Isolation: Revising the estimated risk of sea-level rise

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Abstract

The typical displacement metric for sea-level rise adaptation planning is parcel inundation. However, this metric does not fully capture the wider cascading or indirect effects of sea-level rise. To address this, we propose the consideration of population isolation: those who cannot access essential services. Based on this metric, we find a 39–464% increase in the number of people considered at-risk, compared to the risk from parcel inundation, when considering inundated roadways during mean higher high water tides in the coastal U.S. We also find that isolation may occur decades sooner than parcel inundation. Both estimates of risk are critical elements for evaluating adaptation options and prioritizing support for at-risk communities.

Main

For the past two decades, the burden of sea-level rise (SLR) on communities has primarily been measured by risk of inundation [1–3]. However, mass migration, significant social disruptions, and exacerbated inequities will not be caused by flooded homes alone [4]. Moreover, the interconnectedness of coastal communities with their environment will create ripple effects once non-residential assets are inundated, potentially making critical infrastructure less reliable and limiting reliable access to opportunities. This means that inundation-based estimates, for example, 2.8% of the global population [2] and 4.6 million people in the USA, at-risk of inundation by 2100 (with 0.9m of SLR; Hauer et al., 2016), could be too low for understanding SLR burden. To address this, researchers have begun to examine the impacts of SLR on transportation assets, which when inundated, will cause the burden to be more widespread, and to begin sooner than household inundation metrics might suggest (Jasour et al., 2022).

Metrics that focus on SLR inundation of transportation assets include increased commute time and miles of roadway inundation [5,6]. As an example, Hauer et al. (2021) found that some commuters in coastal counties may experience an additional 643 minutes of commute time per year by 2060 given current sea-level rise trajectories, due to reduced speeds on inundated roads. Yet, climate adaptation policy is still reliant on estimating the number of displaced people and the timing of this displacement [7]. This may be due, in part, to the relative nascent consideration of transportation burden used in the adaptation planning literature. For instance, the research is limited in geographic scope [6,8], does not consider alternative routing due to flooding [5], uses aggregated spatial scales (e.g., census tracts or counties) that make it challenging to decipher distributional impacts on individuals [9,10], or considers only changes in travel time without consideration of congestion and connectivity [9,10].

Isolation provides a complementary measure for the impact of SLR that can offer a more precise spatial and temporal indication of localized burden, along with when the burden may commence. In this work, we appraise coastal “isolation” - meaning a localized lack of physical connectivity by roadway to public accommodations - by building upon the recent literature at the intersection of transportation accessibility and community resilience [11–13]. Although isolation has been overlooked in the adaptation literature, isolation is a particularly salient indicator for two reasons. First, isolation due to inundated roadways signals a loss of access to essential services. That is, residents will be unable to reach supermarkets, work, education, healthcare facilities, or be reached by emergency services. Secondly, beyond these losses, it is not guaranteed that residents who experience isolation will be able to safely remain in their homes, even if their home remains dry. Horizontal (i.e., networked) infrastructure is often co-located with roadways; therefore, if a home losses road access, it is possible that other infrastructure services provided to the home are affected (electricity, internet, etc.), even if their homes remain untouched by inundation [14].

Therefore, to better estimate displacement and improve our ability to adapt communities to the impacts of SLR, we ask:

1) How many people are at risk of isolation and at risk of inundation?

2) What is the spatial distribution of people at risk of isolation and how does this compare to people at risk of inundation?

3) What are the temporal differences between the onset of isolation and the onset of inundation?

To address these questions, we use all U.S. coastal counties as a case study and measure the inundation and isolation risk for communities at the census block level (the smallest census geographic unit). More specifically, to measure the risk of isolation, we intersect the OpenStreetMap (OSM) road network for the U.S. with each of NOAA's mean higher high water (MHHW) scenarios for global mean sea-level (GMSL) rise between 0.3 and 3 meters (1 and 10 feet) and determine whether there is an unflooded path between each block centroid (projected to the closest road) and its closest essential facility (i.e., fire stations, medical services, and primary schools). Not only are these destinations important, but they are also often collocated with community assets that provide wider opportunities, including employment, entertainment, and other essential services. The risk of inundation is measured by intersecting building footprints with NOAA's MHHW scenarios. The proportion of the block's 2020 population at risk of inundation is estimated using the proportion of flooded building footprints. This is the finest resolution analysis and contrasts with alternative approaches that use flooded area proportions of census block groups (e.g.,[1]), thus offering better spatial accuracy.

