Dear Editor,

I am pleased to submit a revised version of the paper entitled “Exposure of properties to the 2018 Hurricane Florence flooding: an expanding bull’s-eye perspective” for consideration on the Special Issue on Hydroclimatic extremes and impacts at catchment to regional scales, on the journal Natural Hazards and Earth System Sciences on behalf of co-authors and myself.

In our study, we aim at quantifying what was the total value and area of properties exposed to the flooding associated with Hurricane Florence. We first generate a map of the maximum flood extent from the combination of the extent produced by FEMA obtained from the interpolation of high water marks and flooded areas obtained by means of spaceborne radar remote sensing. Such map is, then, used for estimating the value and area of properties exposed to flooding and the distance of such properties from permanent water bodies. Lastly, we study and quantify how the urban development over the past years and decades over the regions flooded by Hurricane Florence might have impacted the exposure of properties and population to present-day storms and floods, to account what colleagues are starting to address as the “expanding bull’s-eye effect” in which ‘‘targets” of geophysical hazards, such
as people and their built environments, are enlarging as populations grow and spread.

We appreciate the input and suggestions provided by reviewers and we have done our best to include them. In this regard, we have moved a relatively large section of the manuscript dealing with radar data in the Supplementary Material, we have shortened the Conclusions and have (hopefully) improve the style, as requested. In this regard, we believe that the combination of radar data and FEMA maps is an important aspect of our paper as it shows the complementary nature of these datasets. In some cases, we were not able to satisfy the requests by reviewers, especially when it comes to expressing the exposed property value in terms of percentage of taxes or other metrics. We are currently working on this aspect and it takes some time before this can be done. We think this is outside of the scope of our manuscript and reporting absolute values will allow our results to be compared with others reported in the literature.

We hope you will find the revised version improved. We are attaching two versions: one showing the changes and another one without showing them. We hope this would help reviewers and the editor in reading the revised version.

Sincerely,
M. Tedesco and co-authors
10/25/2019

Anonymous Referee #1

1. General: The writing style should be more formal and should rely more on active verbs. In general, the manuscript should be edited down to simplify the sentence structure. In addition, there are many errors of punctuation and grammar that are distracting.

R: We have revised the document and we hope the reviewer finds the new version improved in style.

2. Findings: The inadequacy of FEMA flood mapping should be reinforced and contextualized. For instance, how can this method augment or support alternative determinations of spatial risk in the housing market? I would like to see some analysis of the method and findings within matters of local and federal policy. For instance, could this method compliment Hazus? Maybe or maybe not. At its core, this is about land use and zoning and you should be explicit about this.

R. We agree that this is an important point and consideration. We have added a section to page 11 in which we briefly identify the potential complementary nature of the radar and FEMA extents as a way to more holistically capture the event impact areas. Additionally, we agree that the specific type of land that is captured as flooding by the radar might have to be considered in regards to any potential policy implications. It is beyond the scope of this paper to actually test this, but we do note on page 11 that more research would be necessary to fully understand the utility of the method moving forward.

3. Line 45: There is also some counter- and supporting-evidence on the horizon that is worth reading:

Gibson, M., J. Mullins, and A. Hill 2017. "Climate Change, Flood Risk, and Property Values: Evidence from New York City". Working paper, University of Massachusetts-Amherst.

Murfin, J. and M. Spiegel 2018. "Is the Risk of Sea Level Capitalized in Residential Real Estate?" Review of Financial Studies Climate Finance Call, Conditionally Accepted.

R: We thank the reviewer for the suggestion. We have searched for the material on the web and we were not able to locate a published version of the first paper and the copy we found of the second one mentions not to cite it as it is an incomplete version. We will definitely read and include this paper in our future studies.

4. Present Value: When citing valuations, it is always good practice to cite the associated dollar year.

R: We thank the reviewer for this suggestion and we have added a sentence in the introduction specifying that we use 2018 as a dollar year.

5. Lines 58-70: This should be significantly edited-down. I think it is also useful to highlight the economic distinctions between stresses and shocks because they have different theoretical pricing elasticities.

R.The distinction has been added to pages 4-5. We now distinguish between market stressors and shocks as they pertain to the specific types of flooding events, the potential impacts on elasticity, and the identification of Hurricane Florence as our focus within that context.

6. Line 86: "Of particular importance to the recent market response is the fact that increased probability seems to be an important driving force." A "fact" and "seems" are

contradictory language here.
R : we replaced "sems to be"with "is"
7. Lines 103-108: It is critical that you use the precise language of exposure and sensitivity within the conceptual framing of vulnerability. Much of your pivot argument around urban development is fundamentally about exposure that has merit independent of climate attributed phenomena.
R. Thank you for this comment and we completely agree. We have attempted to make that clear in the most recent version of the paper with statements like "It is important to note that much of the vulnerability associated with building development in these areas should be considered independent of climate change to this point. However, moving forward, these types of storms are expected to increase in intensity and the link between climate change and potential exposure is likely to be tied more closely together. In fact, we are already seeing these trends as they relate to tidal flooding events and one might expect that the low probability-larger storms are likely to become more empirically linked to our changing climate as well".
8. Dates: We only need years–not days and months (unless you are referencing SAR).
R: We apologize with the reviewer but it is not clear what he/she is asking. We use day, month and year for describing the series of events that characterized the Florence hurricane. Having days of the month helps to put things in the context of the SAR data and to explain why the SAR data has missed the maximum flood extent. Again, we are not sure what the suggestion is.
9. Metric System: I would recommend converting to the metric system.
R: We are now using the metric system throughout the entire document.
10. Line 130: I would go ahead and define the "bulls-eye."
R: We thank the reviewer and we have defined the "bull's-eye" as the eye of the storm.
11. Line 138, et seq.: Please define acronyms in their first usage.
R: We have done this, thanks for the suggestion
12. Section 2.3: Are there other data sources from which you can triangulate and validate assessed value with market value to normalize across the distribution to account for varying appraisal methods and time limitations? I'm not sure I understand how this relates to the Zillow data that you later cite.
R. We make use of both ATTOM and Zillow data because they are measuring 2 qualitatively different values. The ATTOM data comes directly from the county Assessor's Office and includes the most accurate version of the Assessment Value, per the county's specific approach to quantifying the local tax base. In addition to that, we were interested in the potential Market Value impact. For that data, we turned to Zillow's aggregated Zestimate. The Zillow data is an automated market value product which should better represent the current market value of any home, or group of homes, relative to the current state of the respective location. As an example of the quality of the metric, see the image below which documents the longitudinal tracking of the Zillow market value estimate against the Case-Schiller Actual Home Value Index.

https://wp.zillowstatic.com/blogs-legacy/1/files/2010/04/image002.png

On the other hand, the Assessment data simply provides a tool from which the local government can understand its tax-base… even if that number is not as accurate as the actual market value.

13. Page 14, Line 369-70: "An explosion in new properties occurred between 1950 and 2000 (Figure 370 9c), likely as a consequence of the economic stimulus following World War II." This is not a sound association over the cited length of time. Economic research would suggest that "half-back" population shifts associated with these areas being low-cost retirement areas for high-cost Northeaster residents is the primary driver of coastal development patterns here.
R: We thank the reviewer for this suggestion. We admit that our phrase, the way it is written, excludes this possibility. In view of this, we have decided to remove the sentence, also to improve the readability of the manuscript.
14. Page 5, Line 125: " no study, to our knowledge, has focused on the impact of urban development on the property exposed to Hurricane Florence." I suppose this is true, but the real contribution is the time-space distribution effects on absolute exposure– independent of climate change attributed events. This exposure has happened and exists whether or not climate change impacts are measured or not.
R: We agree with the reviewer. We are not sure what the reviewer is asking and we did not change the sentence as we specifically focus on Hurricane Florence in this article through the use of the flooded areas for estimating the financial exposure.
15. Page 14: If you could find a weighted average assessment tax, it would be helpful to contextual how important these properties are to local tax bases (county-level). The raw numbers are hard to contextualize.
R. We report in the current version of the paper that the total losses reported amount to about 10% of the total property value across the entire study region. Additionally, due to the inconsistency associated with the way tax rates are created, the market value was seen as a more reliable indicator of proportional impact. We do have students working on the compilation of county level tax rates so that we can look into this in the future.
16. Page 16: When you cite the increase in valuation, my first question is: so what? You really need to another metric for contextualizing exposure. Citing 1940s valuation is methodologically not particularly sound anyway. Again, I recommend looking at local tax base and operating in percentage share.
R. Our data are cross-sectional and represent the 2018 housing stock, but when looking at the impact on total value over time we find that there was little deviation from the 10% affected rate.We thank the reviewer for this suggestion and, as mentioned above, we have started to look into this. However, this might take time and we prefer to keep the absolute values in the current version of the manuscript. Moreover, many of the estimates in the literature and media are reported in absolute $, making our estimates comparable to those.
17. Overall: This paper needs to be significantly edited and simplified. The work is largely solid, but it meanders too much. The connections to climate change are somewhat disconnected as a matter of attribution. The value is the observation method and the context of expanding exposure. The science appears to be well-grounded (beyond my competency to full evaluate), but the economics needs some work.

R: We have revised the manuscript according to this and other suggestions by reviewers. We hope the reviewer will find the new version improved.

REVIEW – nhess-2019-209 (Tedesco *et al.*)

This manuscript aims to quantify an "expanding bull's-eye effect" in the densely developed region of the US Atlantic Coast hit hardest by Hurricane Florence in 2018. Overall, the concept for the article is engaging, and represents a useful analysis of how exposure of physical property to coastal flood risk has changed over time.

I have some broad suggestions (organised by line number) for the authors that I hope might improve the manuscript. I do think there is one major issue (see remarks on Section 3.3, below) that will need to be resolved before this work is ready for publication.

- L45 – the "now problem" phrase is cumbersome and seems unnecessary. Consequences of flooding from sea-level rise has been a fixture of IPCC reports, etc – I think the authors should simplify/clarify this rhetorical line or cut it for a straighter delivery.
- *R: We removed that sentence*
- L50 – I don't understand the counterpoint in this sentence/paragraph. This work is also examining "damaged areas over large regions, hence missing the details necessary to capture the impact of disasters on single unit houses or small areas". Or are the authors suggesting that their remote- sensing work, by contrast, is able to isolate individual buildings? If so, they are missing a significant body of academic literature that examines parcel- by-parcel damages from hurricanes. For example (and works related):

o Deyle, R. E., Chapin, T. S., & Baker, E. J. (2008). The proof of the planning is in the platting: An evaluation of Florida's hurricane exposure mitigation planning mandate. *Journal of the American Planning Association*, *74*(3), 349-370.
o Highfield, W. E., Peacock, W. G., & Van Zandt, S. (2014). Mitigation planning: Why hazard exposure, structural vulnerability, and social vulnerability matter. *Journal of Planning Education and Research*, *34*(3), 287-300.
o Hamideh, S., Peacock, W. G., & Van Zandt, S. (2018). Housing Recovery after Disasters: Primary versus Seasonal/Vacation Housing Markets in Coastal Communities. *Natural Hazards Review*.

R: We thank the reviewer for the suggestion on the papers and we do realize that our sentence might suggest to exclude some existing work. We have, therefore, removed this sentence.

- L65 – Revisit this sentence? The deaths of 51 people did not leave homes without power – just needs a grammatical fix.
- *R: Done, thanks !*
- L70 – "how the locals are dealing with these trends" – rework this sentence for better precision.
- *R: This sentence has been removed to make the paper more readable, as requested by both reviewers.*
- L74 – Statement needs references.
- *R: We have added a reference as requested.*
- L94 – Saying that "permanent water bodies are excluded" here confuses a later calculation of distance to permanent water bodies. Suggest rewriting this to clarify that permanent water bodies are effectively set aside as their own category. They need to be differentiated from the flood extent, but they're still saved for another stage of the analysis.

- *R: Thanks ! We have revised the sentence to clarify this point.*

Section 2, more generally – The methods section sits as a big technical block, relative to the rest of the manuscript, as though a tool-based remote-sensing exercise has been jammed into an analysis that is otherwise conceptually straightforward. (That is, what was the total exposure of properties that ended up inside the flood footprint of Hurricane Florence near its landfall?) The authors might want to relegate much of the technical detail to a supplement, for readers who want to follow along, and only retain a stripped-back version in the main text.
R: We moved a large portion of the technical description concerning SAR in a Supplementary section. We thank the reviewer for this suggestion as the manuscript readability has been considerably improved.

Furthermore – and more importantly – it's not clear from the text WHY the authors undertake the merger of satellite-based and FEMA data for flood extent. The merger forces the authors to spend significant page space trying to explain inconsistencies and uncertainties. That's fine, and important to do, but only if it's clear to the reader why this data synthesis (and remote-sensing exercise) is necessary in the first place. There is a sense that the authors are working with two papers here: one on the data- synthesis approach they describe, and another on the property stock under the flood footprint they derive. At the moment, these two elements are more competitive than mutually supportive.
R: We understand that, in its original form, the role of SAR and FEMA data might have been perceived as "competing". As pointed out by reviewers, this might have also due to the larger role played by the description of the SAR methods in the original manuscript. We have, now, moved a large portion of the SAR technical section into a supplementary material and the manuscript is, hopefully, more balanced. In our manuscript we show that the SAR approach might miss the maximum flood extent because of the acquisition time and that the FEMA approach might miss some of the flooded areas captured by SAR, because of potential intrinsic limitations of the FEMA tool. In view of this, we think that the two approaches are actually complimentary (rather than competitive). We also think that adding SAR information in our manuscript might promote knowledge of alternative techniques to the ones developed by FEMA for those readers who do not have a remote sensing background.

- P11, LX00 [the line numbers get cut off once there are more than two digits, so I've switched convention] – Could the authors clarify here whether "total area" of the properties affected is the total taxed area of the building? Or the simple, plan-view physical footprint?
- *R: We added it is the physical footprint*
- P12, LX07 – first sentence is ungrammatical (and unclear as a result). Given those numbers (and the authors' explanation in that paragraph) FEMA's extent is by far more complete – which further begs the question, described above, about the utility of the satellite method here? Given the limitations to the image analysis the authors lay out, how confident are the they in the $3.3B that the satellite identified but FEMA did not?

Does that render the satellite aspect of this work unnecessary (and a confusing addition), leaving the authors able to focus on FEMA's flood footprint and the property data?
R: We thank the reviewer for this suggestion. We have re-written the sentence. We think that showing the values missed by the FEMA approach, despite being relatively small, shows that the two methods are complementary. As we point out in our manuscript, the FEMA method might miss some of the flooded areas because of issues related to interpolation and/or lack of spatial coverage (either related to missing data collected on the ground or to the model's domain). These points are not missed by the SAR. The combination of the two methods, therefore, increases our confidence in the fact that more flooded areas will be captured. Given the issues at stake, we would like to keep the estimates from both methods. The confidence of the SAR method comes from the comparison of the two water masks obtained from the two methods, giving us high confidence on the estimated values.

- P13, LX35 – Why use Zillow for a median house price and not the ATTOM property dataset (and thus apples to apples)?
- *R: We have replaced the Zillow esrimates with those from our database. We originally used Zillow as that it is easily accessible to readers but we agree with the reviewer that this is a better option.*
- P13, L55 – Suggest that this explanation of the expanding bull's-eye effect needs to go up to the beginning of the document, at first mention (around P5, LX30).
- *R: Following also another reviewer's suggestion, we have added that in the Introduction section.*
- **Section 3.3 – There is a significant issue with the analysis here that the authors will need to explain or address.** At P9, L38, the authors state, "Beside property values, the database also contains the year when each property was built, which we use for our expanding bull's-eye effect analysis."

Information for year built is useful, but it is not a time-series. Unless I missed it (and apologies, if so), the authors do not say when their property data were compiled – but it looks like the dataset is housing stock as of 2018. In that case, they have a current snapshot of stock, not a continuous record of stock through time (i.e., annual records of all properties). That means that the dataset will be inherently skewed toward newer properties, as old buildings get replaced. (See the same issue in Armstrong, S. B., Lazarus, E. D., Limber, P. W., Goldstein, E. B., Thorpe, C., & Ballinger, R. C. (2016). Indications of a positive feedback between coastal development and beach nourishment. Earth's Future, 4(12), 626-635.)
To demonstrate their bull's-eye effect, Ashley & Strader (2016) work with a semi-empirical spatio-temporal model of housing stock in tornado zones over time. Year-built records are not the same. Unless the authors can imagine a way to overcome this limitation in their analysis, they may not have the information they need to actually measure an expanding bull's- eye. The housing stock in their area of interest has certainly grown dramatically over time – the bull's eye is evident from space – but their properties dataset can only capture it indirectly.
R: To clarify: we use the year when the property was built with the property value computed for the year 2018 to calculate the potential exposure of properties to the

flood generated by hurricane Florence. Said this, we acknowledge that the reviewer point is important. The bulls-eye effect is the product or our indirect visualization of the change over time based solely on the data from 2018. As such, we are unable to employ the same spatio-temporal due to the cross-sectional nature of the data. Moving forward, it would be very interesting to incorporate such a technique with temporally varying data, especially given the fact that storms and flooding could dramatically change the landscape by completely removing previous development from the 2018 housing stock.

