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UNITED STATES EARTHQUAKE EARLY WARNING SYSTEM: HOW THEORY AND ANALYSIS CAN SAVE AMERICA BEFORE THE BIG ONE HAPPENS

by

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The United States is extremely vulnerable to catastrophic earthquakes. More than 143 million Americans may be threatened by damaging earthquakes in the next 50 years. This thesis argues that the United States is unprepared for the most catastrophic earthquakes the country faces today. Earthquake early warning systems are a major solution in practice to reduce economic risk, to protect property and the environment, and to save lives. Other countries have already built earthquake early warning systems, but only after they suffered devastating earthquakes. In the United States, ShakeAlert is the available solution, but it only operates on a test basis in California and still lacks sufficient capability and sustained funding to become operational. This thesis applies an input-output model of political systems theory to analyze how the National Earthquake Hazards Reduction Program, which controls the development of ShakeAlert, functions in the United States. Using this model provides a framework for a discourse of the analysis to determine how the consequences of catastrophic earthquakes shape our decisions and policies for ShakeAlert.

This thesis also examines what changes are required within our political system for ShakeAlert to launch as quickly as possible on a national scale and to allow for its sustained integration within the American preparedness culture. Perhaps most importantly, the implementation of ShakeAlert will help prepare the people, businesses, infrastructure, economies, and communities, hopefully before the next significant earthquake impacts the United States. Will the United States have to experience a devastating earthquake before implementing a solution that is recognized to save lives?

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UNITED STATES EARTHQUAKE EARLY WARNING SYSTEM: HOW THEORY AND ANALYSIS CAN SAVE AMERICA BEFORE THE BIG ONE HAPPENS

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ABSTRACT

The United States is extremely vulnerable to catastrophic earthquakes. More than 143 million Americans may be threatened by damaging earthquakes in the next 50 years. This thesis argues that the United States is unprepared for the most catastrophic earthquakes the country faces today. Earthquake early warning systems are a major solution in practice to reduce economic risk, to protect property and the environment, and to save lives. Other countries have already built earthquake early warning systems, but only after they suffered devastating earthquakes. In the United States, ShakeAlert is the available solution, but it only operates on a test basis in California and still lacks sufficient capability and sustained funding to become operational. This thesis applies an input-output model of political systems theory to analyze how the National Earthquake Hazards Reduction Program, which controls the development of ShakeAlert, functions in the United States. Using this model provides a framework for a discourse of the analysis to determine how the consequences of catastrophic earthquakes shape our decisions and policies for ShakeAlert.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACEHR	Advisory Committee for Earthquake Hazards Reduction
AEL	annualized earthquake loss
ANSS	Advanced National Seismic System
GSN	Global Seismic Network
CEPEC	California Earthquake Prediction Evaluation Council
CIDIR	Center for Integrated Disaster Information Research
CUSEC	Central United States Earthquake Consortium
DOD	Department of Defense
EERI	Earthquake Engineering Research Institute
EEWS	Earthquake Early Warning System
FEMA	Federal Emergency Management Agency
FY	fiscal year
GAO	Government Accountability Office
ICC	Interagency Coordination Committee
ICSSC	Interagency Committee on Seismic Safety in Construction
IPAWS	Integrated Public Alert and Warning System
JMA	Japan Meteorological Agency
NASA	National Aeronautics and Space Administration
NEHRP	National Earthquake Hazards Reduction
NEPEC	National Earthquake Prediction Evaluation Council
NDRF	National Disaster Recovery Framework
NHERI	Natural Hazards Engineering Research Infrastructure
NIED	National Research Institute for Earth Science and Disaster Prevention
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
NRF	National Response Framework
NSF	National Science Foundation
OMB	Office of Management and Budget

RTRI	Railway Technical Research Institute
SAS	Sistema de Alerta Sismica
UrEDAS	Urgent Earthquake Detection and Alarm System
USGS	United States Geological Survey
WEA	wireless emergency alerts

EXECUTIVE SUMMARY

Earthquakes are one of the most devastating natural disasters. The United States has a long history of earthquakes that have resulted in devastating losses of life, property, and the economy. Four regions in the United States have a high probability of catastrophic earthquakes in the next 30 years according to most experts; the Cascadia subduction zone in Washington and Oregon, the San Andreas fault in California, the New Madrid seismic zone located in the Midwest across eight states, and the Wasatch fault zone in Utah and Idaho. The economic losses alone from any one of these events would run into the hundreds of billions of dollars. The question is not if, but when, one will occur.

Earthquake early warning systems are a major solution in practice today to reduce economic risk, protect property and the environment, and save lives in the event of an earthquake. These systems provide alerts to nearby geographic areas that will experience ground shaking after a real-time detection of an earthquake. Other countries have already built earthquake early warning systems, but only after they suffered devastating earthquakes. To prepare for these impending catastrophic events, the United States has been developing its own system, called ShakeAlert; however, the system is still underfunded, and the trajectory for its completion remains elusive. Experts argue that the day ShakeAlert goes live, coupled with a sustained educational program, is the day we start on a path toward a more resilient nation where earthquakes are concerned. As a result, lives can be saved, and billions of dollars in losses can be avoided.

This thesis argues that the United States is unprepared for the most catastrophic earthquakes and uses a political systems theory model to examine what steps are necessary to minimize the consequences of such disasters through the use of an earthquake warning system. In general, people have an expectation that authorities will protect society from natural disasters. Public opinion assumes that because other countries have earthquake early warning systems, then the United States should have one as well. Motivations for ShakeAlert in part exist because people sympathize with others in foreign countries they see in distress during earthquake disasters. Motivations for ShakeAlert are also partly due to the idea that the government should perform its civic duty and provide public safety services.

However, in the United States, preparedness efforts predominately focus on response requirements and lack any substantial coordination concerning long-term recovery or significant investment in mitigation measures. Current implementation methodologies are unable to establish baseline operational requirements, let alone adapt to the speed of technological change. This thesis argues that the current model has two primary complications: difficulty in demonstrating the value of the solutions it creates for society and an inability to empower a broad range of stakeholders to become critically involved with the decision-making process.

