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Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States

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Abstract

Because sea level could rise 1 m or more during the next century, it is important to understand what land, communities and assets may be most at risk from increased flooding and eventual submersion. Employing a recent high-resolution edition of the National Elevation Dataset and using VDatum, a newly available tidal model covering the contiguous US, together with data from the 2010 Census, we quantify low-lying coastal land, housing and population relative to local mean high tide levels, which range from ~0 to 3 m in elevation (North American Vertical Datum of 1988). Previous work at regional to national scales has sometimes equated elevation with the amount of sea level rise, leading to underestimated risk anywhere where the mean high tide elevation exceeds 0 m, and compromising comparisons across regions with different tidal levels. Using our tidally adjusted approach, we estimate the contiguous US population living on land within 1 m of high tide to be 3.7 million. In 544 municipalities and 38 counties, we find that over 10% of the population lives below this line; all told, some 2150 towns and cities have some degree of exposure. At the state level, Florida, Louisiana, California, New York and New Jersey have the largest sub-meter populations. We assess topographic susceptibility of land, housing and population to sea level rise for all coastal states, counties and municipalities, from 0 to 6 m above mean high tide, and find important threat levels for widely distributed communities of every size. We estimate that over 22.9 million Americans live on land within 6 m of local mean high tide.

Keywords: sea level rise, VDatum, climate change, flooding, coastal flooding, hazard mapping

1. Introduction

Anthropogenic greenhouse gas emissions by 2100 may be sufficient to irreversibly commit the planet to 4–6 m of global sea level rise within the next several hundred years [1–3]. This century, global rise may approach 1 or

even 2 m [4, 5]. In the coming few decades, rising seas threaten to interact with localized storm surges to generate more frequent floods reaching just as high [6, 7]. And factors such as land subsidence [8, 9] and shifting ocean currents [10–12] are expected to boost sea level increases in some regions. Together, these findings underscore the

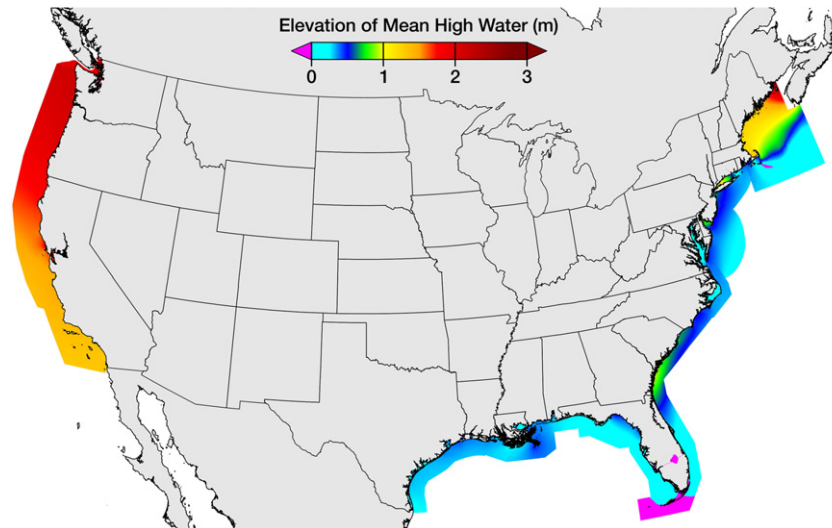


Figure 1. Modeled elevation of Mean High Water according to NOAA’s VDatum [24]. Units of meters in North American Vertical Datum of 1988.

critical importance of quantifying land, population and infrastructure in low-lying coastal zones—or what might be called topographic vulnerability—as a basic input for risk assessments and policy decisions.

However, geographic variation in baseline water levels has posed an important complication for completing this work at US regional to national scales. Topographic vulnerability to sea level rise at any location must properly be assessed with respect to local water levels, not an arbitrary external reference (e.g. a nationwide definition of elevation zero). The most involved approaches integrate projected sea rise with modeled standard local flood levels, such as annual or century flood levels. Requiring significant detail, data and computation, this family of methods has been applied narrowly in some US cities and states [13–16]. More simply, sea level rise can be referenced against high tide levels as measured by local tide gauges [17]. Some wide-area studies have gone to great lengths to interpolate and infer high water elevations extensively [18, 19]. However, other state through national-scale studies have skipped this labor-intensive step and not incorporated local water level references at all [20–23].

A valuable development now signals the time for a new national assessment at the scale of the contiguous United States (CONUS): the National Oceanic and Atmospheric Administration (NOAA) has just completed and validated tidal elevation models covering the entire coast at fine resolution. Outputs are available through a product called VDatum (vdatum.noaa.gov; [24]). It is now relatively straightforward to conduct a national-scale analysis of potential sea level rise impacts that accounts for local differences in mean sea level and tidal amplitude, which together determine high tide levels. Based on VDatum estimates, the 99% range of the elevation of mean high tide at shoreline is -0.2 to 2.8 m (North American Vertical Datum of 1988, or NAVD 88) for CONUS (see figure 1), a scale of variation that clearly cannot be ignored in analyses of coastal

vulnerability contemplating the critical first meter-plus above the water line.

Steady and widespread improvement in elevation data since the last national analysis of topographic vulnerability to sea level rise in 1991 [18] also suggests the timeliness of a new effort.

In this letter, we estimate the land, housing and population within 0–6 m in elevation of local high tide lines across the contiguous US, and present aspects of this topographic vulnerability at CONUS, state, county and municipal levels. We capitalize on VDatum and use best-available CONUS-wide elevation data to develop a new dataset characterizing elevation above local mean high tide, and employ this as the basis for our analysis. We also compare this approach against one without tidal adjustment, to assess the importance of taking local tide levels into account; and against two further methodological variants, to demonstrate the robustness of our approach.

