Effectiveness of Past California Earthquake Scenarios in Motivating Mitigation

Final Report

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Disclaimer

Abstract

Scenarios of potential earthquake damage have been prepared and used in California for over 50 years. Practitioners in California have long considered scenarios of plausible, hypothetical earthquakes to be an effective part of their "toolkit" for mitigation progress, as evidenced by continued widespread use. We investigated the effectiveness of earthquake scenarios in motivating, supporting and guiding earthquake risk mitigation through semi-structured interviews and literature review. Over 60 interviews of scenario users and developers provide insights into how scenarios are used in mitigation work and characteristics that make them effective.

Scenarios have been widely used as part of California's earthquake resilience "ecosystem" and have had a significant role in the development or adoption of major mitigation programs for buildings and infrastructure. Scenarios are often paired with damage from real events to advocate for mitigation measures, with the role of scenarios being to communicate the potential for future damage. Interviews in particular point to the often complex and interdependent relationships between scenarios, other significant sources of influence, and contextual factors in motivating or supporting subsequent mitigation actions.

Both users and developers viewed scenarios very positively, as measured by a high Net Promoter Score. Interview participants named the following characteristics as making scenarios effective for motivating mitigation: (a) a robust, collaborative development process including multiple disciplines and end users/stakeholders from the beginning, with involvement throughout; (b) scientific and technical credibility, both through the reputation and standards of the organization that prepared the scenario and the quality of the particular work; (c) plausibility and realism of the event; (d) practical applicability, with results clearly describing impacts of importance to end users; (e) recommendations developed that specifically identify potential actions, policies and mitigation measures, and plans to implement them; with clear mechanisms for follow-on work with stakeholders that supports implementation of mitigation measures; and (f) communication in clear language and graphics, using appropriate channels for each audience and with graphics such that people who are not earthquake professionals can understand the findings and act on them.

Significant, focused effort building on a foundation of sustained advocacy by the professional community and a supportive policy context are required to move from even the best-prepared scenarios to actual implementation of mitigation measures. Future scenario projects should have adequately-funded stakeholder engagement and a component to create a pathway to implementation for scenario findings, such as a mitigation planning process.

Introduction

Scenarios have been recognized by practitioners in particular, but also researchers, as a powerful process approach and risk communication mechanism for those seeking to prepare communities for earthquakes or mitigate their impacts. Scenarios have been a key part of the practitioner's toolkit, and scenario findings have been interwoven in California's notable efforts toward earthquake safety and resilience over the past half-century. As a result of scenarios often being considered part of the background, studies of scenario effectiveness, or of the role of scenarios in California earthquake risk mitigation, have been rare, despite a substantial body of scenario work containing over 30 publicly available scenarios dating to 1967, when the first study began (Algermissen et al., 1972, for San Francisco).

This paper presents results from a U.S. Geological Survey (USGS)-funded study examining the effectiveness of past California scenarios in motivating earthquake risk mitigation, which is intended to provide insight for future scenarios. This study focuses on practices that have been most useful in guiding, motivating, and supporting pre-disaster risk mitigation, rather than preparedness actions such as emergency preparedness exercises for which scenarios are directly and routinely used.

Definitions

We define a *scenario* as work that examines and depicts the impacts that a plausible-but-hypothetical hazard event or other significant occurrence (i.e. related to climate changes) would inflict on people, the built and natural environments, and/or society. This work is typically presented as a study or publication(s), which may examine more than one scenario event, or the same scenario event in different contextual settings. The scenarios we consider in this research have the following essential components: (a) a science-based assessment of the selected hazard event(s); (b) an estimate of the resulting damage to buildings, infrastructure, or land based on engineering or scientific principles; and (c) an estimate or description of likely consequences, particularly to people but also to society. We define as *a scenario-component study* work that does not contain all of these components. Scenario-component studies often focus on hazard events, which are termed "hazard scenarios" by some researchers. We define *mitigation* as lessening or minimizing of the adverse impacts of a hazard event (based on UNDRR, 2017).

Methodology

We investigate the impacts of past earthquake scenarios through review and analysis of available scenario publications and mitigation, planning and policy documents, and through 63 semi-structured interviews of California scenario users and developers. This study is being carried out in parallel with a larger study, funded separately by the U.S. Agency for International Development (USAID), that also considers landslides and volcano scenarios and applies research findings to develop practice advances for scenarios of geologic hazard events. The USAID-funded study uses the same protocol as in California, and includes 30 interviews each in Ecuador, Nepal and New Zealand. For the California study, we considered four multi-part research questions:

1. How, and to what extent, have decision makers been aware of and utilized scenarios when making decisions or formulating policies to address earthquake risk? If they have not used scenarios, what were the reasons?
2. For those who have used scenarios, what features did they find most important, compelling, and useful? Were particular results, processes to develop the scenario, or ways of communicating results particularly useful? Why? How were these features utilized in subsequent work?

3. What policies or practices to improve earthquake safety were developed, adopted or changed as a result of an earthquake scenario? To what degree did a scenario influence or motivate the change, compared to other factors and influences?
4. How important was credible and detailed hazard information compared to other scenario components (such as loss estimates) to the eventual uptake and use of scenario results in shaping policy and practice? Is there a "threshold" of scientific quality necessary for the scenario to be credible and effective?

For the literature review (joint to both studies), we used conventional online literature survey methods, investigating both practice and academic literature from reputable sources worldwide. We conducted keyword searches in academic databases and search tools (Google Scholar, Scopus) and practice literature compilations (such as PreventionWeb and development agency repositories), and obtained documents from government agency websites, which contain a large fraction of available publications on scenarios and their impacts. We reviewed literature on (a) scenarios and scenario-component studies; (b) scenario impacts; and (c) eight topic areas in which advancements may contribute to more effective geologic hazards scenarios, (1) community engagement at the grass-roots level; (2) risk communication; (3) public policy; (4) guidance for scenario-based mitigation planning; (5) multi-country, cross-border scenarios; (6) secondary or induced hazards; (7) multiple scenario approaches and robust scenario event selection within a single hazard; and (8) methods for using scenarios across multiple geologic hazards.

We applied qualitative research methods to generate robust findings, including primary data collection (e.g., interviewing), coding (e.g., systematically categorizing interview data to identify patterns or themes), and subsequent analysis of interview transcripts. We also compiled and synthesized key findings and themes resulting from a study of literature. Primary data collection included 63 semi-structured interviews of scenario users and developers across California. To identify potential participants, we developed a database of California hazard scenario developers and potential end users. The database was populated with individuals representing range of roles and organizational perspectives, including scientists,[1] elected officials, policymakers, practitioners, and other decision makers. Figure 1 shows participant organizational affiliations, geographic locations, and primary technical disciplines. The interviewers used snowball sampling to expand this initial list by obtaining recommendations from interviewees for other relevant actors. Interviews lasted 60 minutes on average and were conducted via videoconference or telephone calls. Notes were taken during each interview to summarize key observations and document any deviations. All interviews were recorded and transcribed, then quality-checked by the original interviewers for accuracy.

Two members of the research team developed a preliminary list of primary and secondary codes based on themes addressed by the interview questions as well as additional concepts that emerged from a review of and discussion of transcripts and interview notes. They then coded ten percent of transcripts from both scenario users and developers using Dedoose qualitative analysis software and compared their coding of the texts to ensure interrater reliability (e.g., consensus on code definitions and consistency in code application). Additional codes and sub-codes were defined collaboratively while coding the remaining data to incorporate emergent themes. Once this process was complete, the coders reviewed the entire corpus of coded data under each primary code to further refine and revise the lower-level codes as needed.

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[1] The small proportion of social and behavioral scientists in our sample is a limitation of this study. While such disciplines tend to be less well represented on scenario teams overall relative to engineering and earth sciences, as noted above, their involvement in the scenario development process can be critical for highlighting findings that are relevant to decision-making.

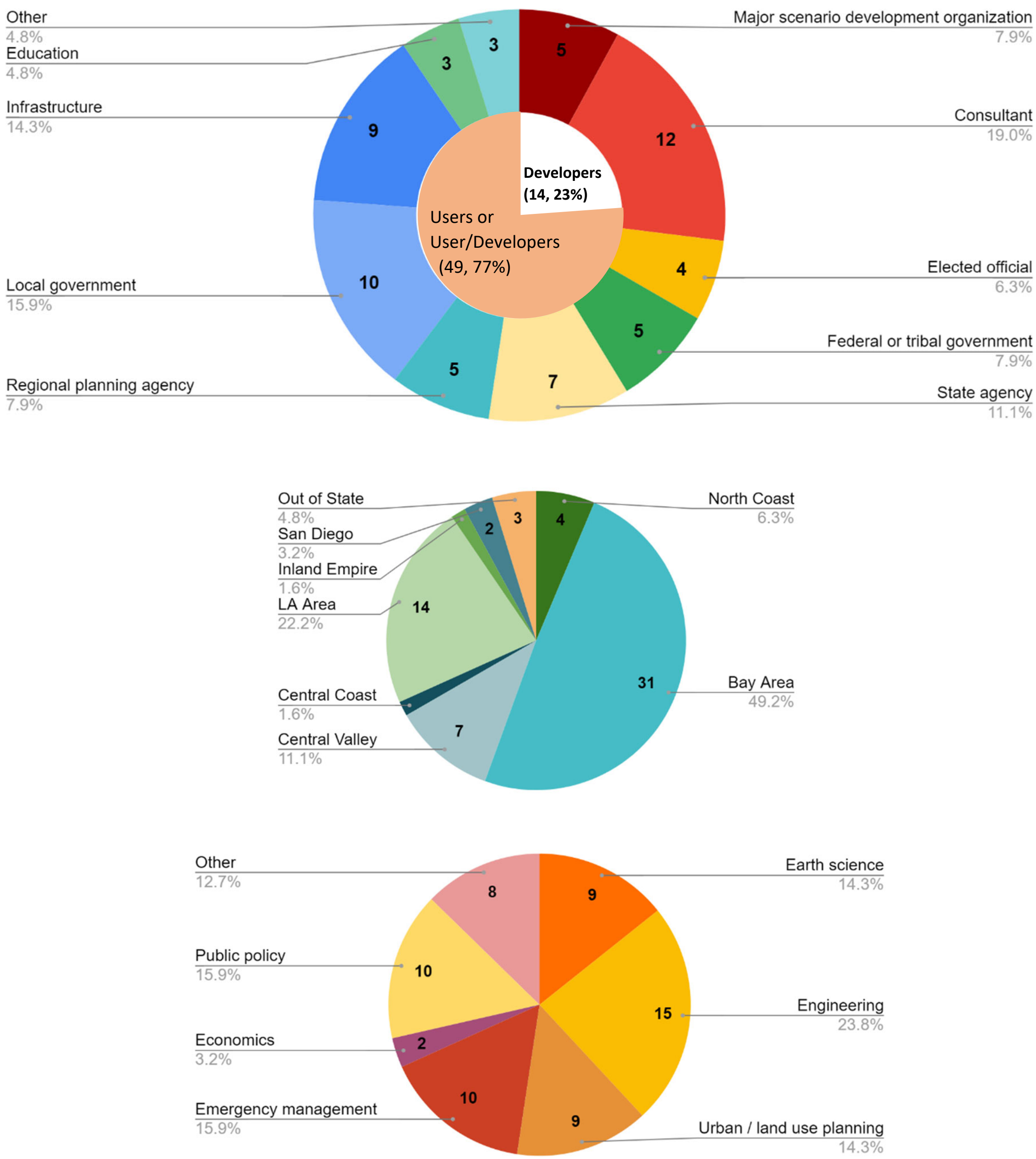

Figure 1. Breakdown of the 63 interview participants by affiliation (top), geographic region (middle) and primary technical discipline (bottom). User/Developers (12, 19%) were primarily consultants but also from federal, tribal, state and local government, regional planning agencies, and infrastructure providers. Developers were either from major scenario development organizations or were consultants.

In addition to analyzing qualitative interview data, we calculated Net Promoter Scores to quantify feedback from scenario users and developers. The Net Promoter Score (NPS) is a core metric that is used in gaining a greater understanding of customer experience in marketing research (Reichheld, 2003). The NPS is a simple, straightforward metric that measures the perception of a product or service by assessing how likely one is to recommend the product or service for future use and can be used as a benchmark for success. In the case of the present study, it provides information about perceived value of the use of scenarios and related studies.