Results

We begin by comparing the number of people at risk from inundation and at risk from isolation due to MWWH for SLR between 0.3 and 3.0 meters (Fig. 1A). The number of isolated people in the U.S. is between 39–464% higher than the number of people threatened by inundation. This difference is greatest for smaller SLR increments (there is a difference of 464% or 1.3 million people at 0.3m of SLR. The percent difference becomes the smallest (39%) at 3.0m, but this also implies that 4.8 million more people are at risk of isolation compared to the number of people identified as being at risk of inundation.

We also consider this difference in terms of when the SLR increment might occur using SLR projections of GMSL from the U.S.'s Fourth National Risk Assessment (Fig. 1c; [15]). This shows (Fig. 1B) that nearly 2 million people could be at risk of isolation by 2040 under extreme and high SLR scenarios and by 2050 under the intermediate GMSL scenario. Further, it shows that 17.5 million people could be at risk of isolation between 2100 and 2130 under extreme and high SLR scenarios. This compares to fewer than 1 million people at risk of inundation by 2050 for all SLR scenarios. Note that these figures do not include projected population and relocation *into* these at-risk areas [1].

So where are these communities located? Figs. 2 show the difference between the population at risk of inundation and isolation at a county level. Not only do these figures further highlight the differences between the population at risk of isolation and inundation, but they also show the geographic variability in these differences. While Fig. 2A shows this difference for 1.8m of SLR, results for all increments of SLR between 0 and 3m can be explored interactively on our dashboard https://projects.urbanintelligence.co.nz/slr-usa/. Figure 2B ranks each coastal state in terms of its percentage of its population at risk of inundation at 3m of SLR. By comparing the state rank order against the bar heights, we observe that risk of isolation means some states (notably Maine, Delaware, Rhode Island, and Oregon at 3m) may experience a significantly higher burden than they currently realize based on risk of inundation alone. Additionally, at much lower levels of SLR (0.9m), which may occur as soon as 2060 based on the Extreme GMSL Scenario, Florida, Hawaii, Louisiana, and South Carolina may dramatically underestimate the impact of SLR on its residents.

The risk of isolation will not only affect areas previously recognized as low risk but is also likely to result in a burden and potential for displacement earlier than the risk of inundation would indicate. That is, inundation-based forecasts of risk are underestimating when the impacts will occur, and this difference can be considerable. Figure 3 shows the differences between forecasts of when risk of isolation could first occur and when risk of inundation could first occur. Figure 3A shows this as a set of histograms of the SLR for which the risk of isolation commences, faceted by the U.S. population at risk of inundation for 0.3m to 3m of SLR. These left-side histogram tails show that some residents will be isolated by SLR 2 meters lower than when they would expect inundation. Figure 3B translates this into years, based on the GMSL scenarios. Under the extreme scenario, some blocks that are at risk of inundation in 2060 could be at risk of isolation as early as 2030.

Figure 4A breaks this down further, showing a histogram of the lag time for the risk of inundation. It also demonstrates how more than 5 million residents are at risk of isolation, but are never at risk of inundation, for 3 meters or less of SLR (the tall bar on the right of Fig. 4A). This means that current planning efforts that rely on risk of inundation may ignore or overlook these communities when distributing resources or other support. Figure 4B investigates when the risk of isolation may start for these > 5 million residents and shows that some could be isolated before 2050 in both an intermediate and extreme scenario. Again, this varies geographically; in Fig. 4c we show histograms of the lag time for the risk of inundation at the state level. This means that many regions need to prepare for additional burden stemming from SLR, decades before inundation is expected.

Discussion

Two key dimensions of current adaptation policy and planning are the number of displaced people and the timing of this displacement [7,16]. Our study shows that evaluating this metric using property exposure to inundation and then relying primarily on this metric for adaptation planning underestimates the magnitude of the burden of SLR. Isolation – where residents are cut off from opportunities and critical services (e.g., education, healthcare, food) and may lose infrastructure services (e.g., electricity, potable water) - can pose additional burden on individuals, potentially inducing many to relocate sooner than a displacement metric measured by parcel inundation would suggest.