2. Methods

2.1. Data

The National Elevation Dataset (NED) and VDatum constitute the core data inputs for our analysis. The NED is a digital elevation model (DEM) produced by the United States Geological Survey (USGS) and available at a variety of horizontal resolutions. Elevations are provided in NAVD 88. Previous regional and national sea level rise analyses have used the 1 arcsec NED (~ 30 m resolution) [23, 22], but the USGS has now completed coverage of coastal CONUS at 1/3 arcsec resolution (~ 10 m). We use the 1/3 arcsec dataset, the finest resolution data publicly available with full coastal coverage. The USGS has most recently estimated vertical root mean square error for the 1 arcsec NED at 1.89 m [40], down from 3.74 m in 1999 [25], as the dataset has been revised to incorporate more source lidar data

and improved algorithms for interpolation. Local error levels generally depend on the quality of local NED source data [26, 27], and may commonly be lower than average in coastal plains [21]. A recent study suggests 1/3 arcsec data perform slightly better than 1 arcsec data for sea rise vulnerability analyses [17].

VDatum makes available NAVD 88 elevations for different modeled tidal datums on lattices of varying resolution, but near-shore point spacing is generally on the order of 100 m. 36 regional models, adding up to total coverage of the CONUS coast, are each calibrated across extensive networks of water level stations. Standard deviation of vertical error is on the order of 0.1 m in each region [28, 29]. We use VDatum version 01, except for parts of the Gulf of Mexico where we use version 02, released in a 10 August 2011 update.

2.2. Analysis

Our analysis consists of four main steps: delineating land area, incorporating tidal elevations, identifying potential risk zones and tabulating assets within various administrative boundaries.

Ocean or saltwater marsh misclassified as land leads to overestimates of susceptible total land area [19]. We therefore begin by admitting 1/3 arcsec NED cells as land according to a consensus of three independent data sets. First, the cells must be designated as land (have non-zero elevation) within the NED itself. Second, we include only cells with centers landward of NOAA's Medium Resolution Digital Vector Shoreline (shoreline.noaa.gov). Finally, we eliminate NED cells with centers inside areas classified in the National Wetlands Inventory (NWI, [30]) as estuarine or marine wetland or deepwater. In computing *total* land area susceptible, we include NWI freshwater wetlands. We also compute dry land area susceptible, excluding NED cells with centers inside areas classified as freshwater wetlands. True water chemistry may vary from NWI classification.

For each delineated land cell, we estimate what we call 'tidally adjusted elevation', or TIDEL—the elevation above local Mean High Water. Mean High Water is formally defined by NOAA as the elevation of high tides averaged within a reference 'epoch', or period (currently 1983–2001 for most locations). To calculate TIDEL, we first assign a Mean High Water value to each NED cell by matching it with the nearest point covered by VDatum. We then subtract the cell's assigned Mean High Water elevation from its unadjusted elevation (UNEL) given by the NED. We use Mean High Water and UNEL as expressed in NAVD 88. In areas where spring high water—not available in VDatum—extends well above Mean High Water, this study understates vulnerability.

After calculating values for TIDEL, we identify potential risk zones at different elevations using four methods for comparison. (1) For our main analysis, we simply identify cells under each threshold from 0 to 6 m according to each cell's TIDEL. (2) We use the same method applied to UNEL values, in order to evaluate the error that would be introduced by ignoring the difference between NAVD and Mean High

Water. (3) From the sets of cells under each TIDEL threshold, we eliminate areas not contiguous to the ocean via eight-way connectivity [31]. And finally, (4) we employ the first method but substitute the 1 arcsec NED for 1/3 arcsec (both editions from February 2011). Neither 1/3 arcsec data nor VDatum were available for previous wide-area studies, but these studies are split between using pure thresholds [20, 32, 22, 17] or also enforcing connectivity [21, 16, 23]. We emphasize the pure threshold approach here for simplicity and in a spirit of conservative protectiveness. Apparently isolated depressions may be connected to water via porous bedrock geology, a feature of densely populated southeast Florida, one of the most topographically vulnerable areas nationwide [33, 34]. Depressions may also be connected via channels the NED fails to pick up, due to error or limited resolution. In addition, sea level rise may cause problems in isolated low zones during rainstorms by reducing drainage and creating backups into wastewater treatment facilities [35].

To tabulate population and housing potentially affected, we use block-level data from the 2010 US Census (www.census.gov), and assume development on dry land only, following Gill *et al* [36]. For each Census block, we divide the population and number of housing units by the number of dry land cells with centers inside the block. We assign the resulting per-cell density values back to each cell, creating two new 1/3 arcsec raster data sets for population and housing unit density. To estimate the population or housing at risk for a particular water level and method, we simply add up population and housing densities of land cells affected under the specification. Our analysis considers the elevation of land upon which housing stands, and makes no special provision for elevated or multi-story buildings.

To tabulate risks within states, counties or municipalities (alternatively, 'cities', by which we here refer to incorporated towns or cities, or Census Designated Places, of any size), we total affected area, population and housing within administrative boundaries as specified by 2010 Census TIGER Line data.

2.3. Error and the resolution of vertical increments

We conduct our analyses at 1 m vertical increments, following previous work with equal or finer vertical resolution [32, 16, 17, 23]. At the same time, a recent review cautions that NED elevation error is too great to support inundation vulnerability map-making with 1 m intervals [27]. This concern sensibly applies with respect to confidence in the classification of each individual point on a map as higher or lower than closely spaced elevation thresholds. However, sub-meter vertical resolutions should be acceptable for aggregate vulnerability analyses at municipal and larger scales, where numerous individual errors should largely offset each other across $\sim 10^3$ – 10^{20} elevation values. Recent work comparing vulnerable area tabulations using 1 arcsec NED data versus high accuracy lidar-based data implicitly supports this argument, finding agreement within 4–9% at scales from 10 to 4000 km² for the affected area, despite

Table 1. Coastal state land and features on land less than 1 m above local Mean High Water (<1 m TIDEL), with rankings. Total area includes freshwater, but not marine or estuarine, wetlands, as classified by the National Wetlands Inventory. Dry land area includes no wetlands. Unit of area, km².

