual chance) and 500-year (0.2 percent annual chance) floodplain are employed: the generally more conservative floodplains created using the Federal Emergency Management Agency's Hazus-MH software, the generally more extensive floodplains included in the proprietary Flood Hazard Data product from KatRisk LLC and the regulatory floodplains from the National Flood Insurance Program. The number of housing units within both the 100- and 500-year floodplain increased from 1990 to 2010 throughout the Atlanta region. Housing unit growth within the regulatory 100-year flood zone was slower than growth elsewhere, suggesting that the National Flood Insurance Program may have been marginally effective overall. Results using the KatRisk product reveal both greater overall and a greater increase in housing units at risk within the 100-year floodplain than the regulatory product suggests. The results argue that heightened flood exposure, particularly in areas experiencing new development, is an important factor to consider when addressing the impact of the flood hazard over time.

Keywords Hazards · Exposure · Floods · Flood policy · Atlanta · 100-year floodplain

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Published online: 24 March 2017

1 Introduction

Weather and climate disaster losses have been increasing at an alarming rate (Gall et al. 2011), even as scientific knowledge about hazards accumulates (White et al. 2001). Though disaster attribution science is in its formative stages, there is evidence that climate change may be influencing some hazard frequencies and magnitudes, which, in turn, can affect the extent of resulting disasters (Pielke and Downton 2000; Kunkel et al. 2013; Walsh et al. 2014; Herring et al. 2015). That said, most of the research that has investigated disaster trends has revealed that the primary drivers of surging disaster losses, at least to date, have been due to societal reasons—e.g., increases in population and wealth (Changnon et al. 2000; Downton et al. 2005; Barredo 2010; Bouwer 2011; Field et al. 2012; Simmons et al. 2013; Ashley et al. 2014; Mohleji and Pielke 2014). Moreover, there is evidence that the increasing footprint of humans and, in particular, their developed environment is amplifying the potential for future disasters (Ashley et al. 2014; Rosencrants and Ashley 2015; Strader et al. 2015; Strader and Ashley 2015).

Floods, with their myriad impacts on human society, are a prominent geophysical hazard. The losses caused by flooding each year in the USA are immense. For example, flooding in the USA has resulted in nearly 5000 deaths in the last half century (Ashley and Ashley 2008) and tens of billions of dollars in economic losses per decade (Jenkins 2004); these losses have been increasing rapidly (Pielke and Downton 2000; Cartwright 2005). It is logical to inquire whether the increasing flood impacts are due to societal or environmental change, or, perhaps, a combination of the two.

Using a disintegrative approach by focusing on a singular vulnerability factor (Mileti 1999; Pelling et al. 2004; Douglas 2007; Morss et al. 2011; Fekete 2012), this research assesses how changes in human and built-environment exposure may be altering flood disaster potential and resulting losses. Specifically, the investigation quantitatively estimates changes in the residential built-environment exposure to flooding across the large and sprawling metropolitan area of Atlanta, Georgia (Yang and Lo 2003), which has recently experienced a major flood (Shepherd et al. 2011). In doing so, we isolate the effects of exposure changes on flood disaster magnitude for a two decade period, discounting any possible effects from changing precipitation patterns or human-induced changes on the hydrologic system that may have occurred during that time. Four questions are explored: (1) Did areas within estimated standard floodplains see an increase in residential development from 1990 to 2010? (2) Have residential growth rates varied between different flood exposure levels? (3) If so, have areas with greater flood risks developed more or less quickly than areas outside estimated floodplains? and (4) Has the National Flood Insurance Program (NFIP) been effective in curbing residential floodplain development in the Atlanta metropolitan statistical area (MSA)? Though we focus on the Atlanta MSA and flooding, these issues are pertinent to many areas in USA and for a variety of hazards.

2 Background

2.1 Floods

Floods theoretically have a clear hazard profile; excepting the case of some urban flash floods, most floods all take place near existing bodies of water in areas known as floodplains. Knowing this, it should be possible for humans to avoid building in locations exposed to floods. However, there are many potential economic benefits to building inside floodplains, which may be feasible as long as it is undertaken responsibly (White 1945). The simplest representation of climatological risk is the return period flood, which is the predicted area that will be inundated when a flood of a particular probability, frequently one percent, occurs. Return period floods are often used to plan structural flood defense measures such as levees and dams (Apel et al. 2004). The extent of the one percent flood, frequently referred to as the 100-year flood, guides the NFIP, the flood adaptation and mitigation program in the USA. However, the return period flood is a limited measure of climatological risk; flood risk is a continuous function, not an all-or-nothing border (James and Hall 1986). Representing flood risk as an all-or-nothing border or as a definite continuous function disregards uncertainty, which arises from short hydrometeorological observation records and various approximations made during the flood modeling process (Morss et al. 2005). No matter how simple or complex, only measuring the extent of potential floods is not sufficient. The depth of a flood at a particular location determines what damage an affected building will suffer (Fedeski and Gwilliam 2007; Huttenlau et al. 2010), but estimates of flood depth and resulting damage are, like measurements of flood extent, uncertain (Merz et al. 2004). Despite the uncertainties, the combination of flood extent and flood depth information, along with information on building stock, should be enough to estimate the hazard profile of and exposure to a flood.

It has long been known that urbanization, with its attendant increase in impervious surface, the amount of land underlain by sewers, and new drainage structures can modify the drainage characteristics of a basin (Leopold 1968; Graf 1977). The overall effects of urbanization combine to increase the magnitude of peak discharge rates, variability of discharge rates, and decrease the amount of time between peak rainfall and peak discharge, known as lag time. These changes cause floods to become more frequent (Booth 1991). Numerous studies have confirmed these assertions (Ferguson and Suckling 1990; Changnon et al. 1996; Zhang and Smith 2003; Villarini et al. 2009; Yang et al. 2013). It is important to note that increases in impervious surface do not increase the overall volume of water involved over the entire duration of a flood (Reynolds et al. 2008). For this to change the source of flooding, precipitation must change.

Changes in precipitation patterns also alter the profile of potential flooding. The frequency and intensity of heavy rainfall events across the USA appears to be increasing (Karl and Knight 1998; Kunkel et al. 2013; Villarini et al. 2013). The southeastern USA is no different (Kunkel et al. 2012). These trends may be a result of ongoing climate change (Min et al. 2011; Trenberth 2011; Andersen and Shepherd 2013). In other words, while the amount of water involved in the most extreme flooding events in the Southeast may be the same, other large events may become more frequent due to climate change. Even without any alteration in regional precipitation due to climate change, urban areas may induce a change in local precipitation. Urbanization enhances the urban heat island effect, which induces a thermally direct circulation that leads to increased precipitation over and downwind of the urban core (Changnon 1980; Changnon and Westcott 2002; Shepherd et al. 2002). This same effect leads to urban-induced thunderstorms during the warm season (Changnon 2001; Ntelekos et al. 2007; Bentley et al. 2010; Ashley et al. 2012; Haberlie et al. 2015), which is important because intense rainfall is the most significant component of urban flash flooding (Smith et al. 2002, 2005). By altering the frequency of heavy precipitation, large-scale climate change and local-scale effects due to urbanization alter hydrometeorological characteristics that lead to more frequent and sometimes larger floods. Along with the effects of impervious surfaces previously discussed, it is clear that the hazard profile of a flood is highly variable when urban development is involved.

Despite the increasing complexity and sophistication behind flood risk assessments, this study represents floods using the simple extent of the 100- and 500-year flood. While clearly not the optimal way to represent flood risk, these return periods, in particular the 100-year return period, are what that the USA bases flood policy around.

2.2 US flood policy and exposure

The eventual convergence on the 100-year floodplain as the American standard for representing flood risk began during the 'structural era' of flood management. Also called the engineering approach, this era, which began to be subsidized on the federal level in 1917, saw the construction of many dams, locks, levees, and other flood defense mechanisms (White 1945). Originally, the design flood for these structural defenses varied between projects. Both the Tennessee Valley Authority (TVA) and the United States Army Corps of Engineers (USACE) began to augment their numerous structural projects with non-structural floodplain management programs in 1953 and 1960, respectively (Robinson 2004). Soon after the USACE began their non-structural program, the TVA switched to the 100-year standard; floodplain management programs that existed at the state level followed suit soon afterward. The NFIP was signed into law in 1968; the 100-year flood was chosen as the standard for the new program, although it was not specifically a rule until 1971 (Robinson 2004). Discussions over which standard to use would continue over the next decade, but there has been little talk of changing since 1983, despite numerous alterations to other rules within the program.

