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Indicators and participatory processes: a framework for assessing integrated climate vulnerability and risk as applied in Los Angeles County, California

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Abstract

Climate vulnerability research is enhanced by stakeholder engagement as coastal communities are increasingly vulnerable to climate-driven impacts, yet these impacts are rarely evenly distributed across space and stakeholder feedback is not always well incorporated into the process. While often used in applied management applications, integrated spatially explicit assessments of multi-faceted vulnerability and hazard less commonly appear in the scientific literature, especially those that are transferable across geographies and risk metrics. Since many geographies lack an integrated, stakeholder-driven assessment of multiple hazards and vulnerabilities within the same assessment, scientists with the National Oceanic and Atmospheric Administration's National Centers for Coastal Ocean Science developed a transferable and integrated community vulnerability assessment framework (Framework) that relies primarily upon available secondary data and is supplemented with stakeholder-derived primary data. Using blended approaches in stakeholder engagement, we present the Framework's six methodological steps as recently applied in Los Angeles County, California: iterative partner engagement, indicator and index development, vulnerability assessment, hazard assessment, risk assessment, and reengagement for adaptation action. We conclude that boundary-spanning organizations such as Sea Grant Extension programs can play a crucial role in participatory science and stakeholder needs assessments, and emphasize the need for continued stakeholder engagement in climate science.

Keywords Integrated community vulnerability assessment · Climate risk · Stakeholder engagement · Social vulnerability · Indicators · Partner advisory committee

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1 Introduction

Coastal communities are increasingly vulnerable to flooding and erosion worldwide. Climate change is exacerbating these and other effects, including drought, heavy precipitation, heat waves, and overall increasing temperature (International Panel on Climate Change 2014; Trenberth et al. 2007). Yet, these impacts are rarely distributed evenly across space due to variations in topography, projected hazard profiles, and other geographic and climatic influences. Similarly, socioeconomic and structural inequalities alter the ways in which the impacts of these hazards are felt across communities and populations (Frazier et al. 2014). As the last few years have shown, socioeconomic inequalities are further exacerbated by unforeseen impacts from global health crises (Manzanedo and Manning 2020; Ogedegbe et al. 2020), amplifying inequities. Spatial variation can complicate local and regional adaptation planning efforts to mitigate potential climate-driven impacts. As a result, vulnerability assessments have become more common, although many use a sectoral approach by primarily focusing on one aspect of hazard, vulnerability, and/or risk (Colburn et al. 2016; Li et al. 2015; Thomas et al. 2016; Yankson et al. 2017) or use an econometric modeling approach that largely omits spatial effects (Ciscar et al. 2011). While often used in applied management applications, integrated spatially explicit assessments of multi-faceted vulnerability and hazard are less common in the scientific literature, especially those that are transferable across geographies and risk metrics (Holsten and Kropp 2012; O'Brien et al. 2004). This relative absence is concerning because community vulnerability assessments are often among the first steps taken to advance local climate adaptation planning, and communities need to be confident in their assessment methodologies and resulting information.

The need for stakeholder and partner engagement in climate vulnerability science is recognized in the literature, but not always well incorporated. Many discuss the need to inform stakeholders (Li et al. 2015) or to effectively communicate their findings (Papathoma-Köhle et al. 2019; Thomas et al. 2016), while others describe minimal stakeholder engagement, but speak to the importance of including stakeholder engagement in future research (Holsten and Kropp 2012; Krellenberg and Welz 2017). While fewer academic vulnerability studies successfully integrate stakeholder engagement into their research processes, those that do use a variety of methods. To inform the development of community vulnerability indices to flooding, Yankson et al. (2017) held stakeholder meetings and interviews with local community leaders, and Antwi et al. (2015) held focus groups, household interviews, and key informant interviews. From a spatial perspective, Hung and Chen (2013) collected and integrated local stakeholder knowledge of climatic hazards via a participatory geographic information system (GIS). Borrowing from the fields of coastal and marine spatial planning, not only can active stakeholder participation be achieved, but it can also better support end-user decision making (Gopnik et al. 2012; Tompkins et al. 2008). When stakeholders are engaged throughout the process, they are able to provide insights relevant to appropriate data sources, but also become key in the research process itself. Furthermore, in addition to sourcing local expert knowledge, stakeholders are the recipients and users of final products (Phillipson et al. 2012), underscoring the importance of their iterative inclusion.

Despite their drawbacks (Libório et al. 2022; Spielman et al. 2020), the use of indicators is prevalent in climate change vulnerability, hazard, and risk assessment research (Colburn et al. 2016; Krellenberg and Welz 2017; Li et al. 2015; Papathoma-Köhle et al. 2019; Thomas et al. 2016; Yankson et al. 2017). Indicators reduce the complexity of multidimensional issues through proxy quantification (Heink and Kowarik 2010; Hinkel 2011), resulting in the ability to analyze, compare, and communicate complex ideas. In this manner, an indicator-driven vulnerability assessment is able to integrate data from various disciplines. Contributions to the theory of community vulnerability incorporate input from fields including emergency management (Pearce 2003), planning (Lee 2014), coastal science (Özyurt and Ergin 2010), and social science (Cutter et al. 2003). While the literature struggles to provide a single definition of vulnerability (Fuchs et al. 2011), many of these fields treat vulnerability as a function of exposure, sensitivity, and adaptive capacity. Following this and the definitions provided by the Intergovernmental Panel on Climate Change (IPCC) in its sixth assessment report (2021) and the U.S. Climate Resiliency Toolkit (2021), we define vulnerability as the propensity or predisposition of assets to be adversely affected by hazards. Related, we define exposure as the presence of people, assets, and ecosystems in places where they could be adversely affected by hazards (United States Global Change Research Program 2021). Hazards are defined as coastal and climate-driven events or conditions that have the potential to cause injury, illness, or death to people or damage to assets (United States Global Change Research Program 2021). Lastly, risk is defined as the potential for adverse consequences of a climate-related hazard (United States Global Change Research Program 2021).

In this manuscript, researchers at the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal Ocean Science present an integrated vulnerability assessment framework as applied in Los Angeles (L.A.) County, California.[1] This approach iteratively integrates partner and stakeholder engagement to a) develop indicators and indices of various facets of community vulnerability and climate-driven hazard and b) spatially assess social, structural, and natural resource vulnerability or exposure to coastal and climate-driven hazards. We first provide geographic context for application in L.A. County before presenting the framework methods, including guidance on the selection of relevant aspects of hazard and vulnerability, determination of the unit of analysis, development and aggregation of indicators and indices, and methods for risk assessment. We then provide example results and discussion from framework application in L.A., and conclude with framework benefits and future applications.

2 Geographic context for application in Los Angeles

L.A. County is one of the nation's largest and most populated counties, at over 4,000 square miles and home to more than 10 million residents (United States Census Bureau 2010, 2018). It has an elevation range of over 10,000 feet, 75 miles of Pacific coastline, 28 square miles of marshland (Los Angeles Tourism Board 2022), and contains eight major watersheds (Los Angeles County Department of Public Works 2019). The County's geography, ecology, and communities are highly variable, with extreme variation in social and economic factors, including disparities in income, education, and employment opportunities. The hazard portfolio of L.A. County is more diverse than in many other geographies, given its exposure to the ocean, mountains, desert conditions, and the bowl-shaped air system over the City of L.A. Many of these hazards are adversely

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[1] This framework approach was previously applied for two study areas within the Chesapeake Bay (Fleming et al. 2017; Messick et al. 2016).

influenced by a changing climate, and may be considered climate-driven. They include extreme heat, wildfire, drought, deteriorating air and water quality, erosion, stormwater flooding and mudslides, earthquakes and tsunamis, and coastal flooding from storms, sea level rise, and El Niño events, among others (Finzi Hart et al. 2012; Grifman et al. 2016; Noriega and Ludwig 2012; Schubel et al. 2015; Wisner 2003). With climate and land use changes, it is anticipated that many of these hazards will intensify in frequency, strength, and/or duration (Moser et al. 2012). Average temperatures across the State of California increased by 1.7°F (0.9 °C) from 1895 to 2011, and climate models suggest that California will warm by 2.7°F (1.5 °C) above year 2000 averages by year 2050. Models indicate a range of an additional 4.1–8.6°F (2.3–4.8 °C) by year 2100 (Moser et al. 2012).