NPS provides an estimate regarding the percentage of respondents that would recommend the use of scenarios to others. NPS is calculated from a single survey item (e.g., "How likely are you to RECOMMEND that decision and policy makers use scenarios of geologic hazard events in their mitigation and preparedness planning?") that is rated on a scale ranging from 1 "Very Unlikely" to 10 "Very Likely." To calculate the score, the respondents are partitioned into the three categories:

Promoters: Percentage of respondents who provide ratings of 9 and 10.
Passives: Percentage of respondents who provide ratings of 7 and 8.
Detractors: Percentage of respondents who provide ratings of 0 to 6.

Promoters are those who provide strong support for use of the scenarios of geologic hazards events in mitigation and preparedness planning. Detractors are those who do not feel that the scenarios meet their needs and thereby do not support their use and do not recommend it to others. Passives, as the name implies, do not indicate strong negative or positive feels toward the use of scenarios.

The NPS is calculated by subtracting the percentage of Detractors from the percentage of Promoters (NPS = % Promoters - % Detractors). This score can then range from the highest score of 100 (100% Promoters – 0% Detractors) to the lowest score of -100 (0% Promoters - 100% Detractors). The higher the NPS, the more support exists for the use of scenarios in mitigation and preparedness planning efforts. The general rule of thumb for interpreting Net Promoter Scores falls along the continuum from: Excellent (71 to 100) to Needs Improvement (-100 to 0).

We created a log of mitigation impacts mentioned by interview participants as related to scenarios, which included insights on the relative role of scenarios and contextual factors that influenced mitigation decision-making. We corroborated interviewees' observations linking a specific scenario with mitigation policies or actions with primary source documents (e.g., government reports, municipal ordinance or legislation text) where possible.

Background on Broader Scenario Practice

The use of scenarios for much broader purposes, particularly in organizational and business strategy, emerged from military and defense uses in the mid-20th century—prior to the first earthquake scenarios—through work by Herman Kahn and colleagues at RAND Corporation and the Hudson Institute, and Royal Dutch Shell and others as Van der Heijden (1996) describes. Following these original civilian uses, scenarios have been utilized to provide insight into a wide variety of issues in diverse fields including strategic planning (see lists in Kahane (2012) and Ramirez and Wilkinson (2016), climate adaptation (e.g., Dockerty et al., 2005; Winfree et al., 2011; Rose and Starr, 2013), public health (e.g., Monaghan, 2004; Schoch-Spana et al., 2017; JHCHS, 2019), and socio-political decision making (e.g. le Roux, 1992; Ramphele et al., 2009).

Types of Scenarios

Scenarios are a part of a group of methods in the field of futures studies, and are frequently used to support decision making, particularly in situations where significant uncertainties exist (Ramirez and Wilkinson 2016), in order to "minimize regret" for decisionmakers rather than maximizing benefits (Strong Carpenter, and Ralph 2020) by identifying courses of action that yield acceptable results across a variety of potential future contexts. These types of scenarios explore a small set of three to four distinctive futures, generally through collaboratively developed narratives, which illustrate impacts of various actions (and inaction). In this paper, we describe this as the alternate futures approach—as opposed to "scenario planning" often used in the strategic and organizational planning literature—to distinguish it from the very different type of scenario work typically used to plan for earthquakes. The practice and theoretical foundations of alternate futures scenario methods are discussed elsewhere (e.g., Van der Heijden, 1996; Schwartz, 1996; Kahane, 2012; Ramirez and Wilkinson, 2016). This large body of knowledge has seldom been brought into scenario work for earthquakes; a recent exception is the use of HayWired scenario (Detweiler and Wein, 2017) results in the Horizon / Futures planning effort (MTC and ABAG, 2020). Observations from interviews echo findings from strategic planning literature regarding the beneficial impacts of scenario development processes in broadening perspectives and fostering collaboration.

In contrast, earthquake scenarios are typically event-and-consequences disaster scenarios based on a technical "core" of a fault source, shaking distribution, and loss estimate for one or more plausible earthquakes occurring now or in the near future. Event-and-consequences type earthquake scenarios are prepared for a near time horizon both to emphasize the immediacy of the threat (an earthquake can happen any time), to directly support emergency response planning and exercises, and to avoid challenges inherent in foreseeing and conceptualizing changes to the built environment, population exposure, communications, and emergency response capabilities a decade or more in the future. While most event-and-consequence scenarios are broad-based and examine overall effects on the built environment and (often) society, others are purpose-built, narrowly focused on a specific earthquake risk problem (such as vulnerability of particular building types or an infrastructure system), or rapid, which provide basic consequence information and are algorithmically generated (USGS PAGER scenarios, Earle et al., (2009) are an example).

Existing Scenario Development Guidance

Guidance for scenario developers reflects existing understanding—primarily among practitioners—regarding characteristics that make scenarios effective in achieving their intended purposes. Because scenarios are used in diverse fields as discussed above, these purposes vary greatly. Available guidance is practice-oriented and tailored to specific scenario practice domains. For event-and-consequences earthquake scenarios, the Earthquake Engineering Research Institute (EERI) prepared a guidance document (Preuss and Godfrey 2006) originally as a resource for local EERI chapters to use when preparing scenarios for their cities and regions. EERI also provided updated guidance (Greene et al., 2010) that, in 2021, was incorporated into the 2006 document as part of an update by members of the current project research team. Prior to this, FEMA-177 (FEMA, 1989) provided guidance for loss estimation studies (which were primarily scenario-based at the time) based on a user needs survey and workshop, and experiences of professionals in the Western U.S., and particularly California in preparing scenarios for emergency management and planning purposes and using them to develop and advocate for mitigation measures. Earthquake scenario developers have also published their experiences (e.g., Perry et al., 2011), which provide insights into effective practices, and researchers have proposed potentially effective approaches (e.g., Davies et al., 2015).

Guidance exists for related fields including general disaster risk reduction (e.g., Strong, Carpenter, and Ralph 2020; Sarkar-Swaisgood and Dewi Bernadet 2020) and emergency planning (e.g., Alexander, 2000; Alexander, 2016). Many books and documents provide guidance for methods commonly used in corporate and organizational strategic planning and socio-political change efforts (e.g., Van der Heijden 1996; Schwartz 1996; Ogilvy 2002; Searce, Fulton, and GBN Community 2004; Kahane 2012; Ramirez and Wilkinson 2016). In this paper we describe these as alternate futures methods to distinguish them from the distinct methods used in planning for earthquakes. Guidance documents for scenarios used in climate change (e.g., Rose and Starr 2013), transportation planning e.g., (FHWA 2011; Ange et al. 2017), and urban planning (e.g., Stapleton 2020) describe applications of alternate futures scenario planning methods to those disciplines.

Available guidance documents provide details on a variety of techniques and approaches that their authors consider effective (in appropriate contexts and conditions) that include observation, modelling, expert elicitation, workshops, narrative writing, and community and team participatory approaches of various types. The latter four techniques/approaches are often used together in alternate futures scenario planning, typically with professional facilitation. In alternate futures approaches, methods of developing the scenarios are highly participatory, rely heavily on input from knowledgeable and thoughtful people, utilize narrative techniques, and rely on computational modelling or analysis to varying degrees, depending on the subject matter. They produce a small set of future scenarios, often described in brief narratives, that can be used to identify and test courses of action.

Preuss and Godfrey (2006) and its 2021 update draw from the broader scenario development guidance described above in their guidelines for earthquake scenarios, particularly the emphasis on collaborative work, though they provide guidance for an event-and-consequences scenario. Guidance focuses on practical steps in the development process, including task sequencing, people to involve, team organization, data collection, review processes, and communicating and using results. Descriptions of these steps include practical recommendations on how to make scenarios effective. These include using 'best available' science and engineering, involving multiple disciplines and stakeholder/user groups from the beginning, and tailoring results for specific audiences (Preuss and Godfrey, 2006), Perry et al. (2011) list key scenario development criteria, and emphasize that a focus on end user needs and communication products tailored to key audiences were essential to the effectiveness of the ShakeOut scenario (Jones et al., 2008), as was social science research to present disaster impacts in ways that were pertinent to decision-making. The ShakeOut scenario included substantive work by disaster sociologists, economists and decision scientists (Perry et al., 2011).

Though some of the same themes are emphasized (i.e., collaboration), the methods and processes used in alternate futures scenario work have substantive differences from those used in almost all earthquake scenarios. There are a few notable exceptions, such as the Horizon alternate futures planning effort for Plan Bay Area 2050 (MTC and ABAG, 2020) which includes earthquakes as one shock in the San Francisco Bay Area, using the HayWired scenario results (Detweiler and Wein, 2017). Greater absorption of the broader alternate futures/scenario planning body of knowledge has the potential to provide additional tools and methods that improve the effectiveness of the processes used to create earthquake scenarios.

Earthquake Scenarios and Their Uses

Scenarios examining the damage and consequences from hypothetical earthquakes exist for most regions of moderate to high earthquake hazard worldwide. California has one of the largest bodies of scenario knowledge, with more than 30 publicly available scenarios and numerous unpublished scenarios prepared for a variety of purposes. Scenarios display a wide range of complexity, level of detail, types of impacts, intended audience, and methods of presentation. California also has abundant scenario-component studies that examine one element of what we define as a scenario for this research, such as the ground shaking hazard (using, for example, USGS scenario ShakeMaps, Wald et al. 2003), as well as numerous probabilistic risk studies, often for the insurance industry, that utilize thousands to tens of thousands of scenarios. As with other disasters, earthquake scenarios were originally used, and are still most frequently used, in emergency planning and preparedness (e.g., Alexander 2000a). As we will show, California earthquake scenarios have also been frequently used to identify and highlight earthquake vulnerabilities and potential impacts, and to motivate mitigation.

Table 1 provides a list of publicly available California earthquake scenarios (with the three essential components defined previously), identified from the literature review, including from sources such as the California Geological Survey digital library, Federal Emergency Management Agency (FEMA, 1989) and Earthquake Engineering Research Institute compilations, and through project interviews. Not listed are a large number of additional unpublished scenarios, with varying levels of detail, that have been prepared by private companies, utilities, and government for their own internal purposes or that of clients, including mitigation program design and to support local hazard mitigation planning; these were not available or not readily available. As we discuss in subsequent sections, we were able to document substantial mitigation impacts from many unpublished scenarios despite not having access to the studies themselves, which indicates their effectiveness. Also not listed are scenario-component studies for earthquakes, and scenarios prepared for California for other types of hazard events (e.g., Porter et al., 2011; Ross et al., 2013) or for urban, transportation, strategic, or emergency management planning.