The NFIP, along with structural flood defenses, have heavily influenced flood exposure in the USA. Structural flood defenses, in particular levees, which are still prominent in the USA, have led to a situation where people believe the land behind them is safe, increasing exposure by removing the brakes on further development (White 1945; Tobin 1995; Merz et al. 2010). In truth, these lands are a levee failure away from disaster (Tobin 1995; Burby 2006). Despite many changes to the program over the years, the NFIP still focuses on the 100-year floodplain. A new property inside the 100-year floodplain would pay an actuarial rate, while the same new property placed just outside would get a 'preferred risk' rate. The name '100-year flood' along with this unambiguous representation of the flood hazard 'conveys a false impression of safety to those outside and only a vague impression of danger to those inside' (James and Hall 1986). A better description of risk for the average homeowner would be that their new home has a 26 percent chance of flooding over the 30-year term of their home loan (Riggs 2004). The impression of safety outside the official floodplain is clearly false; in some places over half of properties that incur repeated flood damage are located outside this boundary (Highfield et al. 2013).

While the NFIP fails to completely stop floodplain development, it may not be in and of itself driving new development (Evatt 2000). Additionally, the rate of increase in flooding exposure inside the 100-year floodplain in selected counties in North Carolina has been lower relative to areas outside (Patterson and Doyle 2009), suggesting the program has been somewhat effective as a deterrent to construction. Nevertheless, the Patterson and Doyle study shows that the NFIP, and by extension the return period flood, does have an impact on development decisions and is thus a valid way to study exposure in the USA.

3 Data

3.1 Flood

The flood hazard profile is estimated using three different sources of data. The first is derived using the Federal Emergency Management Agency's (FEMA) Hazus-MH version 2.2 software. The program is used to estimate potential impacts from a range of different hazards. One option presented to the user when simulating a riverine flood is to allow the program to derive both a synthetic stream network and delineate estimated floodplains using only a seamless digital elevation model (DEM) as the input, termed a level one analysis (Scawthorn et al. 2006). This process is suitable for county-level estimations of flood extent, but generally unsuitable for use at smaller scales (Banks et al. 2015). Ideally, this study would only need to use NFIP Digital Flood Insurance Rate Maps (DFIRMs), but 500-year floodplain data are not available for the entire study area. A previous study found that an older version of Hazus-MH can reasonably estimate floodplains when DFIRMs are not available (Gall et al. 2007). Additionally, higher-resolution DEMs, recommended by Gall et al., are now widely available. Furthermore, a sensitivity analysis of the Hazus flood model also suggests improving the input DEM over the baseline 30-m input (Tate et al. 2015). Improved DEMs were obtained from the United States Geological Survey's National Elevation Dataset (NED). The 1/3-arc-second-resolution, or about 10-m-resolution, NED was used.

While using level one Hazus-MH analyses to delineate floodplains is a relatively easy task, the simplicity of only needing to provide a DEM comes at the cost of accuracy. Hazus-MH level one analyses tend to underestimate the extent of floodplains (Gall et al. 2007; Ding et al. 2008; Banks et al. 2015). Additionally, there is evidence that the regulatory floodplains are underestimated as well (Criss 2016). Therefore, another modeled flood output is utilized—the proprietary Flood Hazard Data from KatRisk LLC (KatRisk 2016). The model can produce depths as shallow as 1 cm and, in this research, is used to measure housing units at an increased relative risk of flooding that may also reside outside the regulatory floodplains. Due to modeling uncertainties in producing 1 cm depths and the relatively low amount of damage such a flood would cause, the KatRisk-based results are not a perfect comparison with the other results.

The final source of flood data is the NFIP's regulatory floodplains, the result of flood insurance studies that FEMA undertakes periodically across the country. These floodplains are estimated using hydrologic models that, depending on the resources available to FEMA for the particular flood insurance study, may incorporate local surveying work and engineering information on drainage structures.

The limitations of these flood data sets are similar to those of any flood data that represent a return period flood as an absolute boundary. In some areas, the studies used to make the NFIP floodplains are old thus the estimated floodplains are likely now inaccurate. Most important for this study is that the flood hazard profile does not change throughout the period examined. Therefore, this study examines riverine flooding exposure while holding both the hazard profile and social vulnerability constant; feedback effects over time from urbanization to the hazard profile are not modeled and assumed stationary.

3.2 Housing units

Housing unit (HU) data are used as a direct measure of residential exposure. The HU data comes from the United States Census via the National Historical Geographic Information System (Minnesota Population Center 2011). Census blocks, the smallest scale aggregation unit available, recommended for use to combat the modifiable areal unit problem and issues arising from the fact that census boundaries change over time (Schlossberg 2003), are used. Unfortunately, finer-scale HU data were not available for the Atlanta region for a time period long enough to accomplish the goals of this research.

3.3 Study area

This research examines changes in HU exposure to flooding in one metropolitan area, the Atlanta MSA. This region, defined by the United States Office of Management and Budget, consists of 29 counties as of 2015 (Fig. 1). The major river in the MSA is the Chattahoochee River; the upper reaches of the Flint, Ocmulgee, Oconee, Tallapoosa, and Coosa rivers are also within the region. The region has undergone steady growth in population since 1990. As people have flocked to Atlanta, the boundaries of the urban area have been pushed outward at a rapid pace, giving the city a sprawling character (Yang and Lo 2003) with attendant increases in impervious surface (Rose et al. 2008) where forest and cropland were previously located (Yang and Lo 2002), amplifying exposure to thunderstorm hazards (Paulikas and Ashley 2011). Additionally, precipitation patterns have changed due to urban effects (Shepherd et al. 2002; Bentley et al. 2010; Ashley et al. 2012; Haberlie et al. 2015).

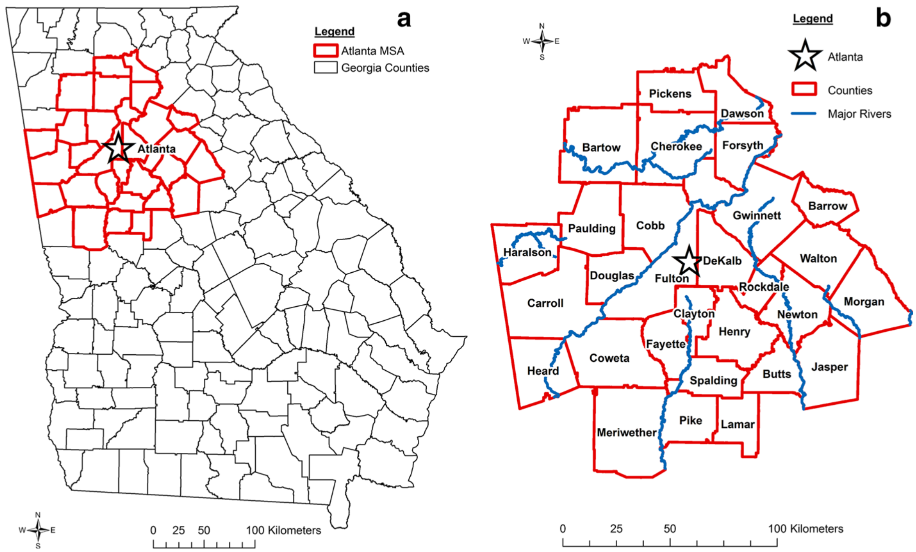

Fig. 1 **a** Atlanta MSA within the state of Georgia; **b** the 29 counties of the Atlanta MSA

4 Methods

4.1 Determining exposure

In order to determine exposure, estimated floodplains are prepared using the three different data sources. After importing appropriate 1/3-arc-second NED DEM panels, the stream network within each county was derived using the minimum drainage threshold available within Hazus-MH, 0.65 square kilometers (0.25 square miles). Hazus-MH produced a shapefile of the boundary of each floodplain; these were exported for later use.

Floodplains from the NFIP are prepared according to their flood zones. The initial source for the data is the National Flood Hazard Layer product. First, any polygon with the zone subtype 'Area of minimal flood hazard' is removed. Remaining polygons are then selected based on their flood zone (Table 1) (FEMA 2007). Any remaining area within flood zones A, AE, and AO are together selected, exported, dissolved, and clipped by county with the results representing the extent of the 100-year floodplain. Starting over after the initial removal of minimal flood hazard areas, zones A, AE, AO, and X are selected, exported, dissolved, and clipped by county and represent the extent of the 500-year floodplain.