Given the confluence of large population size, a suite of existing climatic threats, and the likelihood for these threats to increase with climate change, many studies have examined hazards, vulnerability, and/or risk within L.A. County (Grifman et al. 2016; Schubel et al. 2015; Wisner 2003). Similar to national findings, however, gap analysis of local research revealed that most studies examined the impacts and vulnerability of a single hazard (Grifman et al. 2013; Rodrique 1993; Tayyebi and Jenerette 2016; Toké et al. 2014), and few place-based studies looked at the interactions among hazards and vulnerabilities simultaneously. Further, while Grifman et al. (2013) involved diverse stakeholder engagement, the majority of these studies largely omitted robust stakeholder engagement efforts.

3 Framework overview

Community vulnerability assessments are critical for climate adaptation planning because they can help identify vulnerable populations, prioritize areas for future investment of resources, and qualify communities for grants and adaptation action funds. Since many geographies lack an integrated, stakeholder-driven assessment of multiple hazards and vulnerabilities within the same assessment, scientists with NOAA's National Centers for Coastal Ocean Science developed a transferable and integrated community vulnerability assessment framework (Framework) that relies primarily upon available secondary data supplemented with stakeholder-derived primary data. This methodology utilizes a place-based vulnerability framework (e.g., (Cutter and Finch 2008)) to examine social, structural, and environmental vulnerability to climate variability and impacts. Advancing methods used by Wu et al. (2002), indices of social vulnerability, structural vulnerability or exposure, and natural resource exposure are employed alongside hazard indices. Our six-step Framework process is shown below.

(1) Engage local partners and stakeholders to identify aspects of vulnerability and/or exposure and climate-driven hazard within the study area
(2) Develop indicators and indices for each vulnerability/exposure and hazard
(3) Assess social vulnerability, structural vulnerability/exposure, and natural resource exposure within the study area
(4) Assess hazard within the study area
(5) Intersect vulnerability or exposure and hazard profiles to assess risk
(6) Engage local partners and stakeholders for prioritization of adaptation areas and next steps to mitigate climate-driven impacts

Table 1 Summary of key partner and stakeholder engagement points

Engagement	Action	Participants[a]
Project conceptualization	Establish partner advisory committee	PAC
Pre-workshop 1 (2017)	Pre-workshop questionnaire	PAC
Workshop 1 (2017)	Prioritization of vulnerability themes session	PAC + IS
	Prioritization of hazards session	PAC + IS
	Geography mapping session	PAC + IS
	Unit of analysis determination	PAC
	Study area determination	PAC
Interim	Establish criteria for additional assessment geographies	PAC
Workshop 2 (2019)	Presentation of preliminary results	PAC + IS
	SNAP exercise for intersecting vulnerability and hazard to assess risk	PAC + IS
	Geography mapping session	PAC + IS
Assessment review and dissemination (2019–2020)	Validation of assessment results	PAC
	Dissemination to stakeholders and communities	PAC + IS
	Facilitation of data into local research/policies	PAC + IS

[a] Partner advisory committee = PAC; Invited stakeholders = IS

The Framework initiates and concludes with partner and stakeholder engagement and develops indicators and indices for selected vulnerabilities/exposures and hazards, assesses each vulnerability/exposure and hazard independently, and then intersects vulnerability/exposure with hazard to assess risk. Depending on available data and local needs, vulnerability can include concepts of sensitivity, exposure, and adaptive capacity, and hazard profiles may incorporate location, extent, previous occurrences, and future probability. The result is an integrated climate vulnerability assessment that is both indicator- and stakeholder-driven. Resulting products can be used by local partners and stakeholders for prioritization of adaptation areas to mitigate climate-driven impacts and reduce vulnerability.

Although local partner and stakeholder engagement are the first and final steps of the Framework, we recommend an iterative approach to engagement efforts throughout the course of Framework implementation. Integrated stakeholder engagement is a critical aspect of applied research for use in community spatial planning and decision making (Gopnik et al. 2012; Pearce 2003; Tompkins et al. 2008), and will be a primary focus of this paper. For our assessment of L.A. County, we formed a partner advisory committee during the project's proposal phase through partnership with the University of Southern California (USC) Sea Grant Extension and NOAA's Office for Coastal Management. Our partner advisory committee was initiated using existing professional networks and consisted of professionals with knowledge of the L.A. region who were involved in coastal research, policy, outreach, and education. This partner advisory committee recommended appropriate local stakeholders based on their regional knowledge of stakeholder needs, interests, and capacities. In addition to their stakeholder connections, the partner advisory committee provided regional guidance to refine the project scope and ensure actionable and relevant project outcomes. They also validated assessment findings, strategized the dissemination of final products, and helped facilitate the incorporation of data into local research efforts and community use. Partner advisory committee and stakeholder participation is summarized in Table 1 and referenced in the following sections.

4 Choosing relevant aspects of hazard and vulnerability

Following a scoping period and literature review with gap analysis, our partner advisory committee was sent an informal questionnaire that reminded partners of the project scope and collected information to best leverage existing research, identify data needs, assign the scale of the study area, and capture regional aspects of vulnerability and climate hazard (Table 1). Responses were voluntary and were used to develop materials for an in-person workshop. Since the Framework outputs are intended as tools for local prioritization for adaptation planning, it is critical that the contributing components represent local stakeholder priorities. To establish these key components, our partner advisory committee assisted with identifying and inviting local stakeholders, including municipality planners, climate sustainability professionals, and natural resource managers, to the workshop. In addition to our partner advisory committee, four local organizations participated. Drawing upon lessons in effective participant engagement (Cuocco 2014; Scherhaufer 2014; van Asselt Marjolein and Rijkens-Klomp 2002), the facilitated workshop sessions incorporated a series of consensus-building prioritization exercises, including both participatory mapping for spatial priorities and conceptual mapping for climate, hazard, and vulnerability topics.

First, participants were shown workshop materials on flip chart pads and given colored sticky notes that corresponded to each participant's organization. We then asked participants to consider the vulnerability themes informed by the pre-workshop questionnaire and written under the broader categories of social, structural, natural resource, and "other" vulnerabilities. Participants were encouraged to collectively discuss the potential for missing themes among the existing lists via facilitated discussion. Where applicable, additional themes were added across the four lists and denoted with an asterisk. Using their color-coded sticky notes, participants were then asked to actively select their top three choices within each list. We asked participants from the same organization to consolidate their prioritization, which resulted in break-out deliberations. After participants had placed their sticky notes and returned to their seats, we facilitated a collaborative discussion to solidify the final rankings. In some cases, participants altered their choices after hearing another participant's perspective. Following a short break, this workshop session was repeated for coastal and climate-driven hazards (example outputs shown in Fig. 1).

Lastly, we engaged participants in a geography priority mapping exercise, where participants were given colored dots and asked to consider key areas of climate interest or concern. Similar to the previous sessions, we asked them to place dots on their top three geographies within an enlarged, table-top map of L.A. County (Fig. 2). In addition to dot placement, participants were asked to complete short ranking sheets that asked for their three locations and brief reasoning for choosing each. This session also ended with facilitated discussion about regional needs. Results from these workshop sessions were used to inform decisions throughout implementation of the Framework.[2]

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[2] Participants also engaged in an economic analysis needs assessment, and those results informed additional analyses outside of framework implementation.

