Analysis of flood vulnerability and transit availability with a changing climate in Harris County, Texas

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ABSTRACT
Hurricanes and other extreme precipitation events can have devastating effects on population and infrastructure that can create problems for emergency responses and evacuation. Projected climate change and associated global warming may lead to an increase in extreme weather events that results in greater inundation from storm surges or massive precipitation. For example, record flooding during Hurricane Katrina or more recently, during Hurricane Harvey in 2017, led to many people being cut off from aid and unable to evacuate. This study focuses on the impact of severe weather under climate change for areas of Harris County, TX that are susceptible to flooding either by storm surge or extreme rainfall and evaluates the transit demand and availability in those areas. Future risk of flooding in Harris County will be assessed by GIS mapping of the 100-year and 500-year FEMA floodplains and most extreme category 5 storm tide and global sea level rise. The flood maps have been overlaid with population demographics and transit accessibility to determine vulnerable populations in need of transit during a disaster. It was calculated that 70% of densely populated census block groups are located within the floodplains including a disproportional amount of low-income block groups. The results also show a lack of transit availability in many areas susceptible to extreme storm surge exaggerated with sea level rise. Further study of these areas to improve transit infrastructure and evacuation strategies will improve the outcomes of extreme weather events in the future.

INTRODUCTION
Extreme weather events such as hurricanes have had devastating impacts on communities and infrastructure and affected the most vulnerable populations in flooded areas. For example, category four Hurricane Harvey, generated 103 storm-related deaths, widespread flooding of more than 50,000 homes and over 500,000 vehicles, more than 17,000 water rescues, and 126 billion dollars of economic damages in Texas (1). Rainfall of over 1000 mm (~40 in) in the Houston metropolitan area, in particular in Harris County led to extreme flooding because of slow movement of the storm system. The effect of this storm on the Houston metropolitan area is unique because ~91% of the commuters in the Houston Metro area travel alone by car, making it one of the most auto-dependent places in the United States. Inundation of major roadways require evacuation strategies that adapt to these conditions. The projected extreme weather events amplified by climate change require a risk assessment of how vulnerable populations and infrastructure are affected by flooding from sea level rise, storm surge, and extreme rainfall events.

Sea Level Rise
Assessing global and regional sea level rise (SLR) due to global warming is of great interest to coastal populations, such as those along the Gulf of Mexico, due to increased tidal flooding and storm surges (2). Global mean temperature is expected to increase over 3°C by 2100 due to anthropogenic-induced greenhouse gas emissions into the atmosphere (3) that lead to increased sea level by melting of ice sheets, in particular the Greenland ice sheets, and associated ice
shelves and glaciers. Melting of ice sheets leads to a decrease in albedo that represents a positive feedback loop amplifying global warming due to increased heat absorption (4). In addition to melting of ice masses, sea level changes by thermal expansion due to predicted rise in global mean temperature contributes to a rise in global mean sea level (GMSL). The geologic record of the last million years suggests that during ice ages, sea level is low due to build-up of ice sheets and glaciers (5).

Vertical land movement is a significant factor in regional sea level change. Subsidence resulting from extraction of groundwater or other resources can effectively raise the sea level by lowering the land elevation. In addition, sediment deposition in the Gulf of Mexico originating from the Mississippi River runoff enhances this subsidence.

Projected SLR is characterized by substantial uncertainties, because of the range of future changes in radiative forcings as defined by representative concentration pathways (RCP), and because of the uncertain rate of melting of ice sheets and mountain glaciers. In the most extreme scenario, the RCP 8.5 “business as usual” scenario, sea level is predicted to change by 2.4 m or ~8 feet due to massive melting of the Greenland ice sheet, glaciers, and thermal expansion (4).

**Storm Surge**

In the past decades, low sloping beaches and near-coastal areas of Gulf Coast of the U.S have been affected by an increase in intense tropical storms with associated storm tides and heavy precipitation (6). Storm surges, and associated erosion and landscape changes, threaten critical infrastructure such as roads and bridges and can cause wide-scale flooding. Understanding storm surge and storm tide and how it will increase with climate change is essential to protecting vulnerable areas into the future.

A storm surge is a rise in water produced by a storm above the normal tide level, while a storm tide is that storm-generated surge on top of the astronomical high tide. While coastal locations are particularly vulnerable, storm surge inundation from hurricanes can move inland significantly. The magnitude of the storm surge depends on a variety of factors including the wind stress from the storm, slope of the beach, water depth, bottom friction, wave height, precipitation, atmospheric pressure, and other factors (7).