KatRisk 100-year and 500-year floodplains were provided as a raster where each cell has a value that corresponds to a particular flood depth. The rasters are reclassed into a system where any cell with water is classed as 1 while all other cells are changed to NoData. The results are then converted into polygon format and clipped by county.

Once the sets of estimated floodplains are prepared, the number of exposed HUs can be estimated. This study employs an areal weighting technique using the floodplains and modified census blocks. While a previous study of flood risk in New York showed that using a more sophisticated dasymetric technique employing tax parcel data yielded more accurate results (Maantay and Maroko 2009), a lack of parcel data in some parts of the Atlanta MSA led to the use of a binary dasymetric method (Eicher and Brewer 2001; Wu et al. 2005). Each census block is reduced in size by the areas identified by the National Land Cover Dataset (NLCD) as containing any land cover except for urban or developed. The 1992–2001 Retrofit Change, 2001, and 2011 NLCD are used to reduce the 1990, 2000, and 2010 census blocks, respectively. In the case of the retrofit product, 1990 census blocks are reduced by all pixels except those that remained urban from 1992 to 2001 and any pixel that changed from urban to a different class. The census block reductions are mostly accurate at identifying land that is actually developed (Fig. 2). The areal weighting technique is rather simple. For example, if 25% of a reduced census block with a value of 10 HU is within Fulton County's 100-year floodplain, the number of HUs within that census block that are estimated to be within the floodplain will be 2.5 HU. The major

Table 1 Regulatory flood zones found in the Atlanta metropolitan statistical area

Flood zone	Description
A	Extent of the 100-year flood; water surface elevation not determined
AE	Extent of the 100-year flood; water surface elevation has been determined
AO	Locations where the 100-year flood produces depths between 1 and 3 ft
X	Extent of the 500-year flood (shaded), area of minimal flood hazard (unshaded)

Fig. 2 2010 census blocks after reduction by 2011 National Land Cover Dataset non-developed classes. Satellite image is from 2013

weakness is the assumption that HUs are evenly distributed across each reduced census block, which is rarely the case. As seen in Fig. 2, reduced census blocks still include golf courses and commercial areas, where HUs are not located, leading to errors when those blocks are intersected by the floodplain. Overestimates may occur when a very large census block is intersected and will occur when an intersected census block includes apartment buildings that are away from the floodplain. Despite these drawbacks, a previous study using census data suggests that areal weighting is the most reliable compromise between counting only blocks that fall completely within a floodplain, counting blocks that are at least intersected by the floodplain, and counting blocks whose centroid resides within the floodplain, three methods which also introduce unreasonable assumptions of their own (Schlossberg 2003). Additionally, the areal weighting technique has been used previously in a study that examines exposure to tornadoes (Ashley et al. 2014). The number of exposed HUs between the 100-year and 500-year flood boundaries, termed the marginal 500-year floodplain (Patterson and Doyle 2009), are estimated by subtracting the number of exposed HUs within the 100-year floodplain from the number of HUs within the 500-year floodplain. Finally, the numbers of HUs outside any flood boundary are estimated by subtracting the number of HUs within the entire 500-year plain from the number of HUs in the whole county.

4.2 Analysis of exposure

After estimating exposure within the 100 and 500-year floodplains, trends over time and between different exposure levels are analyzed for each of the three sets of floodplain estimates. Analysis focuses on the change in HU density over three time periods: 1990–2000, 2000–2010, and over the full 1990–2010 period. The different exposure levels are the 100-year floodplain, marginal 500-year floodplain, and the area outside of any defined floodplain (Fig. 3). The areal unit for analysis is the 2015 extent of the 29 counties in the Atlanta MSA. While using the county areal unit is arbitrary, counties represent the

Fig. 3 Example of different flood exposure levels

smallest governmental unit that can both affect development decisions and are relatively stable in size and shape.

The first step is to establish that changes in HU in each exposure level across each of the time periods of interest are or are not significant. This is accomplished using the Wilcoxon signed-rank test, which is similar to a paired *t* test but does not assume normally distributed data (Wilcoxon 1945; Woolson 2008). For these tests, the HU densities within each exposure level for 1990, 2000, and 2010 are used. If the changes are established as significant, the raw increases in each exposure level across each time period of interest will be converted to a percentage change. The use of HU density and percentage change corrects for the disparities in the amount of land available within each exposure level and between each county; the raw HU increase outside of any estimated floodplain will almost certainly dwarf raw changes within a floodplain. Once this is completed, percentage change within a particular exposure level will be compared between the 1990–2000 and 2000–2010 periods to explore if growth rates changed between the two decades. Finally, the percentage change between the different exposure levels but within the same time period will then be tested.

5 Results

First, it is important to keep in mind the general differences between each set of estimated floodplains. The Hazus floodplains are complete across the entire study area but tend to be slightly less extensive than NFIP floodplains in areas where both exist. NFIP 100-year floodplains are a regulatory product that covers most, but not all, of the Atlanta MSA. NFIP 500-year floodplains are only delineated across some of the study area—8 counties do not have any delineated 500-year floodplains. Finally, the KatRisk floodplains, also complete across the entire MSA, tend to be more extensive than both the NFIP and Hazus floodplains, simulating riverine flooding in smaller streams than either of the other products and simulating flooding due to pooling effects (KatRisk 2016) (Fig. 4). It must also be reiterated that the KatRisk-based results show housing units at a higher relative risk of flooding than areas far away from streams and, due to modeling uncertainties and the limited damage that would be incurred by very shallow flooding, will exaggerate the number of exposed housing units when comparing strictly to Hazus and the regulatory floodplains.

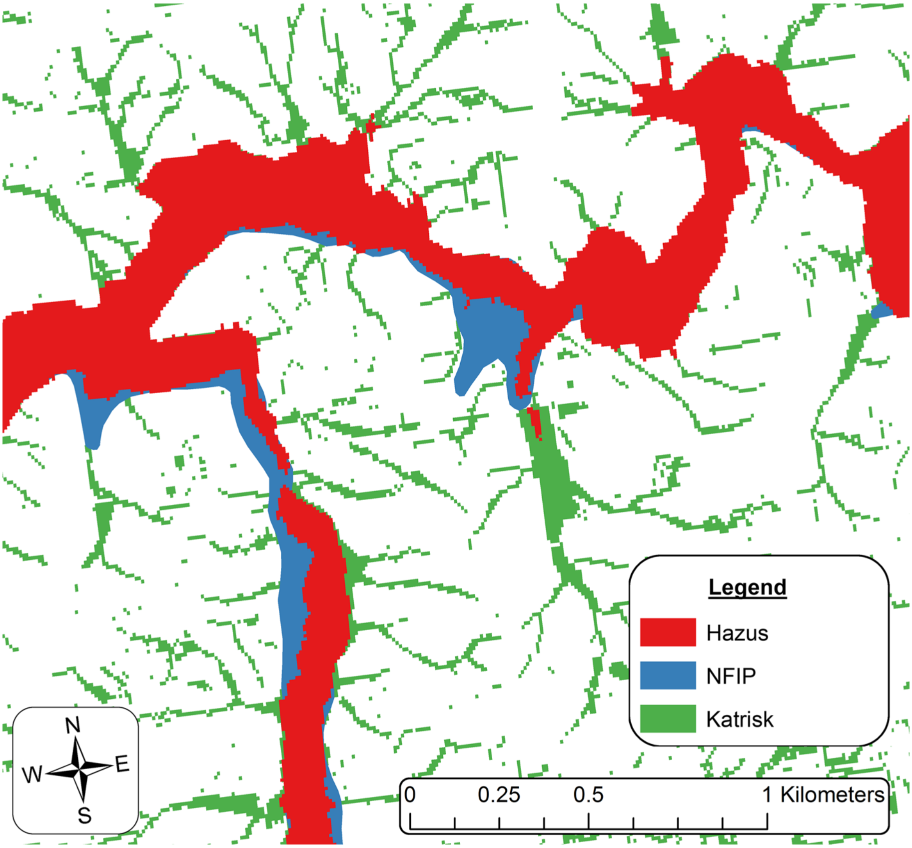

Fig. 4 Overlapping extent of the Hazus, KatRisk, and NFIP 100-year floodplains

5.1 Regional results

Taking a broad view across the entire Atlanta MSA, the total number of HUs grew from 1,271,963 in 1990 to 2,172,051 in 2010, representing an increase of 70.1%. Within the 100-year floodplains, affected HUs grew from 42,200 to 65,682, from 183,228 to 300,910, and from 38,308 to 59,247 within the Hazus, KatRisk, and NFIP floodplains, respectively (Table 2). HUs exposed within the marginal 500-year floodplain grew from 6686 to 10,979, from 35,739 to 59,490, and from 10,358 to 16,937, respectively. When comparing the percentage of overall HUs to the percentage of area within each exposure level, HUs tend to be underrepresented within floodplains (Table 3). In other words, despite growing over time, HUs are less numerous than would be expected if they were distributed evenly across the study area. However, of particular note is the large number of additional HUs the KatRisk model suggests may be at an increased relative risk of flood, which is an indication that the regulatory floodplains may be insufficient.