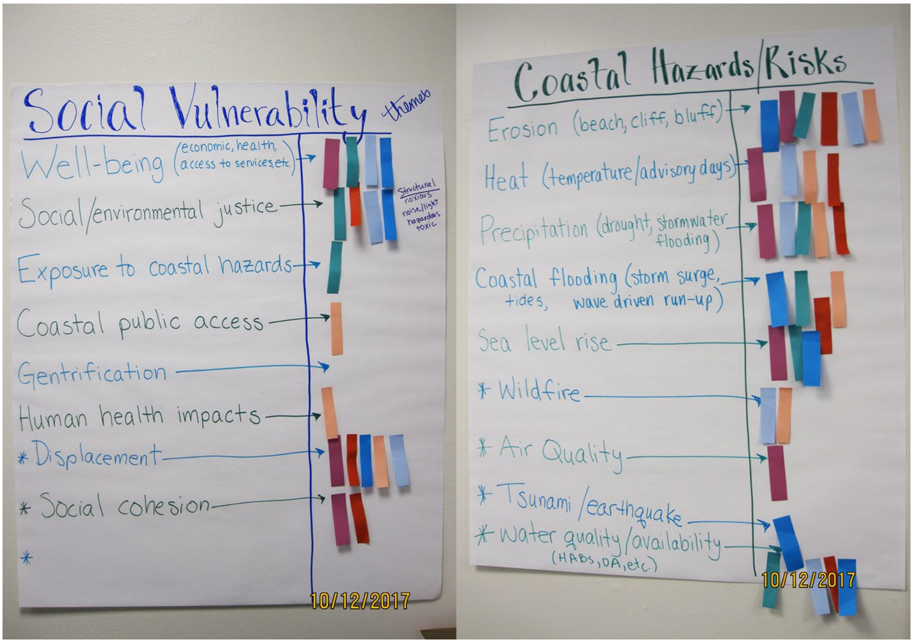


Fig. 1 Example outputs from the prioritization workshop sessions —Social vulnerability results (left) and hazard identification (right) [*Note*: This photograph incorrectly conflates hazards with risks. Our research team re-evaluated and updated our terminology post-workshop. For more information, please, see footnote 4.]

While stakeholder input is essential to Framework implementation, the Framework also contains means to mitigate stakeholder burden. Although less impactful than other research efforts (e.g., clinical trials, epidemiological studies), stakeholder engagement still bestows burden upon its participants, and social scientists are held to ethical and legal standards to reduce this burden where possible (Paperwork Reduction Act 1995). For this study, coordination through USC Sea Grant Extension allowed for minimal targeted interactions directly with stakeholders while allowing continuous local feedback through our partner advisory committee. The Framework also strikes a balance between stakeholder partnership and theory-driven research. While key research decisions were strongly influenced by partner and stakeholder input, their feedback was not deterministic. Following partner and stakeholder recommendations and stated preferences, we assessed data availability, consulted the literature, and performed feasibility checks on the proposed concepts before drafting regionally specific sets of candidate indicators for each metric (see Sect. 6). Our partner advisory committee was also consulted whenever our chosen metrics diverged from previously expressed preferences, and they were invited to suggest project modifications where appropriate.

5 Determining unit of analysis and scale

The scale and resolution of analysis for vulnerability assessments is often dependent upon data availability (Fekete et al. 2010), size of the study area (Bukvic et al. 2020), and ecosystem service priorities (Dick et al. 2014), and should align with desired management

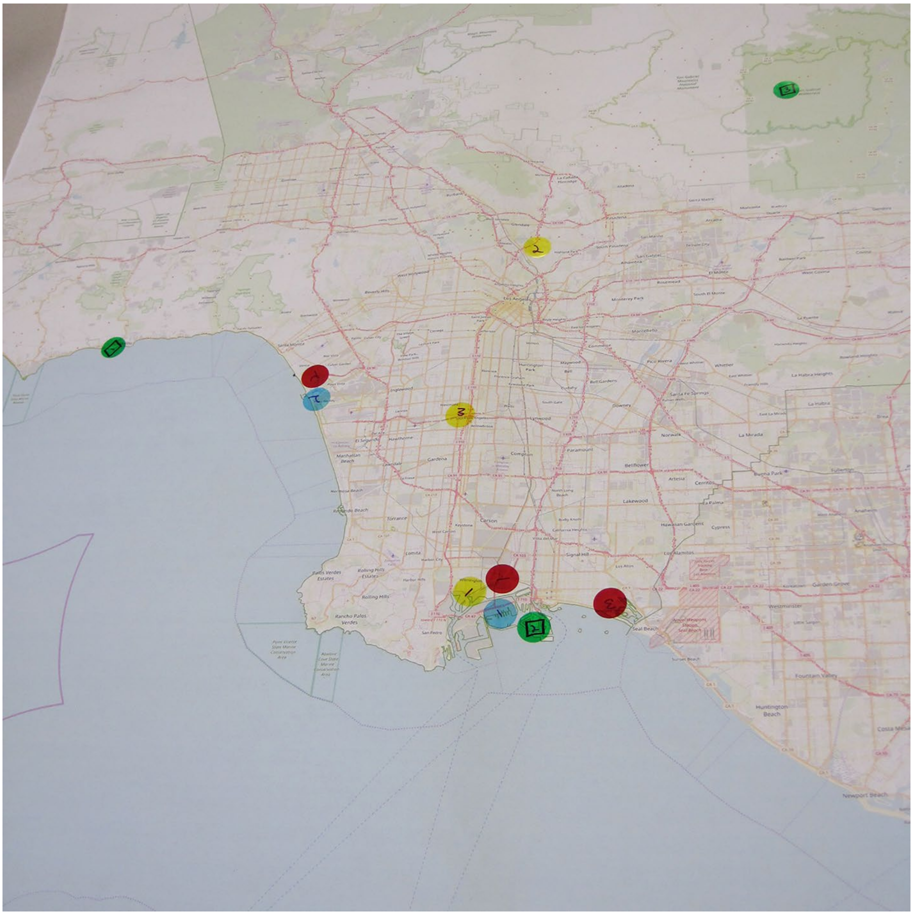


Fig. 2 Geography mapping results

objectives (Pelosi et al. 2010), among other considerations. L.A. County has a large spatial footprint, and datasets needed to cover the entirety of this footprint in order to be incorporated. The County also has high variability in population density, making use of the standard population-based geographies potentially challenging. The integration of social data with ecological data streams presents additional obstacles, such as alignment with Census-derived boundaries and personally identifiable information (PII) concerns. For example, ecological data may be available as a 1×1 m raster, but downscaling socioeconomic data to this level introduces high uncertainty and violates privacy, if it is possible at all. Additionally, while data transformation and interpolation techniques exist for some ecological data based on high-resolution landscape features, interpolation of data based on human populations has proven problematic (Hay et al. 2005), although new advances in processing "big data" have shown promise to allow for better high spatial and temporal population estimates (Yao et al. 2017).