Water masses in the Gulf of Mexico are pushed onshore in a multifaceted process that is dependent on intensity, speed, size of the storm, angle of approach, and central pressure as well as the shape and topography of the basin (8). Surface waves generated by winds move in the direction of the winds and can be a source of significant transport of water masses to the shore (7). The buildup of water masses on the downwind side of a basin known as “wind set-up” effectively raises the sea level on the coast if the wind is directed toward the coast, and water penetrates the basin comparable to the tides. Separate from wind set-up, “wave set-up” can also occur when water carried toward the shore by breaking waves piles up near the shore and contributes to an overall higher surge (9).

The atmospheric pressure of a hurricane is a major contributing factor in the intensity of the storm. A deeper low pressure center results in a significant pressure gradient force which, combined with the Coriolis force, leads to higher geostrophic winds and tighter counterclockwise rotation. Sea level rise due to atmospheric pressure plays a less significant role in storm surge than wind, but nonetheless contributes to the height of the storm surge. In theory, the sea level rises directly under the low-pressure center 1 foot for every 1 inch drop in mercury reading. Hurricane Katrina had a central pressure of 27 inches of mercury, with 30 being average. This means that the sea level under the hurricane was elevated approximately 3 feet simply due to the low-pressure system (10).
The significant precipitation that occurs with tropical cyclones is also a contributing factor to coastal flooding. Heavy precipitation reaching 1500 mm (60 in) in a short period has been observed with Hurricane Harvey and led to rapid flooding of rivers, reservoirs, and low-elevated areas. Reducing or reversing the drainage of rivers by the storm surge can amplify the flooding (7).

**Storm Surge Modeling**

In order to model hurricane storm surge to predict inundation heights and locations, the National Weather Service (NWS) developed the Sea, Lake, Overland Surges from Hurricanes (SLOSH) model. The model integrates terrain, bathymetry and physical barriers along with the physics equations of motion to show how surge waters flow inland with landfall of a hurricane (11). SLOSH incorporates specific data from hurricanes such as atmospheric pressure, direction, and speed to model the winds and storm surge along the coasts. Geographically-specific polar grids are applied to basins, and there are SLOSH basins to cover the entire coast from Maine to Texas. Each basin represents inland topography; waterways such as bays, lakes, and rivers; and a section of continental shelf (11). SLOSH is able to simulate hurricane maximum envelopes of water (MEOWs) based on input parameters (pressure, speed, direction, size), or maximum of MEOWs (MOMs) that represent a worst-case scenario. MEOWs and MOMs are generated through computing the maximum surge for thousands of theoretical storms with varying parameters within each basin (12). MOMs are available as a mean-tide product or a high-tide product where high tide values are added to the storm surge height. SLOSH can also simulate historical models of past hurricane storm surges that compare well to the historical data.

SLOSH uses the equations of motion as developed for wind tide by Platzman (13) and modified by Jelesnianski (14) for storm surge to include bottom stress. The equations are:

\[
\frac{\partial u}{\partial t} = -g(D + h) \left[ B_r \frac{\partial (h - h_0)}{\partial x} - B_l \frac{\partial (h - h_0)}{\partial y} \right] + f (A_r V + A_l U) + C_r x_\tau - C_l y_\tau \\
\frac{\partial v}{\partial t} = -g(D + h) \left[ B_r \frac{\partial (h - h_0)}{\partial y} - B_l \frac{\partial (h - h_0)}{\partial x} \right] - f (A_r V + A_l U) + C_r y_\tau - C_l x_\tau \\
\frac{\partial h}{\partial t} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}
\]

(1)

(2)

(3)

where \( U, V \) denotes the meridional transport of water masses, \( g \) is the gravitational acceleration constant, \( D \) is the depth of quiescent water relative to a common datum, \( h \) denotes the height of water above datum, \( h_0 \) is the hydrostatic water height, \( f \) denotes the Coriolis parameter, \( x_\tau, y_\tau \) are surface stresses, and \( A_r, ..., C_l \) are bottom stresses.