While these are relatively small numbers of exposed HUs compared to the overall number in the region, there is a large disparity in the amount of land within each exposure level. Thus, it is prudent to also examine the density of exposure. The estimated density of at-risk HUs within the Hazus (Fig. 5a) and KatRisk (Fig. 5b) floodplains shows a consistent pattern—HU density increases as one moves farther away from a river. This pattern was present in 1990 and persisted through 2010. Additionally, the percentage change in HU density from 1990 to 2010 showed a similar pattern within the Hazus (Fig. 6a), KatRisk (Fig. 6b), and NFIP (Fig. 6c) floodplains. All three exposure levels had increases in HU density over time with the percentage change increasing slightly as one moves from inside the 100-year floodplain to areas outside either floodplain, suggesting that, while exposure is amplifying, it is doing so more slowly than the increase in unexposed HUs.

On the surface, the MSA-wide pattern of exposure using the NFIP floodplains appears to be markedly different than the pattern shown by the other two sets of floodplains. In this case, while the pattern in percentage growth is similar, HU density is greatest not outside either floodplain, but within the marginal 500-year floodplain (Fig. 5c). This would suggest that large numbers of HUs are located just outside the 100-year floodplain boundary, avoiding the additional costs of flood insurance and flood-proofing required within the regulatory 100-year floodplain while increasing exposure to lower probability events—a manifestation of the concept of risk transference (Etkin 1999). Additionally, considering the uncertainties in determining flood risk and the dynamic nature of flood risk discussed previously, it is possible that HUs in the marginal 500-year floodplain may currently or in the future be exposed to a higher probability event. However, a closer examination of the county-level data shows that this phenomenon is not as dramatic as it first seems.

Table 2 Number of exposed housing units in the Atlanta metropolitan statistical area

Exposure level	Hazus			KatRisk			NFIP		
	1990	2000	2010	1990	2000	2010	1990	2000	2010
100-year floodplain	42,200	51,462	65,683	183,228	230,237	300,910	38,208	45,636	59,247
Marginal 500-year floodplain	6686	8320	10,979	35,739	45,603	59,490	10,358	12,954	16,937

Table 3 Percentage of total area and total housing units within each exposure level

Exposure level	Hazus		KatRisk		NFIP	
	% of Area	% of HU	% of Area	% of HU	% of Area	% of HU
100-year floodplain	9.14	3.02	19.79	13.85	8.81	2.73
Marginal 500-year floodplain	0.81	0.51	3.10	2.74	0.51	0.78
Outside defined floodplain	90.06	96.47	77.11	83.41	90.68	96.49

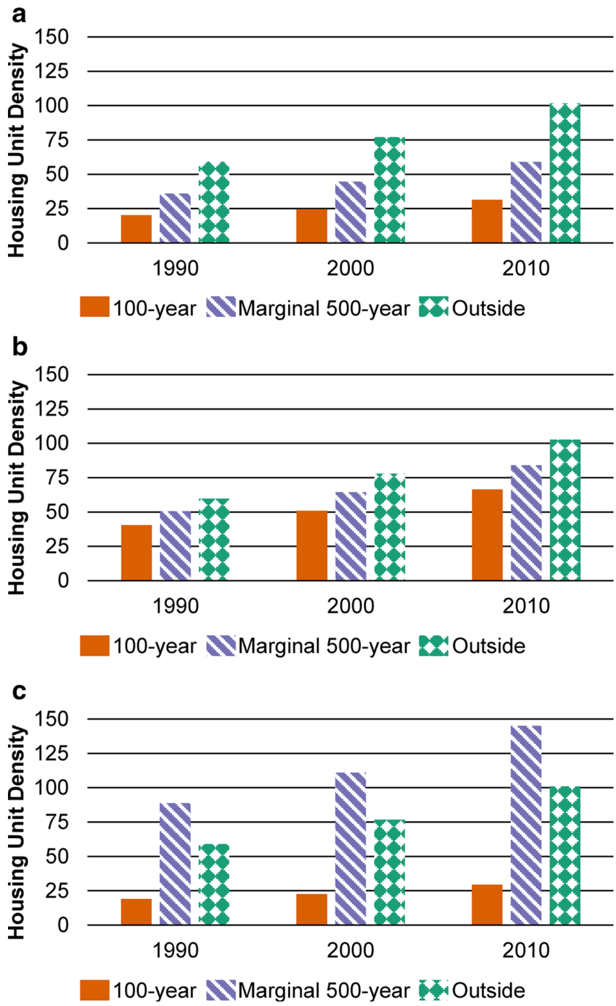

Fig. 5 Estimated housing unit density (housing units km^{-2}) within **a** Hazus, **b** KatRisk, and **c** NFIP-defined flood exposure levels

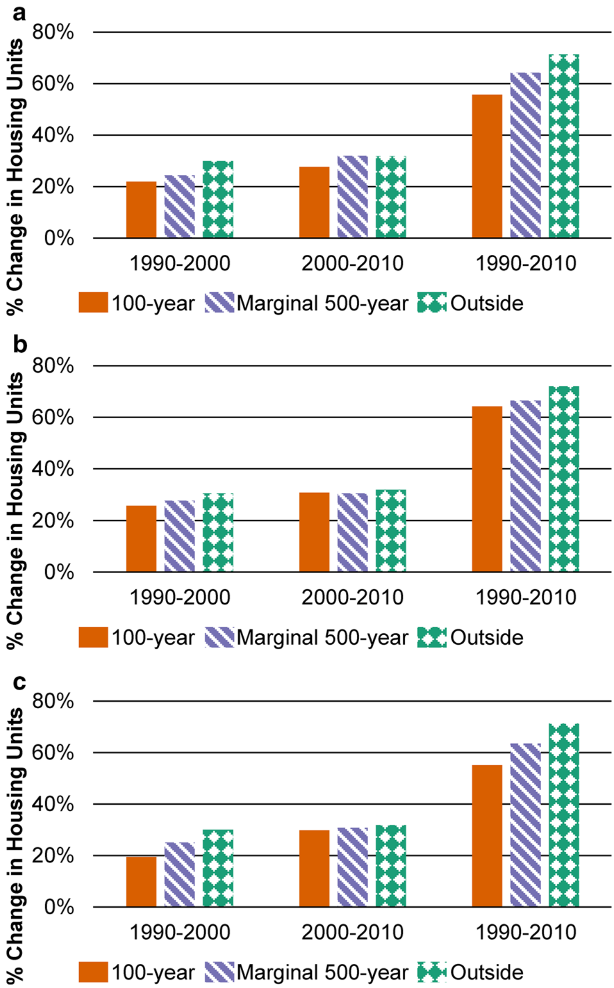

Fig. 6 Percentage change in housing units within **a** Hazus, **b** KatRisk, and **c** NFIP-defined flood exposure levels

5.2 County level results

County-level results suggest the same HU density patterns found at the MSA scale. Examining the raw values, median county HUs within the Hazus 100-year floodplain increased from 383 in 1990 to 820 in 2010. Within the marginal 500-year floodplain, HUs increased from 57 to 136. Fulton County, the largest county by area in the MSA and the location of Atlanta's central business district, had the largest number of exposed HUs within both floodplains. 1990 HU density within Hazus-defined 100-year floodplains ranged from 1.03 HU km^{-2} in Jasper County to 136.41 HU km^{-2} in DeKalb County (Table 4). By 2010, these HU density values would increase by 0.61 and 32.45 HU km^{-2}, respectively. 2010 HU density within the marginal 500-year floodplain varied between 2.31 and 248.32 HU km^{-2}. Outside floodplains, 2010 HU density varied between 6.79 and 456.71 HU km^{-2}. The median county HU density of each exposure level showed the same