This study raises several implications for adaptation policy and planning. First, relying on the risk of inundation while ignoring the risk of isolation and the interdependence of the environment with networked infrastructure may underestimate the number of people significantly burdened by SLR, and when that burden may commence. It is possible that those burdened and who can afford to relocate will, resulting in exacerbated inequalities and localized economic decline should early interventions not be taken. Second, for localized investments in adaptation to be effective, they need to consider the composite SLR risk in coastal areas to ensure resources are expended in a manner that reflects needs and realistic projections of how long the area remains habitable. An approach that relies on consensus building will ensure that adaptation is not piecemeal or collectively inefficient.

Government agencies will need to consider how to administer buyout programs in the face of sea-level rise (e.g., the USA's Federal Emergency Management Agency (FEMA) has a program for acquiring flood-prone properties) [17]. These programs may also need to reflect other impacts of SLR such as risk of isolation rather than simply flood inundation. If the programs are to include risk of isolation, questions such as "at what point is a property no longer habitable?" must be addressed. The United Nations' Universal Declaration of Human Rights, along with numerous other international conventions, identifies adequate housing to be a human right [18]; this includes access to the necessary social services. However, these rights will be infringed as residents are temporarily and ultimately permanently isolated as sea-levels rise and extreme sea-level events (e.g., storms) increase in frequency, resulting in severe demands on residents' mental health and wellbeing. These, and associated social justice issues, must be carefully considered for adaptation planning [19].

Finally, our findings also have implications for adaptive planning approaches. Approaches such as Dynamic Adaptive Pathways Planning (DAPP) rely on signals and triggers to inform when interventions should be made [20–22]. However, if these triggers and signals are based on risk of inundation, we have found that this may be insufficient in some regions. Instead, trigger and signal points should be in terms of a metric that locally captures when the burden of sea-level rise might commence. While risk of isolation as computed in this work might be an effective trigger, another could be risk of isolation based on the probability of temporary isolation due to an extreme weather event. This would require conducting this analysis using models of extreme sea-level, including storm-surge.

This work has shown that relying primarily on the risk of inundation for adaptation planning may underestimate the number of people burdened by SLR, and when that burden may commence. We recommend including the risk of isolation in these considerations in order to support global climate adaptation research and planning to be more targeted, effective, and timely.

Methods

Data

Sea-level rise extent: We used the future sea-level rise scenario maps developed by the National Oceanographic and Atmospheric Administration (NOAA) (cite: https://coast.noaa.gov/slr/). The inundation extents demonstrate how mean higher high water (MHHW) will change with sea-level rise increments from 0.3-3m (1-10ft). This is determined using a bathtub approach that accounts for local and regional tidal variability. The MHHW extent is indicative of the highest high tides but excludes storm surge that may occur during weather events. The maps do not account for erosion, subsidence, or future protection measures. Existing protective measures are captured to the extent that the digital elevation data, used by NOAA, captures the area’s drainage characteristics. The digital elevation map used to create this dataset has a resolution of 10 meters (about 30 feet).

Sea-level rise projections: We match NOAA’s sea-level rise extents with Global Mean Sea Level (GMSL) scenarios used in the 4th National Climate Climate Assessment [15]. These are shown in Fig. 1.

Road network: The road network was sourced from OpenStreetMap (OSM) through the geofabrik.de API. OSM is an online, user-contributed, open-source database including the street network, direction of travel, speed, stops, and turns. It has been favorably reviewed for its accuracy in the U.S. [23,24]. The data is improving globally, offering great potential to extend this analysis to other regions [25]. To modify the road network based on the exposure to the hazard (i.e., to remove impassable flooded roads), an appropriate format of the same OSM layer was acquired through the Python package OSMNX [26].

Origins and Population: We use 2020 census data (most recent) to determine census block populations. In the U.S., the census block is the smallest geographical unit used by the U.S. Census Bureau and is often akin to an ordinary city block bounded by streets. They are not based on population, as some have zero population, but the next largest geographic unit (the Census Block Group) usually has between 250–550 housing units. Data is retrieved from the National Historical Geographic Information System (NHGIS) [27]. The geographic centroids of the blocks are used as the origins for the distance calculation and the population is assigned to that point.

Building Footprint: Computer-generated building footprints are available from Microsoft Maps for the United States (https://github.com/microsoft/USBuildingFootprints). This data set is based on satellite imagery. While the dataset prohibits filtering out commercial and industrial buildings, this limitation is mitigated by estimating population data based on the census block data; blocks with significant commercial and industrial zoning tend to have fewer residents, thus acting to filter out non-residential areas.