The surface stress \( (\tau) \) represents meteorological data with many variables, and the bottom stress term represents frictional forces with many variables. Coefficients for these terms are derived using empirical data from past storms and surges. There are some coefficients such as surface drag and vertical eddy viscosity coefficients that cannot be empirically determined and must be specified (11). Topographic data are acquired from U.S. Geological Survey (USGS) three-dimensional elevation program in 1 arc second segments and incorporated into SLOSH for inundation modeling.
Storm Surge Measurement

Storm surge data have been collected by utilizing a combination of tide gauges, high water marks, and pressure sensors. Tide gauges operated by the National Oceanic and Atmospheric Administration (NOAA) that measure water levels at 175 locations along the coast can be used to recover storm surge height data (8). The United States Geological Survey (USGS) measures high water marks after a storm surge event. The marks indicate the maximum water level of the surge, and are used to determine inundation height. Trained personnel are disbursed in the area following a storm surge to identify and measure mud lines, seed lines, foams lines and other indications of high water (15). Prior to a predicted storm, USGS deploys temporary sensors to the area expected to be inundated that collect data on water level and barometric pressure. Some of these sensors use water pressure to determine the water level while others measure water level directly while also recording the barometric pressure (16).

As noted in the National Hurricane Center Tropical Cyclone Report on Hurricane Harvey, the storm tide produced inundation levels of 6 to 10 feet in the area of landfall. Tide gauge data indicated a maximum of 6.7 feet above mean high water at Port Lavaca, Texas, while temporarily installed sensors at Hynes Bay indicated a water level of 8.7 feet above mean high water. Surveys of high water marks conducted in the area indicated inundation of 11-12 feet, but were likely influenced by waves (1).

Floodplains

Flood risks from extreme rainfall include riverine flooding, coastal flooding, and shallow flooding. Floodplains have been developed to assess the risk of potential flooding in riverine and watershed areas, coastal areas, and other topographically low-lying areas. Riverine flooding occurs in watershed areas and is defined as any event when water rises over the banks of a channel and flows into a floodplain. Overbank flooding is the most common form of riverine flooding and occurs when the downstream channels receive more water from the watershed than normal (17). The topography of the region plays a large role in the extent, depth, and velocity of the flood. Flash flooding occurs when a particularly large amount of rain falls in a short period of time that overwhelms the banks of the channels. Urban areas with little permeable surfaces are particularly vulnerable to flash flooding. In addition to channels being inundated with water masses, the increased velocity of water masses during a flood promotes erosion of the river banks that can enhance flooding. In depressed areas, shallow area flooding can be enhanced by holding-up, slow permeation of soil, or damming of water masses referred to as ponding.

The Federal Emergency Management Agency (FEMA) utilizes the National Flood Insurance Program (NFIP) classifications of floodplains to develop Flood Insurance Rate Maps (FIRMs) for almost every community in the nation (18). These maps typically show floodways, a 100-year floodplain, a 500-year floodplain, as well as any other flood hazard areas such as coastal flood zones. Riverine flooding, shallow flooding, and coastal flooding are all considered when assessing floodplain classification.

A floodway is a river or stream channel that carries most floodwaters where building is limited. The 100-year floodplain refers to a probability of one-percent that a flood of that magnitude will occur in any given year and is also referred to as the one-percent annual chance flood. Similarly, the 500-year floodplain is the 0.2% probability that a flood of that magnitude will occur in any given year. The different types of flooding are studied in detail by FEMA scientists and engineers to generate FIRMs that show the locations of the floodplains and floodways. Floodplains are derived by combining elevation mapping with hydrology studies to
determine the floodwater elevation above ground. These FEMA floodplain maps are useful tools
to determine flood risk, but extreme weather events such as Hurricane Harvey produced a flood
that exceeded the 500-year flood, and was in fact a 0.1% probability flood or 1000-year flood
(1). A study conducted for FEMA to analyze the effects of climate change and population growth
on floodplain classification predicted an average increase in the 100-year floodplain area of up to
45% by 2100, with 70% of that change attributed to climate change alone (19).

Transit Availability
Flooding makes roads impassable therefore complicating evacuation efforts during disasters.
Many people reliant on public transit may be stranded in the case of a flooding emergency due to
lack of transit availability, or a lack of knowledge that their home is in a floodplain. Low-income
neighborhoods rely the most on public transit and these neighborhoods are most likely to be
located within a floodplain.

Research indicates limited transportation options exist in low-income, sprawling areas, and
this restricts employment opportunity and upward mobility as well as access to medical care.
Low-income households are less likely to own a vehicle or enough vehicles to transport all
members of the household. Addressing transit deserts is important for engaging broader social
issues such as inequity and welfare dependence (20).