Table 4 Estimated housing unit density (housing units km^{-2}) within Hazus-defined exposure levels

County	100-year floodplain			Marginal 500-year floodplain			Outside defined floodplain		
	1990	2000	2010	1990	2000	2010	1990	2000	2010
Barrow	5.88	8.58	14.53	10.32	13.82	20.33	29.86	43.64	66.64
Bartow	10.19	14.58	19.74	17.51	24.13	32.21	18.82	24.70	34.32
Butts	3.31	4.44	5.10	6.59	9.78	13.25	12.29	16.31	20.77
Carroll	6.90	8.33	11.85	11.07	13.91	20.30	22.74	27.94	36.45
Cherokee	10.45	13.29	22.22	16.97	24.43	39.59	32.15	49.61	78.58
Clayton	70.61	71.28	87.77	114.88	121.27	167.54	205.66	248.25	300.89
Cobb	85.60	96.10	118.05	126.28	145.75	184.07	225.59	283.39	341.61
Coweta	4.32	6.28	10.98	8.60	11.40	19.27	19.30	31.42	47.41
Dawson	2.53	3.85	5.15	4.68	7.36	10.48	8.24	13.54	19.68
DeKalb	136.41	149.88	168.86	248.32	281.22	340.42	346.58	391.23	456.71
Douglas	19.02	21.81	34.70	25.35	34.08	53.28	54.47	71.82	106.30
Fayette	10.83	13.71	15.24	20.70	27.52	34.39	47.76	70.49	88.17
Forsyth	4.22	9.39	18.35	8.66	21.54	41.35	31.76	64.66	113.29
Fulton	91.97	103.81	121.63	183.53	211.32	255.25	227.78	267.44	336.68
Gwinnett	53.46	81.49	107.81	76.56	116.28	159.22	127.79	194.66	271.21
Haralson	2.48	3.69	4.34	3.90	5.05	5.71	13.33	15.76	18.05
Heard	1.52	1.68	1.71	3.72	4.74	4.71	4.90	6.29	7.17
Henry	5.88	11.56	21.49	9.65	21.96	51.04	27.06	54.89	97.19
Japser	1.03	1.43	1.64	4.13	4.82	6.42	4.00	5.28	6.79
Lamar	1.70	2.51	3.06	4.28	5.96	7.32	11.38	13.78	16.73
Meriwether	1.60	1.69	1.92	2.04	3.53	2.24	6.97	7.63	8.27
Morgan	1.32	1.54	1.64	2.31	3.03	5.80	5.65	7.20	8.67
Newton	6.10	6.94	11.10	14.29	14.19	21.84	23.26	34.80	58.08
Paulding	6.12	12.08	18.61	8.36	16.84	30.02	19.84	37.98	68.14
Pickens	4.95	9.02	9.58	6.28	11.17	11.56	10.97	18.19	23.37
Pike	1.59	2.03	2.71	2.34	3.52	4.67	7.20	9.63	12.90
Rockdale	13.28	19.67	25.34	26.43	39.59	41.93	63.28	79.15	105.08
Spalding	7.43	6.93	8.65	12.94	16.42	21.45	43.83	48.82	56.77
Walton	2.86	4.87	7.21	5.57	9.19	14.43	18.29	28.27	40.76

pattern seen in the MSA-level analysis (Table 5). Changes in HU density within each exposure level over time between 1990 and 2000, 2000 and 2010, and from 1990 to 2010 were shown to be statistically significant to at least the $p = 0.05$ level. Additionally, the differences in HU density between exposure levels were shown to be statistically significant to at least the $p = 0.05$ level during each year examined.

Using the KatRisk flood model, the number of HUs with at least an elevated relative risk was found to be greater than using Hazus, an expected result given the more extensive flooding depicted by the product. Within the 100-year floodplain, median county HUs increased from 2126 in 1990 to 4689 in 2010 (Table 5). Fulton County had the greatest number of exposed HUs (Table 6). Inside the marginal 500-year floodplain, median HUs grew from 429 to 734. Hundred-year floodplain HU density at the beginning of the studied

Table 5 Median county housing unit density (HU km^{-2}) in the Atlanta metropolitan statistical area

Exposure level	Hazus			KatRisk			NFIP, median of all counties			NFIP, median excluding counties without defined 500-year floodplain		
	1990	2000	2010	1990	2000	2010	1990	2000	2010	1990	2000	2010
100-year floodplain	5.88	8.58	11.85	12.82	19.48	30.07	5.71	8.32	11.32	5.91	9.95	16.65
Marginal 500-year floodplain	9.65	14.19	34.80	18.86	27.08	44.55	27.09	39.84	60.79	27.09	39.84	60.79
Outside defined floodplain	22.74	34.80	56.77	23.19	35.79	59.04	22.59	34.64	56.45	31.93	49.28	78.23

Table 6 Estimated housing unit density (housing units km^{-2}) within KatRisk-defined exposure levels

County	100-year floodplain			Marginal 500-year floodplain			Outside defined floodplain		
	1990	2000	2010	1990	2000	2010	1990	2000	2010
Barrow	16.09	22.24	34.54	23.08	32.45	49.95	30.75	45.24	69.07
Bartow	16.75	22.09	30.07	20.31	27.01	37.51	18.10	23.91	33.33
Butts	7.00	8.99	11.04	12.06	16.17	20.44	12.52	16.71	21.33
Carroll	12.82	15.40	20.28	19.65	23.40	31.00	23.19	28.57	37.36
Cherokee	18.96	28.38	43.60	28.68	41.36	62.25	32.54	50.15	79.94
Clayton	138.88	158.26	190.60	226.06	252.45	296.64	208.01	254.17	309.80
Cobb	153.49	182.17	220.11	198.21	232.46	279.80	227.16	286.91	346.07
Coweta	8.63	13.79	22.39	13.84	27.08	41.16	19.99	32.28	48.54
Dawson	5.56	9.26	12.66	10.07	16.55	22.28	8.15	13.34	19.51
DeKalb	254.80	291.88	343.04	321.61	369.83	434.27	349.29	392.64	457.24
Douglas	32.11	39.31	63.21	35.06	45.81	70.20	55.06	72.87	107.09
Fayette	22.86	31.56	37.83	35.70	52.19	63.51	51.27	76.07	95.61
Forsyth	13.64	28.47	56.41	29.57	51.36	86.13	32.61	66.73	115.29
Fulton	172.69	202.96	255.16	205.54	251.23	318.01	226.74	265.23	332.72
Gwinnett	83.76	125.49	174.32	113.15	163.73	221.05	130.02	198.77	276.69
Haralson	5.35	6.68	7.65	8.20	10.60	12.41	13.91	16.45	18.84
Heard	3.43	4.25	4.68	5.48	7.15	7.80	4.76	6.11	6.97
Henry	13.71	27.96	53.04	18.56	37.27	76.61	28.85	58.49	102.01
Japser	2.63	3.47	4.20	3.78	5.01	6.28	4.03	5.32	6.89
Lamar	6.68	8.07	10.00	9.88	12.07	14.76	11.76	14.29	17.27
Meriwether	3.47	3.78	4.07	5.96	6.68	7.04	7.15	7.83	8.49
Morgan	3.30	4.29	5.16	4.99	6.48	8.01	5.77	7.30	8.79
Newton	12.74	17.41	28.18	18.86	27.86	44.55	23.87	35.79	59.97
Paulding	10.70	19.48	35.58	14.45	25.69	46.69	20.31	39.15	69.82
Pickens	8.38	13.47	15.59	10.39	16.02	18.49	11.01	18.43	23.88
Pike	4.49	5.88	7.81	6.54	8.75	11.18	7.49	10.05	13.55
Rockdale	34.71	46.04	60.36	59.18	76.85	105.62	63.71	79.41	105.28
Spalding	25.60	28.40	33.18	38.98	44.53	51.82	45.80	50.73	59.04
Walton	12.73	19.29	28.01	16.09	25.50	37.48	18.17	28.22	40.65

time period ranged from 2.63 to 254.80 HU km^{-2} in Jasper and DeKalb County, respectively. Marginal 500-year HU density ranged from 6.28 to 434.27 HU km^{-2} in 2010. During the same year, outside of floodplains, HU density values varied between 6.89 and 457.24 HU km^{-2}. The median county results have a similar pattern to results using the Hazus floodplains. As with the results using the Hazus floodplains, changes within exposure levels during 1990–2000, 2000–2010, and 1990 through 2010 were statistically significant to at least the $p = 0.05$ level. Similarly, differences in HU density between exposure levels during a single year were all significant to at least the $p = 0.05$ level.