State	Total area	Rank	Dry land area	Rank	Housing units	Rank	Population	Rank
Maine	80	18	54	16	8434	15	7439	16
New Hampshire	7	22	5	22	2506	21	2707	21
Massachusetts	121	17	86	14	31 349	9	52 488	9
Rhode Island	14	20	11	20	2705	20	3777	19
Connecticut	33	19	27	19	11 934	13	23 015	12
New York	178	14	155	12	132 991	4	300 532	4
New Jersey	310	12	174	11	107 024	5	154 577	5
Pennsylvania	12	21	7	21	369	22	791	22
Delaware	150	15	90	13	6663	17	7043	17
Maryland	698	9	410	5	19 434	10	27 520	11
District of Columbia	3	23	2	23	188	23	756	23
Virginia	722	6	315	8	36 847	8	75 938	6
North Carolina	4575	3	1288	3	43 102	6	58 679	8
South Carolina	1176	5	439	4	42 610	7	60 614	7
Georgia	711	7	331	7	15 685	11	28 494	10
Florida	5 715	2	1654	2	894 339	1	1609 312	1
Alabama	358	11	35	17	4986	18	3277	20
Mississippi	125	16	34	18	3077	19	4428	18
Louisiana	13 510	1	3058	1	413 900	2	888 679	2
Texas	711	8	284	10	12 513	12	19 618	13
California	2035	4	378	6	138 224	3	325 357	3
Oregon	189	13	54	15	7067	16	9250	15
Washington	394	10	289	9	10 484	14	18 269	14
Contiguous US	31 827		9181		1 946 429		3 682 557	

an order-of-magnitude difference in root mean square error values between the elevation datasets used [21, 17].

We do not conduct our own error analysis here, instead limiting ourselves to generation of best estimates. Data sources of varying quality underlie the NED in a complex spatial patchwork, with varying consequences for vertical error from place to place [26, 27]. Terrain slope and roughness and other factors likely play further roles [37, 21]. A national-scale assessment of NED vertical error in coastal areas, as it applies to various metrics of topographic vulnerability, merits separate and detailed study, and is a continuing project of these authors. Although we do not consider the impact of future shore protection activities on the magnitude of inundation from sea level rise, this study complements a recent assessment that did so [38].

3. Results and discussion

3.1. General impacts

We begin with a focus on pure threshold-based results below 1 m TIDEL, because this level represents the first front of vulnerability, where some impacts should be felt by mid-century as storm surges combine with sea level rise [6]. Furthermore, a recent survey showed almost 60% of Atlantic coastal land under 1 m UNEL is expected for development [38], adding urgency to provision of sea rise risk information at lowest elevations.

We find that ~32 000 km² of total land area, a footprint larger than Maryland, lies less than one vertical meter above the high tide line in the coastal contiguous US, including

~9000 km² of dry land. 1.9 million housing units occupy this land, and shelter 3.7 million people, or 1.2% of the national population. These totals include a fraction of land already below high tide line—for example, in the New Orleans area.

Among states (see table 1), land below 1 m TIDEL is most concentrated in the Gulf and lower mid-Atlantic (Louisiana, Florida, the Carolinas), well-known loci of concern around sea level (see e.g. [23]). With respect to potential population vulnerability, Florida stands out most, followed by Louisiana, California, New York and New Jersey, illustrating significant exposure on every coast. Variable population densities drive the differences among numbers and rankings between population and land. Ranked housing exposure tracks population vulnerability well. For economy of presentation, we focus on land and population over housing results hereafter, but more extensive results are available in tables A.1–A.6 and online (see below).

Results for counties (figure 2) and cities (figure 3) help further pinpoint hotspots of potential vulnerability, even within wider areas of lower topographic risk. Particularly large populations are exposed in: New York City and Long Island; the New Jersey shore; the Norfolk, Virginia area; near Charleston, South Carolina; coastal cities across Florida, especially its southeast and the Tampa area; New Orleans; the San Francisco Bay Area and San Joaquin Delta; and greater Los Angeles. This last center of concern merits special note because recent research suggests that coastal floods may reach locally rare heights more swiftly in southern California than almost any other CONUS area, when considering effects of sea level rise integrated with storm surge patterns [6].

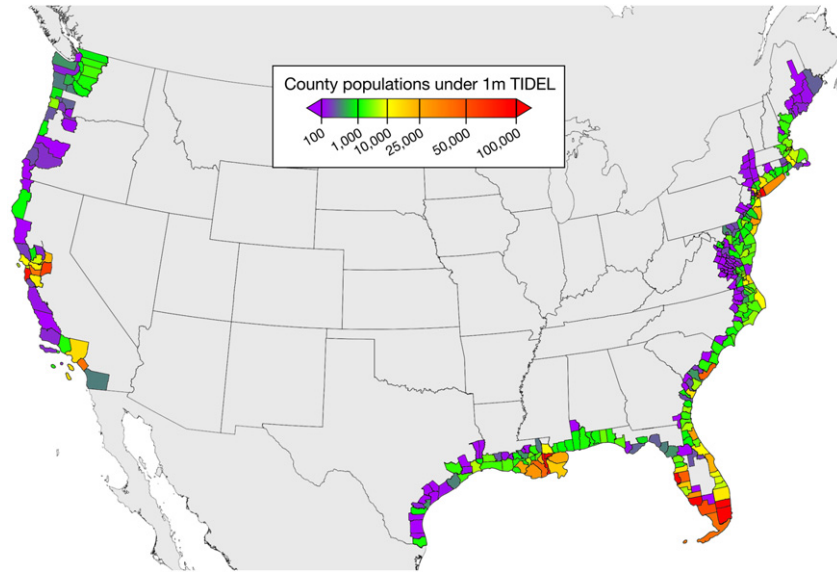


Figure 2. County populations (or Census county equivalents) living on land less than 1 m above local Mean High Water high tide lines (under 1 m TIDEL).