A transit desert is similar to the widely studied topic of a “food desert” which has had great
influence on planning and policy. Transit dependent populations require transit service more than
others and include individuals who are too young, too old, or physically unable to drive as well
as individuals who cannot afford to (20).

Demographic changes that occur in metropolitan regions are geographic; shifting between
urban and suburban. Many middle class and affluent families are moving to the urban centers
with access to services, amenities, and public transportation. The poor are moving to the outlying
areas where services and transportation are lacking. Services in the outer urban neighborhoods
are limited due to the false assumption that people who choose to live in those areas own
vehicles. Transit deserts, therefore, are locations of inequity where those who own cars are not
affected by the inadequacy of transit while those who have no vehicle are disadvantaged (21).

Transit desert communities present dilemmas that fall outside of existing demand forecasting
parameters. Catalytic forecasting operates dynamically in the opposite realm of demand
forecasting, evaluating areas based on the full potential of urban dwellings. Numbers based upon
the maximum frequency of use force communities to plan for accurate and meaningful efforts
towards accessible public transportation. Catalytic forecasting can be deemed a subjective
method in that it puts demand at every parcel in a transit shed, although traditional transportation
planning requires objective forecasting to be useful. Transit deserts are the results of subjective
policy and market forces which created areas that lack transit access and hold an invisible
population. Demand forecasting privileges a certain population and catalytic forecasting is a way
to more accurately reflect the kinds of systems that should be produced to create equity (21).

OBJECTIVES
In order to increase efficient evacuation during extreme weather events, areas of vulnerability
will be identified through analysis of the impacts of flooding from hurricane storm surge in a
rising sea, and increasing rainfall events in a warming climate. The area of focus for this project
is Harris County, Texas, which was devastated by floods during Hurricane Harvey in 2017. The
overall aims of the research are to identify areas prone to flooding from storm surge or extreme
precipitation and evaluate the transit availability of those areas. The results of this project will be
used for future studies involving FEMA and NWC to evaluate the evacuation response to disasters and how the transportation infrastructure is affected by flooding.

METHODS

A Geographic Information System (GIS) was employed and several map layers were utilized including a Digital Elevation Model (DEM), FEMA National Flood Hazard Layer (NFHL), and storm tide inundation (SLOSH) with SLR along with demographic and transit data to focus on vulnerable populations and infrastructure of Harris County Texas.

The DEM layer was obtained through the USGS and includes the tiles USGS NED 1/3 arc-second n31w096 1 x 1 degree ArcGrid 2018 and USGS NED n30w096 1/3 arc-second 2013 1 x 1 degree ArcGrid. The tiles were then combined using the mosaic to new raster function of ArcGIS and the final DEM was clipped to include only Harris County. The layer was then converted from meters to feet and values expressed in increments to better visualize the low elevation areas.

The floodplain map obtained through the FEMA map service center was from the 2015 NFHL that included the latest updates and modern floodplain classifications. The layer combined all of the areas of 1% chance annual flood, 0.2% chance annual flood, floodways, and coastal flood hazard areas as well as areas of minimal flood risk. The map layer’s symbology was altered to remove areas of minimal flood risk and visualize the 1% and 0.2% chance annual flood or 100-year and 500-year floodplains. A new layer was created after removal of areas of minimal flood risk so the layer could be used to join and relate data from demographics and infrastructure such as population and roads.

Storm surge inundation data, not including SLR, was obtained through NOAA and the National Hurricane Center (NHC) and was originally published in the American Meteorological Society Journal of Weather, Climate, and Society in 2014. NHC used the SLOSH model output for MOM at high tide along with the latest elevation model from USGS to create a seamless inundation layer for use in GIS that covers the Atlantic coast from Maine to Texas. The category five high tide scenario was chosen to show the maximum possible inundation in the area and the category three high tide was displayed to demonstrate that significant risk exists with weaker hurricanes as well.

Sea level rise of 8 feet in response to climate change was chosen to add to the category 5 storm tide layer to visualize the storm surge potential into the future. The highest elevation inundated by the storm tide layer was identified using the identify tool of ArcGIS. Raster calculations were used to select the elevations from the DEM that corresponded with the addition 8 feet to the highest elevation inundated by the storm tide. These layers were then overlaid on the storm tide layer and symbolized to emphasize the change in the inundation area with climate change by 2100.