The problem is not necessarily with the agencies or people involved, but the lack of integrated governance, strategy, and results-driven policy-making processes to address earthquake threats in the United States. Some of the best minds in the world continue to work tirelessly on ShakeAlert, tackling the many challenges that come with earthquake science and technology. Understanding earthquakes and creating solutions to prepare for, respond to, and recover from these incidents remains the primary focus of developers. The problem is one of controlling outcomes and execution. This thesis studies how we can apply a different strategy to meet these requirements. By addressing the challenges for funding, education, and adoption, a comprehensive reauthorization with significant expansion to adequately reform the National Earthquake Hazards Reduction Program would best advance seismic research and science and also launch ShakeAlert.

This analysis concludes that today's model for developing ShakeAlert is not working and investment decisions do not reflect stakeholder priorities. This thesis provides numerous interpretations as to what hinders the ability of the United States to implement ShakeAlert. Furthermore, by using this systems analysis approach, this thesis offers specific recommendations outlining the requirements for the advancement and implementation of a national earthquake early warning system across the United States. This alternative approach would foster an environment wherein the public and businesses can crowdsource information regarding methods for applying ShakeAlert and share their techniques for adoption while collectively contributing to the overall network. Innovative approaches and a decentralized strategy may contribute to a more resilient nation, allowing everyone to participate in the reduction of damages and expedite recovery from earthquake impacts.

The primary way for the United States to prepare for the consequences of catastrophic earthquakes is through greater collaboration and commitment toward ShakeAlert implementation. With adequate funding and an integrated, strategic vision for the completion of required seismic networks, earthquake hazard reduction can be improved and put the nation on a path toward earthquake resiliency, ensuring the sustainability of the economy and communities after such disasters. Restructuring the contributions of all levels of government and including the private sector would optimize governance and policy requirements. In turn, this will safeguard the sustainability of ShakeAlert by ingratiating the operational systems into the cultures of preparedness for government, industry, and the general public. Perhaps most importantly, the implementation of ShakeAlert will protect people, businesses, infrastructure, economies, and communities—hopefully before the next significant earthquake impacts the United States.

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I. INTRODUCTION

> Want of foresight, unwillingness to act when action would be simple and effective, lack of clear thinking, confusion of counsel until the emergency comes, until self-preservation strikes its jarring gong—these are the features which constitute the endless repetition of history.
>
> — Sir Winston Churchill, Speech, House of Commons, May 2, 1935

Earthquake early warning systems are a major solution in practice today that reduces economic risk, protects property and the environment, and save lives. These systems provide alerts to nearby geographic areas that will experience ground shaking after a real-time detection of an earthquake. Depending on the distance from the epicenter, these notifications can provide seconds to tens of seconds of precious time to take precautionary actions before shaking begins. In the United States, that available solution is ShakeAlert. However, despite years of testing and scientific research demonstrating that it can save lives, ShakeAlert is not yet operational and is only available in California on a test basis. This thesis outlines four specific catastrophic earthquake situations facing the United States today and examines what changes are required within our political system for ShakeAlert to launch as quickly as possible, on a national scale, and allow for its sustained integration within the American preparedness culture.

This thesis utilizes David Easton's input-output model of political systems theory to analyze how the National Earthquake Hazards Reduction Program (NHERP), which is the program that controls the development of ShakeAlert, functions in the United States. Using this model provides a framework for a discourse of the analysis to determine how the consequences of catastrophic earthquakes shape our decisions and policies for ShakeAlert and why the United States has yet to maximize this opportunity. Moreover, this thesis addresses the demands of and support for the program, known in the model as *inputs*, and examines the process by which the responsible agencies, the *authorities*, convert those inputs into certain decisions or policies, called *outputs*. As a result, these efforts demonstrate the level of capability necessary at all levels of government to implement ShakeAlert before the next catastrophic earthquake occurs in the United States.

The challenge within NEHRP is that the policy-making processes over the past 40 years have remained relatively stagnant, and at the same time, implementing coordinated solutions by the authorities has remained fragmented. The thesis studies how a transition in the strategic direction of NEHRP can more appropriately balance the responsibility for catastrophic earthquake disasters and meet what Easton defines as the "complex of interactions concerned with the authoritative allocation of values for the society."[1]

A. PROBLEM STATEMENT

Earthquakes are one of the most devastating natural disasters. Since 1900, 126 of the largest earthquakes around the world have killed more than 1000 people per incident, resulting in the deaths of more than 2.3 million people.[2] According to the Seismological Society of America, potentially damaging earthquakes may threaten more than 143 million Americans in the next 50 years, and 28 million persons are likely to experience strong shaking.[3] The United States Geological Survey (USGS) has determined that there is a 99.7 percent probability of a 6.7 magnitude or larger earthquake within the next 30 years in California and a seven percent chance of an 8.0 magnitude or greater.[4]

Other countries have already built earthquake early warning systems, but only after they suffered devastating earthquakes. For example, Mexico was an early adopter after the 1985 Mexico City earthquake killed 10,153 people. Japan began making significant investments after the 1995 Kobe earthquake killed more than 6,400 people. In 1999, the Chi Chi earthquake in Taiwan killed 2,415 people, while the Izmit earthquake in Turkey killed 17,127 people, prompting both countries to begin implementing systems. When the

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[1] David Easton, *The Political System, an Inquiry into the State of Political Science* (New York: A.A. Knopf, 1953).

[2] "Earthquakes with 1,000 or More Deaths 1900–2014," U.S. Geological Survey, accessed October 15, 2016, https://earthquake.usgs.gov/earthquakes/world/world_deaths.php.

[3] Kishor S. Jaiswal et al., "Earthquake Shaking Hazard Estimates and Exposure Changes in the Conterminous United States," *Earthquake Spectra* 31, no. S1 (2015): S201–220, https://doi.org/doi:10.1193/111814EQS195M.