Table 1. Publicly available earthquake scenarios for California

ID	Scenario Name	Institution	Reference
North Coast			
CA01	Planning Scenario in Humboldt and Del Norte Counties, California for a Great Earthquake on the Cascadia Subduction Zone	CDMG	Toppozada et al., 1995
San Francisco Bay Area			
CA02	Futures Final Report: Resilient and Equitable Strategies for the Bay Area's Future (Horizon Initiative; includes HayWired results)	MTC	MTC and ABAG, 2020
CA03	The HayWired Earthquake Scenario	USGS	Detweiler and Wein, 2017 (3 volumes)
CA04	1868 Hayward Earthquake: 145-Year Retrospective	RMS	Grossi and Zoback, 2013
CA05	The Coming Bay Area Earthquake: 2010 Update of Scenario for a Magnitude 7.0 Earthquake on the Hayward Fault	EERI	Maffei, 2010
CA06	Here Today---Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Potential Earthquake Impacts (Community Action Plan for Seismic Safety project)	ATC	ATC, 2010
CA07	When the Big One Strikes Again—Estimated Losses due to a Repeat of the 1906 San Francisco Earthquake	CalOES, EERI	Kircher et al., 2006 Stannard, 2006
CA08	Scenario for a M7.0 Earthquake on the Hayward Fault	EERI	EERI, 1996
CA09	Planning Scenario for a Major Earthquake on the Rodgers Creek Fault in the Northern San Francisco Bay Area	CDMG	Toppozada et al., 1994
CA10	Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area	CDMG	Steinbrugge et al., 1987

ID	Scenario Name	Institution	Reference
CA11	Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in the San Francisco Bay Area	CDMG	Davis et al., 1982b
CA12	A Study of Earthquake Losses in the San Francisco Bay Area: Data and Analysis	NOAA	Algermissen et al., 1972
CA22	Cascading Failures: Earthquake Threats to Transportation and Utilities	ABAG	Germeraad et al., 2014
CA23	Lifelines Interdependency Study	City of SF	Johnson, 2014
CA33	The 1906 San Francisco Earthquake and Fire: Perspectives on a Modern Super Cat	RMS	Grossi and Muir-Wood, 2006
CA34	What if the 1906 Earthquake Strikes Again? A San Francisco Bay Area Scenario	RMS	RMS, 1995b
Los Angeles Area			
CA14	The ShakeOut Earthquake Scenario	USGS	Jones et al., 2008 Perry et al., 2008
CA15	Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California	CDMG	Davis et al., 1982a
CA16	A Study of Earthquake Losses in the Los Angeles Area: Data and Analysis	NOAA	Algermissen et al., 1973
CA17	Planning Scenario for a Major Earthquake on the Newport-Inglewood Fault Zone	CDMG	Toppozada et al., 1988
CA28	Loss Estimates for a Puente Hills Blind-Thrust Earthquake in Los Angeles, California	SCEC	Field et al., 2005
CA29	Chemical Hazards, Mitigation and Preparedness in Areas of High Seismic Risk: A Methodology for Estimating the Risk of Post-Earthquake Hazardous Materials Release	NCEER	Seligson et al., 1996
CA30	Summary Report of Structural Hazards and Damage Patterns: Pre-Earthquake Planning for Post-Earthquake Rebuilding	Degenkolb	Degenkolb, 1984
CA31	Estimation of Earthquake Losses in Los Angeles	D&M	Scawthorn and Gates, 1983
CA35	What if a Major Earthquake Strikes the Los Angeles Area?	RMS	RMS, 1995a
San Bernardino / Inland Empire			
CA18	Planning Scenario for a Major Earthquake on the San Jacinto Fault in the San Bernardino area	CDMG	Toppozada et al., 1993
CA21	Collocation Impacts on the Vulnerability of Lifelines During Earthquakes with Applications to the Cajon Pass, California (FEMA 226)	FEMA	INTECH, 1992
San Diego			
CA19	San Diego Earthquake Planning Scenario: Magnitude 6.9 on the Rose Canyon Fault Zone	EERI	EERI, 2020
CA20	Planning scenario for a major earthquake: San Diego - Tijuana metropolitan area	CDMG	Reichle et al., 1990
Statewide and Multi-Area			
CA13	Beyond Button Pushing: Seismic Risk Assessment for California (1 example)	GEM	Rao et al., 2017
CA24	HAZUS Scenario and Annualized Earthquake Loss Estimation for California (56 statewide)	CGS	Chen et al., 2011
CA25	HAZUS Loss Estimation for California Scenario Earthquakes (56 statewide)	CGS	CGS, 2009
CA26	Estimation of Future Earthquake Losses in California (50 statewide)	CGS	Rowshandel et al., 2005
CA27	Metropolitan San Francisco and Los Angeles Earthquake Loss Studies: 1980 Assessment	USGS	Steinbrugge et al., 1981

ID	Scenario Name	Institution	Reference
CA32	Worker's Compensation Risk Assessment California Earthquake (8 examples statewide)	RMS	RMS, 2017

Acronyms used: ABAG = Association of Bay Area Governments; ATC = Applied Technology Council; CalOES = California Governor's Office of Emergency Services; CDMG = California Division of Mines and Geology; CGS = California Geological Survey; D&M = Dames and Moore; EERI = Earthquake Engineering Research Institute; FEMA = Federal Emergency Management Agency; GEM = Global Earthquake Model Foundation; MTC = Metropolitan Transportation Commission; NCEER = National Center For Earthquake Engineering Research; NOAA = National Oceanic and Atmospheric Administration; RMS = Risk Management Solutions; SCEC = Southern California Earthquake Center; USGS = US Geological Survey

Historical Earthquake Scenarios Prepared for California

An in-depth study for a repeat of the 1923 Kanto earthquake in Tokyo, prepared by the government beginning in the early 1960s and published in 1978 (Katayama, 1992), was likely the first comprehensive earthquake scenario. Katayama (1992) describes this effort and subsequent major scenarios in a summary of Japan's first several decades of scenario development.

Scenario practice in the western United States, and California in particular, began in 1967 with planners in the Federal Office of Emergency Preparedness (OEP), the forerunner to FEMA, who drew on experiences using scenarios in nuclear war planning (which also influenced early disaster research in social sciences, Tierney, 2007) and during military service, to transfer and apply those approaches to describe what might happen if a repeat of the 1906 San Francisco earthquake were to strike again, according to statements made by one project interviewee (August 24, 2021). The resulting NOAA report (Algermissen et al., 1972) was the first formal earthquake scenario prepared in California, and in the U.S. as a whole. U.S. scenario builders were not aware of the scenario underway in Tokyo.

A series of planning scenarios/loss estimates followed for hypothetical western U.S. earthquakes, prepared by NOAA and USGS for Los Angeles (Algermissen et al., 1973), Seattle (Hopper et al., 1975), Salt Lake City (Rogers et al., 1976), and as an update to the earlier California studies (Steinbrugge et al., 1981). The California Division of Mines and Geology (CDMG, later the California Geological Survey) carried out a series of major studies in the 1980s and 1990s (Davis et al., 1982a,b; Steinbrugge et al., 1987; Toppozada et al., 1988; Reichle et al., 1990; Toppozada et al., 1993, 1994, 1995). Private sector organizations also produced scenarios for California in the 1990s (e.g., EERI, 1996, RMS, 1995a, b). Beginning in the mid-2000s, a new series of major earthquake scenarios were prepared, aided by the availability of the loss estimation software HAZUS (Hazards-US, Whitman et al., 1997), including Quake'06 (Kircher et al., 2006; Stannard, 2006), ShakeOut (Jones et al., 2008; Perry et al., 2008), , and HayWired (Detweiler and Wein, 2017). A number of purpose-built (e.g., San Francisco's Community Action Plan For Seismic Safety (CAPSS) scenarios, ATC, 2010), rapid and other scenarios were also prepared during this period (e.g., Rowshandel et al., 2005; Grossi and Muir-Wood, 2006; CGS, 2009; Maffei, 2010; Chen et al., 2011; Grossi and Zoback, 2013).

Historical Earthquake Scenarios Prepared Outside California

In the 1980s and early 1990s, often with support from FEMA, state agencies undertook major studies in Alaska (Bessette et al., 1980), Hawai'i (Furomoto et al., 1980), Nevada (de Polo et al., 1996), Washington and Oregon (e.g., Wang and Clark, 1999). More recent earthquake scenarios elsewhere in the U.S. include those prepared for Utah (EERI, 2015), eight states in the New Madrid Seismic Zone (MAE Center and Virginia Tech, 2009), New York (Tantala et al., 2003), and a number of efforts in the Pacific

Northwest/Cascadia region (e.g., Ballantyne et al., 2005; Cascadia Region Earthquake Workgroup, 2013; Paci-Green et al., 2015; Marafi et al., 2019).

Earthquake scenarios began to see more use outside Japan and the United States in the 1990s, including with a colloquium that explored international collaboration on earthquake damage scenarios, particularly in developing countries (Tucker, 1992) and scenarios in India (Arya, 1992), Quito, Ecuador (Escuela Politecnica Nacional et al., 1994), New Zealand (Aggett, 1994, Davey and Shephard, 1995), Turkey (Erdik et al., 1995), Colombia (Cardona and Yamín, 1997), and Nepal (Basnet et al., 1999). The UN's RADIUS initiative promoted fast, low cost scenarios focused on informing mitigation planning, with demonstration projects in nine cities (UNISDR, 1999). Numerous additional in-depth scenarios have since been prepared in countries with moderate to high earthquake hazard around the world. Japan's earthquake resilience programs continue to embed scenarios (e.g., CDMC 2005, 2008, 2013). Scenarios in other countries include Algeria (JICA et al., 2006), Armenia (JICA et al., 2012), China (Rodgers et al., 2019), Iran (JICA et al., 2000; 2004); India (e.g., Rodgers et al., 2014), Nepal (e.g., JICA et al., 2002; JICA, 2018; GHI and GHS, 2018a, b, c; Robinson et al., 2018), New Zealand (e.g., McCahon et al., 2006; Cousins et al., 2014; Robinson et al., 2014; Orchiston et al., 2016; Power et al., 2018), and Turkey (BU-ARC, 2002; JICA et al., 2002), among others.

The Context: Information Used to Develop Policies/Practices Related to Geologic Hazards

Scenarios have long been viewed by earthquake safety advocates as a useful and effective tool for communicating earthquake risk. Insight into the informational contexts in which scenarios are situated and the different purposes for which they are used are key prerequisites for understanding what makes scenarios effective. This section first examines interview findings on the types of information that organizations in California use to develop policies and practices for geologic hazards. This information may or may not come from scenarios. A discussion follows of the different ways that organizations use scenarios, as reported by interview participants.

Respondents reported various information resources that they or their organization used to develop practices and/or policies related to risks from geologic hazards. Scenarios can provide many of these types of information, or can be designed to provide them to meet user needs. Many respondents cited that their organizations used descriptions of population-level impacts and loss estimates. Specific examples include using USGS scenario loss estimates and economic impact information, Hazards-US (HAZUS) loss estimates for impacts on housing and infrastructure, Occupational Safety and Health Administration (OSHA) websites, and network-based loss estimation with System Earthquake Risk Assessment (SERA) for more granular loss estimation and risk estimation assessment.

Use of maps and data visualizations were also reported. Respondents reported using these methods to depict information including a geospatial perspective. Specific examples included USGS and California Geological Survey (CGS) tools and hazard maps, LIDAR (Light Detection And Ranging) mapping data, GIS layered maps, and ArcGIS story maps. To a lesser extent, respondents indicated using scientific information products and summaries from partnering organizations (e.g., USGS communication products, information from San Francisco Bay Conservation and Development Commission) including hazard mitigation plans (e.g., city Local Hazard Mitigation Plans) and resiliency information (e.g., National Establishment Time Series data). A few respondents also stated use of new technologies, for example the Zonehaven technology program to model evacuation scenarios in developing practices and policies.
One final set of responses centered around translation concerns, including those individuals who translate technical details and the scientific data into clear actions for decision-making. A number of users considered technical professionals to be key sources of information. Subject matter experts, in particular,

were cited as critical to this translation effort including, broadly, engineers and technical experts including risk management and legal experts.

Common Uses of Scenarios

As interviewees were selected in part based on their involvement in issues relevant to geological hazard scenarios, most participants indicated that they and/or their organization were generally aware of such studies. However, the extent of engagement with scenarios and the various ways in which they were used varied greatly. Most prominent among the uses identified were planning and mitigation programs. Specifically, scenarios were used as points of reference in developing or updating disaster response and contingency plans. Similarly, the detailed information that scenarios provided made them useful reference points for emergency planning drills and exercises. They were also integrated into tools and data sources for mitigation plans, benchmarks, and programs.

Another common use was policy development at the state and local levels, as scenarios provided evidentiary foundation for policies and policy recommendations. As the sections below discuss, these included numerous municipal ordinances creating mitigation programs or requirements, state legislation and agency actions, and local hazard mitigation plans that comply with national and state policies and delineate local mitigation priorities. Relatedly, several participants indicated scenarios had enabled them to gain political influence and support for policies intended to address earthquake risks, as they relayed credible data about potential impacts and losses of interest to various governing bodies. Scenarios were used to better understand a range of potential losses and impacts, particularly with respect to their geographic distribution. Information concerning social impacts was a key issue of interest and guided considerations about infrastructure needs in the context of social vulnerability, resiliency, and equity. Outside the policy and decision-making realm, participants discussed using scenario content or conclusions for community engagement, education, and outreach purposes. Others had incorporated data from scenarios into various other products, tools, and resources.
In a few instances, responses indicated that participants or their organization did not use scenarios or similar studies, largely due to a lack of understanding or incompatibility with routine organizational practices.