Data on roads were obtained through Texas Department of Transportation (TxDOT) and overlaid on the floodplain and storm tide layers for spatial analysis. Public transit routes including light rail lines, bus routes, bus stops, and transit centers were mapped in GIS in order to evaluate the transit availability and vulnerability to flooding. Population density and mean household income data obtained from U.S. Census were also mapped in GIS by census block group and overlaid on the floodplain and storm tide layers. ArcGIS was utilized to create a new layer of low-income populated areas from selecting block groups that had population density over 3000 per square mile and had median household income of less than $30,000. To highlight the low-income block groups susceptible to flooding, a selection was made of any low-income block groups that were within the FEMA 100-year and 500-year floodplains. To assess risk due
to storm surge, populated areas that overlaid the storm surge layer, as well a low-income block groups were selected to form a layer that represented that risk. That layer was then overlaid with the Houston Metro and TxDOT data layers to assess transit availability.

A transit desert map of Harris County, TX was compiled in GIS to determine walking times from each parcel to the nearest transit center, park and ride, or bus stop. These data were then displayed as a map layer showing walking times of 5, 10, and 15 minutes to determine the locations of transit desert neighborhoods and evaluate those locations for flood vulnerability.

RESULTS

The elevation map overlaid with the FEMA floodplain map displays a correlation between areas of low elevation and areas within the 100-year and 500-year floodplains (Figure 1). The floodways are in the river channels and the floodplains are in areas of low elevation adjacent to the river channels. The map demonstrates which areas would be flooded by an extreme rainfall event that represents a 1% chance annual flood or a 0.2% chance annual flood.

FIGURE 1. The elevation map, in feet, of Harris County, TX showing the FEMA 100-year and 500-year floodplains. The National Flood Hazard Layer (NFHL) 2015 was accessed through the FEMA Map Service Center. The Digital Elevation Model (DEM) was accessed through the USGS national map and includes two 1 x 1 degree grids.
The FEMA floodplain map was overlaid on the population density map to analyze block groups within the floodplains (Figure 2). The map indicates that the floodplains exist in many densely populated areas demonstrating the need to assess the demographics and transit infrastructure of these areas. Densely populated block groups of Harris County within the floodplains are identified and mapped with the population density. Although the entire block group may not be within the floodplain, the entire block groups are selected if the floodplain exists within that block group.

FIGURE 2. The FEMA floodplain map overlaid on the population density map highlighting block groups with dense populations that are within the 100-year and 500-year floodplains.

The transit map of Houston shows the available bus routes and stops, transit centers, and the light rail lines along with the low-income block groups of Harris County (Figure 3). According to Houston Metro data, the system covers approximately 2/3 of the county and offers approximately 370,000 services per day including 1,236 active buses and 76 light rail vehicles. The most used light rail line, the northern route, carries 55,000 passengers daily. Low-income block groups that contain either the 100-year or 500-year floodplains are highlighted to demonstrate the most vulnerable populations in need of transit.
FIGURE 3. The transit map of Houston Metro area highlighting low-income block groups and low-income block groups located in the 100 and 500-year floodplains. Median annual household income data acquired from US census and displayed in block groups. The dark green colored block groups are areas with low income located within the floodplains.

The storm tide map shows the area of inundation from a category 5 and category 3 hurricane making landfall during high tide (Figure 4). The inundation layer corresponds well with the elevation map to demonstrate the vulnerability to storm surge in low-lying areas. As the map shows, areas of low elevation have higher inundation levels and the opposite is true for higher elevation areas. The figure also shows how the storm tide flows up the river channels that can compound riverine flooding during a hurricane. Sea level rise was added to the category 5 storm tide to display the expansion of the inundation under RCP 8.5 SLR scenario (Figure 4). The map shows that areas that are not currently susceptible to the maximum storm surge may be so in the future.
FIGURE 4. The Storm Tide map of Harris County, TX displaying inundation area for Cat 3 and Cat 5 hurricanes. The National Storm Surge Hazard Map was accessed through the National Hurricane Center and clipped to Harris County. SLR scenario of 8 feet displayed to demonstrate how the storm tide area increases with the rising sea.

Densely populated block groups affected by the category 5 storm tide as well as low-income block groups are mapped along with the transit map to evaluate areas exposed to surge (Figure 5). Although the storm tide layer may not inundate the entire area within each block group highlighted, the entire block groups affected in some way by the surge were chosen for evaluation. Selections of block groups within flood hazard regions of Harris County were overlaid on the transit map to display areas that have dense populations and low income (Figure 5). The map shows several densely populated areas within the 100-year or 500-year floodplains as well as many densely populated areas within the storm tide that have no transit availability. The figure also identifies low-income block groups in the flood hazard zones.
FIGURE 5. The transit map of Harris County displaying the areas at risk of flooding and storm tide inundation along with highlighted areas of Median Household Income of less than $30,000.