• P15 – Conclusions section is overlong, I think, and can be distilled more succinctly into key points.

R: WE have revised and reduced the length of the conclusions.

Exposure of properties to the 2018 Hurricane Florence flooding: an expanding bull's-eye perspective

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Abstract. Quantifying the potential exposure of property to damages associated with storm surges, extreme weather, and hurricanes is fundamental to developing frameworks that can be used to conceive and implement mitigation plans as well as support urban development that accounts for such events. In this study, we aim at quantifying the total value and area of properties exposed to the flooding associated with Hurricane Florence that occurred in September 2018. To this aim, we implement a new approach to the identification of affected areas by generating a map of the maximum flood extent obtained from the combination of the extent produced by the Federal Emergency Management Agency's (FEMA) water marks and depth grid with those obtained by means of spaceborne radar remote sensing data. The use of radar in the creation of this extent, allows for the addition of properties commonly missed by FEMA's interpolation methods, especially from pluvial/non-fluvial sources, and can be used in more accurately estimating the exposure and market-value of properties to event-specific flooding. Lastly, we study and quantify how the urban development over the past decades in the regions flooded by Hurricane Florence might have impacted the exposure of properties to present-day storms and floods. This approach is aimed at accounting for what experts are starting to address as the "expanding bull's-eye effect" in which ''targets" of geophysical hazards, such as people and their built environments, are enlarging as populations grow and spread. Our results indicate that the total value of property exposed was \$52B (in 2018 USD, unless otherwise mentioned), with this value increasing from ~ \$10B at the beginning of the past century to the final amount based on the expansion of number

of properties exposed in 2018. We also found that, despite the decrease in the number of properties built during the decade before Florence, much of the new construction was in proximity to permanent water bodies, hence increasing exposure to flooding. Ultimately, the results of this paper provide a new tool for shedding light on the relationships between urban development in coastal areas and the flooding of those areas, which is estimated to increase in view of projected increasing sea level rise, storm surges and strength of storms.

1 Introduction and rationale

The projected rise in sea level, increased floods and storm surge and associated consequences over the 21st century has the potential to do immense economic harm. The economic impact is particularly worrisome in the U.S. due to the fact that much of the most valuable real estate, densest communities, and most productive economic engines are situated disproportionately in coastal regions (Fu et. al., 2016; NOAA, 2013; Kildow et. al., 2014). Recent research has highlighted an ongoing economic signal associated with high-probability flooding events and real estate transactions in coastal communities that can be observed with historical data (see McAlpine and Porter, 2018; Keenan et. al. 2018; and Bernstein et. al. 2019), suggesting that sea level rise (SLR) is already producing meaningful negative economic consequences on coastal communities. Furthermore, there is ample evidence indicating that we are only seeing the first signs of a much more problematic issue both in terms of the flooding scale and the magnitude of associated economic losses (see Fu et al, 2016; Hallegatte et al., 2011; Bin et al., 2011; Bin et al. 2008; Parsons and Powell 2008; Michael 2007). For example: a SLR of ~ 2 meters (e.g., six feet) would flood roughly 100,000 homes only in New York City, with a total value of $39 billion (note that we use 2018 as a reference for the dollar year throughout this manuscript unless otherwise mentioned); a 3 meters (ten-foot) rise would flood 300,000 homes and property with a value of almost $100 billion (Union of Concerned Scientists, UCSUSA, Accessed 29 June, 2019). The equivalent figures for Miami are 54,000 homes and property valued at $14 billion at risk with a ~ 2 meters rise and 130,000 homes and property valued at $32 billion for a ~ 3 meters rise.

Florence was one of the most devastating hurricanes in history as it combined storm surge, strong winds and extreme precipitation. It began as a tropical storm on 1 September, 2018 over the Cabo Verde Islands off the coast of West Africa and peaked as a Category 4 hurricane with winds up to 225 Km/hour before making landfall as a Category 1 hurricane on 14 September, 2018 over Wrightsville Beach, North Carolina. By 5 p.m. on Friday, 14 September, 2018 Florence was downgraded to a tropical storm and early on Sunday, 16 September, it diminished to a tropical depression, with winds of about 360 Km/hour. At least 51 people died as a consequence of flooding associated with rain records (up to 3 feet of rain in some areas according to the Weather Service), with more than 400,000 houses without power and a total damage of $24 billion (https://www.ncdc.noaa.gov/billions/events.pdf). The human cost of Hurricane Florence was a reminder of the power of such storms and these storms are likely becoming more impactful as their surge reaches further inland due to changing tracks, increased strength, and rising seas. The increasing exposure of the public and properties to events similar to Hurricane Florence has unintended consequences of raising the awareness and concern to all types of climate related events (Borenstien and Fingerhut, 2019). Such is likely the case in much of the recent research on real-estate market responses to higher-probability flooding associated with nuisance tidal flooding events (McAlpine and Porter, 2018).

1.1 Sea Level Rise and the economics of flooding

In the previously cited work by McAlpine and Porter (2018) the authors found that properties in Miami-Dade County at risk of frequent tidal flooding had lost over $430 million in potential property value relative to homes that were not a risk of repeated tidal flooding events. Likewise, and also centered in the Miami-Dade region, Keenan et al. (2018) found that homes at lower elevations were being penalized on the market relative to homes at higher elevations. Moreover, in a more comprehensive analysis, the research by Bernstein et al. (2018) found a similar penalty for homes at risk of flooding from increases in SLR, but found that this penalty was primarily driven by investors and an uneven access to information associated with risk. All three of these studies identify an increase in awareness of SLR related flooding events and all document the fact that this trend is relatively new (since about the middle of the last decade). Of particular importance to the recent market response is the fact that increased probability is an important driving force. In the work undertaken by Bernstein et al. (2019), for example, the price penalty for homes at risk of flooding is explicitly driven by the sophistication of investors and their access to risk tools aimed at helping them to make decisions about property value, and long-term appreciation over time. McAlpine and Porter (2018) found, in this regard, that risk associated with being impacted by a Category 1 hurricane is correlated with potential loss property value, but not the probability of being impacted by a higher Category storm. In each of these cases, the research suggests that the real-estate market is becoming more sensitive to the probability of damage associated with inundation from flooding events due to rising seas, storm surges, nuisance flooding and consequences of a changing climate. On the other hand, research out of University of Pennsylvania's Wharton Risk Center by Kunreuther et al. (2019) found that the elasticity concerning the housing market tends to show quick recoveries in areas where the experience of climate catastrophes is characterized as a market shock. Market shocks are generally thought of a one-time (or contiguous time period) events that negatively impact the housing market. Due to the nature of market shocks being lower probability and harder to predict, the housing market tends to see them as unlikely and related to collective internalizations associated with myopia, amnesia, optimism, inertia, simplification, and herding (Kunreuther et.al., 2019). However, market stressors are ubiquitous, high-probability, events that are generally predictable and have historical certainty. In the context in which we are working, increased and unmanageable tidal flooding could be considered a market stressor, while the impact of a single hurricane event could constitute a market shock. Historically, market shocks (such as hurricanes) are much more expensive, in terms of actual economic impacts, and consume more media attention, in terms of the coverage of the events.

Several studies have recently focused on assessing damages from hurricane Florence. Roberson et al. (2019) use overhead imagery, including synthetic aperture radar (SAR) and optical data, to study the impact of Florence related to livestock wastewaters and to crop health. Srikanto et al. (2019) study the spatial distribution of fatalities and associated demographics, indicating that 93 % of the affected buildings were residential structures. The proper quantification of the impact of Hurricane Florence (or more in general of extreme events) is not only helpful for addressing the recovery of the communities impacted by the event but also to provide tools to policy makers, urban planners and city managers that will ultimately guide them through the decision process of reducing the impacts of future events. If it is true, indeed, that climate change is and will be influencing the frequency and strength of storms and floods, it is also true that the impact associated with those events heavily depends on urban development, especially along the coast and in proximity of body waters. Factors such as population growth and the spatial distribution of new properties associated with such growth are key factors for accounting the risks and potential exposure to damage from extreme events.

It is, therefore, crucial to study how the urban development over the past years or decades might have impacted the exposure of properties and population to present-day storms and floods. For example, one of the most devastating hurricanes over the Carolinas before Florence was Hurricane Hugo, reaching the Carolinas on 10 September 1989, with winds up to 260 Km/hour and a total estimated damage of $9.45 billion (in 1989 USD, equivalent to ~ $19B of 2018 USD) and 60 fatalities. Unlike 1989, we have today improved observational and modeling tools that allow us to better estimate the maximum flood extent, a key parameter needed to estimate the potential exposure to damage of properties and other infrastructures. From a modeling point of view, hydrological and hydrodynamic models, in conjunction with improved digital elevation models and the ingestion of gage observation or observation of high water marks, offer the opportunity to generate estimates of maximum flood extent (FEMA, 2019).

1.2 Purpose of this study

Despite recent studies have started to focus on the spatio-temporal variability of property values and human settlements in hurricane-prone areas (e.g., Huang et al., 2019) and on the market responses to increases in observed flooding events (e.g., McAlpine and Porter, 2019; Keenan et. al, 2018), no study, to our knowledge, has focused on the impact of urban development on the property exposed to Hurricane Florence. Addressing this point is crucial to account for those impacts related to the choices that our society makes to continue the expansion of urban areas and that have been addressed by experts as the “bull’s-eye expanding effect” (Ashley and Strader, 2018), in which ‘‘targets” of geophysical hazards, such as people and their built environments, are enlarging as populations grow and spread. We use the term "bull's-eye" to define the eye or center of a storm. Our approach is complementary to those calculating the impact of potential floods under future, possible climate scenarios (e.g., sea level rise or storm surge is changing but the properties distribution remains the same). Ultimately, the merging of the knowledge of the spatio-temporal evolution of properties with future scenarios will allow identifying attributions, improving estimates of damage and risks and supporting urban planning and adaptation strategies. We also aim at understanding the usefulness of remotely sensed satellite data as a method for the identification of impacted areas and for delineating the maximum flood extent. Specifically, we report results concerning the mapping of the flood extent associated with Hurricane Florence estimated from SAR data and compare such extent with the maximum flood extent provided by FEMA. From that exposure, we are able to quantify the property value and total area exposed to Hurricane Florence by combining the flood extent coverage with a database containing publicly available property value attributes.

2 Data and Methods

2.1 Sentinel-1 radar data and identification of inundated areas

From an observational point of view, spaceborne and airborne remote sensing (e.g., Schumann et al., 2011), as well as UAV-based approaches (e.g., Gebrehiwot et al., 2019), offer powerful tools to monitor flood extent (e.g., Domeneghetti et al., 2019; Kordelas et al., 2018; Shumann et al., 2018a, 2018b, Giordan et al., 2018). Optical data can map the presence of surface water at relatively high spatial resolution and accuracy (e.g., Kordelas et al., 2018) but it is limited by the presence of clouds (Shumann et al., 2018). Datasets collected in the microwave region, such as those collected by Synthetic Aperture Radar (SAR), are not limited by the presence of clouds (Shumann et al., 2018, Manavalan, 2017; Huang et al., 2018). The recent launch of Sentinel-1 ESA sensors in September 2014 (Sentinel-1A) and April 2016 (Sentinel-1B, https://sentinel.esa.int/web/sentinel/missions/sentinel-1) allows the mapping of flood extent at unprecedented temporal and spatial resolutions. The combination of the two sensors, indeed, provides a nominal 6-day repeat cycle over the equator and 12-day repeat cycle over North America (Torres et al., 2012). The horizontal spatial resolution of the SAR data is 10 m. For the purpose of this study, we downloaded Sentinel-1 data from the National Aeronautics and Space Administration Alaska Satellite Facility (NASA/ASF, https://earthdata.nasa.gov/about/daacs/daac-asf). More information on the Sentinel-1 sensors can be found at https://sentinel.esa.int/web/sentinel/missions/sentinel-1. Specific details on the SAR-based approach are reported in a supplementary material for reader's convenience.

2.2 FEMA Maximum water extent during Florence

We supplement the radar-derived flood extent with the FEMA's High Water Mark-based Depth Grids and Inundation Polygons from observed and collected Hurricane Florence data. High Water Marks (HWM) are point data collected using high resolution Real Time Kinematic (RTK) GPS systems or other methods. HWM points represent the highest extent of riverine flood or coastal storm surge inundation. The raw data is available at the FEMA Natural Hazard Risk Assessment Program (NHRAP) site and were downloaded for all basins available per FEMAs collection efforts following the hurricane event (https://data.femadata.com/FIMA/NHRAP/Florence/).

The FEMA Maximum Water Extent is distributed as a GIS raster file created to represent the extent of riverine or coastal storm inundation following larger flooding events. The file is created as a derived product following the creation of the Maximum Depth Grids raster file, which is obtained using FEMA HWM data and FEMA's Digital Flood Insurance Rate Map (DRIRM) Base Flood Elevations (LIDAR based elevation data). Using those datasets, a grid is obtained from interpolation to estimate the height of water at any given point between HWM based on base elevation. From this, we extracted a secondary file measuring only the extent of inundation from the storm surge. The FEMA dataset is distributed as an ARCGIS® geodatabase (.gdb format) and we rasterized it at a spatial resolution of 10 m to match the spatial resolution of the SAR data. More information on the FEMA approach for estimating maximum flood extent can be found at https://data.femadata.com/FIMA/NHRAP/Florence.

2.3 Property database

Property value data is compiled from each individual property's county assessor in the form of the property tax assessed value. The data were obtained from a third party provider, ATTOM^{TM} Data Solutions, which provides high quality parcel level information on all properties in the United States and in a value added format (https://www.attomdata.com). The process by which the data are compiled relies solely on publicly available data and the processing, cleansing, standardizing of that data in order to make it available in a user-friendly format. The data used in this analysis include the property's last recorded assessment value for all properties within the states of North and South Carolina. Each county's assessment process varies and, as such, the data are subject to known potential limitations associated with the timing and frequency of home assessments undertaken by local county officials in which the property is located. However, the data also give us the best available comprehensive look at tax base value in a geo-located format for comparison to our storm surge coverage file. Beside property values, the database also contains the year when each property was built, which we use for our expanding bull's-eye effect analysis.

3 Results and discussion

3.1 Assessment of remote-sensing derived areas vs. FEMA maximum water extent

Inundated areas (including permanent water bodies) obtained from Sentinel-1 data are reported as blue regions in Figure 1a, together with the maximum water extent estimated by FEMA (red areas). We used a total of 12 Sentinel-1 images collected between 14 September and 19 September, 2018 and whose footprints are shown in the inset in the top left corner of Figure 1b. Specific names and acquisition times of the radar images are reported in the Supplementary material. We used the 12 images in order to maximize the covered area and to account for the temporal evolution of surface water after the landfall of Hurricane Florence associated with heavy, persistent rainfall.

The comparison between the maximum water extent estimated by FEMA and the water extent mask obtained from Sentinel-1 indicates a matching score (defined here as the percentage of flooded pixels identified by Sentinel-1 with respect to the total number of flooded pixels identified by FEMA) of 11.3 % and a commission error (defined as the relative percentage number of pixels when Sentinel-1 detects flooded areas but FEMA does not with respect to the total number of FEMA flooded pixels) of 9.2 %. When comparing the flood extent obtained with the two approaches we have to remember that FEMA water extent map is based on a combination of modeled and measured quantities and it is, therefore, possible that some areas that were flooded according to the radar images were not included in the FEMA maps, as they are located away from the water bodies (i.e., flood due to rain). For example, Figure 2 shows the maximum water extent from FEMA (red) together with the one derived from Sentinel-1 data nearby the town of Bennettsville, SC (34.6174° N, 79.6848° W). Green dots show the properties within our database. We note that the radar sensor is detecting water over agricultural fields that are not marked by the FEMA maps as flooded, showing the potential improvement on the FEMA maps. Our analysis of the Sentinel-1 backscattering coefficients (not shown here) indicates that the backscattering values recorded for those regions where flood was identified were relatively low (e.g., well below the threshold value and on the order of ~ -20 dB or below), indicating that those were, indeed, inundated areas.