[4] *Whole Lotta Shakin': An Examination of America's Earthquake Early Warning System Development and Implementation, Hearing Before the U.S. House of Representatives Committee on Natural Resources, Subcommittee on Energy and Mineral Resources*, 113th Cong. (2014), https://www.hsdl.org/?abstract&did=755458.

2008 Wenchuan earthquake killed 87,587 people, China began developing its system.[5] Other countries including Chile, Israel, Italy, Mongolia, Romania, and Switzerland now have experimental systems. However, in the United States, ShakeAlert is still not entirely operational in California. Additionally, it remains far from being applied nationally, which begs the question, will the United States have to experience a devastating earthquake before implementing a solution that is recognized to save lives?

This thesis argues that the United States is unprepared for the most catastrophic earthquakes and uses Easton's political systems theory model to examine what steps are necessary to minimize the consequences of such disasters through the use of an earthquake warning system. Although almost all 50 states are vulnerable to earthquakes to some degree, four areas pose a significant risk of a catastrophic earthquake in the next 30 years.[6] They are the Cascadia subduction zone in Washington and Oregon, the San Andreas Fault in California, the New Madrid seismic zone located in the Midwest across eight states, and the Wasatch Fault zone in Utah and Idaho. Concerning the immediate human impact and direct-only economic losses, planning estimates for a major earthquake in each of these areas are show in Table 1.

[5] Erin R. Burkett, Douglas D. Given, and Lucile M. Jones, *ShakeAlert—An Earthquake Early Warning System for the United States West Coast* (Reston, VA: U.S Geological Survey, 2014), http://pubs.er.usgs.gov/publication/fs20143083.

[6] Mark D. Petersen et al., *Documentation for the 2014 Update of the United States National Seismic Hazard Maps* (USGS Open-File Report 2014–1091) (Reston, VA: U.S. Geological Survey, 2014), https://pubs.usgs.gov/of/2014/1091/.

Table 1. Areas of Significant Catastrophic Earthquake Risk

THREAT	MAGNITUDE	DEATHS	INJURIES	COST (billion)
Cascadia Subduction Zone[7]	9.0	11,700	26,600	USD 81
New Madrid Seismic Zone[8]	7.7	3,500	86,000	USD 300
San Andreas Fault[9]	7.8	3,600[10]	53,000	USD 219
Wasatch Fault Zone[11]	7.0	2,500	9,400	USD 33

The economic losses alone from any one of these events would run into the hundreds of billions of dollars. For example, with approximately 40 million residents throughout the state of California, coupled with the millions of visitors and tourists at any given time, an earthquake of this scale would be the deadliest and costliest disaster in U.S. history.[12]

For decades, the United States has been conducting research to address the reduction of earthquake hazards and promote earthquake preparedness. In 1977, through the National Earthquake Hazards Reduction Act, Congress established NEHRP to

[7] Federal Emergency Management Agency, *Cascadia Rising 2016 Exercise Joint Multi-State After Action Report* (Washington, DC: Federal Emergency Management Agency, 2016), https://www.fema.gov/media-library-data/1484078710188-2e6b753f3f9c6037dd22922cde32e3dd/CR16_AAR_508.pdf.

[8] Amr S. Elnashai et al., *Impact of Earthquakes on the Central USA* (Urbana, IL: University of Illinois, Mid-America Earthquake Center, 2008), https://www.ideals.illinois.edu/handle/2142/8971.

[9] California Emergency Management Agency [Cal EMA] and Federal Emergency Management Agency [FEMA], *A Southern California Catastrophic Earthquake Response Plan* (Sacramento, CA: California Emergency Management Agency and Federal Emergency Management Agency, 2010), http://www.caloes.ca.gov/PlanningPreparednessSite/Documents/SoCalCatastrophicConops (Public)2010.pdf.

[10] The initial earthquake is projected to cause 1800 deaths. Then due to disrupted lifelines, such as petroleum and natural gas pipelines or power transmission lines, the subsequent 1600 fires, including dozens of large that merge into conflagrations, destroying hundreds of city clocks, will double the death toll, bringing the projected total to 3,600. Cal EMA and FEMA, *A Southern California Catastrophic*.

[11] EERI Utah Chapter, *Scenario for a Magnitude 7.0 Earthquake on the Wasatch Fault-Salt Lake City Segment: Hazards and Loss Estimates* (Salt Lake City, UT: Earthquake Engineering Research Institute, 2015), http://utah.eeri.org/wp-content/uploads/2015/08/EERI_Scenario_-_FINAL_VERSION_July_16_2015.pdf.

[12] Rong-Gong Lin II and Rosanna Xia, "Risk of 8.0 Earthquake in California Rises, USGS Says," *Los Angeles Times*, March 10, 2015, http://www.latimes.com/local/lanow/la-me-ln-chance-of-80-earthquake-in-california-rises-usgs-says-20150310-story.html.

coordinate the government's effort toward improving the nation's earthquake resilience.[13] The four federal agencies in charge of NEHRP are the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), the Federal Emergency Management Agency (FEMA), and the USGS.[14] As a requirement of the 2004 reauthorization, NEHRP established the Interagency Coordinating Committee (ICC), which includes the administrator of FEMA and the directors of NIST, NSF, USGS, White House Office of Science and Technology Policy, and the Office of Management and Budget (OMB). The director of NIST chairs the ICC.[15] Furthermore, this legislation created the Advisory Committee for Earthquake Hazards Reduction (ACEHR) to support and advise the ICC.[16] This thesis assesses how these newly formed governance structures influence NEHRP and what the consequences have been on the model of inputs, outputs, and the systemic feedback loop based on Easton's systems theory. Collectively, these agencies and the committees form the "authorities" represented in Easton's model.

This thesis argues that NEHRP to date has two primary complications: difficulty in demonstrating the value of the solutions it creates for society and an inability to empower a broad range of stakeholders to become critical components of the decision-making process. The problem is not necessarily with the agencies or people involved, but the lack of integrated governance, strategy, and results driven policy-making processes to address earthquake threats in the United States. Easton published *A Systems Analysis to Political Life* in 1965 and the parallels of his book to this dilemma seem evident. Easton's system theory applies to to NEHRP in that

> it is principally about (1) the varieties of inputs and the challenge they offer to the stability and persistence of political systems; (2) the contribution of

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[13] National Earthquake Hazards Reduction Program [NEHRP], *Annual Report of the National Earthquake Hazards Reduction Program for Fiscal Year 2014* (Washington, DC: National Earthquake Hazards Reduction Program, 2016), http://nehrp.gov/pdf/2014NEHRPAnnualReport.pdf.