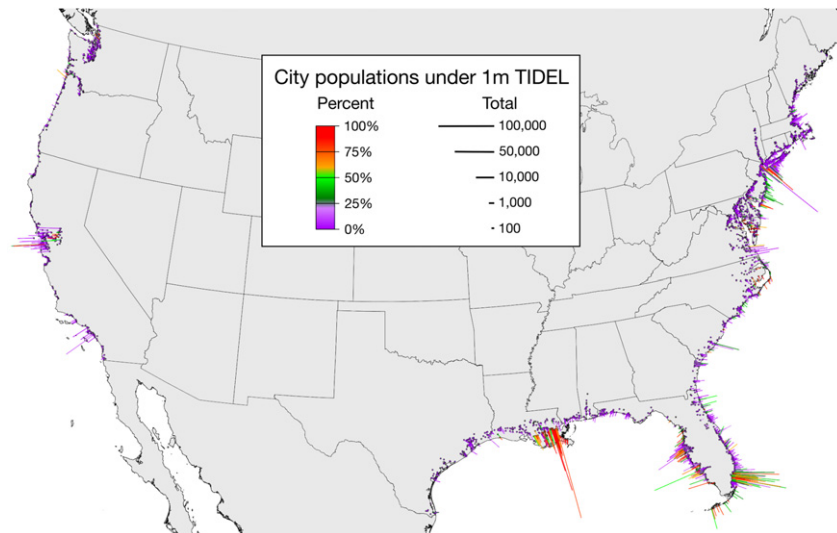


Figure 3. City populations living on land less than 1 m above local Mean High Water (under 1 m TIDEL). Line lengths proportional to square roots of affected populations.

An alternative perspective considers the fraction, not total, of county and city populations at vulnerable elevations, disentangling the influence of population density. More than 10% of the population lives below 1 m TIDEL in 38 counties and 544 cities (mean city population, 13 200). Half of these municipalities are in Florida and Louisiana, but North Carolina and New Jersey include over 40 each, New York 37, Maryland 27 and California 26. In 196 cities, more than 50% of the population lives below 1 m TIDEL. All told, 2150 towns and cities in the contiguous US have at least some residents living within one vertical meter of the high tide line.

Expanding our analysis to include higher water levels, we find a total area of $\sim 127\,000\text{ km}^2$ under 6 m TIDEL ($\sim 70\,000\text{ km}^2$ of dry land), occupied by 11.1 million housing units and 22.9 million people, or 7.4% of the national

population. 6 m represents a possible multi-century sea level rise commitment based on greenhouse gas emissions this century. Table 2 shows land, housing, and population statistics below 0 m TIDEL (some land is below water level but protected by levees, such as in New Orleans) and then in 1 m elevation bands up to 6 m TIDEL. The most striking feature is how dry land population density varies inversely with TIDEL, underscoring vulnerability. Louisiana (with high densities under 0 m TIDEL) and Florida (with high densities under 2 m TIDEL) drive this trend (see tables A.5 and A.6). However, CONUS dry land population density under 0 m TIDEL still appears slightly greater than at any level from 1 to 6 m, even when Louisiana and Florida are excluded (figure A.1).

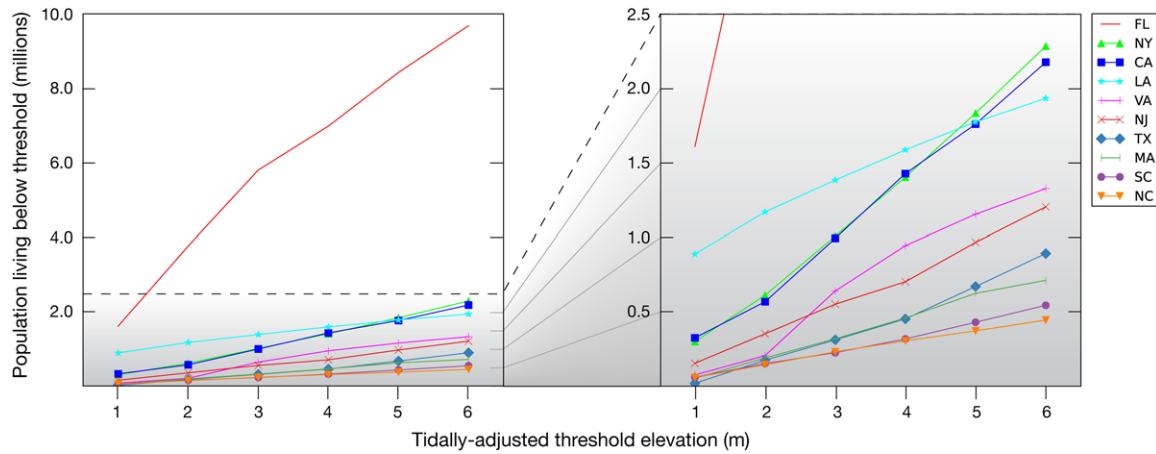


Figure 4. Topographically vulnerable population in the ten most vulnerable states (as evaluated at 6 m TIDEL). Estimates for Florida are 42–49% of the contiguous US total (22 states and District of Columbia) across each of the levels shown here.

Table 2. Topographic vulnerability within elevation bands for the contiguous US. Same land classifications as table 1. Population and housing can persist below high tide line (<0 m TIDEL) because of protective local topography, levees, seawalls or other features. Roughly 80% of the land below 0 m, and two-thirds of population and housing, are above –1 m. Population density calculated using dry land area.