Ultimately, project partners considered scale at the in-person workshop (Table 1) and led to our decision to use the Census block group as the most appropriate unit of analysis. This unit provided the best overall granularity for County-wide analysis;

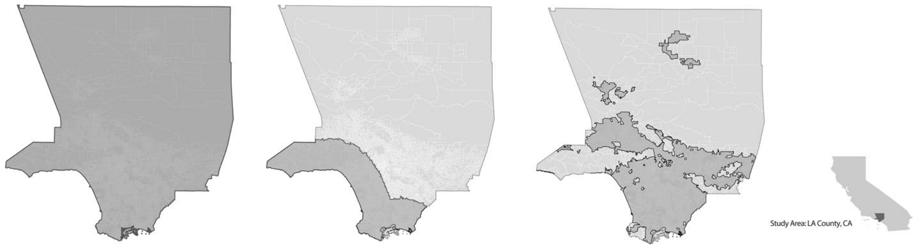


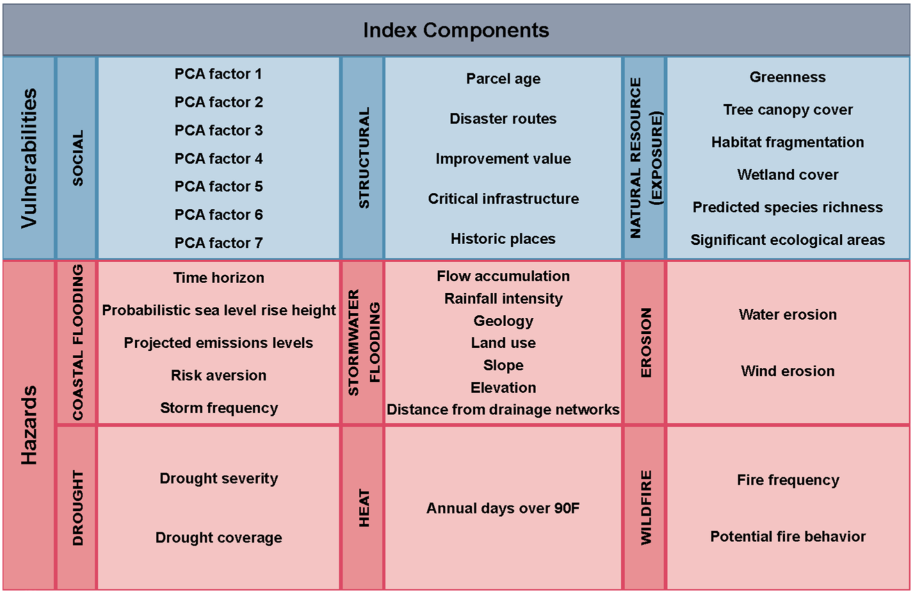
Fig. 3 L.A. County assessment geographies: the County, a 10-mile coastal band, and an urban footprint

however, visualization of data for the densely populated and therefore small Census block groups within urban centers was somewhat problematic, as was interpreting ecological data from within the large rural block groups. These challenges of data integration were accompanied by inherent tradeoffs, and scalar decisions influenced the results and focus of the study. As such, stakeholder engagement was critical to these early decisions.

Similar scalar considerations defined the study geography. Previous regional studies (Ekstrom and Moser 2013; Grifman et al. 2013) had assessed aspects of vulnerability within the City of L.A., yet this boundary excludes many communities of stakeholder interest (e.g., Westside, Marina del Rey, Long Beach) and limits the inclusion of a wider range of climate-driven hazards. Defining the study area was especially important since the Framework relies on an index approach that is relative to the range of values found in the study geography. While partners ultimately directed us to use the County boundary as this project's study area, they also identified the need for other sub-geography assessments within this primary boundary, resulting in the addition of a 10-mile coastal band and an urban footprint (Fig. 3).

Engagement with our partner advisory committee (Table 1) determined which block groups to include in the additional assessment geographies. The 10-mile coastal band geography included any block group for which the centroid was within 10 miles (Euclidean) of the coastline. This 10-mile buffer was chosen in concert with local partners to better understand variations in vulnerabilities within the coastal region of L.A. County. To create the urban footprint geography, block groups were compared with Coastal Change Analysis Program (C-CAP) land cover data, and block groups with 50% or greater land cover of high intensity, medium intensity, and low intensity development were included at partner request. Instead of using the Census Bureau's delineations of urbanized areas, which are based on population, C-CAP data were used primarily because partners were interested in potential structural vulnerability, and these land cover types align with rates of current development. For each assessment geography, industrial block groups (e.g., the L.A. port complex) and block groups with null Census data were removed.

The decision to incorporate multiple geographies addressed variations in coastal versus inland populations, as well as variations in Census block group size. It also resulted in more refined results for managers and climate adaptation specialists at different scales of jurisdiction while exploring the concepts of vulnerability, hazard, and risk relativity. Additionally, since the Framework is a relative metric in which the total data influence the final results, the total number of units analyzed alters the relative level of vulnerability or hazard per unit.



Index Components						
Vulnerabilities	SOCIAL	PCA factor 1 PCA factor 2 PCA factor 3 PCA factor 4 PCA factor 5 PCA factor 6 PCA factor 7	STRUCTURAL	Parcel age Disaster routes Improvement value Critical infrastructure Historic places	NATURAL RESOURCE (EXPOSURE)	Greenness Tree canopy cover Habitat fragmentation Wetland cover Predicted species richness Significant ecological areas
Hazards	COASTAL FLOODING	Time horizon Probabilistic sea level rise height Projected emissions levels Risk aversion Storm frequency	STORMWATER FLOODING	Flow accumulation Rainfall intensity Geology Land use Slope Elevation Distance from drainage networks	EROSION	Water erosion Wind erosion
	DROUGHT	Drought severity Drought coverage	HEAT	Annual days over 90F	WILDFIRE	Fire frequency Potential fire behavior

Fig. 4 Vulnerability/exposure and hazard measures and index components for L.A. application

6 Indicator development

6.1 Index development

In step 2 of the Framework, we incorporated partner and stakeholder priorities to develop indicators that captured two measures of vulnerability (social and structural), one measure of exposure (natural resource), and six measures of hazard (coastal flooding, stormwater flooding, erosion, drought, heat, and wildfire)[3] for the three selected geographies within L.A. County (Fig. 4). The development of each index relied upon close examination of existing literature, data availability, regional needs, and iterative partner engagement and feedback. Indicator development processes for all chosen vulnerabilities/exposures and hazards are explained in the project's technical report (Fleming et al. 2020).[4] Here, we present descriptions of social and structural vulnerability for the County assessment (see Freitag et al. (2021) for an exploration of natural resource exposure), as well as County-wide stormwater flooding and erosion hazards (coastal flooding, heat, drought, and wildfire are omitted). These examples are used to highlight the Framework's ability to integrate stakeholder- and indicator-driven metrics.

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[3] A seventh hazard measure was incorporated at partner request that combined coastal and stormwater flooding (combined flooding).

[4] As noted in Fig. 1, our research team re-evaluated and updated our terminology in 2022 to better align with established climate adaptation networks and in accordance with the Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report (2021). Revised terminology is used in this manuscript.

6.1.1 Social vulnerability

To assess social vulnerability in the event of a climate-driven hazard, we utilized a modified Social Vulnerability Index (SoVI) methodology, first proposed as a national metric by Cutter et al. (2003), and since implemented in a variety of geographies (e.g., Chakraborty et al. 2014, 2020)). SoVI incorporates a principal components analysis (PCA) (Thompson 2004) that is generally calculated at the county scale and includes 29 variables in the latest iteration, SoVI 2010–14, that integrates 2010 U.S. Decennial Census data and 2010–2014 U.S. American Community Survey (ACS) 5-Year Estimates data (5-year rolling estimates to supplement data gaps between decennial census data collections) (Hazards and Vulnerability Research Institute 2016). In this analysis, we modified the variables due to the change of scale from county to Census block group, and all data were derived from the 2012–2016 ACS 5-Year Estimates. PCA was used to determine the factors and variables to include in the final index, and each variable was standardized using z-scores before running the PCA. The PCA analysis used a Varimax rotation with 25 iterations and a required factor loading of at least 0.50. Cross-loading variables were removed, with the exception of inverse cross-loadings (Costello and Osborne 2005; Cutter et al. 2003; Cutter and Emrich 2017). The resulting Kaiser–Meyer–Olkin Measure of Sampling Adequacy was 0.902, and the Bartlett's Test of Sphericity was significant ($p \leq 0.001$), indicating that the data were suitable for factor analysis and there was sufficient sampling adequacy. Number of factors was determined using a combination of the Kaiser Criterion and Cattell's Scree Plot (Costello and Osborne 2005; Fabrigar et al. 1999).