Another factor complicating the comparison between Sentinel-1 and FEMA inundated regions is that the acquisition times of the radar images do not coincide with the time of the maximum water extent associated to storm surge. Figure 3a shows the time series of the water height (mean sea level in meters) for the ocean tide gauge located in Wrightsville Beach, NC (id #8658163), where Hurricane Florence made landfall. Maximum water height was reached on the same day around 15:00 UTC. The image also shows the acquisition times of the Sentinel-1B (14 September, 2018, 11:15:05, UTC) and Sentinel-1A (14 September, 2018, 23:05:48, UTC) as vertical, dashed lines, indicating that the images were, unfortunately, acquired before and after the maximum water height. On the other hand, river gages data show that the maximum water discharge and gage heights inland occurred a few days after hurricane Florence made landfall, because of the heavy precipitation. In this regard, Figures 3b and 3c show, respectively, the daily discharge (in cubic meters per hour) and daily gage height (in meters) recorded at the river gauge station of Lumberton, NC (34.6182° N, 79.0086° W), located about 150 km inland. The data shows the peak discharge and water heights late in the evening of 17 September, 2018. For this area the radar data were collected when the tide gage recorded peak values, confirming the usefulness of this tool to capture flooding that FEMA might have been missing that. As a further example, we show in Figure 4 the flooded areas detected by Sentinel-1 (blue filled regions) on 19 September, 2018 nearby Pasley, Duplin County, NC (34.7854° N, 77.9005° W) and a photograph of the same area collected on 18 September, 2018 by the NOAA Remote Sensing Division to support emergency response requirements (https://storms.ngs.noaa.gov/storms/florence/index.html#7/35.360/-77.820). Most of the flooded areas identified by the NOAA photograph are properly captured by Sentinel-1, with differences between the two also due to the different acquisition times. Nevertheless, for this area, the FEMA map does not indicate any flooding, confirming the complementary nature of the radar dataset.

The complementary nature of the FEMA and SAR-based approaches is helpful to provide more robust maximum flood extent maps than the ones that can be obtained from the two approaches separately. If this is proven to be a reliable method for extent identification, one could easily see it being incorporated in to standard techniques used to identify damage estimates (for instance, into Hazus models). That being said, it is also clear that the radar tends to pick up flooding in agricultural/less populated spaces and that distinction is important and worth spending more time confirming. Given these considerations, for this study we merge the FEMA and Sentinel-1 flood extent maps to generate a maximum composite flood extent map that will be used to assess the property exposure to Hurricane Florence flooding. We will refer to this dataset simply as the "maximum flood extent" in the remaining sections of the manuscript.

3.2 Exposure of property to Hurricane Florence flooding

Figure 5 shows the spatial distribution of the properties within our database overlaid with an image of the eye of Hurricane Florence when it made landfall. Our results indicate that the total area of properties affected by the maximum flood extent water was 70,964,700 m^2 (e.g., physical footprint) being 17.55 % of the total area within our database. When considering only the flood extent estimated by Sentinel-1, the total area of properties affected by the estimated flood extent reduces to 3.2 %, corresponding to 12,939,432 m^2. In order, to quantify potential biases associated with co-registration issues or resampling procedures, we computed the number of properties exposed to the extent of our permanent body water dataset. Our analysis shows that less than 0.2 % of properties was overlapping with the permanent body waters. Consequently, we removed these properties from our analysis.

The total property value exposed estimated using the merged FEMA and SAR flooded areas is $52,079,520,584 (2018 USD, corresponding to ~ 9.5 % of the total property value within our database). The exposed property value is $9,437,931,512 when considering only Sentinel-1 data. The exposed property value computed over the flooded regions estimated by Sentinel-1 but not by FEMA is $3,278,098,601. The relatively small exposure area and property values obtained with Sentinel-1 are due to the limitations discussed above and the difficulties of SAR data to detect flooding in urban areas (e.g., Notti et al., 2018), where the basic assumption for detecting flooded areas by Sentinel-1 is violated by the presence of dense vegetation or buildings. In this case, the radar signal will bounce on the vertical structures (e.g., buildings and trees) after being reflected by the water surface, increasing the amount of energy reaching the radar receivers rather than reducing it, as expected in the case of flooded areas. Despite the presence of flooding on the surface, the backscattering values will not belong to the "wet" Gaussian distribution and the masking effect of buildings and trees will misclassify those areas as dry (e.g., Schumann, 2018a, 2018b). Another reason for the underestimation of property exposure derived from Sentinel-1 data can be seen in Figure 4, where it appears evident that Sentinel-1 is detecting flooding over rural and agricultural areas, where the number of properties is smaller than in highly density populated areas.

In Figure 6 we report the distribution of the number of properties exposed to flooding within our database as a function of property value. A power law function (as reported in Eq. 1)

$$Y = a*x^n \tag{Eq. 1}$$

Fitting the histogram is also plotted as a dashed, black line with *a* and *n* obtained from the fitting as $a = 1.9544*10^6$ and n = -1.1216. The power law function here selected was chosen after testing several functions (e.g., exponential decay, logarithmic, etc.) as the one showing the highest regression coefficient (R = 0.99). According to Zillow©, the median home values in North Carolina and South Carolina are, respectively, $ 184,200 (North Carolina) and $ 166,300 (South Carolina) with a median price of homes of \$196,600 in the case of North Carolina and \$1878,800 for South Carolina. We use these estimates to set to \$200k the median price within our database and evaluate the number of properties this value using Eq. 1. We find that 40 % of the properties exposed to Hurricane Florence flooding were below the selected value. The properties valued between \$200k and \$500k account for another 25 % whereas the properties with values between \$500k and \$1M account for another 25 %. As a reference, the total number of properties valued below \$200k represent ~ 50 % of our database, those between \$200k and \$500k are ~ 25 % and those between \$500k and \$1M roughly 15 %.

Distance from water bodies, especially coastal and riverine bodies, is also a useful indicator of properties vulnerability and potential exposure in hurricane prone areas. Consequently, we expanded our analysis to consider the distance of the properties that were flooded during Florence within our database from permanent water bodies (Figure 7). Values along the x-axis in the plot are obtained as the minimum distance from any of the closest element of the permanent water bodies mask (e.g. ocean, rivers, lakes) to each property within our database. The figure also shows the exponential decay function fitting the histogram and the fitting parameters. From this, we estimate that ~ 95 % of the number of properties exposed to flooding fell within 10 km from body waters. This number increases when considering only the distance from the ocean because of the inland flooding associated with heavy precipitation. We, therefore, use the distance of 10km as a maximum distance for studying the relationship between new properties, their distance from water bodies and the exposure to the Florence flood extent.

3.3 Impact of expansion of urban areas on property exposure

As mentioned in the Introduction, the exposure to floods and other extreme events depends not only on the geophysical hazard but also on how urban growth and infrastructures have been, are and will be evolving in the areas at risk. This concept is well synthesized in what has been named “the expanding bull’s-eye effect” (Ashley and Strader, 2016), arguing that ‘‘targets’’—people and their built environments— of geophysical hazards are enlarging as populations grow and spread. In order, to investigate the impact of the expanding bull’s-eye effect on the property exposed to the flooding of Hurricane Florence, we calculated what would have been the property area and values exposed to the

Florence flood should that have occurred 10, 50 or 100 years ago by using the information contained within our database on the years when properties were built. For the purpose of this analysis, we clarify that we are assuming the same sea levels and topography of today.

Figure 8 shows the spatial distribution of the properties within our database that were built during the a) 1800 – 1900, b) 1900 – 1950, c) 1950 – 2000 and d) 2000 – 2018 periods. We considered the first period as a 100-year one (Figure 8a) because of the relatively small number of properties that were built then. Most of the development between 1900 and 1950 (Figure 9bb) occurred inland and along the coast north of Wilmington, with a relatively small number of new properties built close to water bodies (either rivers or ocean). An explosion in new properties occurred between 1950 and 2000 (Figure 8c), likely as a consequence of the economic stimulus following World War II. The period 2000 – 2018 shows a relatively smaller number of new properties with respect to the previous periods (Figure 8d). This is partially related to the shorter period considered for the last panel. However, our analysis performed on the 10-year period of number of properties built within our database (Figure 9) shows that before 2010 the number of houses built had been increasing exponentially ($Y = 5e\text{-}22 * \exp^{0.0314*X}$, R = 0.99, with X being the year) and that the number of new properties after 2010 drastically dropped, reaching values similar to those observed before the 1950s. This might be due to the 2008 "house crisis" that occurred during that period.

Figure 10 shows the time series of total value of exposed property (in 2018 $B). The inset reports the relative change of the exposed area and value between two consecutive time steps (10 years). Consistent with the results discussed above, a relatively small increase in the exposed property value occurs before the 1940s (from ~ $10B to ~ $12B). The increase becomes substantial after 1940s, driven by the building of new properties (Figure 8), reaching a maximum value of exposed property of ~ $52B in 2018. We fitted the increase in exposed property value after 1900 with an exponential function ($Y = a*\exp^{bX}$) and computed the coefficients providing best fitting ($a = 1.0627*1e^{-13}$, $b = 0.167$, R = 0.97). The maximum relative increase is reached around the year 2000 with a relative increased exposed value of ~ $8B between two successive decades. After then, the relative change in exposed property values decreases to values close to those obtained in the early 1950s.

Distance from permanent water bodies can play a critical role in terms of exposure, with flooding due to Hurricane Florence reaching properties that were up to ~ 10 km from the closest water body. Therefore, we further studied how the property value evolved in terms of the distance from water bodies between 1800 and 2018. As an example, in Figure 11 we show the distribution of properties built during different periods in proximity of Wrightsville beach, where hurricane Florence made landfall, highlighting the expansion of urban areas along the coasts and water bodies especially between 2000 and 2018. In Figure 13 we show the total value of exposed properties within our database as a function of distance from water bodies between 1800 and 2000 (using a 25-year time step) and for the period 2000 – 2018. We note that the curves referring to early periods reach a plateau within a relatively short distance than those referring to later periods, with the saturation values (e.g., the value when the curve becomes flat) being of the order of 1500m in the case of the 1975 – 2000 period. Interestingly, the period 2000 – 2018 does not show a plateau but the exposed property values continue to increase as the distance from water increases. This implies that, despite the most recent decades were characterized by a relatively smaller number of new properties (Figure 9), the potential exposure to Florence of such properties was higher because of the higher number of the exposed properties close to body waters.

4 Conclusions

Increased flooding associated with sea level rise, storm surges and other extreme events has the potential to economically disrupt many areas around the world, with most of valuable real-estate, densest communities and most productive economic engines situated in coastal regions. The specific goal of our study was to quantify the exposure of properties to the flooding associated with Hurricane Florence that hit the Carolinas in September 2018 and to study how the spatio-temporal evolution of new properties during the past century and most recent decades has impacted the property exposure. It is important to note that much of the vulnerability associated with building development in these areas should be considered independent of climate change to this point. However, moving forward, these types of storms are expected to increase in intensity and the link between climate change and potential exposure is likely to be tied more closely together. In fact, we are already seeing these trends as they relate to tidal flooding events and one might expect that the low probability-larger storms are likely to become more linked to our changing climate as well. In order, to properly quantify the exposure of properties to Florence flooding, we developed a maximum flood extent map from the combination of the FEMA maximum extent map generated through the merging of high water marks, the outputs of a model and the flooded areas detected by means of spaceborne radar data acquired by the ESA Sentinel-1 sensors. We found that the total value of property exposed to flooding was ~ \$52B and that this value has increased exponentially from ~ \$10B (2018 \$US) in the early 1900s. This is due to the increase in the number of properties that came to a halt at the beginning of the 2000s, likely as a consequence of the 2008 housing crisis, when the number of new properties built after 2010 was almost half of those built only a decade before. Despite this, the exposure to Florence flooding for those properties built after 2000 continued increasing, because of the number of new properties built within proximity of permanent water bodies and coastlines.

Our work cannot only provide new insights for policy makers and city planners but it also does provide a tool to better estimate how the property market will respond to future disasters. Recent work (e.g., McAlpine and Porter, 2018; Keenan et al., 2018) has found that homes at lower elevations were being penalized on the market relative to homes at higher elevations and that houses exposed to sea level rise (SLR) sell for approximately 7% less than observably equivalent unexposed properties equidistant from the beach (Bernstein et al., 2019). For our future work, we plan to expand our analysis to other modern-day (e.g. Irma, Michael, Katrina and Sandy) and historical (e.g. Hugo in 1989) hurricanes to address similar questions to those addressed in this study. Moreover, we plan to improve the detection of maximum flood extent through the implementation of machine-learning techniques combining radar maps with tide gage interpolated data and other ancillary information. Lastly, the combination of the knowledge on how property distribution changed along the years in conjunction with outputs of physical or probabilistic models that can separate the different contributions associated to flood due to SLR, storm surge and rain will allow to properly quantify what is the impact of the different components of the climate-economic system on the total exposure and, eventually, damage. This will provide a crucial tool for policy makers, governments, citizens and those who are, rightly, interested in quantifying the impact of climate change on the economic and house markets.

Author's contribution.

MT conceived the study and wrote the first draft of the manuscript. JP and SM provided and analyzed the property data, permanent water bodies and LULC data. MT developed and implemented the code for the radar dataset. All authors contributed to the final analysis and final version of the manuscript.

Acknowledgments.
MT acknowledges financial support from Columbia University through the RISE program and from FirstStreet foundation.

Code availability. We used a combination of publicly available software and codes developed ad-hoc for the purposes of this study. Specifically, the ESA SNAP software used to pre-process the Sentinel datasets is available at http://step.esa.int/main/download/snap-download/. We also used QGIS 3.4 to export the property data into a shapefile and to analyze the permanent body waters and the FEMA maximum flood extent data. The software is available at https://qgis.org/en/site/forusers/download.html. We developed in-house codes in Matlab for mapping flooded areas from radar data and to perform the analysis of the exposed property values. These are available upon request to the corresponding author at mtedesco@ldeo.columbia.edu

Data availability. Sentinel1 data is freely available at https://earthdata.nasa.gov/about/daacs/daac-asf. The dataset containing the permanent water bodies is available at https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/. Land use land cover attributes obtained from the National Geospatial Data Asset (NGDA) Land Use Land Cover (LULC) dataset is available at (https://www.sciencebase.gov/catalog/item/581d050ce4b08da350d52363. Maximum water extent by FEMA is available at https://data.femadata.com/FIMA/NHRAP/Florence/. Property value data is compiled from each individual property's county assessor in the form of the property tax assessed value and was obtained from ATTOM™ Data Solutions. Those interested in this dataset should reach out to the corresponding author mtedesco@ldeo.columbia.edu or can be obtained at www.attom.com.

Competing interest. The authors declare no competing interest.

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5 Figures

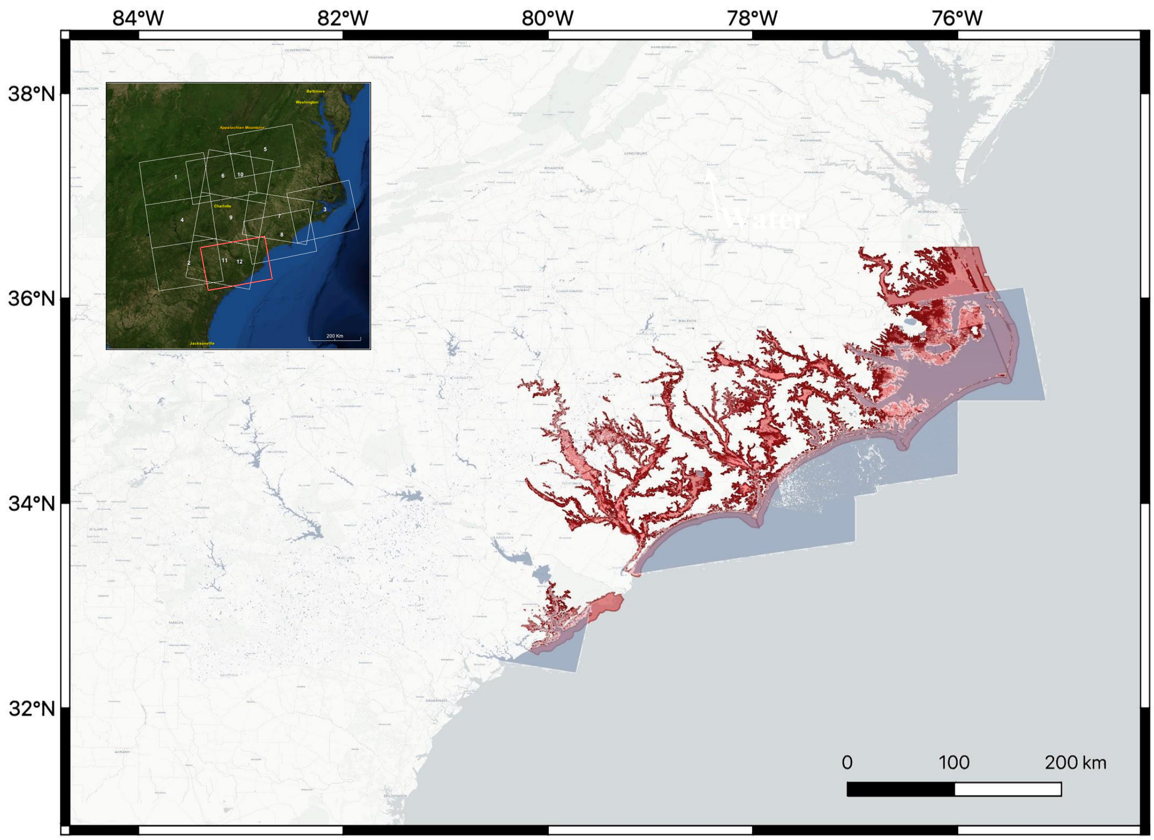


Figure 1 Map of inundated areas estimated by FEMA (red) and by the Sentinel-1 radar images (blue). The inset in the top left corner shows the footprint of the several radar images to create the composite water extent map. Acquisition times and other details concerning the radar images are available in Supplementary material.