[14] Ibid.

[15] Peter Folger, *National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief* (CRS Report No. R43141) (Washington, DC: Congressional Research Service, 2014), https://www.hsdl.org/?abstract&did=757658.

[16] An Act to Authorize Appropriations for Carrying out the Earthquake Hazards Reduction Act of 1977 for Fiscal Years 1998 and 1999, and for Other Purposes, Pub. Law No. 105-47 (1997), https://www.gpo.gov/fdsys/pkg/PLAW-105publ47/content-detail.html.

> supports, diffuse and specific, to the survival of political systems. In this regard, one learns a great deal about the sources of legitimacy—ideological, structural, or personal and of types of ideologies which serve a legitimizing influence; (3) feed-back [sic] and alternative official reactions varieties of outputs.[17]

While keeping the progression of NEHRP in mind, Figure 1 identifies the funding allocations over the past six years per agency as part of the overall NEHRP annual appropriation. These amounts are generally consistent in prior years dating back to the 2004 reauthorization despite many of the new opportunities and technological changes with which each agency must keep pace. The second part of Figure 1 breaks out agency allocations based on strategic goals.

[17] James R. Klonoski, "Book Reviews: A Systems Analysis of Political Life. By David Easton," *Western Political Quarterly* 20, no. 3 (1967): 737–739, https://doi.org/10.1177/106591296702000316.

Figure 1. NEHRP Agency Budgets and Strategic Goals[18]

Enacted Agency NEHRP Budgets ($M)[1]

FY	FEMA[2]	NIST[3]	NSF[4]	USGS[5]	NEHRP Total
2011	7.8	4.1	55.3	61.4	128.6
2012	7.8	4.1	53.2	59.0	124.1
2013	7.8	3.9	52.2	55.6	119.5
2014	7.5	3.9	42.0	58.7	112.1
2015	7.5	3.9	52.2	64.4	128.0
2016	8.5	5.2	54.2	67.0	134.9

Strategic Goal	FY 2016 Funds Requested or Anticipated for NEHRP Goals ($M)[1]				
	FEMA[2]	NIST[3]	NSF[4]	USGS[5]	Total
Goal A: Improve understanding of earthquake processes and impacts.	0.1	0.4	50.7	11.3	62.5
Goal B: Develop cost-effective measures to reduce earthquake impacts on individuals, the built environment, and society at large.	4.0	5.1		2.4	11.5
Goal C: Improve the earthquake resilience of communities nationwide.	2.3	0.4		16.0	18.7
Develop, operate, and maintain NEHRP facilities:					
ANSS				28.3	28.3
GSN			3.5	9.8	13.3
Total:	6.4	5.9	54.2	67.8	134.3

Risks are associated with earthquake risk reduction in the United States. Long-term congressional authorization and funding support remain in question. Without the continuation of NEHRP, the likelihood that earthquake early warning remains a priority and receives funding is uncertain. Allocations for NEHRP have averaged USD 125 million annually since 2009;[19] far from what scientists claim is necessary. A 2011 National Research Council report, *National Earthquake Resilience*, proposed a list of 18 tasks costing USD 6.8 billion for a 20-year return on investment.[20] While considering the risks

[18] Source: Jack Hayes, "National Earthquake Hazards Reduction Program [NEHRP]: Program Overview" (presented at meeting of Advisory Committee for Earthquake Hazards Reduction, Boulder, CO, November 2016), http://www.nehrp.gov/pdf/ACEHRNov2016_NEHRP.pdf, slide 5 [top table]; NEHRP, *Annual Report* (2014), 12 [bottom table].

[19] NEHRP, *Annual Report* (2014).

[20] National Research Council, *National Earthquake Resilience: Research, Implementation, and Outreach* (Washington, DC: National Academies Press, 2011), https://www.nap.edu/catalog/13092/national-earthquake-resilience-research-implementation-and-outreach.

associated with catastrophic earthquakes, this thesis attempts to demonstrate that based on Easton's model of systems theory, the lack of adequate funding for NEHRP (the political system) results in stresses on the responsible agencies (authorities). These stresses influence specific demands of and support for (inputs) solutions that may or may not be adequately prioritized or aligned with results (outputs).

Public acceptance will drive the measurement for the success of ShakeAlert along with data captured through real-world results as earthquakes occur. Other measures may include metrics related to sensor density and mobile application downloads. The most intriguing check for success will be tracking the diversity of solutions implemented by the private sector. The alternative approaches offered, if validated in this thesis, would foster an environment wherein the public and businesses can crowdsource information about applying ShakeAlert and develop their techniques for adoption all contributing to the overall network. Innovative approaches and a decentralized strategy may foster a more resilient nation, allowing everyone to participate in the reduction of damages and expedite recovery from earthquake impacts.

It is hard to quantify in a pre-disaster setting how beneficial ShakeAlert will be. However, the reality is that there are working models around the world that have saved lives. A recent study in Japan revealed that had seismic sensors been in place at the time, it "could have saved many of the 22,000 people killed by the massive tsunami following the 2011 Tohoku earthquake."[21] Furthermore, according to Fujinawa and Noda, "it is suggested that if given 10 seconds of lead time by the EEW [earthquake early warning], deaths can be reduced to 20% and heavy injuries by 10%."[22] During a Cascadia subduction zone earthquake that could mean upward of 2,340 lives saved who would be with their families that next day. In the case of a possible New Madrid event, imagine 8,600 less people sustaining injuries and the massive reduction of costs associated with healthcare

[21] Andy Coghlan, "Seabed Seismic Sensors Would Have Cut 2011 Japan Tsunami Toll," *New Scientist*, May 1, 2017, https://www.newscientist.com/article/2129373-seabed-seismic-sensors-would-have-cut-2011-japan-tsunami-toll/.