The final social vulnerability index for the County was comprised of 26 variables, and resulted in seven factors, labeled Factors 1 through 7. Counter to Cutter and Emrich (2017), our partner advisory committee advised to not name the factors to avoid oversimplification and misunderstanding by local stakeholders and decision makers. These factors collectively explained 68.16% of the variance in the total variability among data for the block groups within L.A. County. Table 2 shows the variables and factors that explained the majority of variance in the data (Suhr 2006; Tabachnick et al. 2007). For example, Factor 1 explained more variance than the other factors alone, but together these seven components provided a better measurement of social vulnerability for L.A. County.[5]

6.1.2 Structural vulnerability

Structural vulnerability indicators were chosen to collectively represent vulnerability of structures in the face of the chosen natural hazards, and relied upon federal, state, and county spatial data. They included parcel age, disaster routes, improvement value, critical infrastructure, and historic places (Fig. 5).

Parcel age was calculated as the percentage of parcels within each block group with an effective build date of before 1978, since building codes in California were substantially rewritten in 1978 to update earthquake standards (County of Los Angeles 2016). Disaster routes included freeway, highway, or arterial routes pre-identified for use in emergencies, and the mileage of disaster routes in each block group was normalized to the block group's land area (Los Angeles County Department of Public Works 2015).

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[5] Some variables contribute to multiple factors, but inversely. For example, median income loads positively on Factor 1, but negatively on Factor 3.

Table 2 Principal components analysis findings (social vulnerability indicators) for L.A. County

Factor Name	Cardinality[a,b]	% Variance Explained	Variables	Loading
Factor 1	+	29.761	% Population in poverty	0.796
			% Households without a vehicle	0.700
			% Households receiving SNAP benefits	0.661
			% Rented housing units	0.561
			% Population unemployed	0.550
			Median rent	−0.544
			Median income	−0.579
Factor 2	+	10.654	% Rented housing units	−0.507
			% Households with occupants over age 60	0.884
			% Households receiving social security	0.878
			% Population over age 65	0.798
			% Population in labor force	-0.696
			Median age	0.636
Factor 3	–	8.561	Median housing value	0.820
			% Households with income over $200,000	0.804
			Per capita income	0.762
			Median income	0.614
Factor 4	+	6.304	Average household size	0.878
			% Family households	0.858
			% Population without high school diploma	0.503
			% Population under age 5	0.502
Factor 5	+	5.119	% Foreign born	0.867
			% Population with limited English proficiency	0.818
			% Population without health insurance	0.514
Factor 6	+	4.370	% Female	0.871
			% Females in labor force	0.847
Factor 7	+	3.391	% Population in extractive employment sector	0.721
			% Mobile homes	0.628

[a] Positive = the factor contributes to vulnerability

[b] Negative = the factor contributes to vulnerability inversely

Improvement value represents the value of the built structures on a piece of land, and values were summed per block group and normalized as a percentage of the maximum block group value (LARIAC 2014). Critical infrastructure and historic places were both location counts per block group of facilities and places, respectively. Critical facilities included power plants, wastewater treatment facilities, dams and reservoirs, police and fire stations, emergency services, educational facilities, and hospitals (Grenninger 2017). Historic places included points registered with the National Register of Historic Places (as of 2017) (National Park Service 2017), which does not incorporate all locally acknowledged places of historical significance, as evidenced by the larger but unfinished-at-the-time-of-analysis database collected by the L.A. Conservancy (2019).

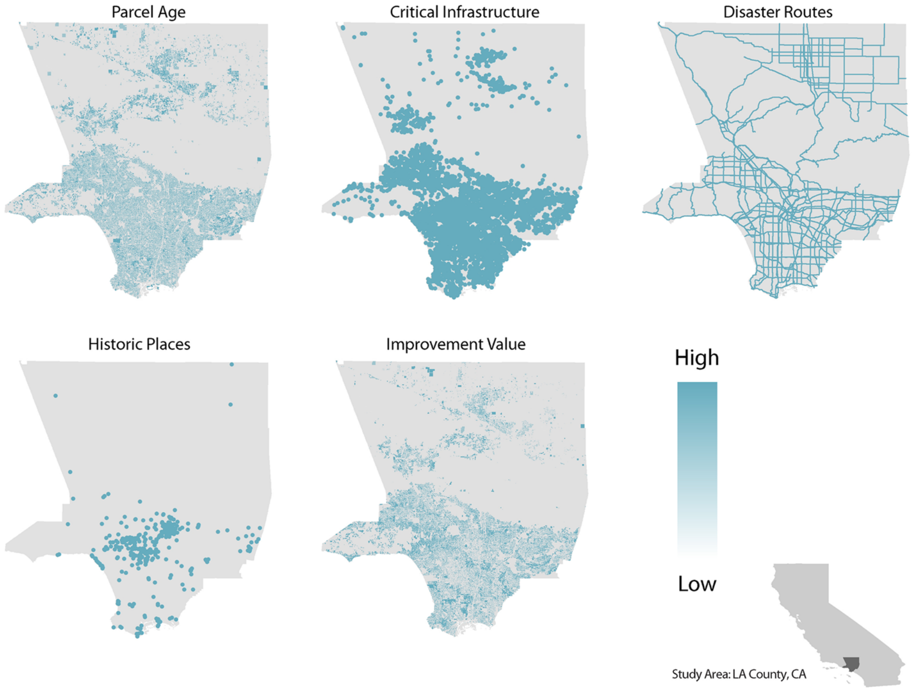

Fig. 5 Indicators of structural vulnerability

6.1.3 Stormwater flooding hazard

To identify areas of stormwater flooding hazard within the County, we developed an index primarily based on the "FIGUSED" methodology used by Kazakis et al. (2015), which incorporates seven parameters commonly used to identify areas of high flooding potential: flow accumulation (Jenson and Domingue 1988), rainfall intensity (Conkle et al. 2006), geology via hydrologic soil groups (Natural Resources Conservation Service 2018a), land use, slope (Conkle et al. 2006), elevation, and distance from drainage networks. Using ArcGIS 10.5 and available, secondary data sources (Los Angeles County Department of Public Works 2006; Natural Resources Conservation Service 2017; NOAA Coastal Change Analysis Program 2010; United States Geological Survey 2016, 2018), we created spatial layers for each parameter and normalized all resulting datasets on a scale of 0–1, first classifying by value for non-continuous variables (i.e., for hydrologic soil group, slope, and land use type). The seven stormwater flooding hazard components are shown in Fig. 6.

6.1.4 Erosion hazard

Since soil erosion rates are most commonly influenced by water and wind (Breshears et al. 2003), we integrated two erosion hazard datasets. To best approximate water erosion, the first dataset incorporated slope and soil properties that influence K Factor (an index used in erosion estimates that quantifies the soil's relative susceptibility to sheet and rill erosion