Impacts of California Scenarios on Mitigation

Scenarios take much of their realism and plausibility from past earthquake experiences and damage. Noted strategic business scenario developer Kees Van der Heijden (1996) describes scenario development as a "practitioner's art" which is particularly applicable to the way that earthquake scenario developers must take real earthquake experiences and damage, and along with hazard simulation, loss estimation techniques and qualitative impact information from risk owners, use them to produce with stakeholders a compelling picture of what can happen during a hypothetical future earthquake. Creating an understandable "picture" from highly technical information is a key element in scenario effectiveness, as we discuss in later sections along with other characteristics of effective scenarios. Scenarios extend past earthquake experience into the future by applying what is known about causes of damage and its consequences to contexts with similar hazard and vulnerability characteristics. For decades, earthquake professionals have paired damage in past real events with scenarios of future damage and impacts to effectively advocate for mitigation efforts. Past earthquake damage is often named as the motivating factor behind mitigation programs, but it is not the only factor; scenarios have also had a significant role, as we discuss below. Earthquake damage allows earthquake professionals to identify physical vulnerabilities in buildings and infrastructure. Creating mitigation programs in other locations to address those same vulnerabilities requires that decision-makers understand the likely impacts of future events, often accomplished by using scenarios.

One of the concepts behind the use of an event-and-consequences scenario is to help motivate policy changes to improve safety that typically occur only after a rare, focusing event (Birkland, 1998) without having to experience the event and the associated loss of life, damage and public suffering; this was mentioned by several interviewees. Corotis et al., (2012) discuss some of the psychological reasons, such as impacts on risk perception, that consuming information on past disasters or scenarios of hypothetical future disasters influences the likelihood of people taking action and help make scenarios effective.

A limited number of studies and less formal evaluations (such as in workshops) exist of the direct impact of California earthquake scenarios on mitigation (e.g., Perry et al., 2011; Corotis et al., 2012; Jones and Aho, 2019; Davis and Shamma, 2019). The present study expands the documented impacts of scenarios through a review of primary source documents and interviews with users and developers of scenarios involved in mitigation work. The sections below discuss California's resilience context and documented scenario impacts on earthquake risk mitigation and resilience programs and policies, which include local jurisdiction-based resilience plans, programs requiring retrofit or replacement of vulnerable buildings, and infrastructure resilience programs.

The California Resilience Context

In California, scenario studies and the development of research practices have grown within an enabling environment that favors risk reduction and investment in the sustainability of its communities. California's legislative action on disasters, receptivity to academic and policy collaboration, resilience investments, and mainstreaming scenario studies into state and local planning all contribute to the state's innovative approach to disaster risk analysis and attendant mitigation. California also has a substantive history of funding and legislation related to climate resilience and natural hazards other than earthquakes which is outside the scope of this study, but is part of the overall resilience context.

California's long history of disasters and the state's response to catastrophic physical disruptions is well known in public policy and technical practice disciplines. Since 1906, state and local officials, along with practitioners and technical experts, have largely acted in the aftermath of major disasters to lessen people's suffering and protect the social fabric of the community. The 1906 San Francisco earthquake, for example, led to the publication of the 1908 Lawson Report (Lawson, 1908), a forerunner to modern disaster scenarios; and the founding of the organizations that advocated for safety codes and earthquake-resistant construction (Perkins et al., 2006). Local action followed suit: after the 1925 Santa Barbara earthquake, Santa Barbara's building codes became the first to explicitly state consideration of seismic safety of structures, and the earthquake served as a priming event that prepared the professional community to act after the 1933 Long Beach earthquake (Olson, 2003). The 1933 event caused extensive damage to unreinforced masonry structures, including schools. It led to landmark laws: the Field Act (passed unanimously in the California legislature within 30 days) mandating public school buildings be designed to be earthquake-resistant (the first seismic state-wide mandate in building codes), and the Riley Act that required cities and counties to establish building departments to regulate construction.

This willingness to implement new safety policies after earthquakes made Californians receptive to acting in anticipation of expected major earthquakes, which scientists would warn of and describe in scenarios. Earthquake safety efforts had already become more proactive in the 1960s, spurred by an increasing research culture and major earthquakes elsewhere (Olson, 2021) when the first scenario began in 1967. The aftermath of the 1971 Sylmar earthquake provided a window of opportunity to implement policies already in development through proactive efforts, and prompted establishment of the Seismic Safety

Commission; improved statewide building codes; and saw passage of the Alfred E. Alquist Hospital Facilities Seismic Safety Act (HSSA). The interspersing of sustained, proactive efforts to identify and communicate risks and mitigation approaches, often using scenarios, with rapid action during politically receptive periods after major earthquakes is a pattern repeatedly observed in California over the past 50 years. Numerous authors (e.g., Jephcott, 1986; Tobin et al., 1992; Housner and Thiel, 1995; Wiley, 2000; Geschwind, 2001; Chakos et al., 2002; Olson, 2003; Perkins et al., 2006; Olson, 2021) discuss the history of seismic safety and resilience efforts in California; readers are referred to these publications. Ongoing public education efforts, using a variety of earthquake hazard information and scenario findings, have also built public awareness of earthquake risk and the need for mitigation.

Public support for mitigation is evidenced by voter-approved state and local bond measures. State bond measures have directly allocated $300 million to seismic safety since 1986 (Miles and Gouran, 2010), and funds from broader school and infrastructure bond measures have been used to improve seismic safety (Chakos et al., 2002), but the amount spent by the state on seismic safety has not been well quantified. Several billion dollars in state transportation funds supported Caltrans' bridge retrofit program (Miles and Gouran, 2010). State funds supplement additional billions from federal disaster response and recovery funds that match local tax monies raised for community recovery and safety (Chakos et al., 2002; Miles and Gouran, 2010; Brocher et al., 2018). In the San Francisco Bay area alone, combined federal, state and local investments since 1989 may top $80 billion (Brocher et al., 2018).

Application of FEMA's Scenario-Based National-Level Policies and City-Level Mitigation Planning

In 1994, FEMA convened a multi-year effort with a broad stakeholder group to develop the risk assessment and loss estimation tool HAZUS (Whitman et al., 1997), which provided a methodology that could be used nationwide to forecast damage and impacts from scenario hazard events. FEMA adopted HAZUS as its default risk assessment tool for national use, allowing communities to develop credible, scenario-based risk studies that FEMA and other federal agencies would use both for disaster response planning and pre-disaster mitigation implementation. The technical system became the backbone of a new approach to disaster safety in 2000. Congress approved the Disaster Mitigation Act of 2000 (DMA2K) that amended the Stafford Act (FEMA's baseline legislation) to create authority for national mitigation planning and the Pre-Disaster Mitigation (PDM) grant program (106th Congress, 2000). Under DMA2K auspices, loss estimates (typically from scenario studies) were required as part of the development of local hazard mitigation plans (FEMA, 2008). In 2020, over 23,000 local jurisdictions and 239 federally recognized tribes had mitigation plans, covering over 84% of the U.S. population (FEMA, 2020).

In California, 502 cities, counties and special districts were covered in scenario-based Local Hazard Mitigation Plans (LHMP) in 2018 (CalOES, 2018). These plans are mandated by law (AB 2140, Hancock, 2006) to be incorporated into all local general plans thereby institutionalizing disaster scenario findings and policies in communities. The Quake'06 scenario (Kircher et al., 2006) led to the development of AB 2140. Two other enacted State Senate bills, SB379 (Jackson, 2015) and SB 1035 (Jackson, 2018), call for more extensive, state-of-the-practice risk planning to ensure mitigation planning is ongoing, resilience-centric and comprehensive (Key et al., 2020). These state efforts have made the use of scenarios prevalent in California, with mitigation policies and actions (as required) enmeshed in the risk reduction operations of towns, cities, counties and special districts.

Several municipal and county-level mitigation planning efforts have strong links to publicly available scenarios, beyond the LHMP process. The City of Berkeley has used scenarios over the years (e.g., Steinbrugge et al., 1987; EERI, 1996) to inform public policies; scenarios galvanized passage of risk mitigation bond measures for school and public facility safety upgrades (Chakos et al., 2002; Chakos and

Zoback, 2018). San Francisco's CAPSS included a scenario-based mitigation planning effort that resulted in a 30-year Earthquake Safety Implementation Program (ESIP, Kornfeld et al., 2011) and significant mitigation actions (Chakos and Zoback, 2018)). CAPSS faced political headwinds until a new mayor, technical and policy support to the city, and a pivot to a scenario-based approach helped move efforts forward (Chakos and Zoback, 2018). Soft-story buildings (discussed subsequently) were the first building type addressed under ESIP; other types are planned.

The City of Los Angeles relied heavily (Jones and Aho, 2019) on findings from the ShakeOut scenario (Jones et al., 2008) to set mitigation priorities in its seismic resilience plan, Resilience by Design (City of Los Angeles, 2014). The four priority areas were soft-story woodframe buildings, nonductile concrete buildings, water systems, and telecommunications infrastructure, discussed in subsequent sections. According to interviewees, contextual factors—ending of the financial and real estate crisis, election of a new, supportive mayor, and targeted, proactive advocacy—were necessary to move from the 2008 ShakeOut scenario to the 2014-2015 planning and implementation effort. Interviewees considered as especially critical the partnership between the USGS and the City of Los Angeles made possible by the support of a recently elected mayor. Prior to this partnership, the ShakeOut scenario had been available for over five years, without significant mitigation actions by the City.

Building Seismic Retrofit Programs

Unreinforced Masonry Buildings

Unreinforced masonry (URM) building programs represented California's first significant attempt to address existing, seismically vulnerable private buildings. Early efforts, the large program initiated by Los Angeles in 1982, and a 1986 state law requiring inventories of URM buildings and plans to address risk (SB-547, Alquist, 1986) have been discussed at length elsewhere (Alesch and Petak, 1986; Tyler and Gregory, 1990; CSSC, 1995). A number of programs have also addressed seismically deficient public buildings, including URMs (e.g., CSSC, 1999; Miles and Gouran, 2010; Brocher et al., 2018). Timelines of mitigation programs (ABAG, unpublished data, 2021) show that URM programs were prioritized and conducted first, due to the state law and the professional consensus it represented regarding the life safety risks of URM buildings and availability of technical solutions (CSSC, 1995).

URM programs are typically considered to have been motivated primarily by severe URM damage in past earthquakes, in California and elsewhere, as this provided compelling evidence of the dangers (see CSSC, 1995 for a summary). Early URM ordinances in Long Beach in 1959 (allowing condemnation and removal) and 1971 (allowing strengthening as a risk reduction option), and in Santa Rosa and Sebastopol appear to have been motivated by earthquake damage without influence from scenarios (Alesch and Petak, 1986; CSSC, 1995). Following these early efforts, scenarios have been used to help 'make the case' for municipal ordinances and state legislation, by quantifying potential URM damage in future earthquakes and portraying its impacts. For example, earthquake casualties and losses caused by URMs described in the 1981 USGS update (Steinbrugge et al., 1981) of the original NOAA Los Angeles scenario (Algermissen et al., 1973) were part of the argument made to the Los Angeles City Council at the first of the final series of meetings that led to ordinance adoption in January 1982 after over a decade of effort (Alesch and Petak, 1986, see p. 77-79). Also, a later study of certain impacts of the LA ordinance (Tyler and Gregory, 1990) names the 1971 San Fernando earthquake and 1981 scenario update in the discussion of the earthquake risk awareness context that supported LA's URM seismic retrofit program ordinance.

Focused scenario-based studies produced for individual cities were similarly used to justify municipal ordinances establishing URM programs in Santa Ana (Alesch and Petak, 1986), Hayward, and Fremont among others, to and inform program design (according to interviewees familiar with the programs). The approach first employed with URMs of citing past earthquake damage, and then using scenarios to extrapolate that damage to areas with similarly vulnerable construction that have not recently experienced a severe earthquake, has been successfully replicated for other types of vulnerable buildings and infrastructure.

Soft/weak Story Woodframe Buildings

Older seismically vulnerable wood frame buildings, typically apartments with parking or storefronts that create a weaker, collapse-risk ground story, represent a significant fraction of the affordable housing stock in many California cities. Earthquake damage creates a life safety risk for those in the ground stories of these buildings, as evidenced by collapses and severe damage in San Francisco's Marina District in the 1989 Loma Prieta earthquake (EERI, 1990), and the Northridge Meadows apartment collapse in the 1994 Northridge earthquake that killed 16 (Lin et al., 1995). Without intervention, damage is likely to displace thousands after future earthquakes (for example, ATC, 2010 and Detweiler and Wein, 2017). For this reason, soft-story buildings have typically been the second private building type, after URMs, that cities have addressed with mandatory ordinances (unpublished mitigation timeline data, ABAG, 2021). Scenarios have been an instrumental part of this effort, as demonstrated in publications (e.g., Bonowitz, 2009; Corotis et al., 2012; City and County of San Francisco, 2013; Jones and Aho, 2019) and underscored by interview participants familiar with these issues.