The transit desert map of Harris County, TX demonstrates the great need for transit availability in areas prone to flooding and/or storm surge (Figure 6). Locations that are more than ½ mile away from a transit stop should be considered for transit desert classification when overlaid with demographic data.
FIGURE 6. The transit desert map of Harris County, TX displays Houston Metro Transit information with walking times to available transit in minutes.

CONCLUSION

Of the total population block groups in Harris County, 30.5% are densely populated, and among these block groups, 70% are within the FEMA 100-year and/or 500-year floodplain (Figure 2). The total number of income block groups with median annual household income of less than $30,000 represents only 5.3%. However, 66% of low-income block groups are within the FEMA 100-year and/or 500-year floodplain (Figure 3). This indicates many of the low-income population of Harris County live in areas that are susceptible to flooding during extreme rainfall events. People living in low-income communities rely on public transit in the case of an evacuation, and of the 1970 bus stops within these communities 66.4% are in the floodplain and will be unusable in the case of flooding.

Within the category 5 storm tide, 171 population block groups represent 8.8% of block groups in Harris County that are affected by maximum surge inundation. About half that number, 4.1%, are at risk from a category 3 storm tide (Figure 4). Of the 103 low-income block groups, 24 are within the inundation area. This represents 23.3% of the low-income block groups located within the storm tide. Of the 171 block groups affected by inundation, less than half, or 46.2% do not have any bus stops, light rail, or metro centers. This represents a high risk of being stranded by floodwaters in the event of a hurricane in those regions of Harris County. With future SLR scenarios included in the storm tide, the inundation area increases by 21% to cover an additional 36 high density population block groups in the worst-case scenario of 8 feet of SLR.
The transit desert map shows the supply of transit and demand by parcel with walking times to transit stops. The need for public transit is greater in low-income neighborhoods and many of these areas seen in Figure 5 are within the transit desert. Many areas in southwest Harris County have no transit access at all which leaves the population with little options for evacuation prior to a hurricane, and limits accessibility by responders due to lack of an existing transit grid.

The results establish the locations most exposed to flood risk from storm surge or extreme precipitation in Harris County and reveal that many low-income neighborhoods reliant on public transit are located within those flood hazard zones (Figure 5). Southeastern Harris County is particularly susceptible to storm surge inundation while possessing little in the means of public transit. Areas east and southeast of downtown Houston are prone to flooding by extreme rainfall events, while containing many low-income neighborhoods in need of public transit. Further study of these areas, as well as any areas currently adjacent to the 100-year or 500-year floodplains will be considered to improve evacuation efforts to get residents to safety in the event of flooding.

**Future Outlook**

To address transit availability and flooding susceptibility, communities should plan transit-oriented development, including affordable housing with multimodality of green infrastructure to build sustainability of the area. Efforts should be made to provide equitable access to transportation options including connected pedestrian, bicycle, and transit routes. Communities should develop guidelines and provide signage to follow during evacuation to help people reach transit. New technologies including electric vehicles should be supported and applied to design strategies to achieve lower carbon emissions. Municipalities and regions should develop climate resistance plans and require climate change analysis of existing laws and regulations. To address public health impacts of climate change in vulnerable communities, transit access to health care centers should be provided before, during, and after a disaster. Building in floodplains should be limited or prohibited to protect life, property, and floodplain function, and natural vegetative buffers should be protected and enhanced. Cities should promote mixed-income housing and mixed-use development that provides access to essential services and promotes green, permeable spaces. Buildings that exist in floodplains should have codes updated to require every first floor to be built of concrete to retain the structure when flooded.

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**AUTHOR CONTRIBUTION STATEMENT**

The authors confirm contribution to the paper as follows: study conception and design: Dr. Arne Winguth, Dr. Diane Jones Allen; data collection: Joshua A. Pulcinella, Niveditha Dasa Gangdhar;
analysis and interpretation of results: Joshua A. Pulcinella; draft manuscript preparation: Joshua A. Pulcinella, Gennadii Prykhodko. All authors reviewed the results and approved the final version of the manuscript.

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