Within the regulatory floodplains, median county HUs increased from 429 to 731 within the 100-year floodplain and from 51 to 97 within the marginal 500-year floodplain. DeKalb County, located directly east of Fulton County and the Atlanta central business district, had the greatest number of HUs within the 100-year floodplain, while Fulton County had the greatest number within the marginal 500-year floodplain (Table 7). The initial contrast between the NFIP results and the other results continues when looking at median county HU density (Table 5; Fig. 7a). 1990 median county-level marginal 500-year floodplain HU density was 27.09 HU km^{-2}, greater than the 22.59 found outside of defined floodplains and much greater than the 5.71 inside of 100-year floodplains. Exposure increased over time within both the 100- and marginal 500-year flood zones. However, when examining HU density values between the counties, it becomes apparent that, of the 8 counties without NFIP-defined 500-year floodplains, all tend to have small HU density values overall, suggesting delineation of 500-year floodplains may be biased toward populated areas. The history of NFIP flood mapping supports this; many parts of the Atlanta MSA

Table 7 Estimated housing unit density (housing units km^{-2}) within NFIP-defined exposure levels

County	100-year floodplain			Marginal 500-year floodplain			Outside defined floodplain		
	1990	2000	2010	1990	2000	2010	1990	2000	2010
Barrow	5.80	8.19	14.82	12.20	8.30	23.91	30.71	44.90	68.39
Bartow	5.71	6.96	8.43	11.95	14.07	19.14	19.11	25.30	35.21
Butts	4.76	6.38	6.96	N/A	N/A	N/A	11.98	15.91	20.31
Carroll	5.79	6.81	10.36	63.32	73.07	104.05	22.59	27.77	36.21
Cherokee	11.05	14.15	21.66	69.94	83.78	167.54	31.93	49.28	78.23
Clayton	82.20	78.76	94.37	90.82	130.75	179.64	205.70	248.09	300.59
Cobb	75.02	83.87	104.74	156.58	185.69	254.82	229.08	287.88	346.42
Coweta	4.21	5.62	9.41	7.34	14.71	17.86	19.28	31.37	47.51
Dawson	2.57	3.85	5.10	6.19	9.61	7.77	8.21	13.50	19.62
DeKalb	147.42	165.03	189.11	244.47	270.40	317.65	348.14	392.89	458.54
Douglas	21.06	22.88	37.53	52.85	65.22	118.98	53.90	71.26	105.26
Fayette	9.18	13.25	16.65	38.09	49.01	60.79	48.46	71.24	88.84
Forsyth	4.91	8.71	16.82	12.56	28.79	67.42	32.10	65.72	115.08
Fulton	68.87	78.20	90.96	92.88	119.29	154.26	231.01	270.64	340.17
Gwinnett	50.75	68.37	94.97	53.92	82.05	108.35	127.67	195.21	271.51
Haralson	3.58	4.77	5.78	N/A	N/A	N/A	12.77	15.15	17.34
Heard	1.54	1.83	1.98	N/A	N/A	N/A	4.82	6.18	7.02
Henry	5.17	10.17	21.54	33.11	93.25	120.73	27.27	55.30	97.80
Japser	2.73	3.59	4.01	N/A	N/A	N/A	3.79	5.00	6.43
Lamar	2.99	4.18	5.00	N/A	N/A	N/A	10.96	13.28	16.12
Meriwether	1.62	1.90	2.06	16.45	21.29	36.25	6.84	7.48	8.10
Morgan	1.56	2.14	2.61	N/A	N/A	N/A	5.74	7.27	8.76
Newton	5.91	6.35	10.08	24.74	23.67	32.92	23.15	34.64	57.84
Paulding	5.50	9.95	17.86	15.17	25.57	49.06	19.38	37.17	66.43
Pickens	5.90	10.03	10.71	N/A	N/A	N/A	10.96	18.21	23.42
Pike	1.13	1.35	1.85	N/A	N/A	N/A	7.03	9.40	12.59
Rockdale	8.40	11.37	14.81	8.67	7.13	10.71	63.22	79.37	105.23
Spalding	8.41	9.02	11.32	4.59	5.95	5.33	43.67	48.55	56.45
Walton	4.86	8.32	12.45	27.09	39.84	49.00	19.14	29.48	42.46

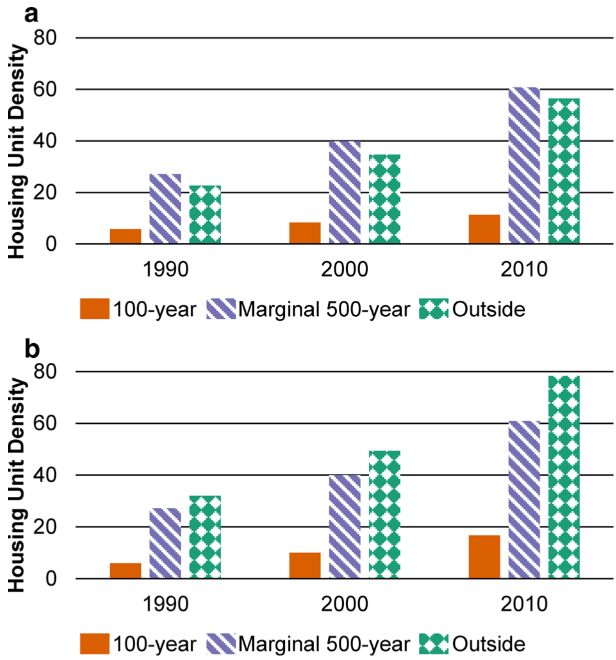

Fig. 7 **a** Median county housing unit density (housing units km^{-2}) within NFIP-defined exposure levels; **b** as in **a**, but excluding counties without NFIP 500-year floodplains

last received new NFIP floodplains during FEMA's Map Modernization Program which, due to time and budget constraints, switched focus from providing the entire USA with an updated flood map to providing new flood maps to a majority of the existing population (FEMA 2006). Removing the counties without 500-year floodplains from the calculation of the median county HU density, the pattern changes (Fig. 7b). This suggests that the HU density pattern—increasing HU density as distance from a river or stream increases—in reality is the same using all three sets of floodplains.

Geographically, HU density follows a similar pattern for all exposure levels using any of the three sets of floodplains. Regardless of flood exposure level, HU density in the Atlanta MSA is concentrated in Cobb, Fulton, DeKalb, and Clayton counties while also undergoing an outward expansion between 1990 and 2010. For example, this distribution was apparent within the area inundated by the KatRisk 100-year flood (Fig. 8). This increase in both intensity and spatial distribution of residential exposure, while restricted to small areas near rivers and streams, is reminiscent of increases in exposure to other geophysical hazards (Ashley et al. 2014; Rosencrants and Ashley 2015; Strader et al. 2015).