Destinations

Services that communities generally rely on including

- Primary schools (Public and Private) [28]

- Fire stations [28]

- Emergency medical services (Urgent care facilities and hospitals) [28]

A geospatial dataset of these services was collated from the U.S. Department of Homeland Security (DHS) Homeland Infrastructure Foundation-Level Data (HIFLD) database for the entire U.S. and used as the destinations to determine how access to these services was impacted.

Methods

We conduct this approach for each MHHW SLR increment between 0.3-3m (1-10ft) at 0.3m (1ft) increments and for each of the destination types listed.

Risk of Inundation: To estimate the population exposed to MHHW, we use the proportion of exposed building footprints within each census block. That is, for each US census block, we determine the proportion of building footprint area that intersects with the MWWH extent. We then estimate the number of exposed residents by multiplying the block's total population by this proportion of exposure. This approach is consistent with Hauer (2021), except we use a finer spatial resolution.

Risk of Isolation: A block is considered at risk of isolation if no route exists between the centroid of the US census block (projected to the closest road) and any facilities of interest during MHHW. That is, a population is considered isolated if they don't have access to any fire stations, primary schools, or medical services - these destinations represent key activity centers and facilities that provide opportunities and essential services for residents. The road network is recompiled to exclude any road links that intersect the MHHW extent for the SLR increment in question [12]. That is, a road is considered impassable if there is any depth of MHHW. This contrasts with the analysis of extreme sea level (or coastal flooding) which typically uses a water depth impassable to vehicles (often 150-300mm) [29]. We assume road infrastructure within the MHHW will quickly become damaged beyond use due to daily flooding and scour. If a destination intersects the extent of the MWWH it is considered closed/removed and therefore ignored.

To determine whether a path exists between origins and destinations we use the OpenSourceRoutingMachine (OSRM). This uses OSM road data to calculate the shortest network distance between any two given points (for further details see [30]). If no possible route exists, this indicates that the origin is disconnected or isolated from the destination.

Limitations

- The analysis relies on NOAA's sea-level rise maps and so the limitations identified in their analysis persist here. Some of these challenges are around collating nationwide digital elevation maps and, as a result, hydrologic/hydraulic features (including stormwater infrastructure, ditches, canals, etc.) are captured only through the quality of the digital elevation data. More detailed local/regional studies would further refine these results.

- The routing analysis is based on today's road network and does not account for future adaptive measures that may strengthen existing routes or provide alternative routes. However, this work can highlight areas that may be considered for such intervention.

- Similarly, the population levels are based on current census reporting and are not projected into the future. Some coastal areas may see significant retreat while others may grow in size [31]. This could be considered in future work.

- We do not formally consider changes in travel distance, travel time, or congestion. When identifying routes with and without inundation, we additionally computed changes in travel distance when a route exists, though we elected to not present those results for simplicity. We argue that computing the change in travel time associated with the changes in travel distance by multiplying the road speed limit by the distance is moot because it does not account for traffic reassignment and thus congestion. To account for congestion, we would need to build a traffic assignment model for all U.S. coastal counties. This would require origin-destination tables with data at the block-level for our level of analysis. The U.S. Census Bureau's Origin-Destination Employment Statistics [32] is at the census tract level. It would also require strong assumptions about user equilibrium that may not hold up during periods of inundation [33]. Regardless, the focus of the work on risk of isolation is purposeful as isolation signals new burdens such as loss of opportunities, which may, in some instances, lead to displacement.

- This work only considers MWWH and does not consider the impacts of coastal flooding and storm surge (extreme sea-level), which could affect and isolate these communities sooner than our analysis indicates.

- Our method assumes that if a block's centroid is inundated, then the population of the entire block is at risk of isolation (because no route exists from the centroid to a destination). This is likely an under- or over-estimate for different places and different severities of SLR.

- In some rare instances, there are clusters of blocks (i.e., a grouping of one or more blocks) that are isolated by SLR from the rest of the region but their centroids remain non-inundated and the cluster contains at least one facility under consideration within its borders. Our method would not identify the residents of the town as isolated because they have access to one of the facilities we consider.

● There are a small number of communities that do not have road access to these amenities even at 0m of SLR (notably the Hawaiian Islands). These communities, therefore, are considered isolated immediately.