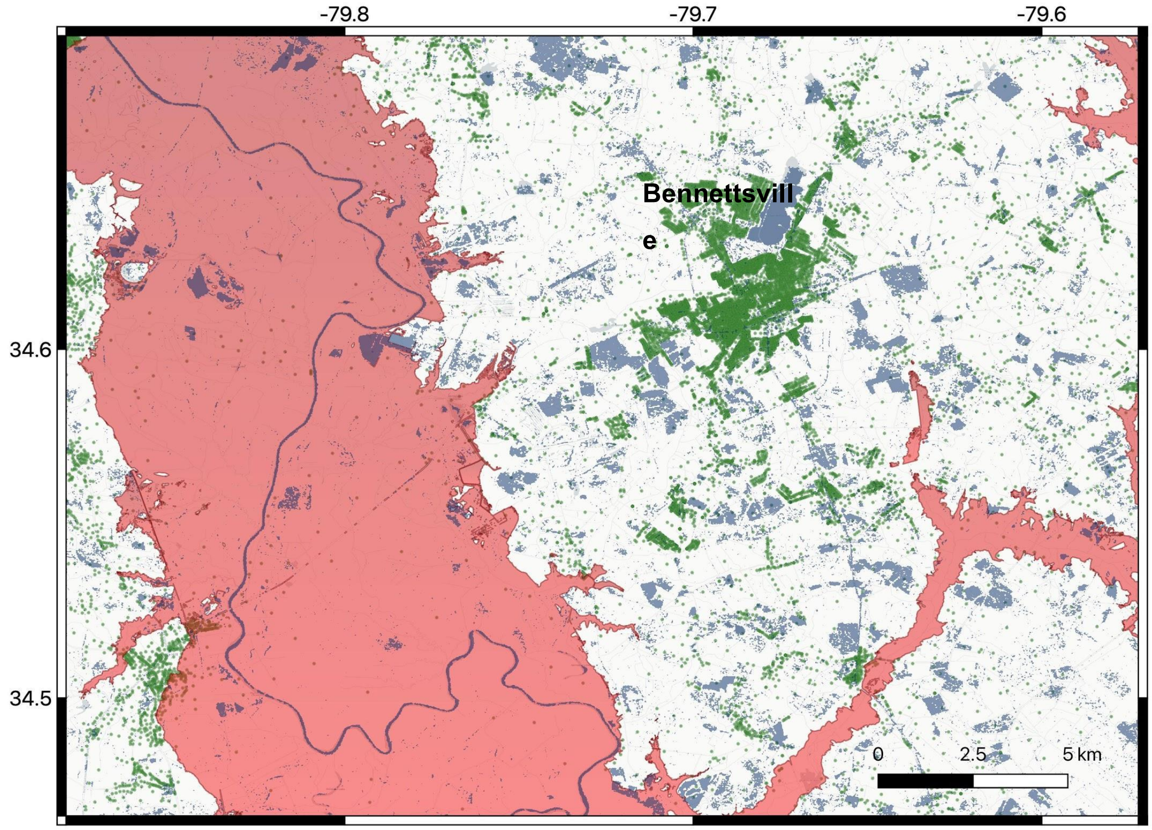
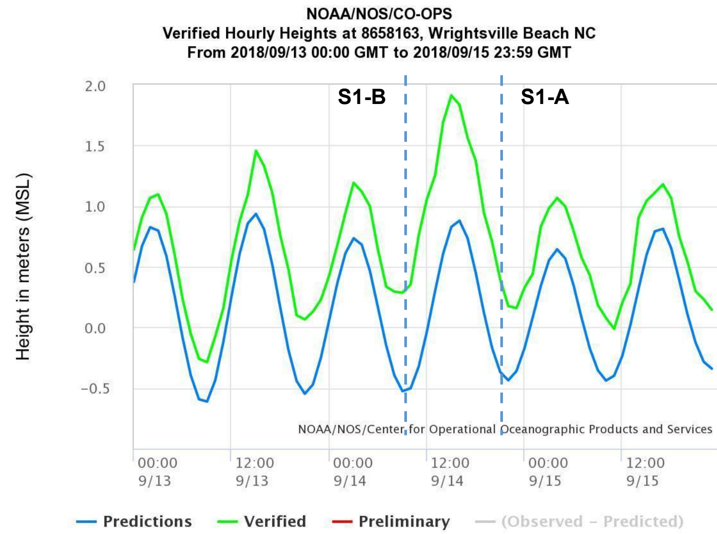


Figure 2 Map of inundated areas estimated by FEMA (red) and by Sentinel-1 (blue) near the town of Bennettsville, SC (34.6174° N, 79.6848° W). Green dots represent the locations of properties for this area.



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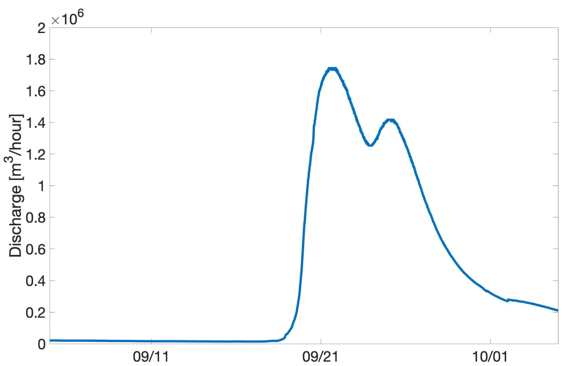

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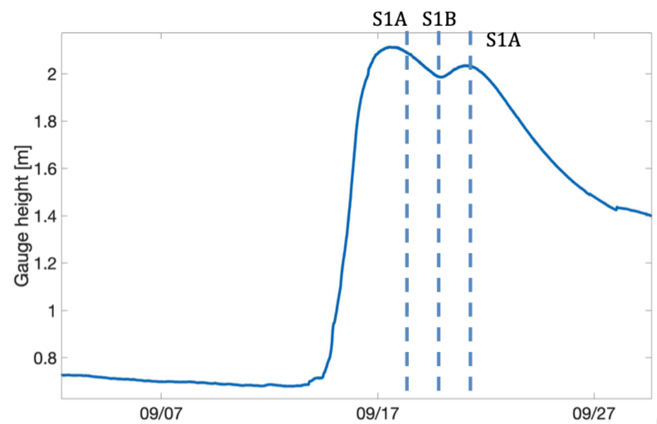

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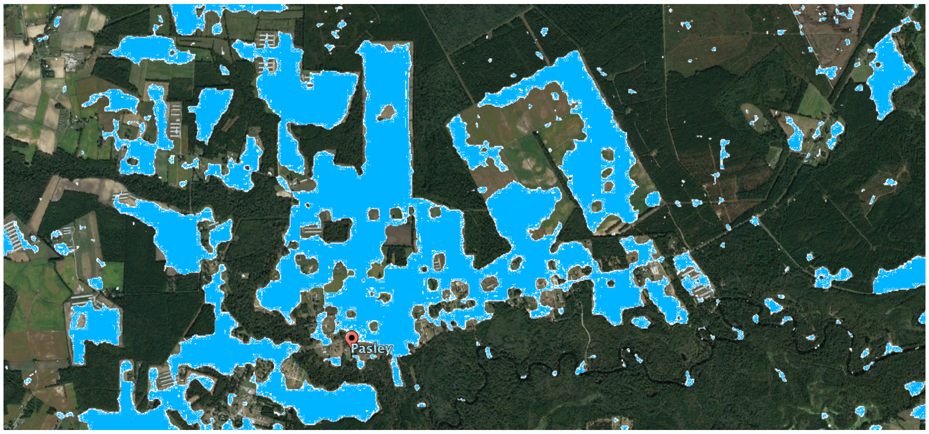
Figure 3 Time series of a) tide gage mean sea level height (meters) recorded at Wrightsville Beach, NC and b) daily discharge (cubic feet per second) and c) daily gage height (feet) recorded at Lumber river (USGS gauge 02134170), NC between 1 September and 30 September 2018. In a) blue line refers to predictions where green squares to verified values. In a) data and plot was obtained from https://tidesandcurrents.noaa.gov/. For data plotted in b) and c) we obtained data and graphs from https://waterdata.usgs.gov/. In a) and c) we also report as dashed vertical lines the acquisition times of the available Sentinel-1 data.



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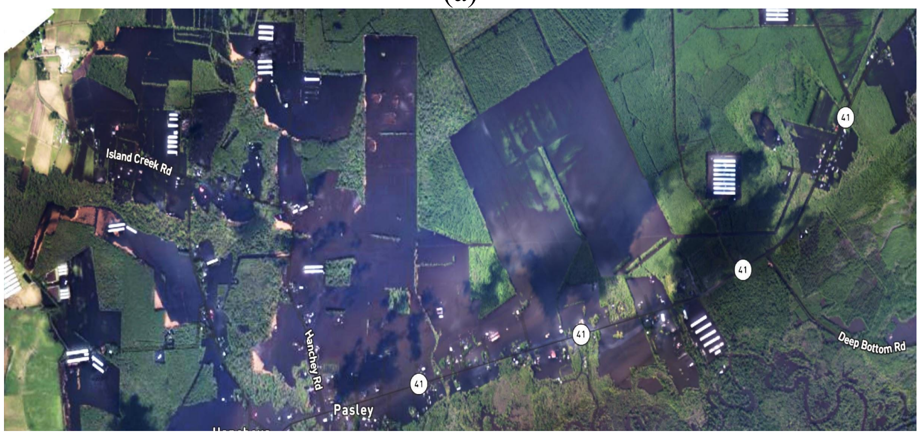

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Figure 4 Flooded areas detected by a) Sentinel-1 data (light blue filled regions) on 19 September, 2018 nearby Pasley, Duplin County, NC (34.7854° N, 77.9005° W) and b) photograph of the same area collected on 18 September, 2018 by NOAA (https://storms.ngs.noaa.gov/storms/florence/index.html#7/35.360/-77.820). Here, dark blue regions show flooded areas.

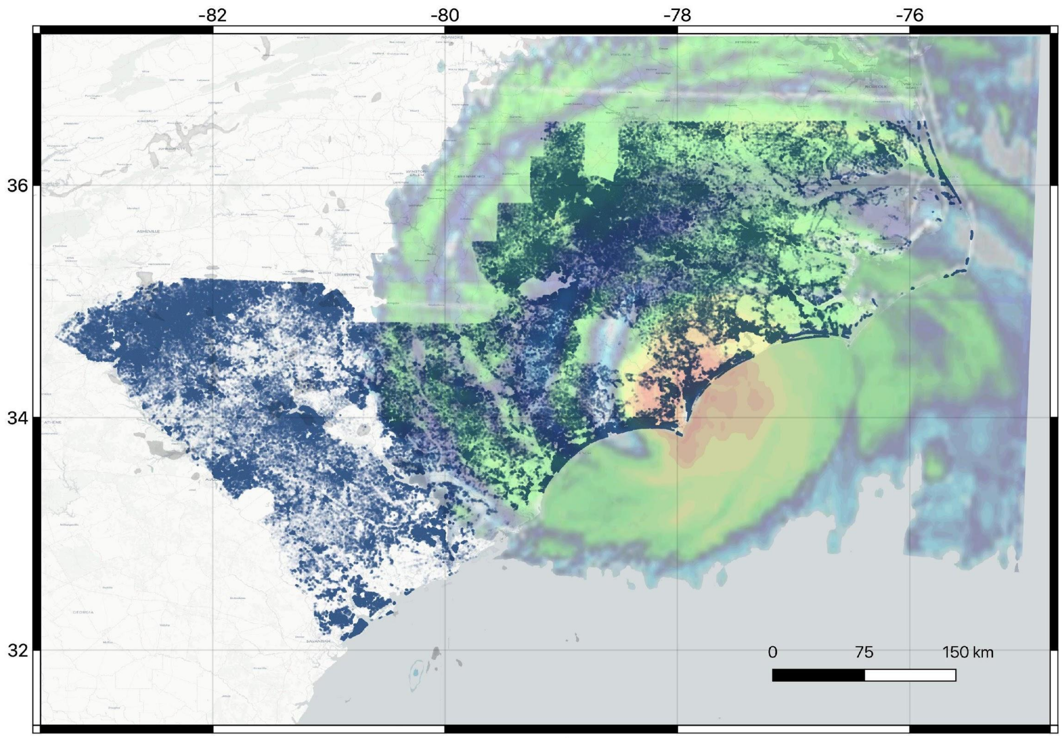


Figure 5 Distribution of properties within our database used to estimate the exposed property damage to Florence Hurricane. An image of the Hurricane Florence making landfall is also reported as a reference (Hurricane image courtesy: Cyclocane).

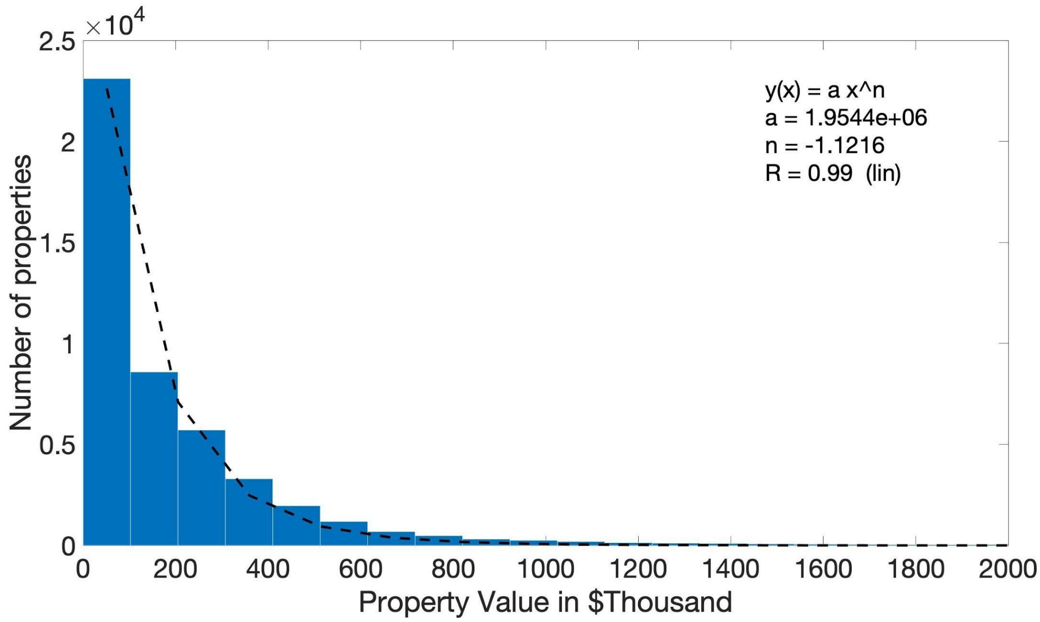


Figure 6 Distribution of the number of properties exposed to flooding as a function of property value. Dashed line represents the power law curve fitting the distribution. The parameters of the fitting power law function are reported in the top right section of the figure.