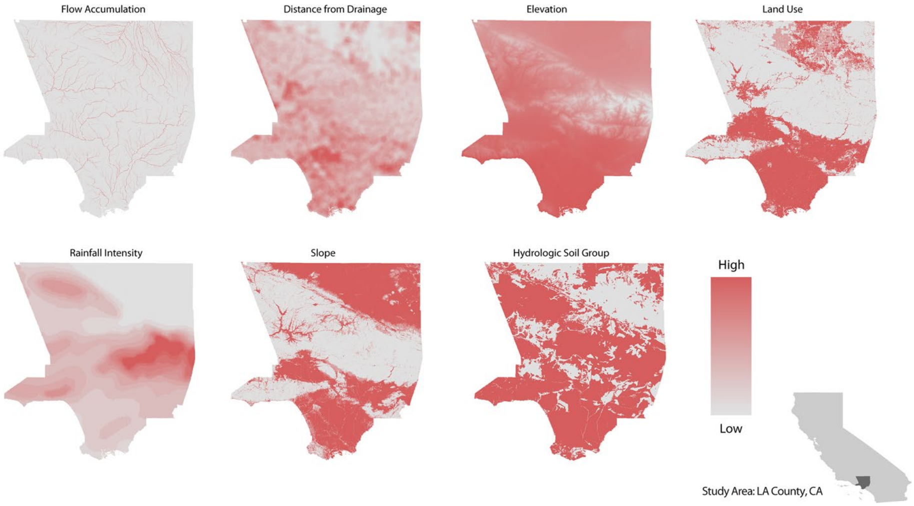

Fig. 6 Indicators of stormwater flooding hazard

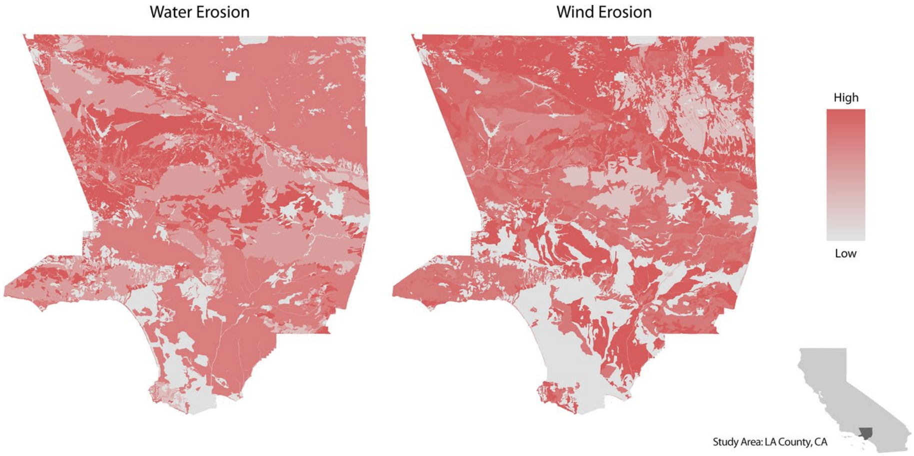

Fig. 7 Indicators of erosion hazard

(Baur 1952; Smith and Wischmeier 1957)), such as soil texture, organic matter content, structure, and hydrological properties (Natural Resources Conservation Service 2018b). To approximate wind erosion hazard, we used the National Soil Survey's Wind Erodibility Index. The final erosion components are shown in Fig. 7.[6]

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[6] Additional erosion by coastal processes was incorporated into the coastal flooding hazard profile, omitted from this manuscript.

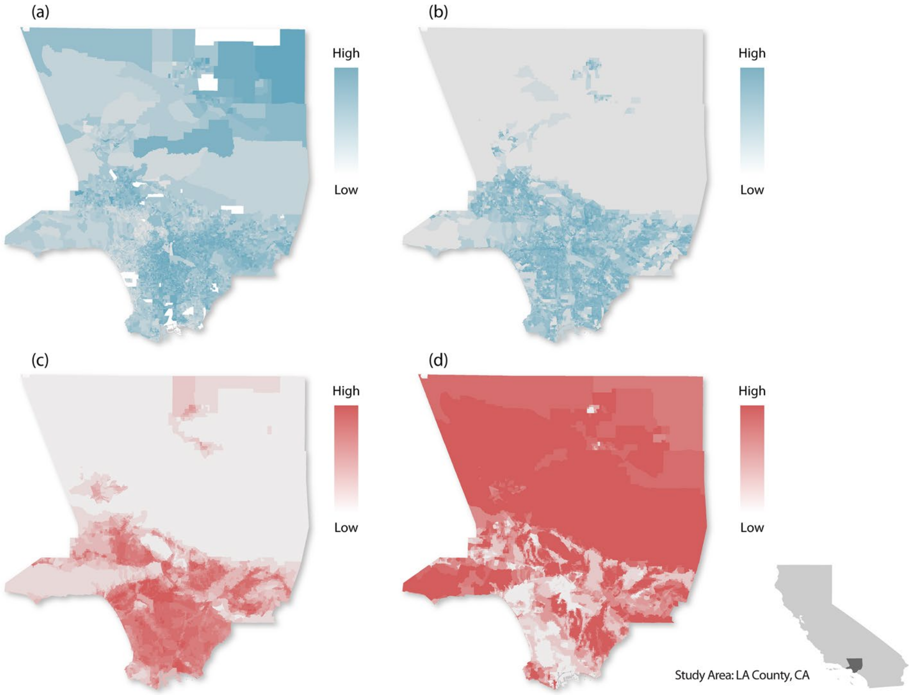

Fig. 8 Final index aggregation for social vulnerability **a**, structural vulnerability **b**, stormwater flooding **c**, and erosion **d**

6.2 Index Aggregation

For each assessment geography, final vulnerability and hazard profiles (steps 3 and 4 of the Framework) were then developed using additive indices. While there are many approaches to weighting and aggregation in index development, Gan et al. (2017) and Fuchs and Thaler (2018) suggest that the chosen weighting and aggregation method should be driven by the objective of the study and the spatial and temporal scales used. The Framework encourages uniformity when possible for better comparisons between different data streams, and as often required, hinges upon the appropriate inclusion of socioeconomic data. We explored implementing a variance-explained weighted additive index for the seven social vulnerability factors, but ultimately decided to weight equally, as Cutter and Emrich (2017) established as common practice. The other profiles were similarly weighted equally during aggregation, although future iterations of this work could consider regional customization of indices through the development of weighting criteria for each index variable, as suggested by Kazakis et al. (2015). In the present context, this would have required additional partner and stakeholder engagement and/or sensitivity analysis of historical data and was beyond the scope of this study.

Figure 8 shows the four selected vulnerabilities and hazards aggregated to block groups for the County. The factors contributing to the final social vulnerability score and profile (Fig. 8a) were adjusted for directionality and placed in an equal-weighted additive model. The social vulnerability index score for each Census block group is presented as a relative score using min–max normalization (Salzman 2003), such that block groups closer to a value of 1 are more socially vulnerable compared to other block groups within the study area. The five structural components were combined in an additive index, where each variable was equally weighted and normalized to a coordinated scale of 0–1. The final score was normalized to fit a “low to high” (0–1) range, with block groups closer to “high” (value of 1) being more structurally vulnerable (Fig. 8b). Stormwater flooding parameters were combined in an additive index, where each variable was equally weighted. The final index values range from 0 to 7 with higher values indicating areas with a higher potential of flooding (Fig. 8c). Lastly, the final erosion additive index score was normalized to fit a 0–1 range, with block groups closer to 1 being more likely to erode (Fig. 8d).

7 Assessing risk through the intersection of vulnerability and hazard

Using individual vulnerability and hazard profiles, step 5 of the Framework assesses relative risk through the spatial intersection of vulnerability and hazard. To visualize the data, we transformed continuous data into categorical data by regrouping all hazard and vulnerability scores per block group to a 1 to 3 scale, using a discrete scaling system for each, and then labeled these three categories “low,” “medium,” and “high.” Bivariate choropleth maps (i.e., maps that depict two thematic variables at once) were created to easily compare vulnerability and hazard with one another. These maps serve as a visual tool to depict areas of high and low risk (where high-risk areas have high vulnerability and high hazard and low-risk areas have the inverse). Risk maps can help prioritize actions and aid in decision making when considering particular aspects of vulnerability and hazard. High-risk areas may be of primary importance, while low-risk areas may be of lesser concern relative to the study region.