The overall history of soft-story building retrofit programs in California as reported by interviewees and in available documents is multi-faceted and includes a number of contextual factors with varying degrees of influence, including emergence of elected and staff champions, leader-follower dynamics between cities, and external events. Modified influence diagrams developed from documents and mitigation impact logs from project interviews visualize some of these relationships and approximate timelines for the San Francisco Bay Area (Figure 2) and the Los Angeles area (Figure 2).

San Francisco Bay Area Cities

For the San Francisco Bay Area, concern over soft-story buildings became more prominent after damage in the Marina District during the 1989 Loma Prieta earthquake. The earthquake reinforced overall seismic safety concerns raised by CDMG's then-recently released Hayward Fault scenario (Steinbrugge et al., 1987), particularly in the City of Berkeley, which sits atop the fault. In 1990, Berkeley's City Council approved a program providing real estate transfer tax rebates for seismic upgrades in one- to four-unit residential buildings, launching a 20-year risk reduction effort in the city and leading the way for other communities to act (Chakos et al., 2002; Chakos and Zoback, 2018). The Quake'06 scenario helped raise awareness of the remaining risk (Kircher et al., 2006), and led to statewide legislation setting retrofit design guidelines (AB-304, Hancock, 2005).

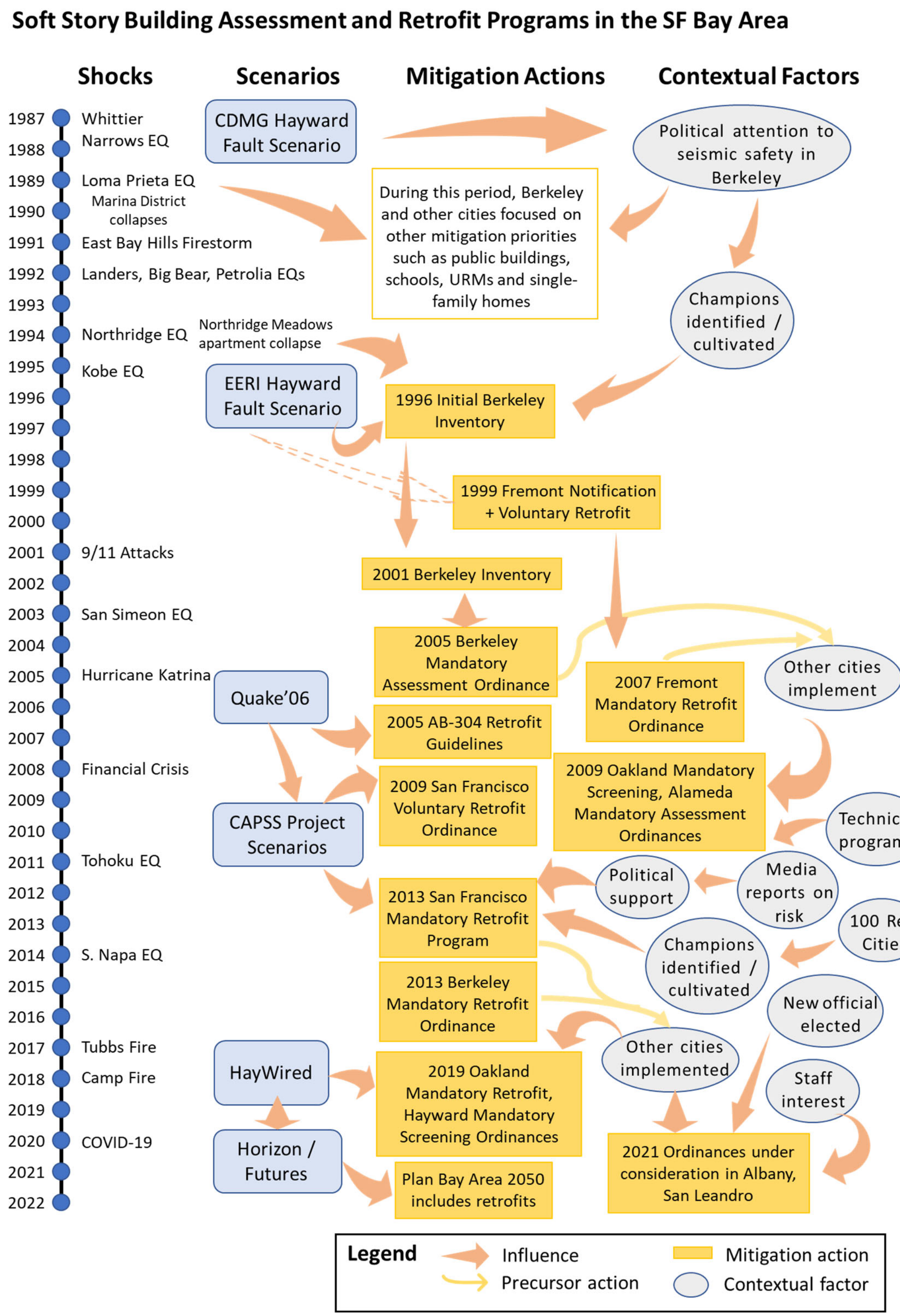

Figure 2. Timeline of shocks and relationships between scenarios, contextual factors, and mitigation actions for soft-story woodframe buildings in the San Francisco Bay Area

The CAPSS project was a scenario-based planning project that used scenario assessments of damage to soft-story apartment buildings (ATC, 2010), prepared for and with a volunteer Advisory Committee with neighborhood and stakeholder representatives. The CAPSS scenario study was cited in the resulting ordinance text (City and County of San Francisco, 2013). Four interviewees and multiple publications (e.g., Corotis et al., 2012; Chakos and Zoback, 2018) mentioned the importance of the CAPSS project scenarios in the adoption of the soft-story retrofit program. Specifically, these sources discussed how using scenarios rather than probabilities (which are more conceptually abstract) to present potential consequences of damage and the benefits of seismic retrofit, helped to better communicate risks and the benefits of acting to the public and built support for mandatory mitigation programs. They also considered essential the CAPSS program's robust public involvement (via the Advisory Committee and its public meetings) and participatory processes such as workshops to build consensus between groups such as building owners and tenants (Corotis et al., 2012). Interviewees familiar with the CAPSS and subsequent soft-story retrofit programs considered this process and resulting stakeholder consensus essential in eventual passage of a strong retrofit ordinance in San Francisco's fractious political climate.

Effective scenario development processes are discussed in a subsequent section. Interviewees also credited support from elected officials and strong staff support, including from a city Chief Resilience Officer supported by an outside grant (Chakos and Zoback, 2018) in moving efforts forward. After San Francisco adopted its ordinance, the Association of Bay Area Governments (ABAG) created a toolkit for other cities to create their own ordinances (Bonowitz, 2017); interviewees in several cities exploring their own programs reported being aware of this toolkit.

Los Angeles and Nearby Cities

The Los Angeles area has a large number of seismically vulnerable multi-family woodframe buildings. The ShakeOut scenario included these buildings in its loss estimates for wood-framed buildings (Graf and Seligson, 2011). The process of developing Resilience by Design (City of Los Angeles, 2014) included using ShakeOut results to identify and recommend mandatory retrofit programs for pre-1980 soft-story woodframe (and nonductile concrete) buildings, for which municipal ordinances were prepared in 2015 (Jones and Aho 2019). In the urgency clause providing the rationale for immediate adoption, Los Angeles' mandatory retrofit ordinance text (City of Los Angeles, 2015) cites a presentation by Dr. Lucy Jones on the Resilience by Design long-term plan, showing the impacts of earthquake damage on soft-story housing. The soft-story ordinance passed in October 2015 (Jones and Aho, 2019); as of March 2022 over 7500 buildings had been retrofitted (LADBS, 2022). Figure 3 illustrates some of the relationships and influences between ShakeOut, Resilience by Design and various actions on soft/weak story buildings.

According to interviewees, a Southern California Association of Governments (SCAG) follow-on program to work with other cities in the region to address priority areas from the ShakeOut scenario, as well as the example of the Los Angeles program, led a number of other cities in the region to adopt their own mandatory retrofit ordinances, including Beverly Hills, Culver City, Pasadena, Santa Monica, West Hollywood. Santa Monica had been the first city in the region to begin addressing soft-story woodframe buildings, with a mandatory ordinance passed after the 1994 Northridge earthquake, but enforcement waned over time due to staff turnover (Lin et al., 2013). Through the scenario-grounded influence of the SCAG program, a new mandatory retrofit ordinance passed in 2017 covering soft story woodframe buildings, plus others (City of Santa Monica, 2022).

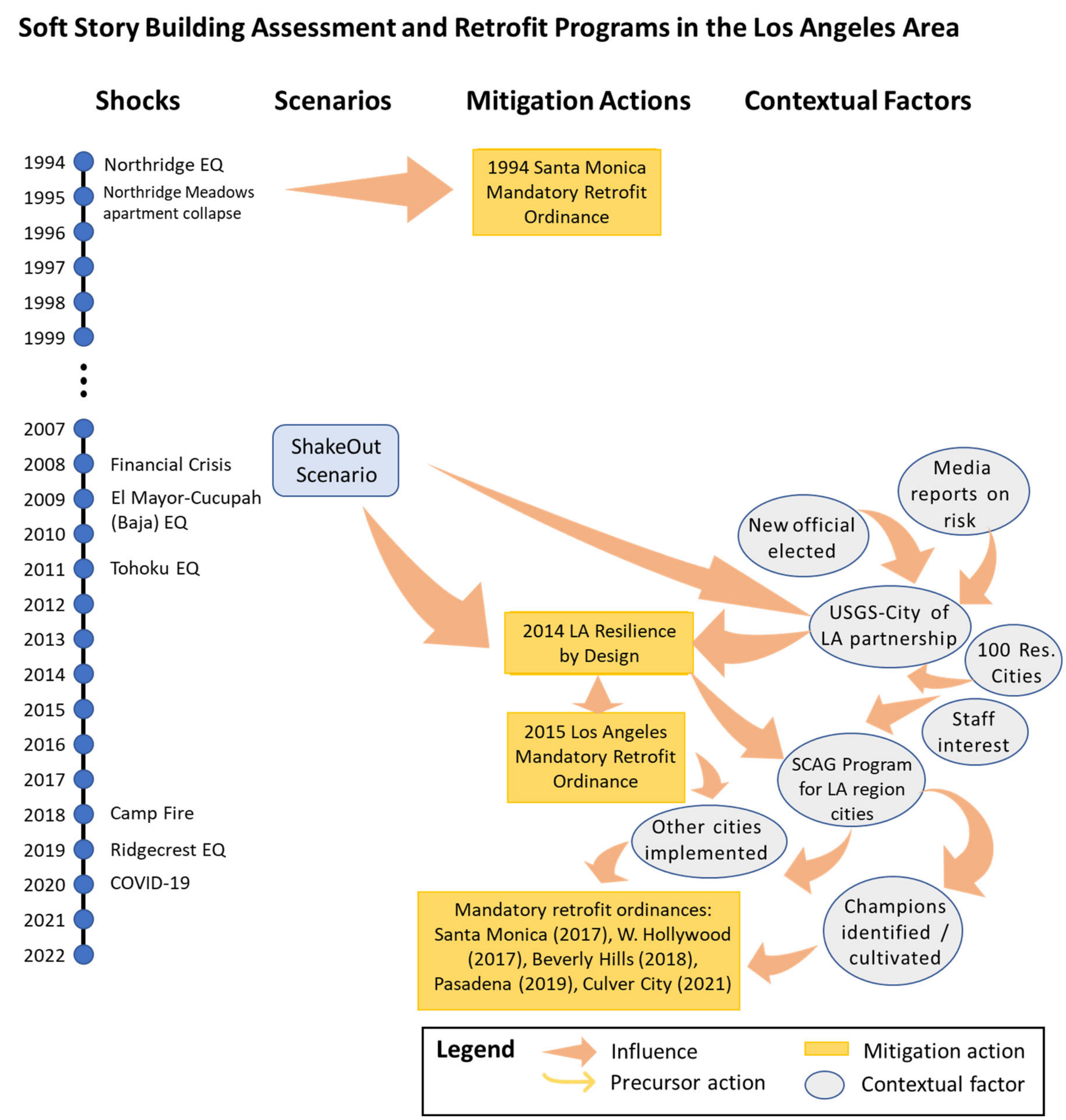

Figure 3. Relationships between scenarios, contextual factors, and mitigation actions for soft-story woodframe buildings in the Los Angeles Area

Other Buildings

In 2015, Los Angeles passed Ordinance 183891 mandating retrofit of pre-1980 nonductile concrete buildings, developed as part of Resilience by Design using ShakeOut findings (Jones and Aho, 2019); contextual issues were discussed under soft/weak story buildings. Santa Monica's mandatory retrofit program discussed in the previous section also covers the city's remaining URMs, and nonductile concrete, concrete tilt-up, and pre-1994 steel moment frame buildings (City of Santa Monica, 2022). West Hollywood has a mandatory retrofit program for pre-1994 welded steel moment-frame buildings, influenced by scenarios as discussed under soft-story buildings (Jones and Aho, 2019).