6 Discussion

The goals of this research were to examine residential exposure to flood hazards, changes in exposure over time, and to assess the relative effectiveness of the NFIP in the Atlanta region. The results strongly suggest that residential exposure to flooding grew from 1990 to

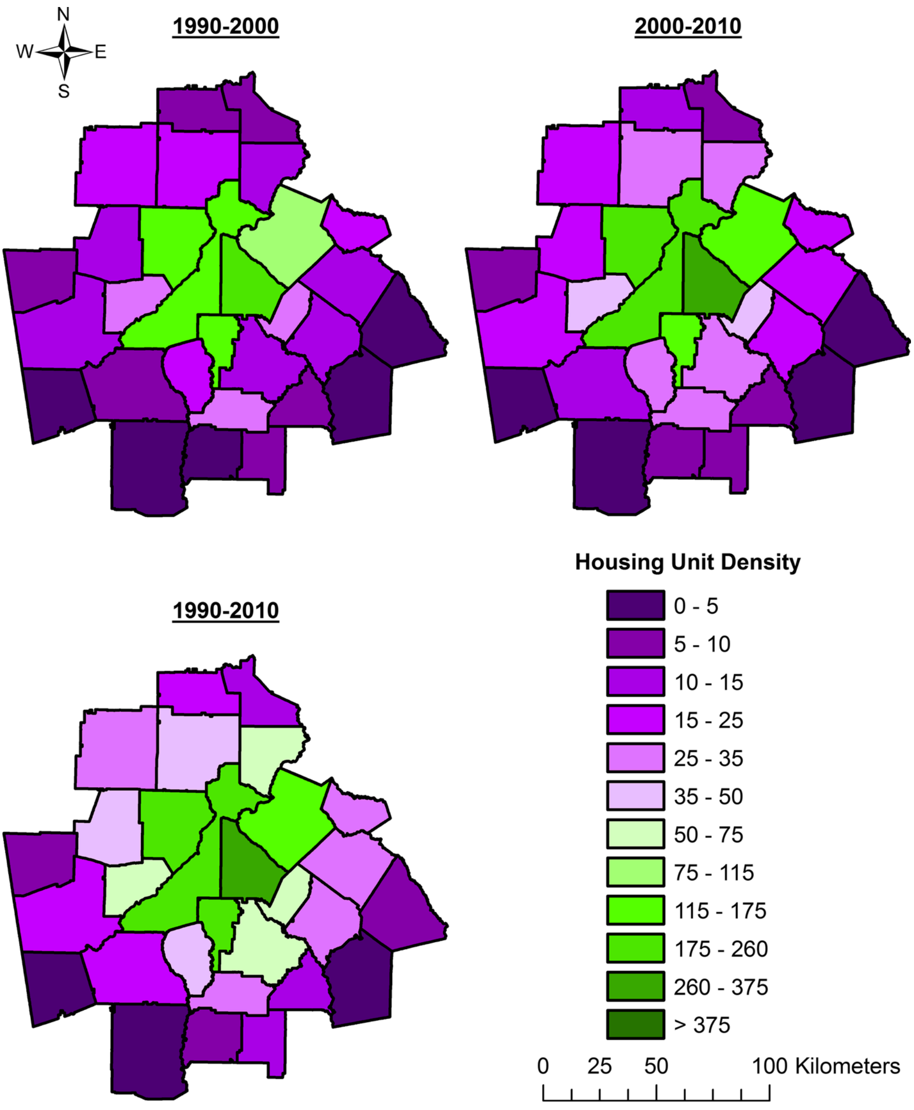

Fig. 8 Housing unit density within the KatRisk-defined 100-year floodplain by county in the Atlanta region

2010. Growth in exposure was strongest where overall development, exposed and unexposed alike, was located, in a ring around the part of the MSA that was already urbanized in 1990. Thus, exposure grew outward from the urban center over the two decades examined. The NFIP appeared to be marginally effective overall, although effectiveness appears to have varied by location within the MSA.

Growth in exposure and wealth plays a vital part in explaining the rise in disaster losses over the past several decades (Mileti 1999; Changnon et al. 2000; Cutter and Emrich 2005; Downton et al. 2005; Barredo 2010; Crompton et al. 2010; Bouwer 2011; Simmons et al. 2013; Ashley et al. 2014; Rosencrants and Ashley 2015; Strader et al. 2015). Exposure to floods, like exposure to other hazards, has continued to grow over time and should be considered when addressing flood loss records. However, it should be noted that, unlike hazards such as tornadoes, the physical profile of the flood hazard is changing over time due to human effects. For example, in some regions of the USA, the frequency and intensity of heavy rainfall events—in other words, those likely to generate a flood—have increased. The southeastern USA appears to be one of these regions; the frequency of extreme precipitation events there has increased (Kunkel et al. 2013). Additionally, overall precipitation in several watersheds that drain the Atlanta MSA has increased, albeit slightly (Maleski and Martinez 2016). There is also abundant evidence that increased urban development will alter both precipitation patterns (Changnon 1980, 2001; Changnon and Westcott 2002; Shepherd et al. 2002; Ntelekos et al. 2007; Bentley et al. 2010; Haberlie et al. 2015) and runoff characteristics (Leopold 1968; Graf 1977; Ferguson and Suckling 1990; Booth 1991; Changnon et al. 1996; Zhang and Smith 2003; Villarini et al. 2009; Yang et al. 2013), which can expand floods of a given return period. Nevertheless, growth in exposure was an important factor with respect to the flood hazard in the Atlanta MSA.

There are a few limitations to this study. The primary limitations arise from the flood data and how they were employed. Modeling a 100-year or 500-year flood is inherently uncertain due to the fact that most streams are ungauged and that nearly all records of flood discharge are shorter than 500 years and most are shorter than 100 years (Morss et al. 2005). The use of three separate representations of a 100- and 500-year flood was a deliberate decision to combat this problem. The weakness in the way these flood data were used was that flood depth was not considered; a simple in-or-out framework was implemented. This removed consideration of severity of damage from the exposure calculations that considering depth can provide (Fedeski and Gwilliam 2007; Huttenlau et al. 2010). While the Hazus and KatRisk data both provided flood depth at every affected cell, the NFIP data lacked flood depth information in most locations. Thus, the in-or-out framework was used in order to generate more consistent results.

A further limitation lies with the process of estimating exposure. While reducing undeveloped areas from the census blocks increases overall accuracy, the method still relied on the assumption that HUs were evenly distributed throughout the remaining area of each block. Limitations in the data—in this case, the quality of the 1992 land cover data and the consistency between the 1992 data and later iterations—required a simpler approach. A recent study examining vulnerability at one time was able to leverage land cover data in a more sophisticated manner (Prasad 2016); in the future, this research could be improved upon once higher-quality ancillary data representing land cover for multiple decades become available for the entire MSA.

Despite these limitations, it is likely that residential exposure to flooding continued to increase from 1990 to 2010 in the Atlanta MSA. While the magnitude of the increase varied by location and by the source used to determine the 100- and 500-year flood level, residential exposure grew in every county over the two decades studied. Despite this, the overall pattern of residential exposure remained the same—HU density increases as distance from a river increases and flood risk decreases, on the surface a logical distribution for reducing flood losses. However, in each case there was a sizable increase in the level of development between the 100-year and marginal 500-year floodplain, reflecting the results found in previous research on flood exposure (Patterson and Doyle 2009). Due to the previously mentioned uncertainties in flood mapping and likely future increases in the flood hazard, this may mean that a significant number of residences are or will be at risk of a 100-year flood. Indeed, the number of HU at risk of being flooded using the KatRisk product is much greater than using the regulatory product would suggest (Table 2). This pattern of development has implications with regards to the NFIP.

On the whole, the NFIP may have been marginally effective at preventing floodplain development where the program is set up to do so. In other words, it may have slowed development in the regulatory 100-year floodplain. Additionally, HU are underrepresented within the regulatory floodplains of the MSA (Table 3). However, apparent effectiveness was far from uniform throughout the MSA. In particular, counties with rapid growth rates or counties on the edge of the developing area were more likely to experience quickest growth within their 100-year floodplains (Fig. 9). Additionally, while some fast developing counties had high amounts of development within the regulatory 100-year floodplain, others did not. These are not unexpected results—floodplain development is most likely where land is scarce (Burby and French 1981) or where rapid development is occurring