[22] Yukio Fujinawa and Yoichi Noda, "Japan's Earthquake Early Warning System on 11 March 2011: Performance, Shortcomings, and Changes," *Earthquake Spectra* 29, no. S1 (2013): S341–S368, https://doi.org/10.1193/1.4000127.

expenditures. These metrics will identify the actual success of ShakeAlert and the value it has to our nation and the people.

In the United States, the problem is not those who are involved with the development of ShakeAlert. Some of the best minds in the world continue to work on it tirelessly, tackling the many challenges that come with earthquake science and technology. Understanding earthquakes and creating solutions to prepare for, respond to, and recovery from these incidents remains the primary focus. The problem is one of controlling outcomes and execution. This thesis studies how we can apply a different strategy to meet these requirements.

B. RESEARCH QUESTIONS

How can the United States increase the nation's resilience to catastrophic earthquakes?

- Why has the United States not fully implemented an earthquake early warning system?
- Could a systems analysis approach add value toward the reduction of earthquake hazards and increase the nation's resilience?

C. RESEARCH SIGNIFICANCE

After the formation of the Department of Homeland Security (DHS) in 2002, 15 national planning scenarios formed "the basis for coordinated federal planning, training, exercises, and grant investments needed to prepare for all-hazards."[23] Scenario 9 necessitates planning for a major earthquake. The intended goal of this thesis is to identify opportunities to advance NEHRP and implement ShakeAlert in the United States. This research leverages the political systems theory model to incorporate innovative concepts, to realign the proper agencies with the appropriate level of funding allocations, including state and local governments, and incentivize the private sector to adopt an integrated approach based on targeted outputs. Ultimately, this provides the mechanisms necessary to

[23] U.S. Department of Homeland Security, "National Planning Scenarios Version 21.3 2006 Final Draft," Public Intelligence, 2006, https://publicintelligence.net/national-planning-scenarios-version-21-3-2006-final-draft/.

protect the environment, stabilize our economy and infrastructure, and most importantly, to save lives during earthquakes.

This thesis provides information to assist with the next reauthorization of NEHRP including specific revisions to the legislation such as changes to lead agencies, funding allocations, and private sector engagement. This systems approach provides focus on the immediate completion and activation of ShakeAlert across the country. Furthermore, by incorporating executable methods, the private sector and local governments become a productive part of the solution. This thesis analyzes the proposed policy options to identify requirements for operational implementation, sustainability, and cultural adoption with the public and the private sectors. Current implementation methodologies are unable to establish baseline operational requirements, let alone adapt to the speed of technological change. By addressing the challenges of funding, operations, and integration, NEHRP will advance seismic research and facilitate contributions of all levels of government, including those of the private sector, to optimize ShakeAlert effectiveness. This conceptual framework will prepare people, businesses, infrastructure, economies, and communities before the next significant earthquake impacts the United States.

D. METHODOLOGY

This thesis analyzes NEHRP based on David Easton's input-output model of political systems theory. Specifically, this research addresses the structure of NEHRP by identifying the demands and support (inputs) of the program and, in turn, framing the decisions and policies (outputs). Furthermore, this analysis captures the flow of effects that influence NEHRP as described by Easton's intrasocietal and extrasocietal environments. Based on the interpretations of this feedback, the authorities representing the decision-making body can then establish processes that convert those inputs and drive the development of their outputs, including ShakeAlert.

The structure of this thesis is divided into five chapters. Chapter I introduces the reader to the subject matter and the associated problem regarding the research questions along with the methodological approach. Chapter II follows with a literature review on the subject of earthquake early warning systems, what they are, why they are necessary, and an orientation to the work of David Easton. His political systems theory model serves as the framework for this analysis of NEHRP. Chapter III provides background material and offers a discussion on the United States strategy for catastrophic earthquakes. We look at the four most significant earthquake risks facing the country today and review the history of NEHRP and ShakeAlert to gain an appreciation for accomplishments thus far. Chapter IV includes the analysis and interpretation, which applies Easton's model to NEHRP. Finally, Chapter V concludes with specific findings of what has been learned and recommendations moving forward.

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II. LITERATURE REVIEW

> Politicians must be simple and clear about how their ideas will serve the national cause. We can no longer use the complexity of today's problems as an excuse for inaction, rhyme or rhetoric that does not meet the challenges before us.
>
> — Alan Siegel, *Simple: Conquering the Crisis of Complexity*

This thesis evaluates many aspects of earthquake warning systems in operation around the world. This literature review provides a focus on areas related to what these systems are, their effectiveness, where there is a need in the United States for these systems, and a case study of Japan where an earthquake warning system has been successful. Furthermore, an assessment of Easton's input-output model serves as a foundation for the systems analysis of NEHRP provided in Chapter IV. Numerous books, scholarly journals, research studies, and scientific articles are available regarding Easton's systems theory and model for public policy analysis. However, there are no continuous inquiries concerning the impacts of earthquake early warning systems to improve performance and usability, as well as training and education efforts related to warnings from a social and behavioral perspective.

A. WHAT IS AN EARTHQUAKE EARLY WARNING SYSTEM?

The idea of an earthquake early warning system began in the late nineteenth century. Published in the *San Francisco Bulletin* in November 1868, just after the San Francisco earthquake on the Hayward fault, Dr. J. D. Cooper developed the idea of having an earthquake bell in the center of San Francisco that would ring after telegraph cables sent signals after detecting ground shaking.[24] Then, in 1909, a telegraph operator published an article in an Iranian newspaper describing a copper wire and magnetic needle system he setup demonstrating an anomaly before the May 27 earthquake in Iran in 1897. After 12

[24] Richard M. Allen et al., "The Status of Earthquake Early Warning around the World: An Introductory Overview," *Seismological Research Letters* 80, no. 5 (2009): 682–693, https://doi.org/10.1785/gssrl.80.5.682.