TIDEL (m)	Total area (thousands km ²)	Dry land area (thousands km ²)	Housing units (millions)	Population (millions)	Population density (km ⁻²)
<0	8.8	2.0	0.5	1.0	475
0–1	23.0	7.2	1.5	2.7	380
1–2	21.1	11.2	2.1	4.0	359
2–3	20.6	12.9	2.1	4.4	340
3–4	18.3	11.1	1.6	3.4	308
4–5	18.2	12.7	1.8	3.9	304
5–6	16.9	12.9	1.6	3.5	275
Total (<6)	126.9	70.0	11.1	22.9	328

Figure 4 shows populations under 1–6 m TIDEL in selected states. Florida commands a far lead in vulnerability at every level. Among other states, California and New York overtake Louisiana as hotspots at the higher elevations, with Virginia and New Jersey not far behind. In 1269 cities, over half the residents live below 6 m TIDEL. Of these cities, 448 are in Florida.

Previous work has generally assumed uniform fine-scale population densities over total land area [16, 17], including at scales considerably larger than the great majority of Census blocks [22]. We refine this approach slightly, by limiting the area over which we calculate density to dry land only. We therefore compute greater densities, over smaller footprints, for Census blocks intersecting freshwater wetland. These footprints tend to occupy slightly higher terrain than mean block elevations, since dry land is generally higher than adjacent wetland. Screening out freshwater wetlands in this way reduces our vulnerable population estimates by 6.4% and 1.7% at 1 m and 6 m TIDEL, respectively, across the contiguous US, but with effects up to 31% in individual states at 1 m.

Other authors have argued that estimates based on uniform density assumptions should be viewed as upper bounds, expressing concern that housing is commonly concentrated within the upper elevation portions of low-lying

Census blocks [36]. To our knowledge, no such bias has been quantified. Such a pattern would mean the results presented here overestimate population and housing vulnerability, and may misconstrue the vertical distribution of coastal population densities at state and national scale. However, over 90% of the susceptible population identified in our analysis (at 1 and 6 m TIDEL alike) reside in Census blocks which exceed the population density threshold set by the US Census to define an urban area ‘core’ (at 386 km⁻², double the density required for ‘surrounding’ urban blocks). Core urban density would appear to leave modest room for housing to sort by elevation within Census blocks, depending upon local geography. Roughly 40% of susceptible population identified lives at densities equal to or greater than that of Washington, DC (3806 km⁻²). Development may also concentrate close to the water in places, biased toward lower elevations (as suggested but not demonstrated by the large-scale elevational gradient of dry land density just described). Future research to refine population and housing vulnerability estimates by quantifying any vertical bias in coastal area development would be a welcome contribution to this field.

3.2. Effects of methodology

We also examine the effects of various methodological choices on our results, summarized in tables 3 and 4. We

Table 3. Differences in CONUS vulnerability estimates across methodology contrasts, at different water level thresholds. Each contrast compares results based on the core methodology—which uses TIDEL, pure thresholds, and 1/3 arcsec data—against an alternative approach differing by one methodological variable, as indicated.

Threshold (m)	Main method per cent difference from analysis based on:					
	UNEL		Connectivity		1 arcsec data	
	Area	Population	Area	Population	Area	Population
<0	189	82.9	63.3	5.6	0.5	1.3
<1	31.6	86.8	3.9	8.2	0.2	0.9
<2	15.2	24.5	1.8	2.3	0.1	0.3
<3	9.3	16.8	4.9	1.3	0.0	0.3
<4	8.0	14.4	1.8	1.4	0.0	0.2
<5	6.9	12.4	1.0	0.9	0.0	0.3
<6	4.9	8.3	0.8	0.4	0.0	0.3

Table 4. Differences in city vulnerability estimates at <1 m TIDEL across methodology contrasts, at assorted percentiles. Each contrast compares results between core methodology and an alternative as in table 3.

Percentile	Main method per cent difference from analysis based on:					
	UNEL		Connectivity		1 arcsec data	
	Area	Population	Area	Population	Area	Population
2.5	-8.1	-10.5	0.0	0.0	-47	-49
5	0.0	0.0	0.0	0.0	-21	-26
25	23	27	0.0	0.0	-1.5	-2.7
50	69	78	0.2	0.0	0.3	0.3
75	263	294	6.6	3.5	4.3	5.0
95	7516	10 707	112	80	36	40
97.5	21 488	31 491	248	173	80	100

compare our core approach, which employs TIDEL, pure thresholds, and 1/3 arcsec data, against three alternatives, which each differ with respect to one of these dimensions.

Making tidal adjustments to elevation—using TIDEL as compared to UNEL—unsurprisingly drives the largest differences among methodologies we explore. CONUS total land area under 1 m increases by 32%, and population almost doubles (87% jump). The difference between land and population effects is consistent with the increasing fraction of dry and thus habitable land with elevation (see table 2).

The contrast between TIDEL- and UNEL-based results must and does decrease asymptotically toward zero with increasing elevation, as the area of non-overlap shrinks relative to the area of overlap. However, at 6 m, TIDEL-based CONUS estimates still exceed UNEL-based ones by 4.9% and 8.3%, respectively, for land area and population vulnerable (table 3). The availability of VDatum combined with the unsurprising but large effects of using tidally adjusted elevation data together suggest that future studies in this area should not neglect to employ tidal adjustments.