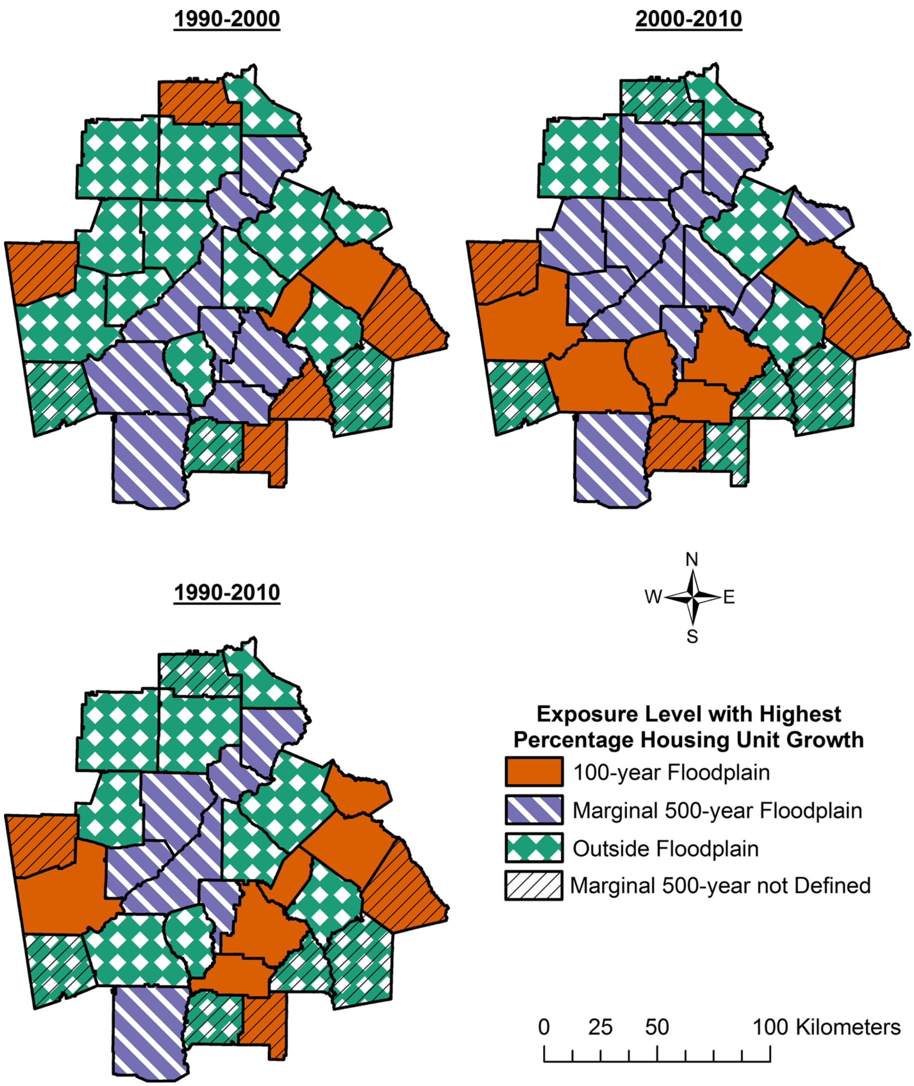

Fig. 9 NFIP-defined exposure level with the greatest percentage growth in housing unit density by county in the Atlanta region

(Montz and Gruntfest 1986; Bollens et al. 1988; Burby et al. 1988) and the effectiveness of local floodplain regulation is known to vary locally (Montz and Gruntfest 1986). FEMA relies on local governments to enact and then enforce floodplain regulations and does not have the resources to rigorously check for compliance (Monday et al. 2006), which could lead to the variation seen in the Atlanta MSA. However, the fast NFIP 100-year floodplain development on the edge of the areas that had high overall growth does not have a clear precedent.

More stringent adoption and enforcement may begin after initial development in some communities. Past evidence suggests that the same factors that drive development in floodplains also stimulate enactment and enforcement of floodplain development restrictions (Burby and French 1981). It appears that, in some communities on the edge of the developed area, adoption and enforcement of floodplain development ordinances may not have occurred to the level needed to prevent floodplain encroachment as the area began to develop. With regards to the marginal 500-year floodplain, the NFIP did not seem to discourage growth within this zone, particularly in some counties that were developing quickly between 1990 and 2010 or had already developed by 1990. This result makes sense given that the bulk of NFIP regulations and the actuarial insurance premiums are focused on the regulatory floodway and the 100-year floodplain. It is important to note that the regulatory flood lines were assumed to be fixed from 1990 through 2010. In reality, many regulatory flood maps were updated during this time period and in the years since 2010, particularly during FEMA's Map Modernization Program that took place from 2003 to 2008. While the major focus of this effort was to digitize the maps that already existed, FEMA attempted to validate or update the flood analysis for 40% of the US population (FEMA 2006). Thus, it is possible that homes were built in locations that were outside the regulatory 100- or 500-year floodplain that are now considered to be at risk. Nevertheless, flood exposure did increase, even within the regulatory framework of the NFIP.

Finally, the NFIP may face significant actuarial challenges if the KatRisk product is correct. By 2010, the KatRisk product suggested that 300,910 HU are at some level of risk of being affected by a 100-year flood. The NFIP floodplains suggest 59,247. Thus, it is possible that over 200,000 HUs may be affected by a 100-year flood but are not within the regulatory zone. While flood insurance is required for federally backed mortgages on property within the 100-year floodplain, it is not mandatory nor is it well promoted for those outside the regulatory 100-year floodplain—many outside are under the impression that they do not need flood insurance (Kennedy and Bynum 2016). It is important to note that some of these extra HU within the KatRisk floodplain would not need to pay higher actuarial premiums due to modeling uncertainty and the very shallow flood depths modeled in some locations. Nevertheless, for those who do purchase insurance, the results suggest that some may be paying an insurance rate that is too low, as rates outside the regulatory 100-year floodplain are not determined actuarially. Those who do not may be in for a surprise when their home is affected and may instead receive other forms of government assistance following a disaster (Yates 2011; FEMA 2015; Hudson 2016). Whether through an insurance payout or disaster relief, society would end up footing a portion of the bill for damage outside the regulatory 100-year floodplain. With annual peak flows likely to increase in the future due to increases in impervious surfaces and climate change (Zhao et al. 2016), any insufficiencies in the NFIP hazard maps will be exacerbated in the future, particularly in urbanizing regions.

7 Conclusion

This research explored the following four questions for the Atlanta MSA: (1) Did areas within estimated 100-year and 500-year floodplains see an increase in residential development from 1990 to 2010? (2) Have residential growth rates varied between different flood exposure levels? (3) If so, have areas with greater flood risks developed more or less quickly than areas outside estimated floodplains? (4) Has the NFIP been effective in curbing residential floodplain development in the region? An increase in residential development within both the 100- and 500-year floodplains did occur. While on the large scale it appeared that areas with greater flood risks developed more slowly than other areas, statistical analysis suggested they were not significantly different. Finally, it was determined that the NFIP may have been marginally effective at preventing development within the regulatory 100-year floodplain but likely not effective at dissuading new construction within the marginal 500-year floodplain. The potential effectiveness of the NFIP appeared to vary by location, with the edge of the developed part of the MSA most likely to experience at-risk growth. However, results using the KatRisk floodplains suggest the regulatory 100-year floodplain may be insufficient to the tune of an additional 241,663 HU that may be affected during a 1 percent chance flood event.

A potential avenue for further research is socioeconomic vulnerability. While counties that saw the most rapid growth within the regulatory 100-year floodplain tended to be located along the edge of the urban area, they were also more likely to be located in the southern part of the MSA (Fig. 9). The contrast between Forsyth and Henry counties—the two counties that grew the fastest overall—is an example of how socioeconomic vulnerability may be involved. Forsyth and Henry counties have different demographic characteristics, in this case race and income, which are factors in determining social vulnerability (Cutter 2003; Cutter and Finch 2007; Cutter et al. 2009). Forsyth and Henry counties have median household incomes of $87,657 and $60,269 (United States Census Bureau 2014a) and have populations that are 85.4 and 53.4% white (United States Census Bureau 2014b), respectively. Additionally, much of the population growth within Henry County from 2000 to 2010 was African-American (Pooley 2015), people who tend to be more vulnerable than white Americans (Fothergill et al. 1999; Cutter 2003). Thus, while changes in exposure, runoff, and precipitation are very important when considering flood risk in the Atlanta MSA, socioeconomic vulnerability may be a significant factor as well.

The Atlanta MSA is not immune to major flooding events. Two recent flooding events, one in December of 2015 and, in particular, the September 2009 flood where discharge exceeded the 500-year level in some areas (Shepherd et al. 2011), underscore the threat of flooding in the region. Even though increasing regional precipitation, enhanced runoff due to urban development, and increased thunderstorm development due to urban effects may have contributed to greater flood risks, it is clear that growth in the number of residences at risk continued to occur between 1990 and 2010, likely leading to greater losses in those floods than would have occurred just twenty years prior.

Acknowledgements We would like to thank KatRisk LLC (http://www.katrisk.com/) for providing us with their Flood Hazard Data. We also thank the anonymous reviewers for their comments and suggestions which lead to a stronger end product. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of NWS, NOAA, or the Department of Commerce.

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