years, he devised a more elaborate system providing six seconds of warning before the January 23 earthquake in Iran in 1909.[25] However, it was not until 1950, when the Japan railway lines started installing accelerometers to ensure proper functionality of its trains, this led to the development of the Urgent Earthquake Detection and Alarm System (UrEDAS). This allowed Japan to launch the first operational earthquake early warning system in the world, as described by Wenzel et al.[26]

Figure 2 demonstrates the basics of an earthquake early warning system. Mainly, a system contains four principal components, and there are four types of systems in development. In an article from the *Journal for Environmental Hazards*, Asgary describes any system as requiring:[27]

(1) a monitoring system composed of various sensors

(2) a real-time communication link that transmits data from the sensors to a computer

(3) a processing facility that converts data into information

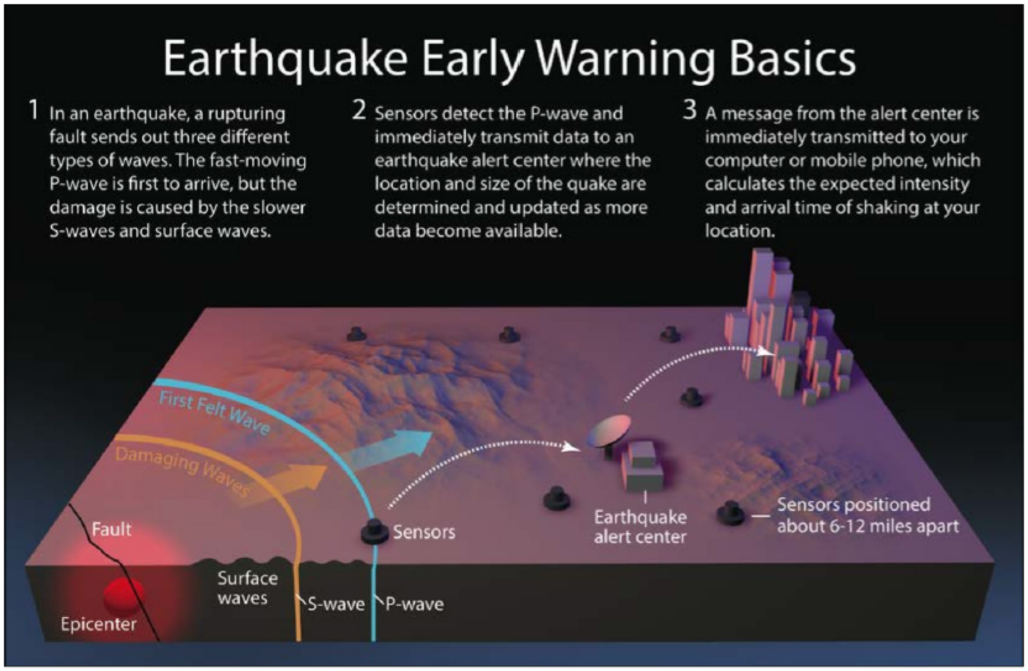
(4) a system that issues and communicates the warning

[25] Manuel Berberian, "Early Earthquake Detection and Warning Alarm System in Iran by a Telegraph Operator: A 116□Year□Old Disaster Prevention Attempt," *Seismological Research Letters* 84, no. 5 (2013): 816–819, doi:10.1785/0220130068.

[26] Friedemann Wenzel et al., "Potential of Earthquake Early Warning Systems," *Natural Hazards* 23, no. 2–3 (2001): 407–416, doi:10.1023/A:1011180302201.

[27] Ali Asgary, Jason K. Levy, and Nader Mehregan, "Estimating Willingness to Pay for a Hypothetical Earthquake Early Warning Systems," *Environmental Hazards* 7, no. 4 (2007): 312–320, https://doi.org/10.1016/j.envhaz.2007.09.003.

Figure 2. Earthquake Early Warning Basics[28]



Between a 2011 National Research Council report and Allen et al., they identify four types of systems:

(1) on-site or single-station warning predict the peak shaking at the time of recording

(2) front detection capture strong ground shaking at a location and transmits a warning to remote locations ahead of the shaking

(3) network-based warnings estimate the size of a growing fault rupture[29]

(4) geodetic networks integrate continuously recording real-time GPS information on large fault displacements[30]

Which solution is best depends primarily on the needs and the tectonic fault structure in the operating environment. UrEDAS is an example of an on-site warning system (described in point 1 above). The original design implemented in Mexico and the

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[28] Source: U.S. Government Accountability Office, *Earthquakes: Additional Actions Needed to Identify and Mitigate Risks to Federal Buildings and Implement an Early Warning System* (GAO-16-680) (Washington, DC: U.S. Government Accountability Office, 2016), http://www.gao.gov/products/GAO-16-680.

[29] National Research Council, *National Earthquake Resilience*.

[30] Allen et al., "The Status of Earthquake," 682.

one in Bucharest, Romania are good examples of front detection systems. However, most developmental systems today are network-based systems for regional warnings. Mexico further connected its original system to a second network, Japan uses a series of networks, and other systems in the United States, Italy, Switzerland, Taiwan, China, and Turkey all utilize a similar approach. Lastly, geodetic networks or GPS systems are relatively new designs and are under development at several institutions in the United States.

B. EFFECTIVENESS OF EARTHQUAKE EARLY WARNING SYSTEMS

On September 14, 1995, a 7.2 earthquake in Mexico triggered a warning system, providing 72 seconds lead time before shaking began in Mexico City, some 190 miles away from the epicenter. According to a 1997 report by Goltz and Flores, titled, *Real-Time Earthquake Early Warning and Public Policy: A Report on Mexico City's Sistema de Alerta Sismica*, schools evacuated in an orderly and coordinated fashion, and residents were able to turn off the gas and lights, evacuate apartments, and assemble at outdoor locations. There were no reports of panicked behavior "such as running, shoving, or other actions associated with extreme fear and flight reactions."[31] Goltz and Flores emphasize the importance of the measures taken by the government of Mexico City to promote earthquake early warning by issuing two million brochures with recommendations about how to best respond. Figure 3 demonstrates warning times for system notifications from this event and others in recent years.[32]

[31] James D. Goltz and Paul J. Flores, "Real-Time Earthquake Early Warning and Public Policy: A Report on Mexico City's Sistema de Alerta Sismica," *Seismological Research Letters* 68, no. 5 (1997): 727–733.