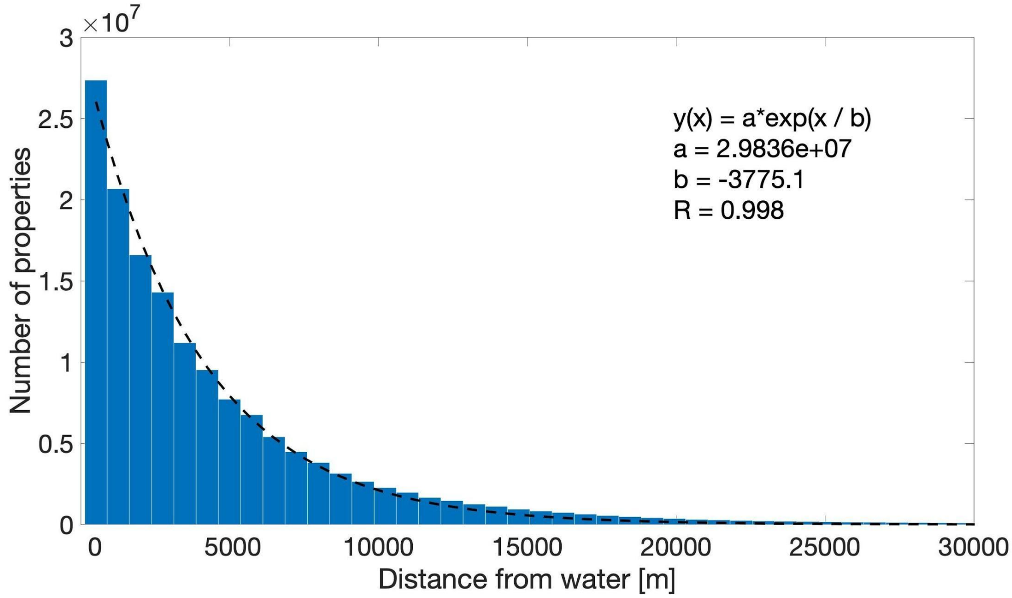
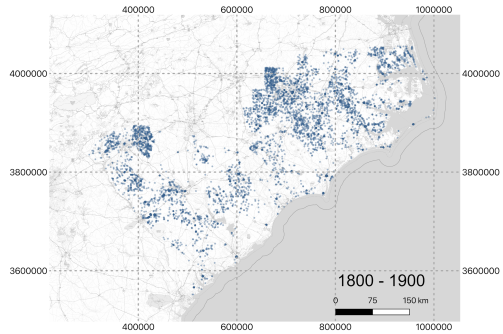


Figure 7 Number of properties as a function of distance from water bodies. Dashed line represents the power law curve fitting the distribution. The parameters of the fitting power law function are also reported in the top right section of the figure.



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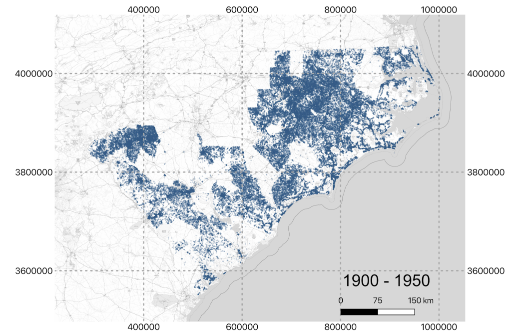

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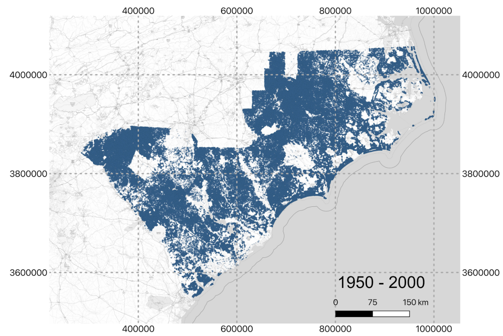

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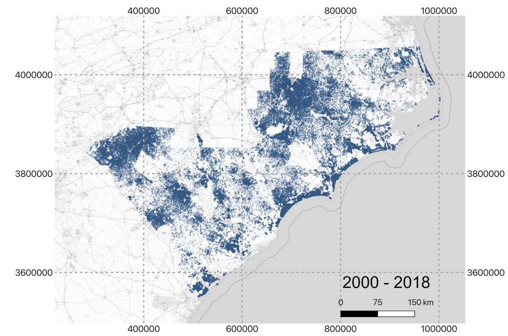

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Figure 8 Spatial distribution of the properties within our database that were built during the a) 1800 – 1900, b) 1900 – 1950, c) 1950 – 2000 and d) 2000 – 2018 periods.

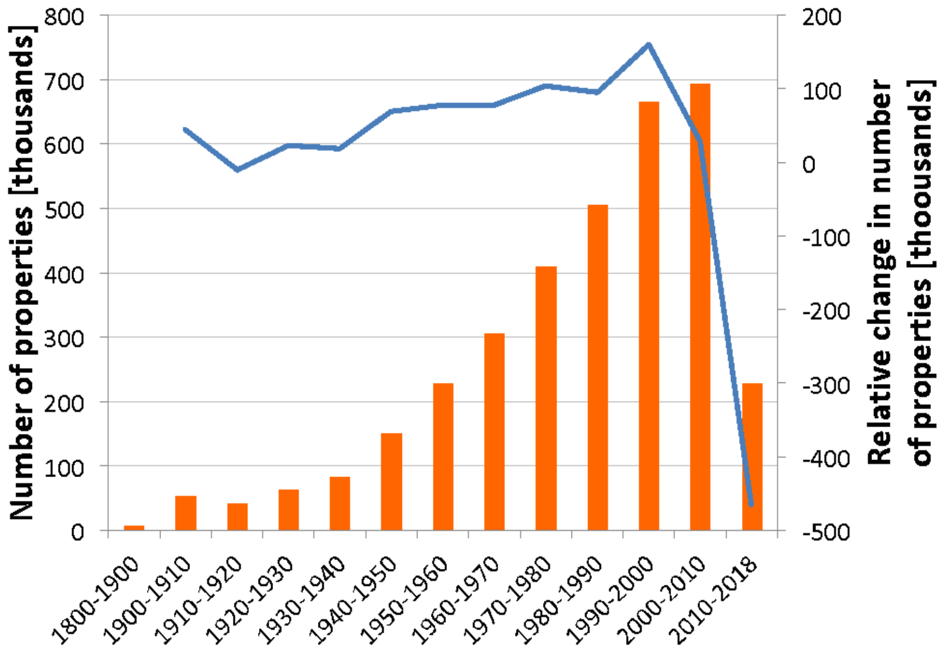


Figure 9 Number of properties (in thousands) built within our data record during different decades (red bars, left axis) and relative change between two consecutive periods (blue line, right axis). Note that the number of properties built between 1800 and 1900 are aggregated as a single value because of the small number of properties built during that period.

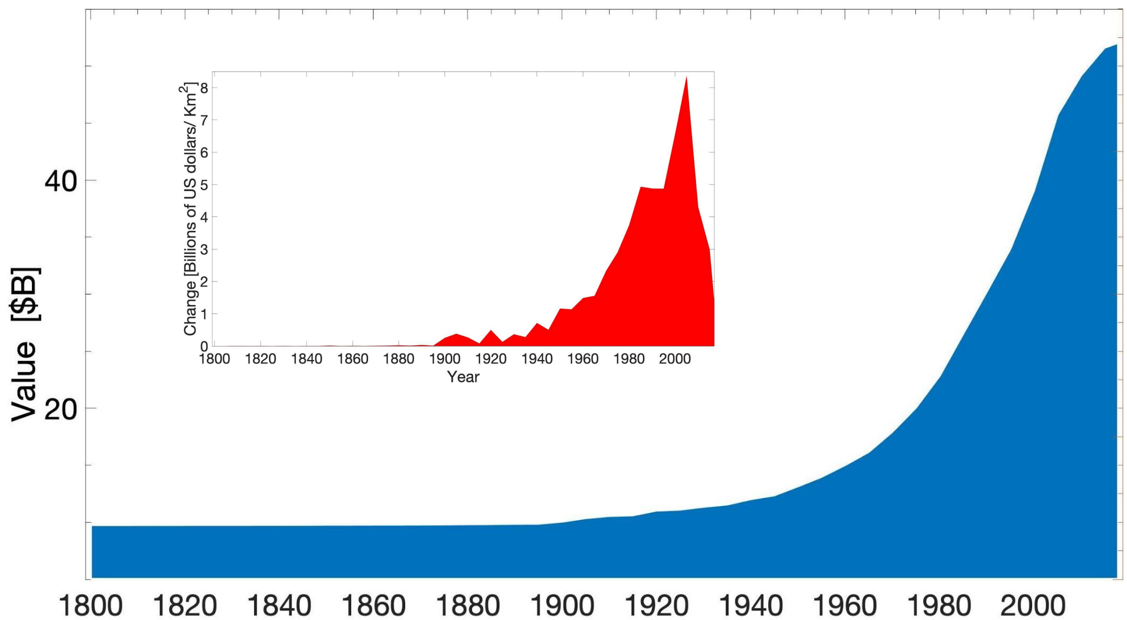
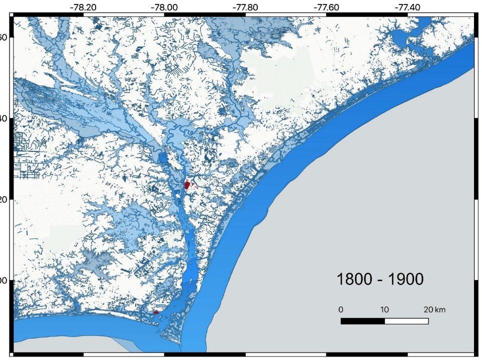


Figure 10 Time series of total value of exposed buildings (in 2018 USD) to the maximum flooded extent region between 1800 and 2018. The inset shows the relative change of the exposed area and value between two consecutive time steps (10 years).



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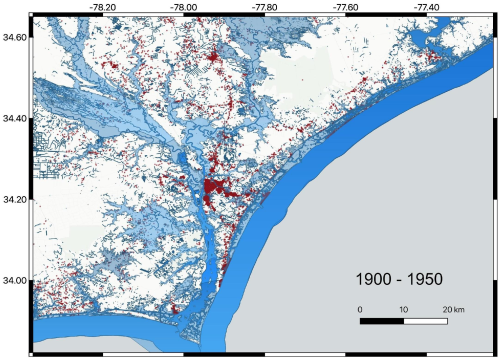

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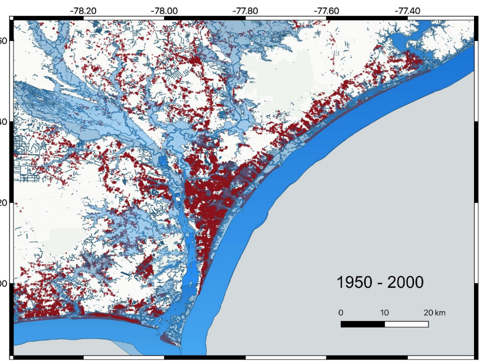

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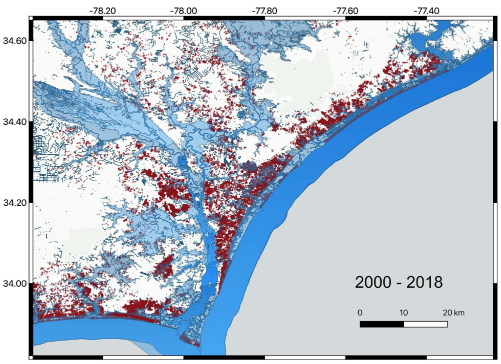

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Figure 11 Distribution of properties (red dots) built a) before 1900, b) between 1900 and 1950, c) between 1950 and 200 and d) between 2000 and 2018 in proximity of Wrightsville Beach, NC where Hurricane Florence made landfall. Dark blue shows permanent body waters where light blue shows the flooded areas.

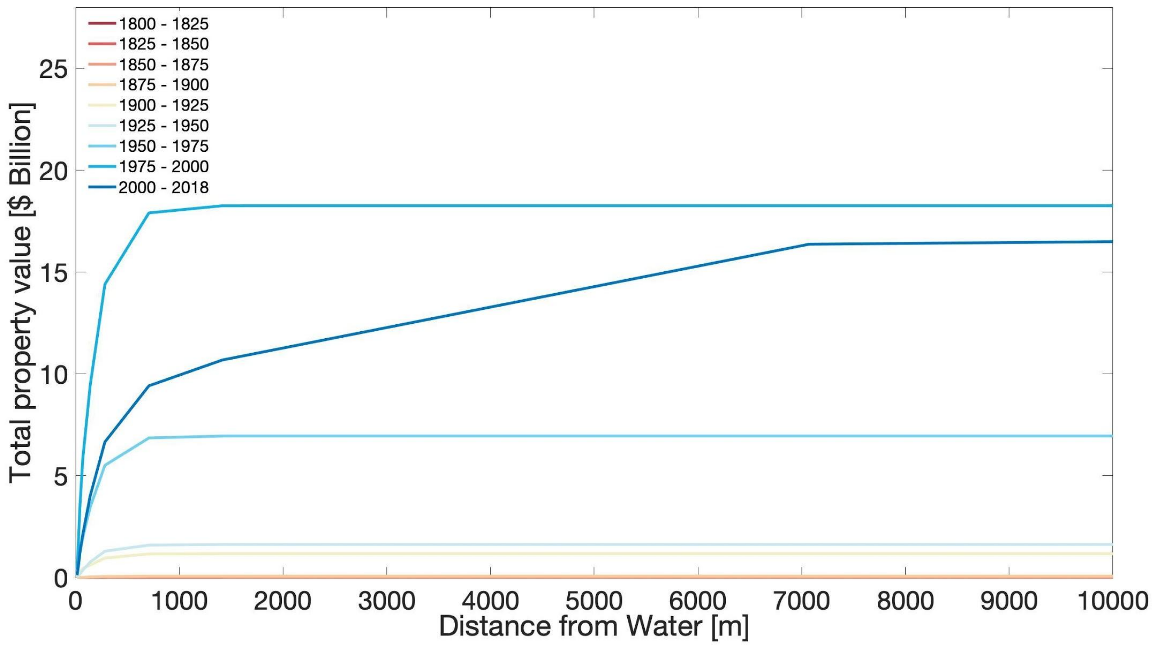

Figure 12 Total value within our database of properties exposed to flooding as a function of distance from water for the different periods reported in the inset.

Exposure of properties to the 2018 Hurricane Florence flooding: an expanding bull's-eye perspective

Marco Tedesco[1], Steven McAlpine[2] and Jeremy R. Porter[3, 4]

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2) FirstStreet Foundation
3) City University of New York - Quantitative Methods in the Social Sciences
4) Columbia University Medical Center - Environmental Health Sciences

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Abstract. Quantifying the potential exposure of property to damages associated with storm surges, extreme weather, and hurricanes is fundamental to developing frameworks that can be used to conceive and implement mitigation plans as well as support urban development that accounts for such events. In this study, we aim at quantifying the total value and area of properties exposed to the flooding associated with Hurricane Florence that occurred in September 2018. To this aim, we implement a new approach to the identification of affected areas by generating a map of the maximum flood extent obtained from the combination of the extent produced by the Federal Emergency Management Agency's (FEMA) water marks and depth grid with those obtained by means of spaceborne radar remote sensing data. The use of radar in the creation of this extent, allows for the addition of properties commonly missed by FEMA's interpolation methods, especially from pluvial/non-fluvial sources, and can be used in more accurately estimating the exposure and market-value of properties to event-specific flooding. Lastly, we study and quantify how the urban development over the past decades in the regions flooded by Hurricane Florence might have impacted the exposure of properties to present-day storms and floods. This approach is aimed at accounting for what experts are starting to address as the "expanding bull's-eye effect" in which ''targets" of geophysical hazards, such as people and their built environments, are enlarging as populations grow and spread. Our results indicate that the total value of property exposed was $52B (in 2018 USD, unless otherwise mentioned), with this value increasing from ~ $10B at the beginning of the past century to the final amount based on the expansion of number

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of properties exposed in 2018. We also found that, despite the decrease in the number of properties built during the decade before Florence, much of the new construction was in proximity to permanent water bodies, hence increasing exposure to flooding. Ultimately, the results of this paper provide a new tool for shedding light on the relationships between urban development in coastal areas and the flooding of those areas, which is estimated to increase in view of projected increasing sea level rise, storm surges and strength of storms.