The methodological choice second in consequence is whether to use only thresholds, or also to enforce connectivity to the sea. This choice may also be viewed simply as a decision about what to measure. Using tidally adjusted elevations, we find that the pure threshold approach generates CONUS estimates 3.9% and 8.2% higher for topographically vulnerable total land area and population, respectively, at 1 m TIDEL. Miami-Dade and Broward counties in southeast Florida account for much of this contrast; without them,

differences in these estimates would drop to 3.0% and 2.7%. A similar dynamic drives results at 3 m TIDEL, where Palm Beach County, also in southeast Florida, includes about two-thirds of the total CONUS land under the threshold but not connected to the ocean. In each of these cases, very narrow and often long, nearly linear margins separate connected and unconnected areas below elevation thresholds, underscoring the sensitivity of results (under connectivity) to fine topographical variation or small NED errors. Southeast Florida has a flat and engineered landscape, full of canals and levees, features likely responsible for the patterns identified here. But the region’s porous geology means seawater may pose lateral threats even where surface topography would appear to block it, and southeast Florida is already struggling with saltwater intrusion into aquifers, exacerbated by recent historic sea level rise [35].

The excesses of threshold—over connectivity—based estimates decline to 0.8% for CONUS land and 0.4% for population by 6 m TIDEL, driven at least in part by the same logic of overlapping areas applicable to the UNEL/TIDEL contrast. The one strong contrast occurs, as expected, at less than 0 m TIDEL, where, in principal, all nontidal land should be protected by levees or other features, leaving zero exposure when connectivity is considered. Our analysis captures some of this protection, but finds 5410 km² of vulnerable land even when applying connectivity. This result suggests limitations in assessing connectivity employing the elevation dataset used, likely due to its horizontal resolution.

Finally, we compare results across 1/3 and 1 arcsec editions of the NED, using TIDEL and the pure threshold approach. At the scale of CONUS, the differences are negligible.

Table 3 summarizes each of these three methodological comparisons at CONUS scale. However, contrasts may be much greater when considering smaller areas, due to the smaller and more geographically concentrated samples of NED cells involved. Table 4 compares distributions of 1 m results for cities, the smallest geographic unit in this study. Results here reconfirm the strong effect of tidal adjustment, the only factor with a notable median influence. At higher percentiles, astronomical TIDEL:UNEL potential impact ratios are not surprising, considering the many municipalities with high tides at or above 1 m UNEL. Pure threshold-based results exceed results enforcing connectivity by no more 4–7% in three quarters of affected cities, although threshold results more than double their counterparts in about 5% of municipalities. Finally, the switch from 1 to 1/3 arcsec NED resolution shows a narrower range of effects. The few changes in total land area greater than doublings or less than halvings are confined to towns under 0.2 km² in size, where stochastic effects from small sample size loom large.

4. Concluding remarks

In this letter, we have presented an analysis of the topographic vulnerability of the coastal contiguous US to sea level rise and flooding, adjusted to account for local high tide levels. This adjustment carries large consequences. We estimate 3.7 million people live within one vertical meter of their local high tide line—87% more than an estimate of population living below 1 m in unadjusted elevation (NAVD 88).

Our simple threshold elevation approach may overestimate vulnerability because it includes areas the NED identifies as isolated depressions, potentially protected from flooding by natural topography or engineered features, such as levees in southeast Florida. However, our threshold-based results are generally quite close to those incorporating connectivity, and are fundamentally more robust: error in one cell or cluster cannot amplify by changing landscape connectivity and thus forcing the inclusion or exclusion of potentially large areas. Both approaches still include areas protected by features not fully represented in the DEM used—for example, low-lying parts of New Orleans protected by levees. The threshold method conservatively includes areas that appear isolated on the surface but might experience impacts via reduced drainage, via channels too fine to appear in the DEM, or via porous bedrock. As already noted, the last appears a key concern in Florida, where connectivity makes the largest difference in our topographic vulnerability estimates. Greater understanding of this threat should be a priority for future research.

More broadly, our main goal is to indicate levels of potential concern, and inspire more detailed local work; not to generate precise flood or risk maps. Topographic vulnerability is an important factor contributing to inundation risk, but it is also one among many acting at various time scales.

For example, patterns of development will probably play one of the strongest roles in both the short and long terms. At the highest level, the amount of population and infrastructure potentially under threat will depend on whether low-lying coastal development continues unabated (see e.g. [38]) or, at the other end of the spectrum, communities begin to retreat. At a secondary level, adaptive measures such as enhancing ecological buffers or building levees or seawalls will influence vulnerability, and already do so today.

Over the long term, coastal erosion may speed impacts, while sediment deposition, wetland accretion and beach migration may buffer vulnerability. However, coastal development inhibits many of these buffers, while often enhancing erosion, and generally more so in more populated areas [39].

As a final factor, the speed of sea level rise itself, and its relationship to the distribution of local flood sizes, will set the pace at which progressively higher elevation zones become exposed to significant risk. It is our hope and belief that analyses of topographic vulnerability, such as this one, combined with assessments of temporal vulnerability (e.g. [6]), can provide useful guidance concerning which locations may see the greatest sea rise induced risks soonest.

Topographic vulnerability estimates for every coastal city, county and state in the contiguous US are available at sealevel.climatecentral.org/data01.

Acknowledgment

We gratefully thank Jim Titus for detailed comments on the letter.

Appendix

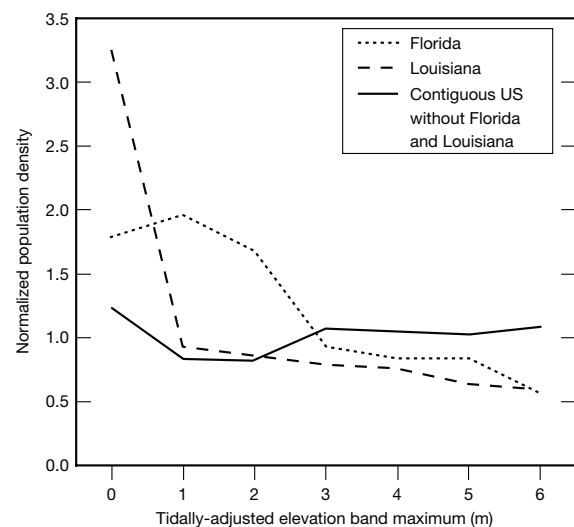


Figure A.1. Normalized coastal dry land population density within various TIDEL intervals. Values normalized by overall dry land population density under 6 m TIDEL for the geographic unit represented by each curve. Values given for each 1 m band of elevation (e.g. 2–3 m TIDEL denoted by 3 on the x-axis), and for the indeterminate band <0 m TIDEL (denoted by 0 on the x-axis).