[32] "How Many Seconds Can Earthquake Early Warning System Save for You?" *Global Times*, August 9, 2017, http://www.globaltimes.cn/content/1060460.shtml.

Figure 3. How Many Seconds in Advance Can Earthquake Early Warning System Notify?[33]

Aug 8, 2017 China

Epicenter: Jiuzhaigou county, Sichuan
Grade: 7.0-magnitude

Recipient location	Warning time
Longnan city, Gansu	19 seconds
Tibetan and Qiang Autonomous Prefecture of Aba, Sichuan	48 seconds
Guangyuan city, Sichuan	48 seconds
Mianyang city, Sichuan	49 seconds
Chengdu city, Sichuan	71 seconds

Apr 20, 2015 China

Epicenter: Waters near Hualien, Taiwan
Grade: 6.4-magnitude

Recipient location	Warning time
Pingtan Island, Fujian	42 seconds
Fuzhou city, Fujian	Around 50 s
Putian city, Fujian	Around 50 s
Quanzhou city, Fujian	Around 50 s
Ningde city, Fujian	Around 50 s

Aug 3, 2014 China

Epicenter: Ludian county, Yunnan
Grade: 6.5-magnitude

Recipient location	Warning time
Zhaotong city, Yunnan	10 seconds
Kunming city, Yunnan	57 seconds

Apr 20, 2013 China

Epicenter: Lushan county, Sichuan
Grade: 7.0-magnitude

Recipient location	Warning time
Ya'an city, Sichuan	5 seconds
Chengdu city, Sichuan	28 seconds

Mar 11, 2011 Japan

Epicenter: Honshu
Grade: 9.0-magnitude

Recipient location	Warning time
Kurihara, Miyagi	18 seconds
Tokyo	About 80 s

Sep 14, 1995 Mexico

Epicenter: Guerrero
Grade: 7.3-magnitude

Recipient location	Warning time
Mexico City	72 seconds

Source: jiemian.com, FETV, MIT Technology Review, cires.org.mx
Graphics: Globaltimes.cn

On August 8, 2017, the 7.0 magnitude Sichuan earthquake in China was a significant test of the China Earthquake Administration's investment in its early warning system. Less than 125 miles from the epicenter, residents of Wenchuan received 40 seconds of warning before the shaking began. This is particularly noteworthy because it was at this location where the May 2008 earthquake, registering a 7.9 magnitude, took the lives of over 80,000 people, costing U.S. dollars (USD) 150 billion in damages. This incident sparked China's investment in earthquake early warning. Although no two earthquakes are alike, the 2017 quake in Sichuan took only 24 lives and injured less than 500 people.

On September 19, 2017, exactly 32 years to the day after the 1985 Mexico City 8.0 magnitude earthquake killed more than 10,000 and injured over 30,000 people, a 7.1 magnitude earthquake struck once again in Mexico City killing 370 people and leaving

[33] Source: "How Many Seconds Can Earthquake?" *Global Times*.

6,000 injured. However, this time, the national investment in its earthquake early warning system provided between 12–48 seconds of warning, depending on location. Interestingly enough, just three hours before the actual earthquake, the city conducted an earthquake drill because it was the anniversary of the 1985 event. Debate continues as to how individual actions unfolded that day and how they corresponded to public perception and behavioral analysis in regard to the drill earlier. Even so, these examples of actual earthquake early warning system alerts demonstrate that this technology is a proven solution that helps save lives during earthquakes.

C. INTERNATIONAL CASE STUDY: JAPAN EARTHQUAKE EARLY WARNING

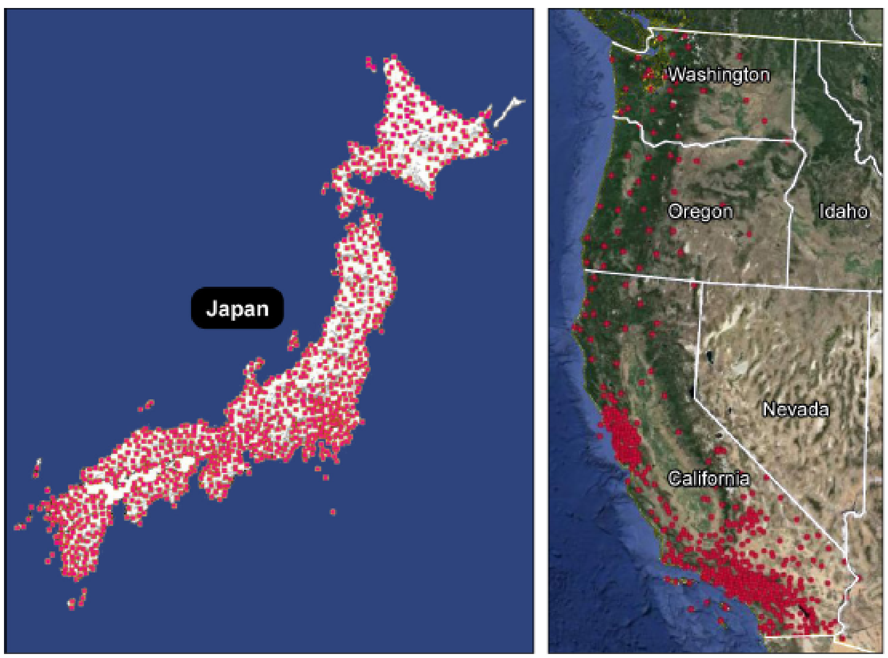
Most experts agree that Japan is the most prepared culture in the world for natural disasters, primarily due to its location on the Pacific Ring of Fire and its unfortunate history of earthquakes. After the Kobe earthquake of 1995 killed more than 6,400 people, Japan initially invested over USD 600 million in developing an earthquake early warning system. In October 2007, Japan became the first country to launch a national earthquake early warning system. Eighteen official warnings were disseminated between the launch of the system and the 2011 Tohuku earthquake. In that event, the earthquake early warning system proved its worth in one example when "only one train, running under test without passengers, derailed that day."[34] The system also provided 114 notifications thereafter, between March 11, 2011, and December 2012, according to the Japan Meteorological Agency (JMA).