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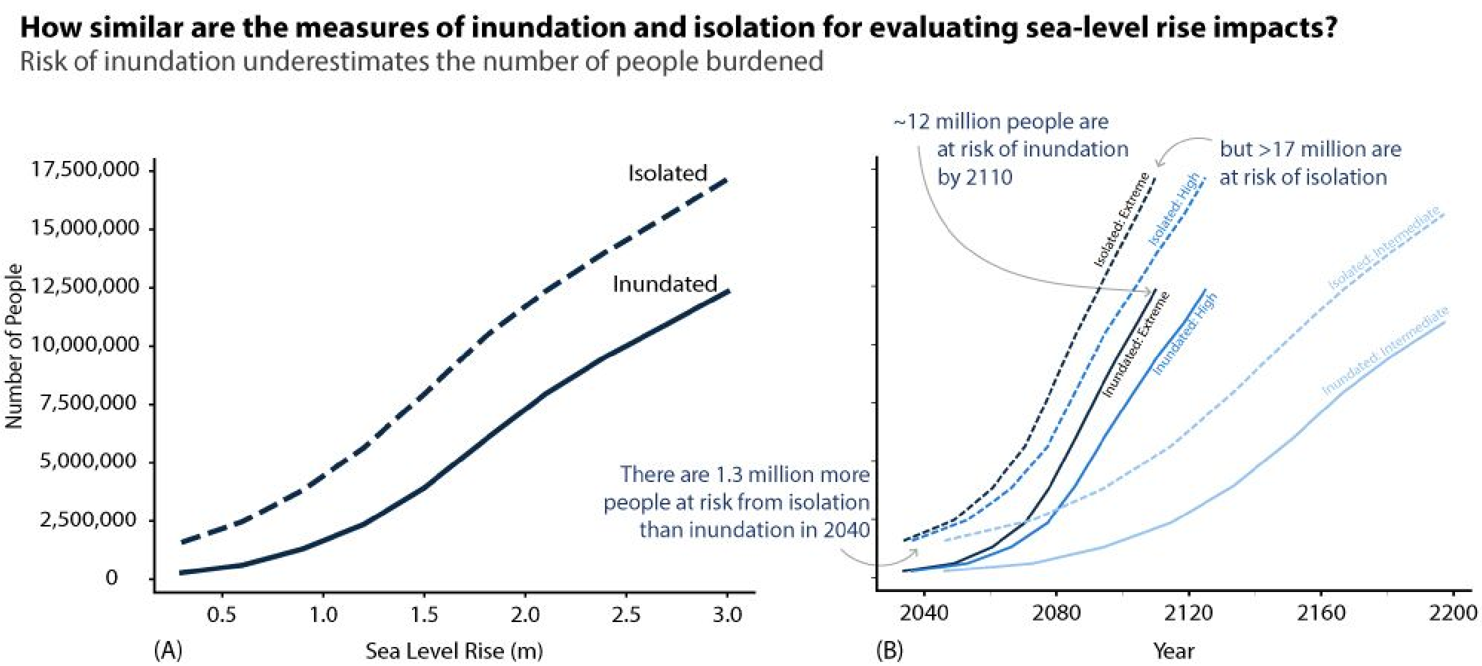
Figures



GMSL Scenario (meters)	2030	2040	2050	2060	2070	2080	2090	2100	2120	2150	2200
Intermediate	0.16	0.25	0.34	0.45	0.57	0.71	0.85	1.00	1.30	1.80	2.80
High	0.21	0.36	0.54	0.77	1.00	1.30	1.70	2.00	2.80	4.30	7.50
Extreme	0.24	0.41	0.63	0.90	1.20	1.60	2.00	2.50	3.60	5.50	9.70

(C)

Figure 1

The number of people burdened by sea-level rise is significantly higher if we consider the risk of isolation than if we simply consider the risk of inundation. (A) shows this difference against the SLR increments in meters. (B) shows this over time under different climate scenarios used in the US's Fourth National Risk Assessment (C).

Figure 2

Comparison of risk of inundation and isolation for the coastal U.S. (A) shows the difference between a county's population at risk of isolation and inundation during MHHW with 1.8m of SLR. An interactive web dashboard showing this data at county and tract levels for all sea-level rise increments between 0 and 3m is available at https://projects.urbanintelligence.co.nz/slr-usa/. This dashboard also enables viewers to explore the percentage of the population at risk at a county or tract level. (B) displays the percentage of each coastal state's population at risk of isolation (bars). Overlaid is each state's risk of inundation (lines). The states are ranked by their risk from 3.0m SLR inundation (the red line).