Recognizing the large number of possible vulnerability and hazard combinations available in step 5 of the Framework, we held a second workshop to present preliminary assessment findings to partners and stakeholders. USC Sea Grant Extension again helped to identify relevant municipality planners, climate sustainability professionals, and natural resource managers (participants from the first workshop were invited along with additional stakeholders). Following a presentation of preliminary results, the team led a SNAP exercise[7] to assist stakeholders in identifying combinations of hazards and vulnerabilities of greatest interest. Participants were asked to write their top two hazards of most concern on individual sticky notes and were then asked to consider the categories of social and structural vulnerability and natural resource exposure. One at a time, participants placed sticky notes under the category they felt most interacted with each of their chosen hazards. As each sticky note was placed, the remaining participants said “snap” if either of their remaining sticky notes also fit in the chosen category and then added their sticky notes to the original in a chain or cluster. These results helped inform the final risk maps delivered to partners.[8] The second workshop also repeated the geographic mapping exercise

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[7] This technique was introduced to the project team by University of Maryland Center for Environmental Science (UMCES) colleagues at a 2019 status report development workshop. More information on SNAP can be found on their blog post: http://ian.umces.edu/blog/2017/12/04/sharing-tools-for-stakeholder-engagement-and-collaboration-at-the-chesapeake-watershed-forum/.

[8] The SNAP exercise also asked stakeholders to consider the drivers of their prioritized vulnerability and risk combinations, and these findings led to additional thematic areas and analysis outside the scope of this manuscript.

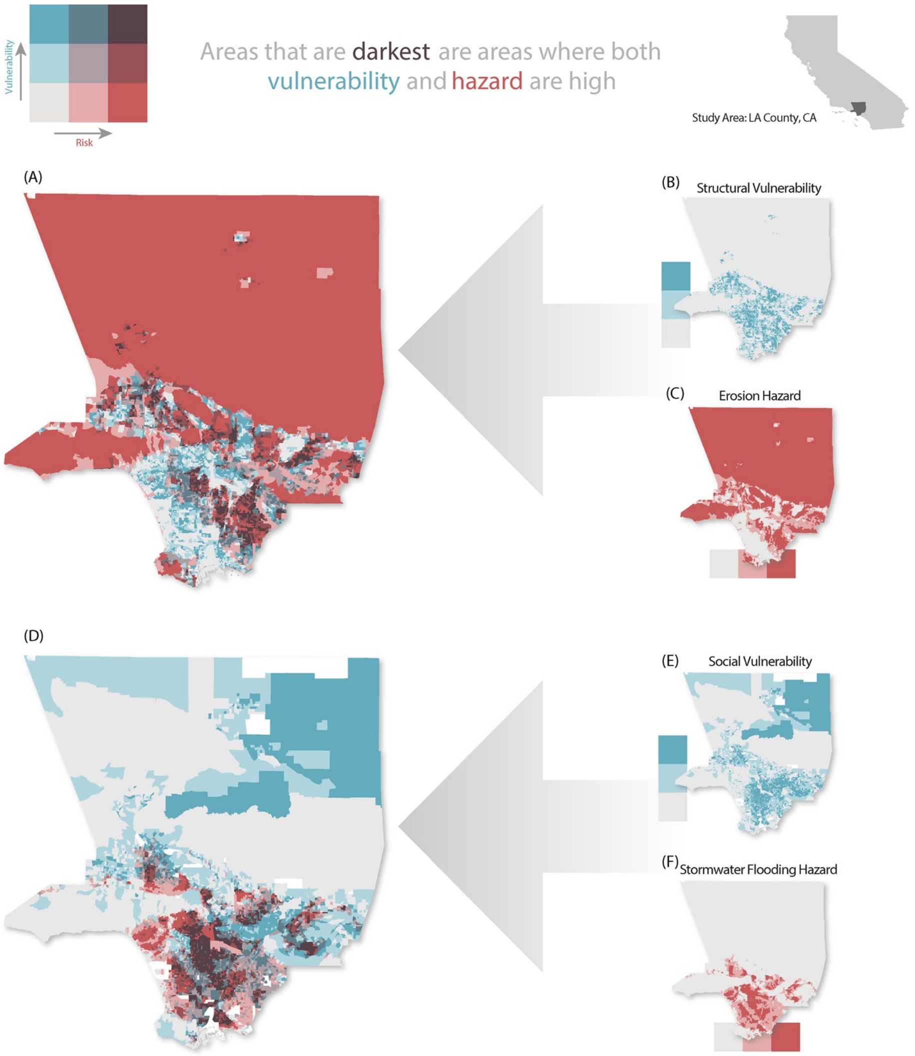

Fig. 9 Structural vulnerability intersected with erosion hazard **a**-**c** and social vulnerability intersected with stormwater flooding hazard **d**-**f** for the County

conducted during the first workshop. Using the same approach, we divided participants into groups and asked them to place colored dots on their top three geographies of interest within an enlarged map of the study region and complete the accompanying ranking sheet. Some areas aligned with previously identified areas, while others represented new perspectives, and this sparked facilitated discussions.

Two of the thematic intersections identified during the SNAP exercise are provided in Fig. 9 as example bivariate map results. Throughout much of the County, erosion hazard is tightly interwoven with flooding hazard and impacts. Figure 9 shows structural vulnerability intersected with erosion hazard (a-c) and social vulnerability intersected with stormwater flooding hazard (d-f) for L.A. County. In Fig. 9a, areas of red cover large parts of the northern county and Malibu peninsula and represent high erosion hazard but low structural vulnerability, relatively. Conversely, there are many block groups in the southern portion of the county with high structural vulnerability but low erosion hazard (blue). Areas of burgundy, however, represent block groups with both high erosion hazard and high structural vulnerability, equating to high risk. Erosion hazard has great potential to adversely impact built infrastructure in L.A. County. Areas of higher risk are more prone to mudslides and landslides, especially when these areas are further subjected to earthquakes, winter storms, or intense or prolonged rainfall (United States Geological Survey 2019). Slip soil maps for southwestern California highlight the inherent dangers to infrastructure throughout much of L.A. County. These analyses show relative susceptibility of hill slopes to the initiation sites of rainfall-triggered soil slip-debris flows (Morton et al. 2003). Many of the mapped susceptibility areas correspond with locations of dark blue block groups (high risk) in the present assessment (Morton et al. 2003), as do U.S. Geological Survey accounts of historical and often fatal debris flows in the Santa Monica Mountains and surrounding area (Campbell 1975). In addition to the impacts of erosion on the structures dependent on those soils, the initial precipitation itself can also impact structures through wind-driven rain surface erosion. Wind-driven rain impact has been shown to erode historic masonry building façades (Erkal et al. 2012), and structures of cultural significance in L.A. County may therefore be exposed to additional hazard and subsequent risk from extreme precipitation events.

In Fig. 9d, while there are blue block groups in the northeastern part of the county representing high social vulnerability but low stormwater flooding hazard, there is a grouping of burgundy block groups in south-central L.A. County, representing high risk. The center of this grouping largely follows the path of the L.A. River and is characterized by lower elevations, flatter slopes, and a general lack of permeable surfaces. The spatial correlation between high social vulnerability and flood hazard is a phenomenon that likely extends to the historical settlement of L.A., and will likely continue into the future. Before recent gentrification, impoverished parts of L.A. tended to be marginal land within the confines of existing development, such as the historic parts of the City along the L.A. River (Hanson and Marty 2012), and this was enabled by a lack of central planning (Cuff 2000). Worldwide, settlement around water tends to trade off small, daily risks (such as the need for water in desert conditions) with large, longer-term hazards (such as 100-year flood storms), and also depends on the societal needs and demands of the moment (Nelson et al. 2010). The impacts of continued sea level rise on stormwater-flooding-prone areas are likely to further influence changes in housing markets, such as demands for houses at elevation, in a process recently named climate gentrification (Keenan et al. 2018). While this process is far from new (Pinke et al. 2016), increasing prices for homes outside of flood zones may exclude more socially vulnerable parts of the population and further limit them to more affordable, flood-prone areas.