Utility Infrastructure Upgrade Programs

Utility infrastructure programs, particularly for water systems, represent some of the most significant mitigation investments motivated by scenario studies. Figure S4 shows some relationships between mitigation actions, scenarios, shocks and other contextual factors. In 1991, the East Bay Municipal Utility District (EBMUD), which supplies water to a large portion of the eastern San Francisco Bay Area, began a seismic risk assessment of its systems from four scenario events on the Hayward Fault (CSSC, 1999). This internal study identified major vulnerabilities in the system, including supply pipelines crossing the Hayward Fault that would be damaged by surface rupture, pumping plants predating seismic codes, vulnerable treatment and distribution systems, and a lack of redundancies, which could cause service interruptions of nearly six months (CSSC, 1999).

To begin mitigating identified vulnerabilities, EBMUD's publicly elected Board of Directors approved a 10-year Seismic Improvement Program that expended $189 million between 1995 and 2006 to seismically upgrade treatment plants, reservoirs, and pumping plants, add a new connecting pipeline in the southern part of the system, and improve other facilities (EBMUD, 2017; Terentieff et al., 2017). EBMUD also completed seismic upgrades to dams and constructed a specially designed tunnel to convey water through the Hayward Fault zone, bringing total mitigation investments set in motion by the original 1994 scenario study to more than $350 million (EBMUD, 2017). EBMUD has conducted a number of additional internal studies (e.g., Terentieff et al., 2017), and participated in the HayWired scenario (Detweiler and Wein, 2017); results from the latter are supporting efforts to improve the resilience of the distribution system, according to interviewees familiar with HayWired.

The ShakeOut scenario and follow-on studies (e.g., Davis and O'Rourke, 2011) demonstrated very significant resilience challenges for Southern California water systems, particularly in Los Angeles. These include impacts that could only be shown by scenario studies, as they were not evident from earthquake damage in Los Angeles over the past century (fault crossing pipeline damage had been observed south of San Francisco in 1906, Eidinger et al., 2006). The most significant is the potentially severe disruption of water supply from the three aqueducts supplying Southern California, which cross the San Andreas fault and could be simultaneously damaged by fault rupture and geotechnical failures in a major surface-rupturing event (Davis and Shamma, 2019). (The potential for San Andreas Fault rupture damage to the aqueducts was previously recognized, but the potential for simultaneous damage to all three, and hindrances to repairs from interdependencies with also-damaged transportation, power, and telecommunications infrastructure were not.) The ShakeOut results and prioritization in the Los Angeles resilience plan Resilience by Design were key motivations for regional efforts through setup of the multi-agency Seismic Resilience Water Supply Task Force (SRWSF) and its subsequent work (Davis and Shamma, 2019). ShakeOut and the following internal studies, as well as the Resilience by Design effort (and associated contextual factors discussed previously) also motivated a substantial Los Angeles Department of Water and Power (LADWP) program to improve system resilience (Davis, 2015). Key LADWP mitigation activities under this program included a new post of Chief Resilience Officer for LA's water system; a seismic resilient pipe network (Davis, 2018), upgrades to aqueducts (in collaboration with SRWSF partners) and other parts of the system, and a joint program on fire following earthquake with the City and Fire Department (Davis, 2015).

San Jose Water Company is using a system analysis prepared for the HayWired scenario to help prioritize capital improvements to their system that will also build seismic resilience, including upgrading older tanks and replacing mains constructed of vulnerable types of pipe, as well as taking a number of preparedness measures (Outsmart Disaster, 2018), according to interviewees familiar with HayWired. For example, a water main crossing the San Andreas Fault was replaced with earthquake-resistant ductile iron pipe with joints designed to allow movement (San Jose Water, 2019).

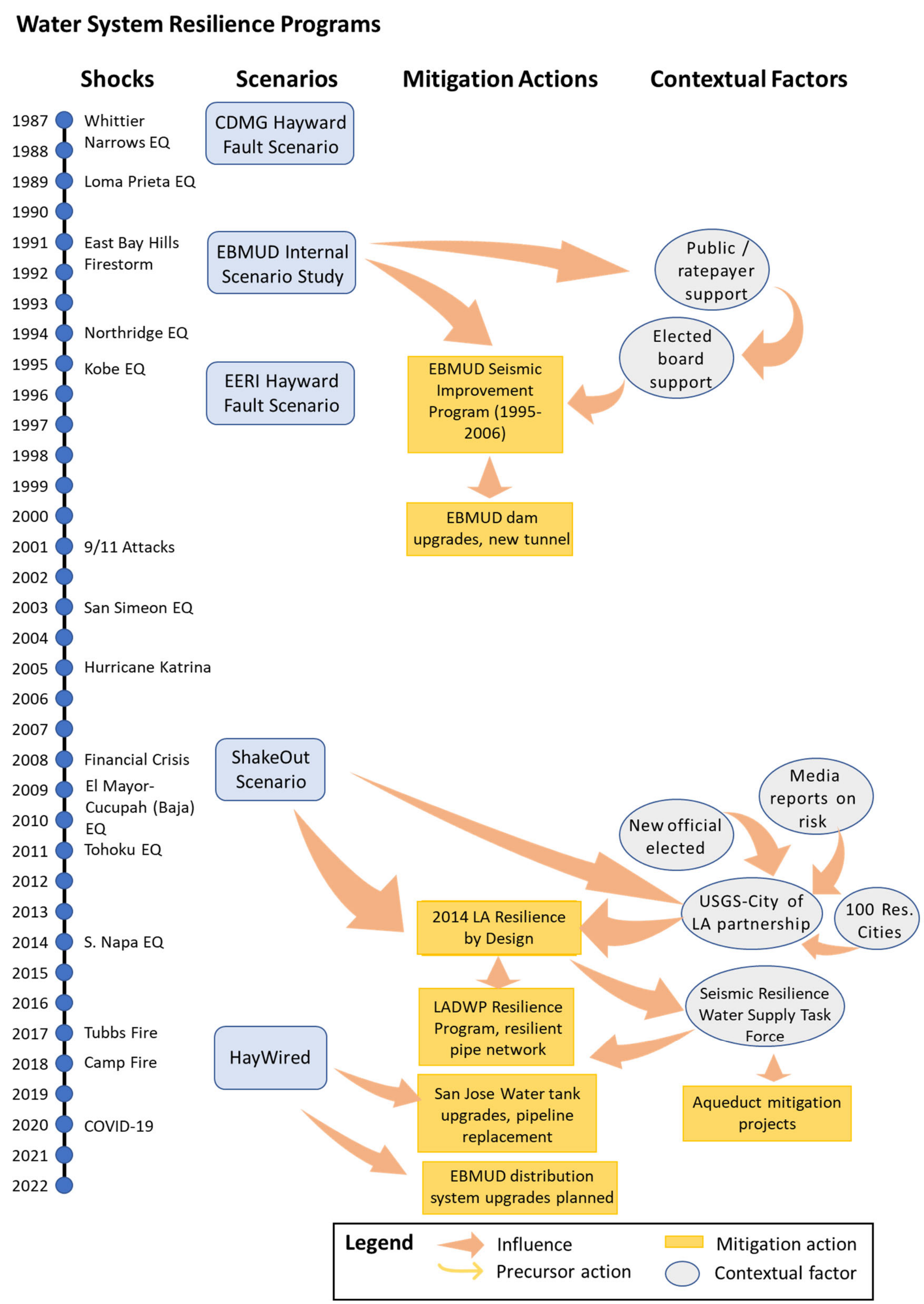

Figure S4. Relationships between scenarios, contextual factors, and mitigation actions for water system resilience programs

The San Francisco Public Utilities Commission (SFPUC) is nearing completion of the Water System Improvement Program (WSIP), a $4.8 billion voter-approved capital program to repair, replace and seismically upgrade the systems that deliver water to the city and region from the Hetch Hetchy Reservoir in the Sierra Nevada. The WSIP was mandated by AB 1823 (2002) amid regional concerns (BAWSCA, 2021). Scenario earthquake displacements on major faults that the system crosses appear to have been used to help identify projects for inclusion in WSIP (CSSC, 2006). We were not able to identify other roles of scenarios in the WSIP.

As part of the Resilience by Design implementation effort, in 2015 Los Angeles passed an ordinance requiring a higher level of seismic design for telecommunications towers (Jones and Aho, 2019).

Transportation Infrastructure Upgrade Programs

State transportation agency Caltrans has spent several billion dollars to retrofit older bridges since the 1971 San Fernando earthquake (Miles and Gouran, 2010). Following the 1989 Loma Prieta earthquake, an inquiry into the damage, in particular to bridges, was requested by the Governor and carried out by a public Board of Inquiry, which reported findings (Housner and Thiel, 1990) that led to significant changes in Caltrans seismic design practices and retrofit programs (Housner and Thiel, 1995). (Bridge retrofit programs began after the 1971 San Fernando earthquake, but were accelerated and expanded after the 1987 Whittier Narrows and 1989 Loma Prieta earthquake in particular.) The Board of Inquiry report mentions prior CDMG earthquake planning scenarios (Housner and Thiel, 1990) for San Andreas (Davis et al., 1982b) and Hayward fault (Steinbrugge et al., 1987) earthquakes, but in the context of discussions of disruption to Bay Area transportation systems rather than in arguments directly for mitigation programs. The Seismic Advisory Board, constituted based on the Board of Inquiry recommendations, prepared a report on bridge performance in the Northridge earthquake (Housner and Thiel, 1995) and recommended further acceleration of the retrofit program with minor adjustments; recently retrofitted bridges had performed well. This report does not mention scenarios. External, formal scenarios appear to have had a minor role in motivating seismic design practice changes and the acceleration of and advances in Caltrans' bridge retrofit programs over the past 50 years, but scenario earthquakes have been used routinely in internal design and evaluation processes, including as part of seismic hazard assessment procedures, according to interviewees familiar with Caltrans seismic programs.

Bay Area Rapid Transit (BART) used a scenario-based Seismic Vulnerability Study completed in 2002 (BART, 2021b) to identify earthquake vulnerabilities in its system and to justify and generate support for the proposed seismic upgrades to decision-makers, neighboring property owners, and the public. The $1.457 billion Earthquake Safety Program is being funded through several bond measures, the largest of which is the $980 million Regional Measure AA (2004), $116 million from Caltrans' retrofit program, and other sources (BART, 2021a). Key mitigation activities include a seismic retrofit of the Transbay Tube and of older structures supporting elevated track, and numerous other seismic upgrades to BART's original system constructed in the 1970s (BART, 2021a, b).

Characteristics of Effective Scenarios

Despite the prevailing views of effectiveness evidenced by continued scenario use discussed previously, few studies or practice-based guidance documents have examined which features make earthquake scenarios effective. Available studies tend to be based on the experiences of scenario developers (e.g., Preuss and Godfrey, 2006; Perry et al., 2011;. Corotis et al., 2012) and often examine a single scenario. The following sections present findings from project interviews on specific characteristics that contribute to scenario effectiveness.