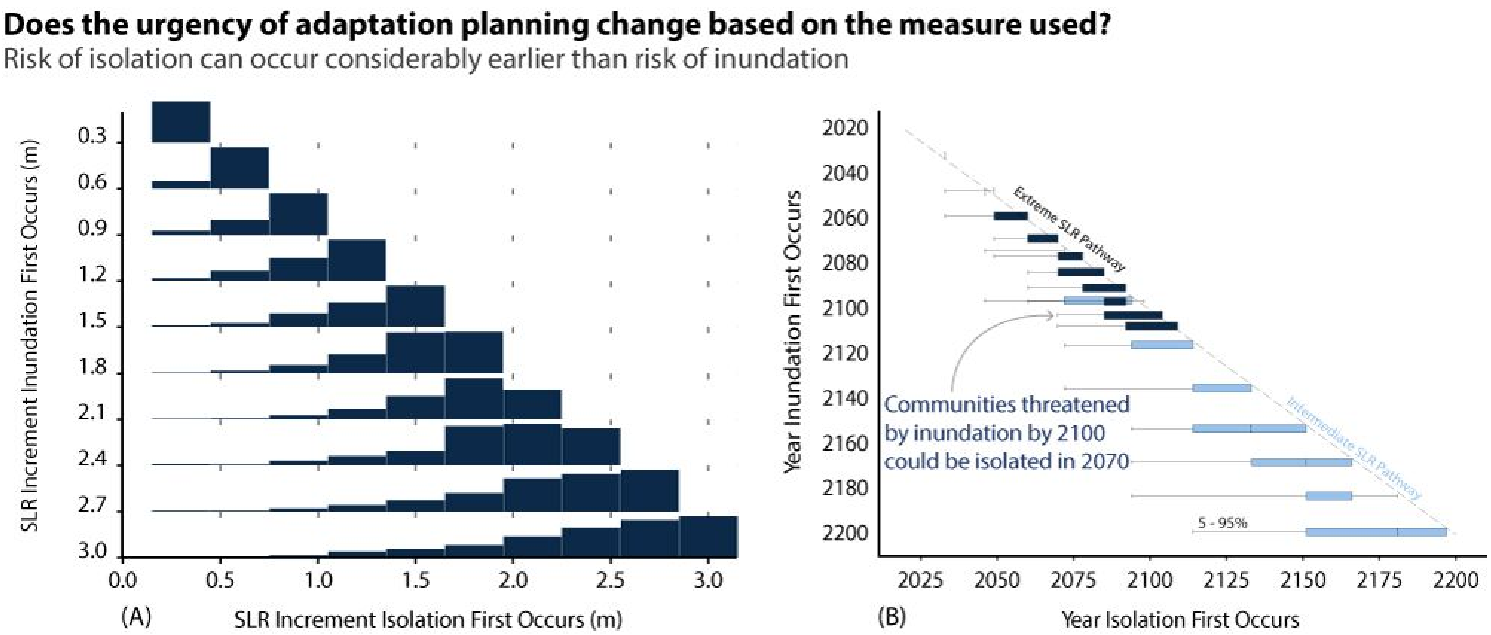


Figure 3

Residents may become isolated long before they are expected to be displaced due to SLR. (A) shows ridged histograms of the U.S. population at risk of inundation (for 0.3m to 3m of SLR, y-axis) discretized based on the SLR that commences their risk of isolation (x-axis) and (B) shows the temporal distribution of when risk of isolation commences for the U.S. population at risk of inundation for selected years between 2020 and 2200, based on extreme and intermediate SLR scenarios. (NOAA does not consider inundation greater than 3m, which occurs around 2110 in the extreme scenario.)

Figure 4

How many years earlier people are likely to be isolated before being inundated by SLR. (A) shows the number of people by the time difference between inundation and onset of isolation. Isolation can occur decades prior to inundation. (B) Some residents are isolated but never inundated within the SLR scenarios we use. This bar chart shows the year that these residents are first isolated under intermediate and extreme scenarios. (C) shows (A) for each affected US state for an intermediate SLR scenario. These results can also be explored using our dashboard: https://projects.urbanintelligence.co.nz/slr-usa/.