Table A.1. Coastal state total land area, including freshwater but not estuarine or marine wetlands, below various TIDEL thresholds. Units of km².

State	<0 m	<1 m	<2 m	<3 m	<4 m	<5 m	<6 m
Maine	43	80	135	196	286	433	547
New Hampshire	2	7	13	18	27	41	56
Massachusetts	43	121	256	385	506	645	764
Rhode Island	4	14	28	50	66	84	105
Connecticut	16	33	63	99	131	169	214
New York	58	178	332	521	652	781	923
New Jersey	79	310	760	1163	1396	1709	2026
Pennsylvania	6	12	38	55	79	140	160
Delaware	15	150	285	424	580	733	908
Maryland	59	698	1346	1898	2429	2924	3426
District of Columbia	1	3	5	10	14	17	20
Virginia	105	722	1384	2366	3072	3690	4481
North Carolina	932	4575	6605	8400	10 271	11 752	12 790
South Carolina	252	1176	2197	2931	4018	5513	6955
Georgia	269	711	1537	2277	3323	4525	4900
Florida	476	5715	12 454	21 166	28 289	34 387	40 821
Alabama	10	358	796	1112	1302	1507	1702
Mississippi	22	125	357	629	822	1101	1346
Louisiana	4650	13 510	16 570	18 882	21 062	23 164	25 015
Texas	69	711	4220	6551	8285	10 612	12 729
California	1370	2035	2482	3087	3649	4081	4793
Oregon	102	189	398	503	616	768	878
Washington	254	394	643	794	957	1226	1385
Contiguous US	8837	31 827	52 906	73 518	91 830	110 002	126 941

Table A.2. Coastal state dry land area below various TIDEL thresholds. Units of km².

State	<0 m	<1 m	<2 m	<3 m	<4 m	<5 m	<6 m
Maine	29	54	96	141	209	330	424
New Hampshire	2	5	11	15	22	34	47
Massachusetts	29	86	199	312	415	532	637
Rhode Island	3	11	23	42	56	72	91
Connecticut	13	27	48	74	103	136	173
New York	51	155	294	468	592	715	851
New Jersey	45	174	454	720	885	1123	1368
Pennsylvania	3	7	25	40	60	116	135
Delaware	6	90	195	316	450	586	742
Maryland	23	410	923	1383	1824	2235	2642
District of Columbia	1	2	5	9	13	16	19
Virginia	25	315	730	1504	2045	2494	2999
North Carolina	128	1288	2614	3835	5096	6084	6778
South Carolina	62	439	1006	1421	2059	2960	3943
Georgia	106	331	830	1379	2197	3110	3407
Florida	74	1654	4238	8646	11 487	14 942	19 459
Alabama	2	35	112	218	301	382	496
Mississippi	3	34	151	289	406	590	740
Louisiana	1077	3058	4998	6620	8237	9984	11 610
Texas	17	284	2117	3894	5323	7315	9216
California	93	378	686	1203	1718	2119	2796
Oregon	27	54	168	218	271	358	425
Washington	185	289	477	590	713	911	1037
Contiguous US	2002	9181	20 399	33 336	44 482	57 145	70 035

Table A.3. Coastal state housing units on land below various TIDEL thresholds.

State	<0 m	<1 m	<2 m	<3 m	<4 m	<5 m	<6 m
Maine	5479	8434	11 599	15 121	20 291	30 211	37 790
New Hampshire	724	2506	5581	7379	9135	12 230	14 794
Massachusetts	12 376	31 349	102 823	172 135	241 239	321 714	368 129
Rhode Island	881	2705	5834	12 778	17 466	22 140	28 245
Connecticut	6743	11 934	19 314	28 079	38 594	51 409	65 943
New York	50 200	132 991	265 481	437 862	602 535	783 836	974 184
New Jersey	27 251	107 024	246 014	358 217	425 639	535 944	635 943
Pennsylvania	141	369	1867	5277	15 492	56 973	85 147
Delaware	304	6663	26 658	41 599	53 525	67 711	81 929
Maryland	883	19 434	60 218	102 018	130 795	158 374	188 736
District of Columbia	42	188	509	2557	5314	9128	12 294
Virginia	2661	36 847	96 961	271 600	397 965	485 677	557 630
North Carolina	5136	43 102	104 104	157 034	199 098	232 914	266 937
South Carolina	11 836	42 610	111 977	158 936	211 961	269 853	330 113
Georgia	2356	15 685	45 513	76 705	117 451	156 544	172 904
Florida	44 681	894 339	1945 323	2932 624	3535 109	4242 478	4861 644
Alabama	1021	4986	15 818	28 372	40 142	47 301	57 435
Mississippi	317	3077	11 274	24 433	38 527	56 931	74 919
Louisiana	270 864	413 900	539 319	629 596	714 039	790 506	855 525
Texas	809	12 513	103 044	172 394	234 159	321 379	407 712
California	28 002	138 224	239 008	409 912	574 074	701 184	857 554
Oregon	4606	7067	10 708	14 086	18 270	24 175	29 415
Washington	5203	10 484	30 778	43 306	56 581	77 698	92 537
Contiguous US	482 515	1946 429	3999 726	6102 019	7697 399	9456 310	11 057 460

Table A.4. Coastal state population living on land below various TIDEL thresholds.