1 Introduction and rationale

The projected rise in sea level, increased floods and storm surge and associated consequences over the 21st century has the potential to do immense economic harm. The economic impact is particularly worrisome in the U.S. due to the fact that much of the most valuable real estate, densest communities, and most productive economic engines are situated disproportionately in coastal regions (Fu et. al., 2016; NOAA, 2013; Kildow et. al., 2014). Recent research has highlighted an ongoing economic signal associated with high-probability flooding events and real estate transactions in coastal communities that can be observed with historical data (see McAlpine and Porter, 2018; Keenan et. al. 2018; and Bernstein et. al. 2019), suggesting that sea level rise (SLR) is already producing meaningful negative economic consequences on coastal communities. Furthermore, there is ample evidence indicating that we are only seeing the first signs of a much more problematic issue both in terms of the flooding scale and the magnitude of associated economic losses (see Fu et al, 2016; Hallegatte et al., 2011; Bin et al., 2011; Bin et al. 2008; Parsons and Powell 2008; Michael 2007). For example: a SLR of ~ 2 meters (e.g., six feet) would flood roughly 100,000 homes only in New York City, with a total value of $39 billion (note that we use 2018 as a reference for the dollar year throughout this manuscript unless otherwise mentioned); a 3 meters (ten-foot) rise would flood 300,000 homes and property with a value of almost $100 billion (Union of Concerned Scientists, UCSUSA, Accessed 29 June, 2019). The equivalent figures for Miami are 54,000 homes and property valued at $14 billion at risk with a ~ 2 meters rise and 130,000 homes and property valued at $32 billion for a ~ 3 meters rise.

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Florence was one of the most devastating hurricanes in history as it combined storm surge, strong winds and extreme precipitation. It began as a tropical storm on 1 September, 2018 over the Cabo Verde Islands off the coast of West Africa and peaked as a Category 4 hurricane with winds up to 225 Km/hour before making landfall as a Category 1 hurricane on 14 September, 2018 over Wrightsville Beach, North Carolina. By 5 p.m. on Friday, 14 September, 2018 Florence was downgraded to a tropical storm and early on Sunday, 16 September, it diminished to a tropical depression, with winds of about 360 Km/hour. At least 51 people died as a consequence of flooding associated with rain records (up to 3 feet of rain in some areas according to the Weather Service), with more than 400,000 houses without power and a total damage of $24 billion (https://www.ncdc.noaa.gov/billions/events.pdf). The human cost of Hurricane Florence was a reminder of the power of such storms and these storms are likely becoming more impactful as their surge reaches further inland due to changing tracks, increased strength, and rising seas. The increasing exposure of the public and properties to events similar to Hurricane Florence has unintended consequences of raising the awareness and concern to all types of climate related events (Borenstien and Fingerhut, 2019). Such is likely the case in much of the recent research on real-estate market responses to higher-probability flooding associated with nuisance tidal flooding events (McAlpine and Porter, 2018).

1.1 Sea Level Rise and the economics of flooding

In the previously cited work by McAlpine and Porter (2018) the authors found that properties in Miami-Dade County at risk of frequent tidal flooding had lost over $430 million in potential property value relative to homes that were not a risk of repeated tidal flooding events. Likewise, and also centered in the Miami-Dade region, Keenan et al. (2018) found that homes at lower elevations were being penalized on the market relative to homes at higher elevations. Moreover, in a more comprehensive analysis, the research by Bernstein et al. (2018) found a similar penalty for homes at risk of flooding from increases in SLR, but found that this penalty was primarily driven by investors and an uneven access to information associated with risk. All three of these studies identify an increase in awareness of SLR related flooding events and all document the fact that this trend is relatively new

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(since about the middle of the last decade). Of particular importance to the recent market response is the fact that increased probability is an important driving force. In the work undertaken by Bernstein et al. (2019), for example, the price penalty for homes at risk of flooding is explicitly driven by the sophistication of investors and their access to risk tools aimed at helping them to make decisions about property value, and long-term appreciation over time. McAlpine and Porter (2018) found, in this regard that risk associated with being impacted by a Category 1 hurricane is correlated with potential loss property value, but not the probability of being impacted by a higher Category storm. In each of these cases, the research suggests that the real-estate market is becoming more sensitive to the probability of damage associated with inundation from flooding events due to rising seas, storm surges, nuisance flooding and consequences of a changing climate. On the other hand, research out of University of Pennsylvania's Wharton Risk Center by Kunreuther et al. (2019) found that the elasticity concerning the housing market tends to show quick recoveries in areas where the experience of climate catastrophes is characterized as a market shock. Market shocks are generally thought of a one-time (or contiguous time period) events that negatively impact the housing market. Due to the nature of market shocks being lower probability and harder to predict, the housing market tends to see them as unlikely and related to collective internalizations associated with myopia, amnesia, optimism, inertia, simplification, and herding (Kunreuther et.al., 2019). However, market stressors are ubiquitous, high-probability, events that are generally predictable and have historical certainty. In the context in which we are working, increased and unmanageable tidal flooding could be considered a market stressor, while the impact of a single hurricane event could constitute a market shock. Historically, market shocks (such as hurricanes) are much more expensive, in terms of actual economic impacts, and consume more media attention, in terms of the coverage of the events.

Several studies have recently focused on assessing damages from hurricane Florence. Roberson et al. (2019) use overhead imagery, including synthetic aperture radar (SAR) and optical data, to study the impact of Florence related to livestock wastewaters and to crop health. Srikanto et al. (2019) study the spatial distribution of fatalities and associated demographics, indicating that 93 % of the affected buildings were residential structures. The proper quantification of the impact of Hurricane Florence (or more in general of extreme events) is not only helpful for addressing the recovery of the communities

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impacted by the event but also to provide tools to policy makers, urban planners and city managers that will ultimately guide them through the decision process of reducing the impacts of future events. If it is true, indeed, that climate change is and will be influencing the frequency and strength of storms and floods, it is also true that the impact associated with those events heavily depends on urban development, especially along the coast and in proximity of body waters. Factors such as population growth and the spatial distribution of new properties associated with such growth are key factors for accounting the risks and potential exposure to damage from extreme events.

It is, therefore, crucial to study how the urban development over the past years or decades might have impacted the exposure of properties and population to present-day storms and floods. For example, one of the most devastating hurricanes over the Carolinas before Florence was Hurricane Hugo, reaching the Carolinas on 10 September 1989, with winds up to 260 Km/hour and a total estimated damage of $9.45 billion (in 1989 USD, equivalent to ~ $19B of 2018 USD) and 60 fatalities. Unlike 1989, we have today improved observational and modeling tools that allow us to better estimate the maximum flood extent, a key parameter needed to estimate the potential exposure to damage of properties and other infrastructures. From a modeling point of view, hydrological and hydrodynamic models, in conjunction with improved digital elevation models and the ingestion of gage observation or observation of high water marks, offer the opportunity to generate estimates of maximum flood extent (FEMA, 2019).

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1.2 Purpose of this study

Despite recent studies have started to focus on the spatio-temporal variability of property values and human settlements in hurricane-prone areas (e.g., Huang et al., 2019) and on the market responses to increases in observed flooding events (e.g., McAlpine and Porter, 2019; Keenan et. al, 2018), no study, to our knowledge, has focused on the impact of urban development on the property exposed to Hurricane Florence. Addressing this point is crucial to account for those impacts related to the choices that our society makes to continue the expansion of urban areas and that have been addressed by experts as the "bull's-eye expanding effect" (Ashley and Strader, 2018), in which ''targets'' of geophysical hazards, such as people and their built environments, are enlarging as populations grow and spread. We

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use the term "bull's-eye" to define the eye or center of a storm. Our approach is complementary to those calculating the impact of potential floods under future, possible climate scenarios (e.g., sea level rise or storm surge is changing but the properties distribution remains the same). Ultimately, the merging of the knowledge of the spatio-temporal evolution of properties with future scenarios will allow identifying attributions, improving estimates of damage and risks and supporting urban planning and adaptation strategies. We also aim at understanding the usefulness of remotely sensed satellite data as a method for the identification of impacted areas and for delineating the maximum flood extent. Specifically, we report results concerning the mapping of the flood extent associated with Hurricane Florence estimated from SAR data and compare such extent with the maximum flood extent provided by FEMA. From that exposure, we are able to quantify the property value and total area exposed to Hurricane Florence by combining the flood extent coverage with a database containing publicly available property value attributes.

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2 Data and Methods

2.1 Sentinel-1 radar data and identification of inundated areas

From an observational point of view, spaceborne and airborne remote sensing (e.g., Schumann et al., 2011), as well as UAV-based approaches (e.g., Gebrehiwot et al., 2019), offer powerful tools to monitor flood extent (e.g., Domeneghetti et al., 2019; Kordelas et al., 2018; Shumann et al., 2018a, 2018b, Giordan et al., 2018). Optical data can map the presence of surface water at relatively high spatial resolution and accuracy (e.g., Kordelas et al., 2018) but it is limited by the presence of clouds (Shumann et al., 2018). Datasets collected in the microwave region, such as those collected by Synthetic Aperture Radar (SAR), are not limited by the presence of clouds (Shumann et al., 2018, Manavalan, 2017; Huang et al., 2018). The recent launch of Sentinel-1 ESA sensors in September 2014 (Sentinel-1A) and April 2016 (Sentinel-1B, https://sentinel.esa.int/web/sentinel/missions/sentinel-1) allows the mapping of flood extent at unprecedented temporal and spatial resolutions. The combination of the two sensors, indeed, provides a nominal 6-day repeat cycle over the equator and 12-day repeat cycle over North America (Torres et al., 2012). The horizontal spatial resolution of the SAR data is 10 m. For the

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purpose of this study, we downloaded Sentinel-1 data from the National Aeronautics and Space Administration Alaska Satellite Facility (NASA/ASF, https://earthdata.nasa.gov/about/daacs/daac-asf). More information on the Sentinel-1 sensors can be found at https://sentinel.esa.int/web/sentinel/missions/sentinel-1. Specific details on the SAR-based approach are reported in a supplementary material for reader's convenience.

2.2 FEMA Maximum water extent during Florence

We supplement the radar-derived flood extent with the FEMA's High Water Mark-based Depth Grids and Inundation Polygons from observed and collected Hurricane Florence data. High Water Marks (HWM) are point data collected using high resolution Real Time Kinematic (RTK) GPS systems or other methods. HWM points represent the highest extent of riverine flood or coastal storm surge inundation. The raw data is available at the FEMA Natural Hazard Risk Assessment Program (NHRAP) site and were downloaded for all basins available per FEMAs collection efforts following the hurricane event (https://data.femadata.com/FIMA/NHRAP/Florence/).

The FEMA Maximum Water Extent is distributed as a GIS raster file created to represent the extent of riverine or coastal storm inundation following larger flooding events. The file is created as a derived product following the creation of the Maximum Depth Grids raster file, which is obtained using FEMA HWM data and FEMA's Digital Flood Insurance Rate Map (DRIRM) Base Flood Elevations (LIDAR based elevation data). Using those datasets, a grid is obtained from interpolation to estimate the height of water at any given point between HWM based on base elevation. From this, we extracted a secondary file measuring only the extent of inundation from the storm surge. The FEMA dataset is distributed as an ARCGIS® geodatabase (.gdb format) and we rasterized it at a spatial resolution of 10 m to match the spatial resolution of the SAR data. More information on the FEMA approach for estimating maximum flood extent can be found at https://data.femadata.com/FIMA/NHRAP/Florence.

2.3 Property database

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Property value data is compiled from each individual property's county assessor in the form of the property tax assessed value. The data were obtained from a third party provider, ATTOM™ Data Solutions, which provides high quality parcel level information on all properties in the United States and in a value added format (https://www.attomdata.com). The process by which the data are compiled relies solely on publicly available data and the processing, cleansing, standardizing of that data in order to make it available in a user-friendly format. The data used in this analysis include the property's last recorded assessment value for all properties within the states of North and South Carolina. Each county's assessment process varies and, as such, the data are subject to known potential limitations associated with the timing and frequency of home assessments undertaken by local county officials in which the property is located. However, the data also give us the best available comprehensive look at tax base value in a geo-located format for comparison to our storm surge coverage file. Beside property values, the database also contains the year when each property was built, which we use for our expanding bull's-eye effect analysis.

3 Results and discussion

3.1 Assessment of remote-sensing derived areas vs. FEMA maximum water extent

Inundated areas (including permanent water bodies) obtained from Sentinel-1 data are reported as blue regions in Figure 1a, together with the maximum water extent estimated by FEMA (red areas). We used a total of 12 Sentinel-1 images collected between 14 September and 19 September, 2018 and whose footprints are shown in the inset in the top left corner of Figure 1b. Specific names and acquisition times of the radar images are reported in the Supplementary material. We used the 12 images in order to maximize the covered area and to account for the temporal evolution of surface water after the landfall of Hurricane Florence associated with heavy, persistent rainfall.

The comparison between the maximum water extent estimated by FEMA and the water extent mask obtained from Sentinel-1 indicates a matching score (defined here as the percentage of flooded pixels identified by Sentinel-1 with respect to the total number of flooded pixels identified by FEMA) of 11.3 % and a commission error (defined as the relative percentage number of pixels when Sentinel-1

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detects flooded areas but FEMA does not with respect to the total number of FEMA flooded pixels) of 9.2 %. When comparing the flood extent obtained with the two approaches we have to remember that FEMA water extent map is based on a combination of modeled and measured quantities and it is, therefore, possible that some areas that were flooded according to the radar images were not included in the FEMA maps, as they are located away from the water bodies (i.e., flood due to rain). For example, Figure 2 shows the maximum water extent from FEMA (red) together with the one derived from Sentinel-1 data nearby the town of Bennettsville, SC (34.6174° N, 79.6848° W). Green dots show the properties within our database. We note that the radar sensor is detecting water over agricultural fields that are not marked by the FEMA maps as flooded, showing the potential improvement on the FEMA maps. Our analysis of the Sentinel-1 backscattering coefficients (not shown here) indicates that the backscattering values recorded for those regions where flood was identified were relatively low (e.g., well below the threshold value and on the order of ~ -20 dB or below), indicating that those were, indeed, inundated areas.

Another factor complicating the comparison between Sentinel-1 and FEMA inundated regions is that the acquisition times of the radar images do not coincide with the time of the maximum water extent associated to storm surge. Figure 3a shows the time series of the water height (mean sea level in meters) for the ocean tide gauge located in Wrightsville Beach, NC (id #8658163), where Hurricane Florence made landfall. Maximum water height was reached on the same day around 15:00 UTC. The image also shows the acquisition times of the Sentinel-1B (14 September, 2018, 11:15:05, UTC) and Sentinel-1A (14 September, 2018, 23:05:48, UTC) as vertical, dashed lines, indicating that the images were, unfortunately, acquired before and after the maximum water height. On the other hand, river gages data show that the maximum water discharge and gage heights inland occurred a few days after hurricane Florence made landfall, because of the heavy precipitation. In this regard, Figures 3b and 3c show, respectively, the daily discharge (in cubic meters per hour) and daily gage height (in meters) recorded at the river gauge station of Lumberton, NC (34.6182° N, 79.0086° W), located about 150 km inland. The data shows the peak discharge and water heights late in the evening of 17 September, 2018. For this area the radar data were collected when the tide gage recorded peak values, confirming the usefulness of this tool to capture flooding that FEMA might have been missing that. As a further

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example, we show in Figure 4 the flooded areas detected by Sentinel-1 (blue filled regions) on 19 September, 2018 nearby Pasley, Duplin County, NC (34.7854° N, 77.9005° W) and a photograph of the same area collected on 18 September, 2018 by the NOAA Remote Sensing Division to support emergency response requirements (https://storms.ngs.noaa.gov/storms/florence/index.html#7/35.360/-77.820). Most of the flooded areas identified by the NOAA photograph are properly captured by Sentinel-1, with differences between the two also due to the different acquisition times. Nevertheless, for this area, the FEMA map does not indicate any flooding, confirming the complementary nature of the radar dataset.

The complementary nature of the FEMA and SAR-based approaches is helpful to provide more robust maximum flood extent maps than the ones that can be obtained from the two approaches separately. If this is proven to be a reliable method for extent identification, one could easily see it being incorporated in to standard techniques used to identify damage estimates (for instance, into Hazus models). That being said, it is also clear that the radar tends to pick up flooding in agricultural/less populated spaces and that distinction is important and worth spending more time confirming. Given these considerations, for this study we merge the FEMA and Sentinel-1 flood extent maps to generate a maximum composite flood extent map that will be used to assess the property exposure to Hurricane Florence flooding. We will refer to this dataset simply as the “maximum flood extent” in the remaining sections of the manuscript.