Clear Utility for End Users

Participants provided perspectives on the usefulness of information provided by scenarios, as well as the processes of developing and communicating scenario findings and recommendations. Participants identified several aspects in which the information produced by the scenarios were useful (strengths). Responses indicated that the information about potential impacts provided a basis for developing mitigation and alternatives and, thus, is useful for practical/planning purposes. This includes information on long-term-term, along with mid-range and short-term, impacts. In this way, the respondents stated that the scenario information expands mitigation actions to reduce risk and hazards proactively. The educational and informational aspects of the scenarios were also cited as useful. The communication and, separately, the communication strategies used to convey this information provide education on the geological hazards to a broad audience and help create a shared mindset among stakeholders.

Scenarios had broadened the perspective (big picture view) for end-users by focusing on regional issues (e.g., interaction of facilities, lifelines, transportation). Literature on scenario use in strategic planning and social change identifies changes in perspective or "re-framing" like these as an outcome commonly achieved through scenario work (e.g., Van der Heijden, 1996; Kahane, 2012; Ramirez and Wilkinson, 2016). In particular, scenarios presented a clearer picture for those who are not technical experts, allowed them to view these issues in different ways, and helped to engender engagement and synergy. A number of respondents observed that policy-makers more readily understood scenarios compared to probabilistic information, which has been observed by other researchers (e.g., Corotis et al., 2012).

Scenarios estimate tangible losses (e.g., building collapses, human casualties, uninhabitable housing units) and describe impacts (e.g., length of water service interruption, people requiring emergency shelter) of interest to policy makers. The scenario served as a source document that contained all the relevant information including maps. Respondents indicated that it is important to consider the end-users' needs to increase their engagement and buy-in. Participants identified the most useful components of the scenarios as follows. Scenarios provided a platform to bring multiple stakeholders to the table to work together to form a broader perspective, thereby impacting interrelationships; presented visualizations to depict losses and impacts; and provided targets to build capabilities in the community.

On the other hand, while the scenarios are useful, some felt that they are often not used well from an organizational and response planning perspective. A few weaknesses were identified. Scenario reports can be voluminous and create confusion about the most important message due to information overload. Another problem is that although scenarios focus on regional issues in general, they may not include issues related to a specific location within that region, or present results for individual jurisdictions. Competing priorities exist, such as COVID-19 and wildfires, that have created disaster fatigue and interfered with the use of scenarios. There is no mechanism to monitor the impact of the scenario.

Synergy with Informational Needs and Networking Uses

When elaborating on the various aspects of the scenario that were used most in work, many respondents described the overall use of scenarios. Examples of overall use of scenarios included background information for general discussions of geohazards with partners, for policy briefings and guidance for programs, to revise response plans and general response focus on response, and as supporting documents for exercises. When providing the more specific elements used, respondents most often cited information on vulnerabilities and disruption data that included projections to systems such as utilities. In addition, related information on impacts to society, including damage and loss estimates, was often used by respondents. To a lesser extent, respondents also reported that they used information on cascading and secondary hazards caused by the initial geohazard (e.g., post-earthquake fire). Finally, visualizations including infographics and maps were referenced by a few respondents. While each of these aspects were used for various purposes (e.g., communication, outreach, establishing priorities), an underlying theme in their use was the enhanced networking that occurs as a result of the use of the scenario. In particular, this networking facilitates development of regional collaborations, enhances policy development, and creates greater synergy among partners.

Scenario Credibility

End users most often reported that the credibility of the scenarios is influenced by the credentials or perceived credentials of those responsible for designing the scenario. This includes the knowledge and expertise of the scientists as well as respect for their sponsoring organizations. They also indicated that the personal relationships with the designers/developers and the end users were critical to perceived credibility. Additionally, quality of the data, or indicators of quality (e.g., recency) support the credibility of the scenarios. Use of lessons learned and best practices from other countries and relevant geohazard events, models and analytic tools used to analyze data, and transparency in the design process were examples of factors that contributed to data quality for the scenarios.

End users also emphasized that a scenario must incorporate diverse perspectives from different individuals representing various organizations. This includes use of multidisciplinary teams as well as inclusion of major stakeholders as partners (e.g., government, community, industry) to that challenge assumptions, complicate analyses, and otherwise bring contrasting or critical assumptions to the process. It should be noted that the partnerships formed by these interactions, including community engagement at all stages of the process, help to build trust among the partners responsible for designing the scenarios and the end users. They were also perceived as contributing to the relevance of the scenario. The respondents reported the scenario must be relevant to a specific group or geographic area to engender buy-in and support. Several participants stated that scenario credibility was determined by the plausibility of the event modeled. These interrelated factors suggest that, in order to be deemed credible by end users, it is critical that scenarios are plausible and defensible such that they are not extreme or unrealistic. In other words, results and outcomes must be relevant and realistic so that they can be used for critical decision-making and needed policy changes.

Comments from scenario developers aligned with several of these themes. When asked how important "scientific quality" was for a scenario to be perceived as credible and effective, developers largely acknowledged that an acceptable level of scientific quality was necessary for a scenario to be viewed as credible. Beyond acknowledging a minimum level of acceptability, however, responses varied. Several framed the issue in relation to the need for scientific consensus. Rather than reaching the highest possible standards per se, responses indicated that it was the ability of a scenario to achieve consensus within the scientific community that signaled to non-experts that a scenario had been appropriately vetted and was sufficiently credible. A few developers noted that scenarios required tradeoffs between achieving the highest levels of precision or other measures of quality and delivering a product that was useful for decision makers. Others explained that the importance of scientific quality varied by stakeholder (e.g., users with differing priorities or capacities for evaluating quality) or application (e.g., whether a scenario was to be used as a way of raising awareness, prompting conversation, or as a basis for building codes or policy). Noting that most non-scientists lacked the capacity to evaluate scientific findings, some noted that credibility was conferred by the endorsement of scientific organizations.

Active Results Dissemination

Developers identified a wide array of information product formats that were used to communicate scenario results. The most common formats were reports and technical publications, reflecting professional norms for disseminating scientific findings. Presentations were also frequently used to share results with various audiences. In addition to engaging scientific peers and general audiences, some developers noted that their teams had tailored presentations to address concerns relevant to specific stakeholders (e.g., local/regional government, associations, school systems), sometimes as invited speakers. A few individuals noted that presentations featuring scenario findings had been developed for use by specific stakeholders, such as emergency managers and Community Emergency Response Teams. Events were another commonly used communication outlet for scenario results. These took a variety of forms, including public meetings, webinars, conferences and symposia, workshops and exercises or drills.

Other text-based products referenced included written summaries; narratives/stories based on the hypothetical incidents modeled by a scenario; websites dedicated to scenarios; brochures and circulars; and toolkits that translate scenario findings into tangible planning guidance and activities. Some developers developed press releases and related content to attract or support media coverage. A few participants discussed visualizations such as maps and models as products that help illustrate expected impacts and their geographic distribution. Less commonly referenced were social media content, multimedia (e.g., videos), and data (typically shared by request with media and special interest groups).

Effective Scenario Development Methods/Processes

When asked to describe the processes and key methods used to develop the scenarios/component studies with which they had been involved, developers overwhelmingly emphasized the importance of collaboration. This was most often referenced in terms of scientific collaboration, including the assembly of teams, conferences, and steering committees, and review panels that brought together subject matter experts to build scientific consensus. Also frequently cited were processes involving co-production with stakeholders such as industry representatives, government agency representatives, and attendees at feedback sessions. Several interviewees credited co-production processes with delivering access to proprietary data, enabling ground-truthing of assumptions, and otherwise diversifying the range of factors considered during scenario development.

Outreach emerged as another significant theme, both to invite feedback and as a mechanism for disseminating findings. Regarding the former, developers reached out to professional communities to identify stakeholders' information needs and iterate rounds of feedback that guided methodologies, interpretation, and framing. Outreach with findings involved a range of activities and information products to engage various audiences with scenario findings, in some instances tailoring these efforts to specific geographies or stakeholder priorities (e.g., implications for schools, soft-story buildings, communications systems). Finally, a few participants described the use of outreach to relay information that would be useful to policymakers.

Demonstrable Value for Decision/Policymaking

Developers pointed to raising awareness and prompting action as the most important aspects of scenarios for decision-making and policymaking. With regard to raising awareness, participants found value in the ways that scenarios serve as exemplars that can break down abstract concepts such as earthquake risk into measurable impacts to systems, interests, and communities. They felt that these features enhanced understanding of how earthquakes and other hazards might unfold and improved understanding of how communities could be affected, thereby making the issues more relevant. Relatedly, developers also credited scenarios with prompting action. Participants described how vulnerabilities highlighted by scenarios made it easier to identify specific measures or policies needed to mitigate them as well as the parties responsible for implementing them. Developers described the use of scenarios in planning (e.g., emergency planning and longer-term city/regional/urban/development planning), stakeholder engagement (e.g., to advocate for or as the basis of policies and to facilitate multi-sector discourse) and mitigation policy.

Yet some participants were hesitant to attribute these outcomes entirely to the development of scenarios, noting that a given scenario may have been one among many notable developments that worked in concert to gain momentum for advocacy efforts to or encourage particular outcomes. Prior sections examined the role of scenarios in motivating, supporting or guiding a number of specific mitigation policies and programs in California and discussed contextual factors that influence mitigation decisions and actions.

Suggestions for Improvement

Participants made a number of suggestions to improve scenarios. Suggestions for improvements to facilitate use included integration into a broader array of products (e.g., brochures as opposed to reports); consideration of intersecting or competing issues (e.g., pandemics, resource constraints); coordination of scenario developers with a broader range of stakeholders (e.g., climate change experts) and greater attention to cascading disasters and multi-hazards.

Suggestions for reducing participant-observed weaknesses primarily focused on communication issues, such as designing the message for developers and practitioners to share when presenting the scenarios to decision makers and the public. This includes communication tips and talking points for those presenting scenarios and summary of key (take-away) points to summarize the more detailed information. Respondents emphasized that messaging should be developed for sharing with the media as well as more broadly on social media. This messaging should include benefits of investments in mitigation efforts in reducing future losses. When considering the information source, participants stated that “champions” should be established to serve as the face of the scenario and engender greater confidence and support.

Net Promoter Score Analysis and Critical Elements of Effective Scenarios

As noted above, we calculated Net Promoter Score (NPS) to quantify feedback from end users and developers regarding the likelihood that they would recommend the use of scenarios to others in their mitigation and preparedness planning. In the present study, the NPSs were calculated for all study respondents combined (NPS=74) as well as separately for users (NPS=76) and developers (NPS=74). The NPS for all respondents combined demonstrate strong support for recommended use of scenarios in mitigation and preparedness planning. Figure 5 depicts the large percentage of Promoters (in green) and relatively small percentage of Detractors (in red) when considering ratings from all respondents combined. As previously noted, a score of 70 is generally considered to indicate a strong level of support for continued use of the scenarios. Further, this support was consistent when considering the NPS among those who used the scenarios as well as those responsible for their development.

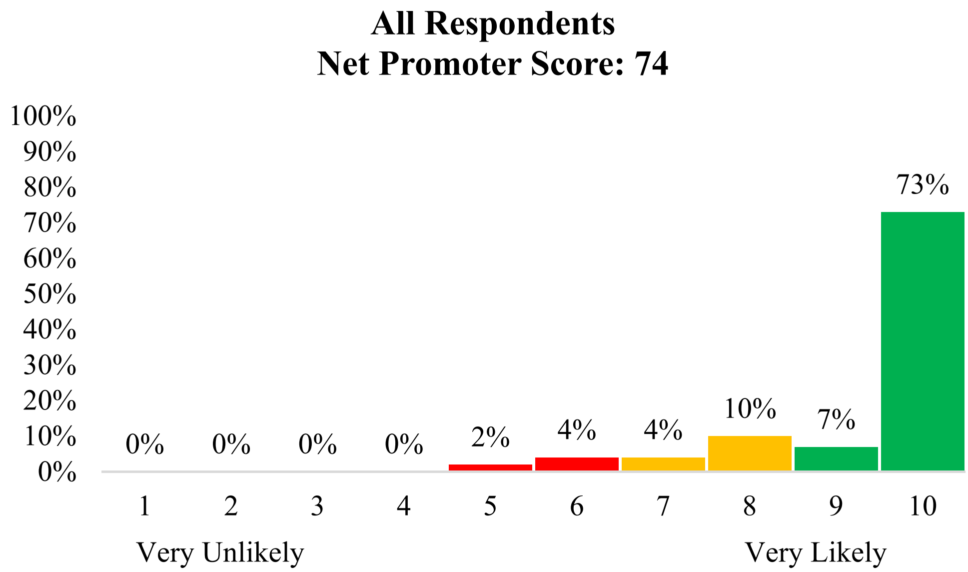

Figure 5. Range of Net Promoter Score Ratings: All respondents

However, to be meaningful, the NPS should be accompanied with an opportunity for the respondents to explain why they provided the rating (Markey et al., 2009). In this study, respondents were asked to elaborate on the most critical elements of an effective scenario to provide a greater understanding of the aspects of the scenarios that lend greater value in influencing policy and practice to mitigate risks from geologic hazards.