Between Fig. 9a and d maps, there are some shared areas of burgundy (high risk), including within south-central L.A., along the L.A. River, northeast of the Malibu peninsula, and hugging the south side of the Angeles National Forest. The intersection of high social and structural vulnerability may be dependent upon demographic and socioeconomic factors, and including these intersections in comprehensive hazard assessments may prove beneficial for mitigation planning (Highfield et al. 2014). Further, overlapping high hazard areas for both erosion and stormwater flooding is intuitive since factors such as coastal flooding, precipitation frequency and intensity, and wind have been shown to increase erosion potential (Breshears et al. 2003; Finzi Hart et al. 2012; Grifman et al. 2016). The relationship between stormwater flooding and erosion is complicated, since changes in each influence the magnitude of the other. Increased erosion can lead to more severe stormwater flooding, while increased stormwater flooding can result in increased erosion. Further, mudslides and other forms of gravity erosion can be triggered by intense rain events and the underlying erosion potential (Xu et al. 2015). Erosion risk and debris-flow susceptibility are further exacerbated following a wildfire, and the rainfall required to trigger a landslide is greatly reduced (Kean et al. 2011). Following L.A. County's Colby Fire in 2014, the U.S. Geological Survey completed a preliminary hazard assessment and found increased probability of debris-flow generation within the burn footprint (United States Geological Survey 2019; United States Geological Survey Landslide Hazards Program 2014).

8 Conclusions

This manuscript presents a participatory, indicator-driven, and secondary data-enabled approach to integrated climate vulnerability assessment planning to researchers and practitioners working to improve coastal community climate adaptation. The Framework's resulting bivariate risk maps serve as interdisciplinary, visual tools that expose corresponding areas of high vulnerability and hazard. These maps and greater assessments simplify messaging for use by a diverse set of stakeholders and can be used to establish adaptation priority areas for the coastal and climate-driven hazards explored in this research. For example, areas of both high stormwater flooding hazard and high erosion hazard may be appropriate locations to pilot mudslide preventative efforts (Holcombe and Anderson 2010; Kolstad et al. 2019), or areas with both high social vulnerability and high stormwater flooding hazard may jointly benefit from the creation of a new park or green space that offers both flood mitigation and mental health benefits (Bowen and Lynch 2017; Schubel et al. 2015). Depending on partner needs, indices may also be further combined prior to intersection. For example, a total vulnerability metric may be useful in certain planning contexts.

Areas of interest identified via the Framework should be used in preliminary adaptation planning and followed by additional, focused investigations. The Framework provides vulnerability, exposure, hazard, and risk analyses in comparison with other block groups (or a similar chosen unit of analysis) within each assessment, which results in findings that are relative to the total number of units analyzed. This approach has been used by other scholars (Cutter et al. 2003; Holsten and Kropp 2012) and provides a tool for identifying priority areas within a given geography. Since the Framework can be implemented for multiple geographies within a given study area, the findings of each assessment can vary between chosen geographies, and prioritized areas may shift when additional units are added or subtracted. This allows for use by different management entities and presents an opportunity for further investigation of potential priority areas, but should not be taken as the final step in adaptation planning efforts. Application of the Framework may additionally support planners in qualifying for grants to advance more focused assessment or adaptation action.

Despite the Framework's emphasis on index development and bivariate risk maps, one tradeoff to integration is the loss of individual variables and components that may also prove useful or even preferable in certain adaptation planning environments. For example, intersecting the "no access to a vehicle" variable of the social vulnerability index with flood hazard may provide spatial insight to emergency response officials during early onset of extreme flooding. As a result, the Framework may serve as a tool for integrated, high-level planning as well as a compilation of more detailed variables to support additional, specific adaptation needs. In the present research, we heavily relied on local stakeholder feedback provided at the second workshop to identify preferences for final map deliverables; however, the underlying data allow for other prioritizations by present and future stakeholders.

Admittedly, the Framework's approach cannot always incorporate all stakeholder-derived content. For example, despite stakeholder preferences to include gentrification, displacement, and homelessness in the overall social vulnerability metric (see Fig. 2), the final index does not fully capture those concepts due to a general lack of available secondary data at required spatial resolutions. Related to homelessness, data on insecure or unstable housing could also enhance the final structural vulnerability index. Individuals experiencing homelessness as well as their temporary housing structures have greater vulnerability to climate-driven hazards, yet are largely omitted from the final indices presented here. For these types of situations, where possible, the addition and integration of primary data streams may enhance final profiles.

The Framework approach marries a nationally applicable methodology with a place-based application. The approach itself is flexible to any geography, but its users can and should tailor the aspects of vulnerability and hazard incorporated to suit regional climate needs.[9] The Framework also attempts to strike a balance between collaborative partnership and more traditional approaches to climate adaptation science. This partner-driven approach hinges upon the iterative inclusion of partner engagement and feedback, and lends support to messaging by Tompkins et al. (2008), Gopnik et al. (2012), and others that active stakeholder participation can not only be achieved, but can also better support end-user decision making. Further, an iterative approach is more likely to result in the coproduction of actionable climate information, and in turn, better climate service projects and outcomes (Kolstad et al. 2019). As community-informed approaches to climate science become more common (e.g., the National Renewable Energy Laboratory's LA100 study and LA100 Equity Strategies project (Cochran 2021)), researchers should be careful to strike a proper balance between stakeholder input and scientific rigor. Effective engagement can take many forms, including through the use of focus groups, workshops, interviews, virtual meetings, charrettes, and public hearings (Cuocco 2014). Ultimately, in order for community vulnerability assessments to be successful, it is critical to incorporate input that reflects the needs of its final end users. For example, engagement primarily with local communities is likely to result in different priorities and final outputs than engagement with industry sectors or environmental nonprofit organizations, and some engagement methods may be better suited to different stakeholder groups. While we argue that local input is necessary for effective climate adaptation research and planning, we recognize that assessment outcomes are inherently biased toward those involved in the partner and stakeholder engagement processes.

In this research, we blended workshops of primarily municipality planners, climate sustainability professionals, and natural resource managers with an advisory group of key partners who remained engaged throughout the project's duration and who provided regional expertise. We advocate for the use of such a group, supplemented with targeted and direct stakeholder engagement sessions, to mitigate stakeholder burnout and other potential drawbacks of stakeholder-driven research (Oliver et al. 2019). Similar to Molino et al. (2020), we conclude that Sea Grant Extension programs and similar boundary-spanning organizations can play a crucial role in participatory science and

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[9] Early iterations of the Framework were conducted in a semi-rural setting in the Chesapeake Bay, but were focused solely on flooding impacts (Fleming et al. 2017; Messick et al. 2016).

stakeholder needs assessments. Partnership decisions are likely to be influenced by geography and opportunity and may also include organizations such as state coastal commissions, watershed or river basin commissions, councils of governments, and conservation and development commissions. In L.A. County, our USC Sea Grant Extension and NOAA's Office for Coastal Management partners not only provided regional expertise, identified local stakeholders, and assisted in the facilitation of our workshop meetings, but they are also facilitating the transition of our Framework indicator approach, findings, and underlying data to local municipalities actively working to incorporate climate adaptation and resiliency strategies into their general plans, hazard mitigation plans, sustainability plans, and/or climate action plans. Elements of this assessment are already being used to support and advance local planning efforts across the County.

We emphasize the need for continued partner engagement in climate science, and future applications of this methodology should rely heavily on local partner participation and engagement in its most appropriate form(s). While we had success with the combination of a partner advisory committee and facilitated workshops, the chosen engagement techniques for future iterations of the Framework may be modified or enhanced. We hope that the presented methodology continues to support advancements in the field of stakeholder engagement and coastal vulnerability assessment and offers a unique perspective to those working to combat climate change impacts in disproportionally affected coastal communities.

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Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Seann D. Regan, Amy Freitag, Heidi Burkart, and Chloe S. Fleming. The first draft of the manuscript was written by Chloe S. Fleming, and all authors commented on previous versions of the manuscript. All authors read, revised, and approved the final manuscript.

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Availability of data and material All data are publically available, secondary data. The authors' analyses are available upon request.

Code availability Not applicable.

Declarations

Conflicts of interest The authors certify that they have no affiliations with nor involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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