3.2 Exposure of property to Hurricane Florence flooding

Figure 5 shows the spatial distribution of the properties within our database overlaid with an image of the eye of Hurricane Florence when it made landfall. Our results indicate that the total area of properties affected by the maximum flood extent water was 70,964,700 m^2 (e.g., physical footprint) being 17.55 % of the total area within our database. When considering only the flood extent estimated by Sentinel-1, the total area of properties affected by the estimated flood extent reduces to 3.2 %, corresponding to 12,939,432 m^2. In order, to quantify potential biases associated with co-registration issues or resampling procedures, we computed the number of properties exposed to the extent of our

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permanent body water dataset. Our analysis shows that less than 0.2 % of properties was overlapping with the permanent body waters. Consequently, we removed these properties from our analysis.

The total property value exposed estimated using the merged FEMA and SAR flooded areas is $52,079,520,584 (2018 USD, corresponding to ~ 9.5 % of the total property value within our database). The exposed property value is $9,437,931,512 when considering only Sentinel-1 data. The exposed property value computed over the flooded regions estimated by Sentinel-1 but not by FEMA is $3,278,098,601. The relatively small exposure area and property values obtained with Sentinel-1 are due to the limitations discussed above and the difficulties of SAR data to detect flooding in urban areas (e.g., Notti et al., 2018), where the basic assumption for detecting flooded areas by Sentinel-1 is violated by the presence of dense vegetation or buildings. In this case, the radar signal will bounce on the vertical structures (e.g., buildings and trees) after being reflected by the water surface, increasing the amount of energy reaching the radar receivers rather than reducing it, as expected in the case of flooded areas. Despite the presence of flooding on the surface, the backscattering values will not belong to the "wet" Gaussian distribution and the masking effect of buildings and trees will misclassify those areas as dry (e.g., Schumann, 2018a, 2018b). Another reason for the underestimation of property exposure derived from Sentinel-1 data can be seen in Figure 4, where it appears evident that Sentinel-1 is detecting flooding over rural and agricultural areas, where the number of properties is smaller than in highly density populated areas.

In Figure 6 we report the distribution of the number of properties exposed to flooding within our database as a function of property value. A power law function (as reported in Eq. 1)

$$Y = a*x^n \qquad \text{(Eq. 1)}$$

Fitting the histogram is also plotted as a dashed, black line with *a* and *n* obtained from the fitting as $a = 1.9544*10^6$ and n = -1.1216. The power law function here selected was chosen after testing several functions (e.g., exponential decay, logarithmic, etc.) as the one showing the highest regression coefficient (R = 0.99). According to Zillow©, the median home values in North Carolina and South Carolina are, respectively, $ 184,200 (North Carolina) and $ 166,300 (South Carolina) with a median

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price of homes of $196,600 in the case of North Carolina and $1878,800 for South Carolina. We use these estimates to set to $200k the median price within our database and evaluate the number of properties this value using Eq. 1. We find that 40 % of the properties exposed to Hurricane Florence flooding were below the selected value. The properties valued between $200k and $500k account for another 25 % whereas the properties with values between $500k and $1M account for another 25 %. As a reference, the total number of properties valued below $200k represent ~ 50 % of our database, those between $200k and $500k are ~ 25 % and those between $500k and $1M roughly 15 %.

Distance from water bodies, especially coastal and riverine bodies, is also a useful indicator of properties vulnerability and potential exposure in hurricane prone areas. Consequently, we expanded our analysis to consider the distance of the properties that were flooded during Florence within our database from permanent water bodies (Figure 7). Values along the x-axis in the plot are obtained as the minimum distance from any of the closest element of the permanent water bodies mask (e.g. ocean, rivers, lakes) to each property within our database. The figure also shows the exponential decay function fitting the histogram and the fitting parameters. From this, we estimate that ~ 95 % of the number of properties exposed to flooding fell within 10 km from body waters. This number increases when considering only the distance from the ocean because of the inland flooding associated with heavy precipitation. We, therefore, use the distance of 10km as a maximum distance for studying the relationship between new properties, their distance from water bodies and the exposure to the Florence flood extent.

3.3 Impact of expansion of urban areas on property exposure

As mentioned in the Introduction, the exposure to floods and other extreme events depends not only on the geophysical hazard but also on how urban growth and infrastructures have been, are and will be evolving in the areas at risk. This concept is well synthesized in what has been named "the expanding bull's-eye effect" (Ashley and Strader, 2016), arguing that ''targets''—people and their built environments— of geophysical hazards are enlarging as populations grow and spread. In order, to investigate the impact of the expanding bull's-eye effect on the property exposed to the flooding of Hurricane Florence, we calculated what would have been the property area and values exposed to the

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Florence flood should that have occurred 10, 50 or 100 years ago by using the information contained within our database on the years when properties were built. For the purpose of this analysis, we clarify that we are assuming the same sea levels and topography of today.

Figure 8 shows the spatial distribution of the properties within our database that were built during the a) 1800 – 1900, b) 1900 – 1950, c) 1950 – 2000 and d) 2000 – 2018 periods. We considered the first period as a 100-year one (Figure 8a) because of the relatively small number of properties that were built then. Most of the development between 1900 and 1950 (Figure 9bb) occurred inland and along the coast north of Wilmington, with a relatively small number of new properties built close to water bodies (either rivers or ocean). An explosion in new properties occurred between 1950 and 2000 (Figure 8c), likely as a consequence of the economic stimulus following World War II. The period 2000 – 2018 shows a relatively smaller number of new properties with respect to the previous periods (Figure 8d). This is partially related to the shorter period considered for the last panel. However, our analysis performed on the 10-year period of number of properties built within our database (Figure 9) shows that before 2010 the number of houses built had been increasing exponentially ($Y = 5e\text{-}22 * \exp^{0.0314*X}$, R = 0.99, with X being the year) and that the number of new properties after 2010 drastically dropped, reaching values similar to those observed before the 1950s. This might be due to the 2008 “house crisis” that occurred during that period.

Figure 10 shows the time series of total value of exposed property (in 2018 \$B). The inset reports the relative change of the exposed area and value between two consecutive time steps (10 years). Consistent with the results discussed above, a relatively small increase in the exposed property value occurs before the 1940s (from ~ \$10B to ~ \$12B). The increase becomes substantial after 1940s, driven by the building of new properties (Figure 8), reaching a maximum value of exposed property of ~ \$52B in 2018. We fitted the increase in exposed property value after 1900 with an exponential function ($Y = a*\exp^{bX}$) and computed the coefficients providing best fitting ($a = 1.0627*1e^{-13}$, $b = 0.167$, R = 0.97). The maximum relative increase is reached around the year 2000 with a relative increased exposed value of ~ \$8B between two successive decades. After then, the relative change in exposed property values decreases to values close to those obtained in the early 1950s.

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Distance from permanent water bodies can play a critical role in terms of exposure, with flooding due to Hurricane Florence reaching properties that were up to ~ 10 km from the closest water body. Therefore, we further studied how the property value evolved in terms of the distance from water bodies between 1800 and 2018. As an example, in Figure 11, we show the distribution of properties built during different periods in proximity of Wrightsville beach, where hurricane Florence made landfall, highlighting the expansion of urban areas along the coasts and water bodies especially between 2000 and 2018. In Figure 13 we show the total value of exposed properties within our database as a function of distance from water bodies between 1800 and 2000 (using a 25-year time step) and for the period 2000 – 2018. We note that the curves referring to early periods reach a plateau within a relatively short distance than those referring to later periods, with the saturation values (e.g., the value when the curve becomes flat) being of the order of 1500m in the case of the 1975 – 2000 period. Interestingly, the period 2000 – 2018 does not show a plateau but the exposed property values continue to increase as the distance from water increases. This implies that despite the most recent decades were characterized by a relatively smaller number of new properties (Figure 9), the potential exposure to Florence of such properties was higher because of the higher number of the exposed properties close to body waters.

4 Conclusions

Increased flooding associated with sea level rise, storm surges and other extreme events has the potential to economically disrupt many areas around the world, with most of valuable real-estate, densest communities and most productive economic engines situated in coastal regions. The specific goal of our study was to quantify the exposure of properties to the flooding associated with Hurricane Florence that hit the Carolinas in September 2018 and to study how the spatio-temporal evolution of new properties during the past century and most recent decades has impacted the property exposure. It is important to note that much of the vulnerability associated with building development in these areas should be considered independent of climate change to this point. However, moving forward, these types of storms are expected to increase in intensity and the link between climate change and potential exposure is likely to be tied more closely together. In fact, we are already seeing these trends as they

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relate to tidal flooding events and one might expect that the low probability-larger storms are likely to become more linked to our changing climate as well. In order, to properly quantify the exposure of properties to Florence flooding, we developed a maximum flood extent map from the combination of the FEMA maximum extent map generated through the merging of high water marks, the outputs of a model and the flooded areas detected by means of spaceborne radar data acquired by the ESA Sentinel-1 sensors. We found that the total value of property exposed to flooding was ~ $52B and that this value has increased exponentially from ~ $10B (2018 $US) in the early 1900s. This is due to the increase in the number of properties that came to a halt at the beginning of the 2000s, likely as a consequence of the 2008 housing crisis, when the number of new properties built after 2010 was almost half of those built only a decade before. Despite this, the exposure to Florence flooding for those properties built after 2000 continued increasing, because of the number of new properties built within proximity of permanent water bodies and coastlines.

Our work cannot only provide new insights for policy makers and city planners but it also does provide a tool to better estimate how the property market will respond to future disasters. Recent work (e.g., McAlpine and Porter, 2018; Keenan et al., 2018) has found that homes at lower elevations were being penalized on the market relative to homes at higher elevations and that houses exposed to sea level rise (SLR) sell for approximately 7% less than observably equivalent unexposed properties equidistant from the beach (Bernstein et al., 2019). For our future work, we plan to expand our analysis to other modern-day (e.g. Irma, Michael, Katrina and Sandy) and historical (e.g. Hugo in 1989) hurricanes to address similar questions to those addressed in this study. Moreover, we plan to improve the detection of maximum flood extent through the implementation of machine-learning techniques combining radar maps with tide gage interpolated data and other ancillary information. Lastly, the combination of the knowledge on how property distribution changed along the years in conjunction with outputs of physical or probabilistic models that can separate the different contributions associated to flood due to SLR, storm surge and rain will allow to properly quantify what is the impact of the different components of the climate-economic system on the total exposure and, eventually, damage. This will provide a crucial tool for policy makers, governments, citizens and those who are, rightly, interested in quantifying the impact of climate change on the economic and house markets.

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Author's contribution.

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MT conceived the study and wrote the first draft of the manuscript. JP and SM provided and analyzed the property data, permanent water bodies and LULC data. MT developed and implemented the code for the radar dataset. All authors contributed to the final analysis and final version of the manuscript.

Acknowledgments.

MT acknowledges financial support from Columbia University through the RISE program and from FirstStreet foundation.

Code availability. We used a combination of publicly available software and codes developed ad-hoc for the purposes of this study. Specifically, the ESA SNAP software used to pre-process the Sentinel datasets is available at http://step.esa.int/main/download/snap-download/. We also used QGIS 3.4 to export the property data into a shapefile and to analyze the permanent body waters and the FEMA maximum flood extent data. The software is available at https://qgis.org/en/site/forusers/download.html. We developed in-house codes in Matlab for mapping flooded areas from radar data and to perform the analysis of the exposed property values. These are available upon request to the corresponding author at mtedesco@ldeo.columbia.edu

Data availability. Sentinel1 data is freely available at https://earthdata.nasa.gov/about/daacs/daac-asf. The dataset containing the permanent water bodies is available at https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/. Land use land cover attributes obtained from the National Geospatial Data Asset (NGDA) Land Use Land Cover (LULC) dataset is available at (https://www.sciencebase.gov/catalog/item/581d050ce4b08da350d52363. Maximum water extent by FEMA is available at https://data.femadata.com/FIMA/NHRAP/Florence/. Property value data is compiled from each individual property's county assessor in the form of the property tax assessed value and was obtained from ATTOM™ Data Solutions. Those interested in this dataset should reach out to the corresponding author mtedesco@ldeo.columbia.edu or can be obtained at www.attom.com.

Competing interest. The authors declare no competing interest.

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5 Figures

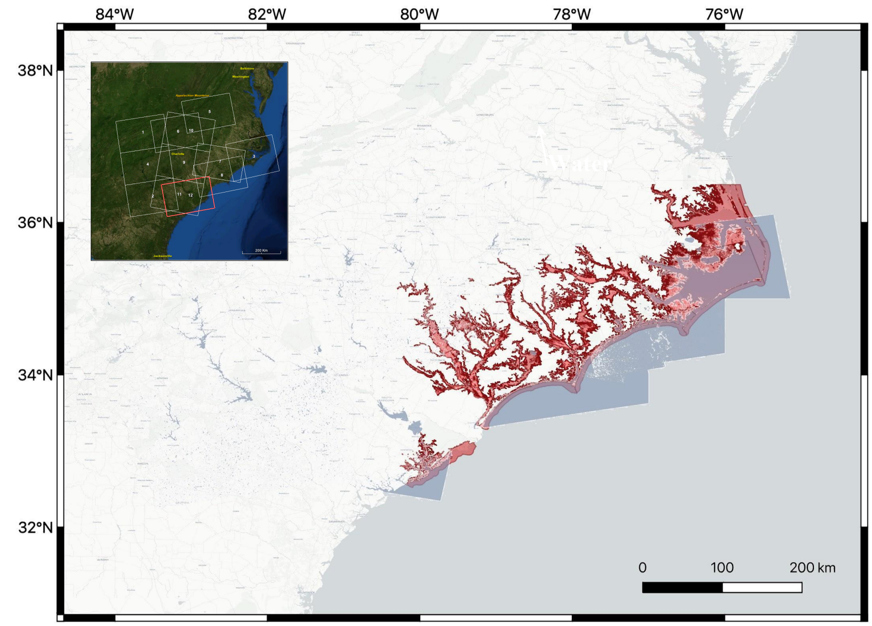

Figure 1, Map of inundated areas estimated by FEMA (red) and by the Sentinel-1 radar images (blue). The inset in the top left corner shows the footprint of the several radar images to create the composite water extent map. Acquisition times and other details concerning the radar images are available in Supplementary material.

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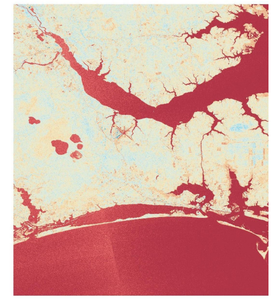

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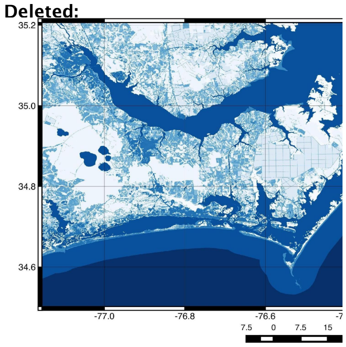

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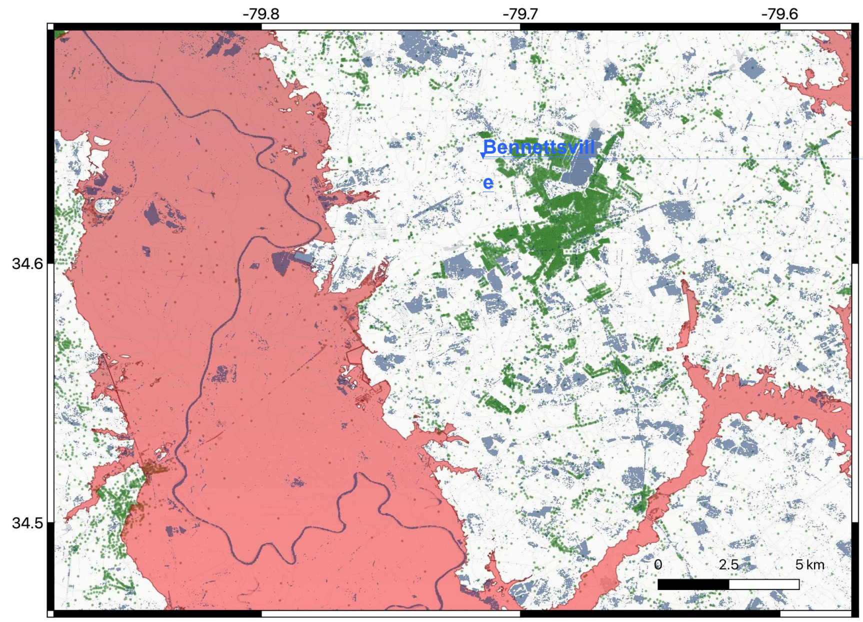

Figure 2. Map of inundated areas estimated by FEMA (red) and by Sentinel-1 (blue) near the town of Bennettsville, SC (34.6174° N, 79.6848° W). Green dots represent the locations of properties for this area.