State	<0 m	<1 m	<2 m	<3 m	<4 m	<5 m	<6 m
Maine	4131	7439	11 339	15 712	22 681	37 163	48 657
New Hampshire	823	2707	6129	8419	11 075	16 956	21 808
Massachusetts	20 414	52 488	190 238	318 875	459 262	625 030	712 653
Rhode Island	1164	3777	8965	20 109	28 424	36 675	47 827
Connecticut	13 227	23 015	36 725	53 745	74 822	101 397	132 427
New York	110 859	300 532	612 317	1009 048	1403 519	1833 309	2284 957
New Jersey	37 474	154 577	352 960	552 019	703 079	967 031	1204 052
Pennsylvania	272	791	5958	14 436	37 945	129 722	189 607
Delaware	415	7043	25 662	43 556	62 878	84 909	111 477
Maryland	1527	27 520	80 692	144 842	204 739	266 134	336 586
District of Columbia	134	756	1572	5851	10 788	16 812	22 090
Virginia	4389	75 938	206 411	640 941	944 981	1154 543	1326 524
North Carolina	6616	58 679	144 952	231 730	306 245	372 581	445 317
South Carolina	18 034	60 614	153 157	225 793	318 289	430 593	544 468
Georgia	4251	28 494	88 991	154 892	247 352	336 356	373 230
Florida	65 508	1609 312	3762 734	5797 413	6979 817	8421 764	9681 746
Alabama	511	3277	12 422	32 840	48 267	60 205	79 481
Mississippi	385	4428	20 687	48 673	78 193	118 553	157 261
Louisiana	581 796	888 679	1170 009	1383 536	1587 139	1774 254	1933 487
Texas	1534	19 618	175 395	312 256	453 236	670 793	892 541
California	62 633	325 357	568 503	993 518	1427 445	1760 176	2176 434
Oregon	5995	9250	15 278	20 642	27 193	37 134	45 797
Washington	9879	18 269	59 229	83 378	108 717	148 553	174 993
Contiguous US	951 973	3682 557	7710 326	12 112 226	15 546 087	19 400 643	22 943 419

Table A.5. Coastal state dry land population density within various TIDEL intervals.

State	<0 m	0–1 m	1–2 m	2–3 m	3–4 m	4–5 m	5–6 m
Maine	144	133	93	96	103	120	122
New Hampshire	435	580	630	495	400	485	362
Massachusetts	703	563	1216	1145	1358	1415	833
Rhode Island	336	352	433	583	583	538	588
Connecticut	1014	716	629	657	739	805	841
New York	2189	1811	2253	2280	3171	3488	3327
New Jersey	841	906	709	748	915	1106	968
Pennsylvania	80	129	290	587	1156	1625	3210
Delaware	73	79	176	148	144	162	170
Maryland	68	67	104	139	136	149	173
District of Columbia	179	428	338	911	1494	1707	1796
Virginia	176	247	314	562	562	467	341
North Carolina	52	45	65	71	59	67	105
South Carolina	292	113	163	175	145	125	116
Georgia	40	108	121	120	113	97	124
Florida	888	977	833	462	416	417	279
Alabama	220	84	120	192	186	148	169
Mississippi	140	130	138	204	251	220	258
Louisiana	540	155	145	132	126	107	98
Texas	88	68	85	77	99	109	117
California	676	920	790	822	843	830	614
Oregon	222	119	53	108	123	114	130
Washington	53	81	218	212	206	201	210
Contiguous US	475	380	359	340	308	304	275

Table A.6. Normalized coastal state dry land population density within various TIDEL intervals. Values normalized by overall dry land population density under 6 m TIDEL for the geographic unit leading each row.

State	<0 m	0–1 m	1–2 m	2–3 m	3–4 m	4–5 m	5–6 m
Maine	1.3	1.2	0.8	0.8	0.9	1.0	1.1
New Hampshire	0.9	1.3	1.4	1.1	0.9	1.1	0.8
Massachusetts	0.6	0.5	1.1	1.0	1.2	1.3	0.7
Rhode Island	0.6	0.7	0.8	1.1	1.1	1.0	1.1
Connecticut	1.3	0.9	0.8	0.9	1.0	1.1	1.1
New York	0.8	0.7	0.8	0.8	1.2	1.3	1.2
New Jersey	1.0	1.0	0.8	0.8	1.0	1.3	1.1
Pennsylvania	0.1	0.1	0.2	0.4	0.8	1.2	2.3
Delaware	0.5	0.5	1.2	1.0	1.0	1.1	1.1
Maryland	0.5	0.5	0.8	1.1	1.1	1.2	1.4
District of Columbia	0.2	0.4	0.3	0.8	1.3	1.5	1.6
Virginia	0.4	0.6	0.7	1.3	1.3	1.1	0.8
North Carolina	0.8	0.7	1.0	1.1	0.9	1.0	1.6
South Carolina	2.1	0.8	1.2	1.3	1.1	0.9	0.8
Georgia	0.4	1.0	1.1	1.1	1.0	0.9	1.1
Florida	1.8	2.0	1.7	0.9	0.8	0.8	0.6
Alabama	1.4	0.5	0.7	1.2	1.2	0.9	1.1
Mississippi	0.7	0.6	0.7	1.0	1.2	1.0	1.2
Louisiana	3.2	0.9	0.9	0.8	0.8	0.6	0.6
Texas	0.9	0.7	0.9	0.8	1.0	1.1	1.2
California	0.9	1.2	1.0	1.1	1.1	1.1	0.8
Oregon	2.1	1.1	0.5	1.0	1.1	1.1	1.2
Washington	0.3	0.5	1.3	1.3	1.2	1.2	1.2
Contiguous US	1.5	1.2	1.1	1.0	0.9	0.9	0.8
Contiguous US without FL	1.8	0.8	0.8	1.1	1.0	1.0	1.0
Contiguous US without FL or LA	1.2	0.8	0.8	1.1	1.1	1.0	1.1

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