The most critical elements of an effective scenario with respect to value in influencing policy and practice to mitigating risks from geologic hazards provided by the respondents were delineated into three broad categories. The respondents indicated that process elements for design and implementation were of great importance to the perceived value of the scenarios. Several of these elements involved engagement and collaboration among end users or other stakeholders in the development or dissemination process. Use of a multiple stakeholder process (e.g., scientists, practitioners, policymakers and representatives from the government and community) in all phases of the process, particularly the design phase, was identified as important because it ensures greater input, buy-in, and support of the scenarios and engenders co-production of knowledge. It also encourages interagency and interorganizational collaboration for networking and sharing of information. Another critical process element was defining the scope of the scenario in that it establishes purpose and importance to the stakeholders. Similarly, it is critical to align the budget, timeline, and goals of the scenario. The inclusion of a "champion" or special advisor that is empowered by the government was also cited as a critical factor early in the process.

Respondents also stated that there were key characteristics for effectiveness that were associated with successful scenarios. The scenarios should be of high scientific quality and credible such that they are based on science but also have practical information and relate to existing policy. They need to be realistic and based on plausible events that are likely to occur and produce information that is relevant and useful in the daily lives of community members and decision makers (e.g., how it affects the stakeholders and why it is important relative to other competing issues of interest). The scenarios must identify clear and specific impact (e.g., economic, social, geographic) and loss data including graphics and visualizations to depict the information.

Finally, the outcomes of the scenarios are critical for success. Respondents highlighted the importance of identifying the potential actions, policies, and mitigations measures to be taken. This includes an action plan with results and dissemination plan with guidelines for how to use it. It must communicate a concise and easily understandable message about the hazard and associated mitigation and actions. Respondents indicated the importance of quantifying the benefits, as opposed to only the costs of the mitigation. Overall, the scenarios should be explained well enough for non-experts (public and public officials) to understand the findings and how they can act on them. This includes a convincing argument to influence people to change.

Noteworthy is that these critical elements are overlapping with the strengths, weaknesses, and suggestions for improvement to the scenarios identified by the users and developers. The convergence among descriptions of key aspects that generate value and utility of the scenarios provides further evidence of the importance of consideration of both sets of these critical factors to encourage greater use and support of the scenarios in future efforts.

Discussion

FEMA 1177 (FEMA, 1989) emphasizes some of the same findings as the present study, including “active participation” of end users throughout the process, preparation by a recognized and credible source, consensus that the scenario earthquake should be plausible (not worst case), and reporting results clearly for end users, and in meaningful ways for specific jurisdictions rather than only regionally, to support actions at local level. Preuss and Godfrey (2006) also mention participation of users, using “best available” science, selecting a plausible earthquake, and dissemination strategies to reach end users. The interview results above indicate that progress has been made on collaboration and participation of end users, though more can be done.

Many interviewees identified the need to make recommendations and “connect the dots” for end users as important, though there was not universal agreement. Some agencies have limitations on developing policy, which constrains ability to take key steps toward implementation during a scenario project, such as making recommendations or conducting mitigation planning. Reflecting on such constraints, one participant explained, “[My organization] can’t be involved in policy. We can't say, ‘Do this, not that.’” Instead, this individual stressed that organizational partners who are policymakers or are otherwise engaged in policy development can be involved in scenario development and that this can empower them to take the lead in making these connections. As shown in previous sections, focused action is needed to move scenario results to implementation. Partnering among various agencies to provide a pathway to implementation is one potential way to address this barrier.

In a similar vein, the use of applications from Behavioral Economics also emerges as a potential area to successfully move scenarios results to implementation. Behavioral economics is a relatively new field of study that combines insights from psychology and economics and may hold promise for influencing these decisions (Thaler and Sunstein, 2009; Linnemayr et al., 2016; Mertens et al., 2022). It provides techniques or nudges that are cost and time efficient, and that can be used to design an environment that effectively motivates decision-makers to use these results in ways to accelerate the mitigation- and policy-related efforts. For example, several respondents reported a need for emphasis on the specific benefits of the mitigation efforts in addition to the associated costs. This need was reported in direct response to the tendency of the end users of the scenarios to focus on the immediate costs of the mitigation activities while citing that the benefits were less prominent, clear, or appeared delayed relative to the costs (referred to as present bias). Behavioral economics provides techniques (nudges) that can be incorporated into the development and use of scenarios that directly address these types of biases, with the intent of increasing uptake in the use of results and positively impacting related mitigation and policy efforts.

This study produced a range of valuable findings that reinforced best practices and revealed key insights from participants with diverse roles and perspectives who have been involved in scenario development and use. However, the data we have presented reflects some key limitations. As noted above, social and behavioral scientists are poorly represented in our sample. Yet the interest expressed by end users in accessing translators who can help identify the social and policy implications of scenarios, in addition to published research indicating that social and behavioral sciences can facilitate such connections (Perry et al., 2011), indicates that input from these scientists may be particularly important to capture. Future studies would benefit from purposive sampling to investigate their perspectives.

Conclusions

Several overarching findings emerged from a synthesis of interviews and documentary evidence. Both documents and interviews point to widespread and effective use of scenarios in mitigation efforts, and to the often complex and interdependent relationships between scenarios, other significant sources of influence, and contextual factors in motivating or supporting subsequent mitigation actions. In many cases, it may not be possible to show that a scenario was directly responsible for a specific mitigation action. This is consistent with observations in the broader scenarios literature about the role of scenarios in creating change (e.g. Kahane, 2012). It is clear that scenarios are an important part of overall approaches that were effective in generating tens of billions of dollars in seismic risk mitigation investments.

In California's highly active seismic environment, earthquake professionals have repeatedly used damage in past earthquakes together with scenario estimates of future earthquake damage when successfully advocating for earthquake risk mitigation measures. Real events provided indisputable evidence of seismic vulnerabilities often prompting swift policy changes as seen after the 1989 Loma Prieta and 1994 Northridge earthquakes, while scenarios quantified potential damage in future earthquakes and portrayed impacts. The confluence of priming and focusing events with technical risk studies and scenarios appears to accelerate resilience action in California.

Interviews indicate a number of characteristics that make scenarios effective for motivating mitigation. These include:

- A robust, collaborative development process including multiple disciplines and end users/stakeholders from the beginning, with involvement throughout;
- Scientific and technical credibility, both through the reputation and standards of the agency that prepared the scenario and the quality of the particular work;
- Plausibility and realism of the event;
- Practical applicability, with results clearly describing impacts of importance to end users;
- Recommendations that specifically identify potential actions, policies and mitigation measures, and plans to implement them. The most effective programs include clear mechanisms for follow-on work with stakeholders that supports implementation of mitigation measures; and
- Communication in clear language and graphics, using appropriate channels for each audience so that people who are not earthquake professionals can understand the findings and act on them.

These observations provide distilled wisdom from more than 50 years of California earthquake scenario development practice. They also show that room for improvement remains, particularly in areas of communication products for a broader set of audiences and making better use of more types of communication channels, messaging on benefits of mitigation instead of only losses avoided, greater attention to cascading and multiple hazards, and related interaction with an even broader group of stakeholders that deal with these hazards.

Significant, dedicated efforts are required to move from scenario development to actual implementation of mitigation policies or programs. Even the best-prepared scenarios did not and will not automatically motivate mitigation without a significant follow-up effort. Mitigation very rarely resulted solely from stakeholder engagement during scenario development and simple dissemination. Despite this, scenario projects often lack a funded component to create a pathway to implementation for scenario findings, such as a mitigation planning process that continues stakeholder partnerships and engagement operating during scenario development.

An exception are purpose-built scenarios prepared as part of local hazard mitigation planning processes. In California, especially in the Bay Area and Los Angeles, LHMPs and resilience planning serve to propel mitigation action. Local hazard mitigation plans conclude with community action plans to reduce risk; these become implementation roadmaps for local jurisdictions. The designated action plan projects and programs open up grant funding opportunities from state and federal agencies. The USGS research on mitigation investments in the Bay Area (Brocher et al, 2018) points to the confluence of triggering events and scenario-driven policies as catalysts for safety action. A parallel example in Los Angeles demonstrates that the ShakeOut scenario prompted the city to tackle its considerable seismic risk through local ordinances and decisive actions based on reducing risk in the built environment. These are but two documented cases in the over 500 adopted LHMPs in the state as of February 2018 (CalOES, 2018). Multiple interviewees expressed the importance of clearly linking scenario findings with potential mitigation measures—which are most effectively co-developed with policy-makers and those affected—that address identified vulnerabilities, in order to “connect those dots” for users, as one participant expressed.

Event-and-consequences scenarios provide a compelling and credible way to communicate potential impacts of earthquake damage to decision-makers (Campbell et al., 2022) which supports effectiveness in motivating mitigation, but these typically do not provide insight into the impacts of mitigation decisions. Alternate futures methods, currently little-used in earthquake scenarios, may be useful in supporting mitigation decision-making.

The enabling environment and the willingness of leaders to act often have decisive influence on whether mitigation policies or programs are implemented. Delays in getting city risk mitigation programs off the ground in both San Francisco and Los Angeles occurred due to a lack of political support, per project interviews. Political will drawn from support by key constituencies, links to existing areas of policy emphasis (for example, housing in urban California), and support of “champions” such as elected officials, technical agency staff, or municipal staff leaders are necessary for the passage of legislation and municipal ordinances that set policy and provide the legal structure and, often, the funding for mitigation programs. Scenarios also contribute to the enabling environment by raising public awareness of earthquake risk.

Recommendations

Based on the observations above, we offer the following recommendations for consideration to increase the effectiveness of scenarios in motivating, supporting and guiding mitigation:

- Emphasize co-production and stakeholder engagement, and include funding support for advocacy and relationship building to help create a supportive enabling environment and cultivate champions;

- Ensure future scenario projects contain an adequately-funded component to use findings to develop and begin implementing recommendations, such as a mitigation planning process; and
- Explore alternate futures methods to more effectively communicate the impacts of mitigation decisions and support decision-making.

Scenarios are well regarded and have been widely used in mitigation work in California, as part of a larger “ecosystem” of risk analysis, mitigation planning, political action, funding allocation and community engagement. The scenario development process offers a solid foundation for coordinated risk assessment, co-production and engagement, and attendant action. This study demonstrates that scenarios have made valuable contributions to earthquake risk mitigation in California. The impacts of future scenarios on mitigation and public safety could be further amplified through scenario development practices that intentionally integrate evidence-based practices that are known to enhance their effectiveness. The vehicles of local hazard mitigation planning and mitigation programs, infrastructure modernization programs and state mandates that require coordinated policy development and resilience action hold promise to continue translating scenario findings into long-term seismic resilience improvements. California’s future earthquake scenarios should strengthen links among technical, community and political stakeholders to mobilize sustainable financial mechanisms that will move seismic resilience forward.

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Project Data

As described in the project's data management plan, project interview data are kept confidential in compliance with the project's Institutional Review Board-approved research protocol.

A bibliography of literature assembled during the project will be made publicly available on GeoHazards International's website (www.geohaz.org) and in the reference sections of project journal articles and other publications.

Bibliography

The research team prepared two journal articles, which have been submitted for publication, and a poster. The following publications resulted from the work performed under the award:

Rodgers JE, Chakos A, Campbell NM, et al. (2022) Effectiveness of California Earthquake Scenarios in Motivating Mitigation. Earthquake Spectra Under review.

Campbell NM, Sarpy SA, Rodgers JE, et al. (2022) Characteristics of Effective California Earthquake Scenarios. Earthquake Spectra Under review.

Rodgers JE, Campbell NM, Stenner H, et al. (2022) Effectiveness of California Earthquake Scenarios in Motivating Mitigation: Initial Results. Poster, USGS Northern California Earthquake Hazards Workshop.