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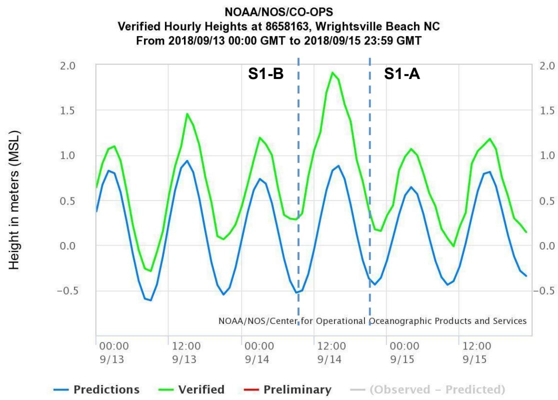

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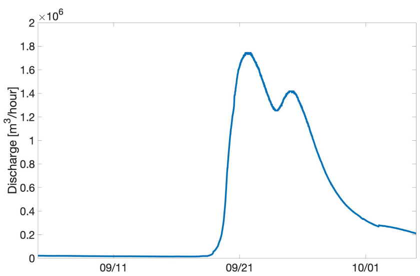

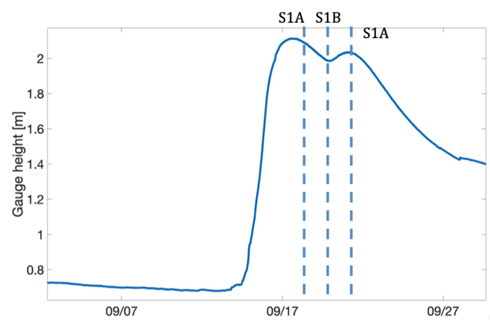

(b) (c)

Figure 3. Time series of a) tide gage mean sea level height (meters) recorded at Wrightsville Beach, NC and b) daily discharge (cubic feet per second) and c) daily gage height (feet) recorded at Lumber river (USGS gauge 02134170), NC between 1 September and 30 September 2018. In a) blue line refers to predictions where green squares to verified values. In a) data and plot was obtained from https://tidesandcurrents.noaa.gov/. For data plotted in b) and c) we obtained data and graphs from https://waterdata.usgs.gov/. In a) and c) we also report as dashed vertical lines the acquisition times of the available Sentinel-1 data.

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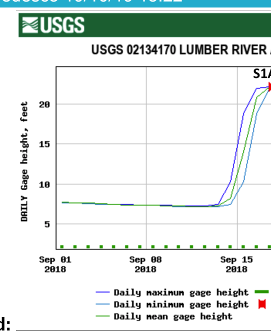

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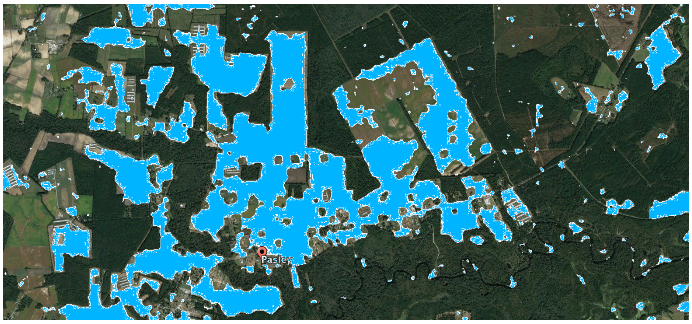

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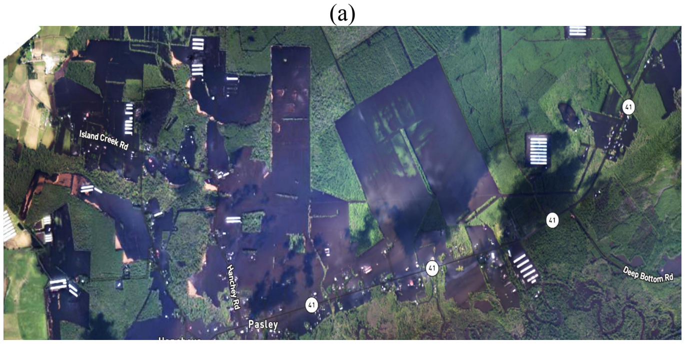

(b)

Figure 4 Flooded areas detected by a) Sentinel-1 data (light blue filled regions) on 19 September, 2018 nearby Pasley, Duplin County, NC (34.7854° N, 77.9005° W) and b) photograph of the same area collected on 18 September, 2018 by NOAA (https://storms.ngs.noaa.gov/storms/florence/index.html#7/35.360/-77.820). Here, dark blue regions show flooded areas.

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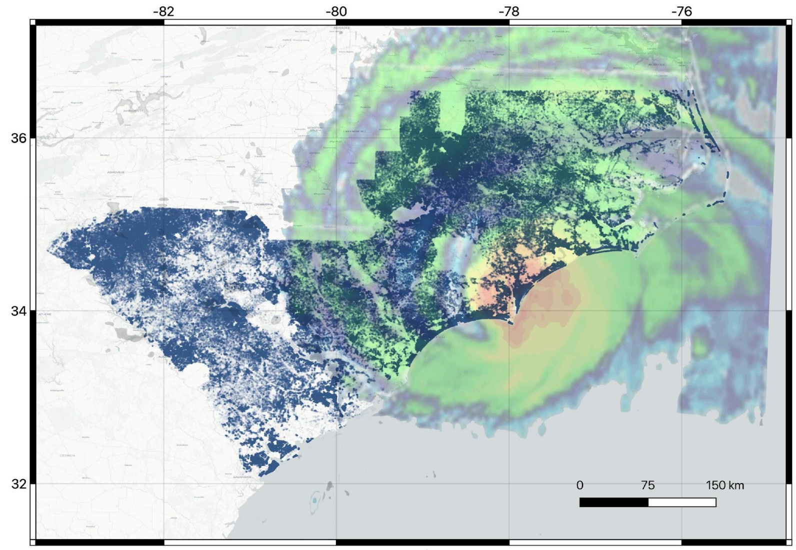

Figure 5 Distribution of properties within our database used to estimate the exposed property damage to Florence Hurricane. An image of the Hurricane Florence making landfall is also reported as a reference (Hurricane image courtesy: Cyclocane).

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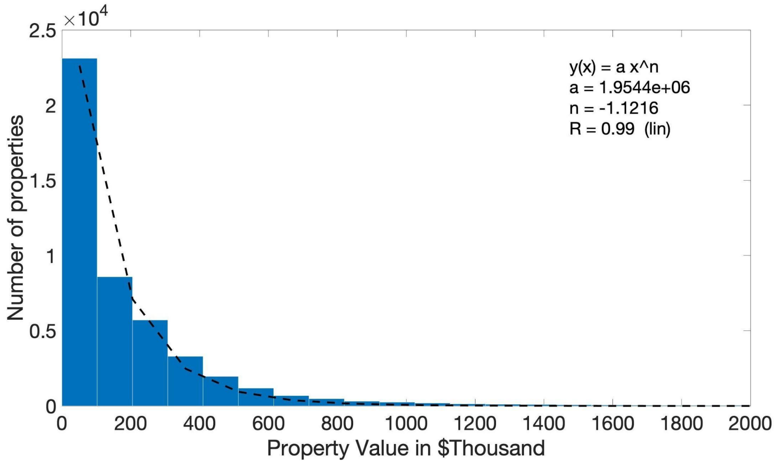

Figure 6. Distribution of the number of properties exposed to flooding as a function of property value. Dashed line represents the power law curve fitting the distribution. The parameters of the fitting power law function are reported in the top right section of the figure.

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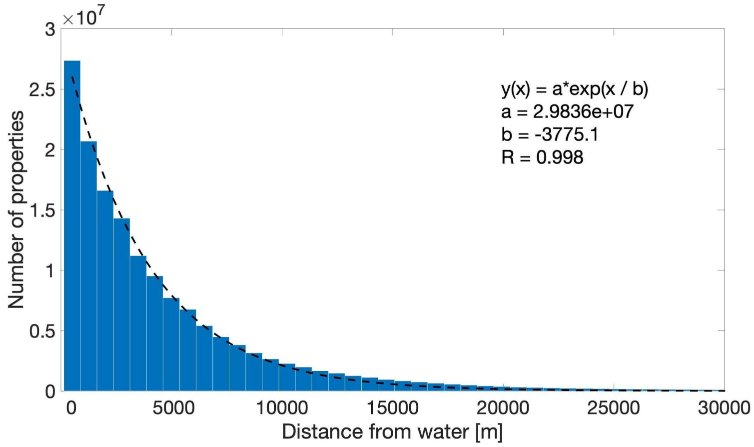

Figure 7. Number of properties as a function of distance from water bodies. Dashed line represents the power law curve fitting the distribution. The parameters of the fitting power law function are also reported in the top right section of the figure.

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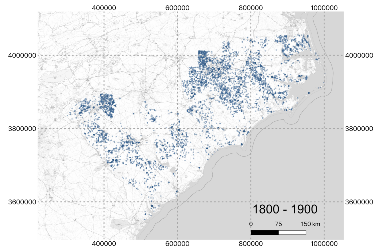

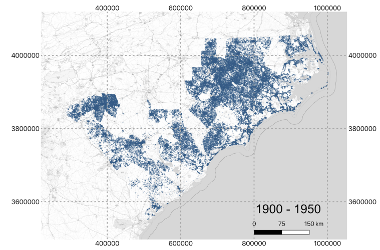

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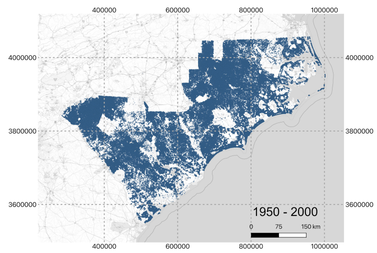

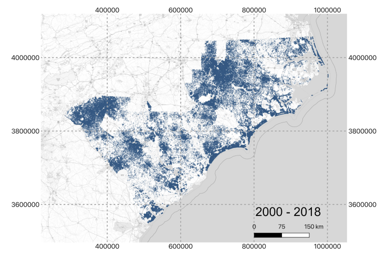

(c) (d)

Figure 8. Spatial distribution of the properties within our database that were built during the a) 1800 – 1900, b) 1900 – 1950, c) 1950 – 2000 and d) 2000 – 2018 periods.

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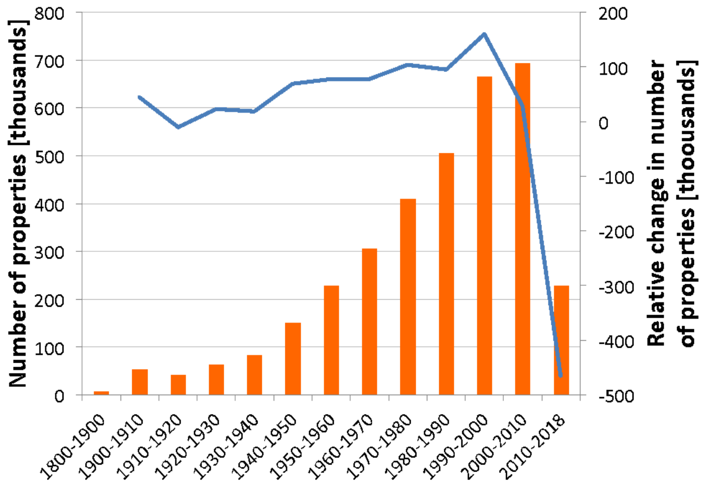

Figure 9. Number of properties (in thousands) built within our data record during different decades (red bars, left axis) and relative change between two consecutive periods (blue line, right axis). Note that the number of properties built between 1800 and 1900 are aggregated as a single value because of the small number of properties built during that period.

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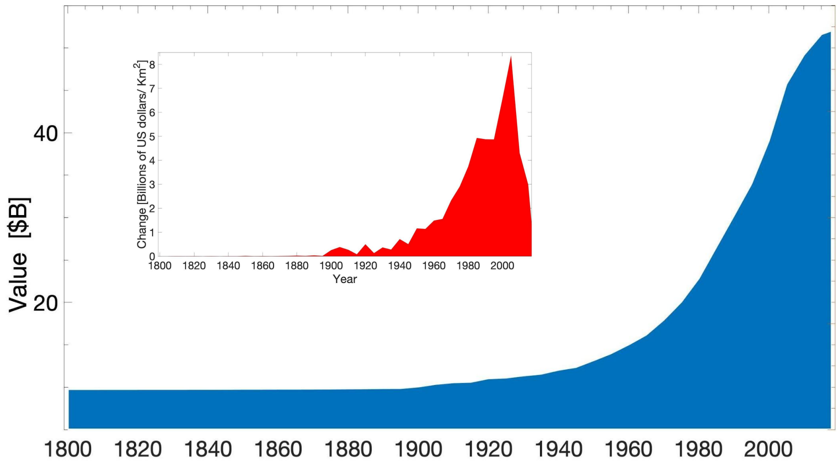

Figure 10. Time series of total value of exposed buildings (in 2018 USD) to the maximum flooded extent region between 1800 and 2018. The inset shows the relative change of the exposed area and value between two consecutive time steps (10 years).

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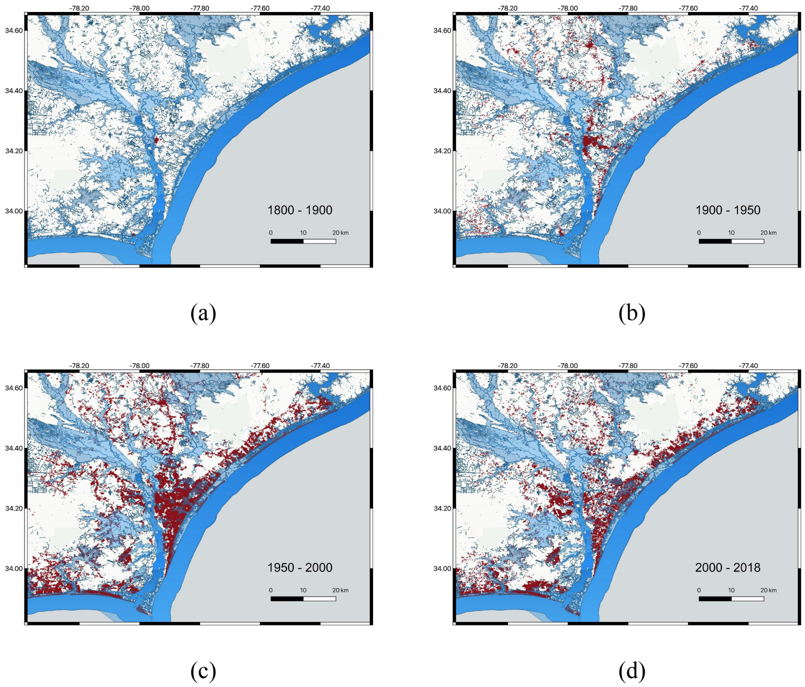

Figure 11 Distribution of properties (red dots) built a) before 1900, b) between 1900 and 1950, c) between 1950 and 200 and d) between 2000 and 2018 in proximity of Wrightsville Beach, NC where Hurricane Florence made landfall. Dark blue shows permanent body waters where light blue shows the flooded areas.

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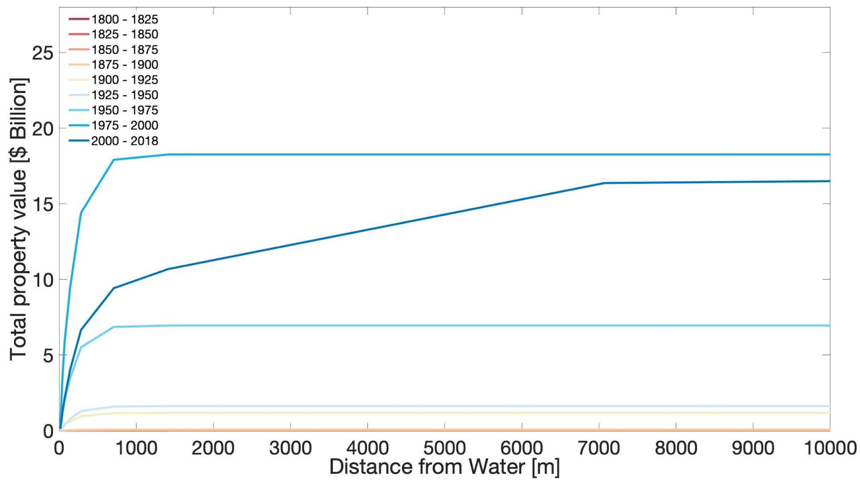

Figure 12. Total value within our database of properties exposed to flooding as a function of distance from water for the different periods reported in the inset.

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