Japan has a straightforward and structured approach to research, oversight, and regulation of its EEWS through the JMA and the National Research Institute for Earth Science and Disaster Prevention (NIED). These two agencies drive all efforts related to the national EEWS and invest heavily in the integration with the private sector to implement solutions. The principal private sector entities include Japan's Railway Technical Research Institute (RTRI), all four major telecommunications companies, and the Real-time

[34] "How Japan's Rail Network Survived the Earthquake," Railway Technology, June 27, 2011, http://www.railway-technology.com/features/feature122751/.

Earthquake Information Consortium, which consists of 70 organizations throughout the country who collaborate with JMA and NIED on numerous earthquake early warning system installations and applications. Recognizing the need to collaborate on many levels, Japan has made it a priority for the private sector to lead the way with earthquake early warning system solutions. Correspondingly, the government plays an integral role in supporting infrastructure requirements and station density. As seen in Figure 4, Japan invests significantly more money towards network density for the quantity of seismic stations in comparison to California.

Figure 4. Station Density in Japan (2007) versus California (2016)[35]



Japan has made a significant investment in EEWS. It has taken the country roughly 10 years to build its network across the country at the cost of USD 1 billion. Annual maintenance figures were unavailable but could be significant as each earthquake may take a toll on the network through seismometers going offline from blackouts and disruptions of communication lines. Upgrades and replacement costs due to rust and dust as well as

[35] Source: U.S. Government Accountability Office, *Earthquakes*.

ensuring continuity during repairs are also factors. NIED's High Sensitivity Seismograph Network off the southeast coast of Japan added 25 sensors on the seafloor (S-Net) in August 2011, then an additional 25 sensors in March 2016. Japan is now extending S-Net with an additional 125-station network off the northeast coast of Japan where the 2011 Tohoku earthquake occurred. However, these costs are justified. Studies have recently determined that had these upgrades been in place in 2011, it could have saved many of the 22,000 lives lost from the subsequent tsunami because people would have had an extra 23 minutes of warning to reach higher ground.[36]

As the model society for EEWS implementation, Japan has set the standard regarding political support, financial commitment, operational standardization, and social investment toward earthquake hazards reduction. The United States can gain farreaching insights as to best practices and lessons learned from the Japanese system and should look at viable opportunities domestically to replicate these efforts, particularly those related to private sector integration. While the United States continues to piecemeal its way just to install sensors for minimum network density to activate ShakeAlert, Japan's development efforts have expanded beyond just issuing warnings. Dedicated earthquake early warning systems are specifically designed for operational preventative measures including:

(1) Fire department systems

(2) Medical systems

(3) Home electronic systems

(4) School systems

(5) Outdoor activity systems

(6) Plant systems

(7) Liquefied petroleum gas systems

(8) Building maintenance systems

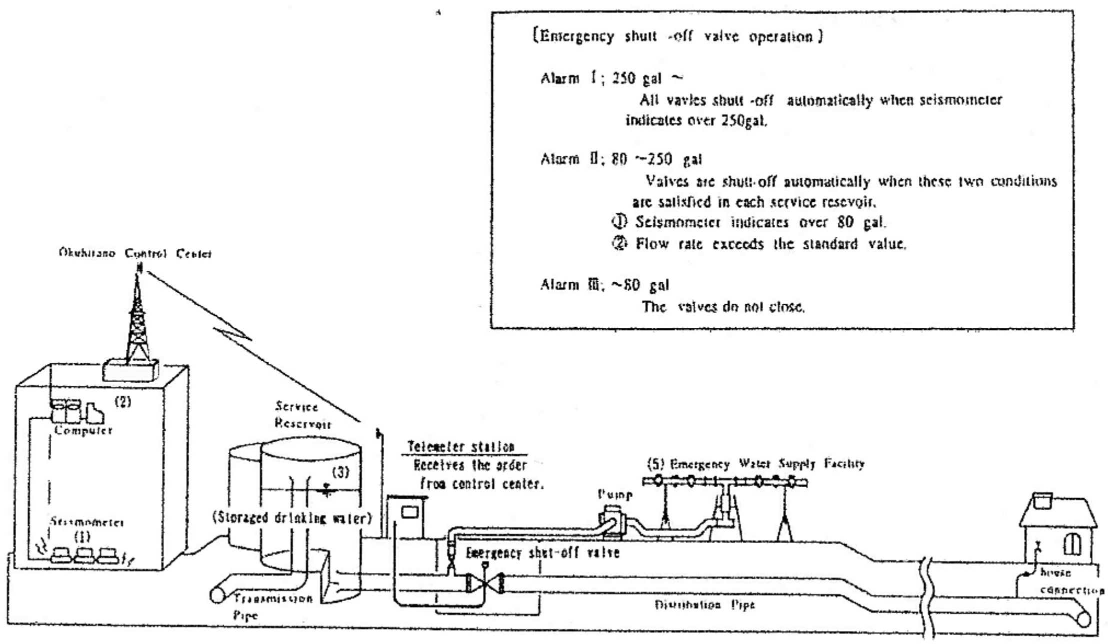
(9) Elevator systems

(10) Dam maintenance systems

[36] Coghlan, "Seabed Seismic Sensors."

Figures 5 and 6 demonstrate a couple of examples of these automated solutions in place in Japan. The first relates to the water supply system in Kobe City and how automated shutoff valves operate. Depending on what type of alarm is triggered by the seismometer, the valves close based on flow rates and volume differentials after receiving signals from the earthquake early warning system.[37]

Figure 5. Kobe, Japan—Water Supply System and Automated Shutoff Valves from EEW Alerts[38]



In the example in Figure 6, the Tokyo city gas network is configured to receive earthquake early warning sys7tem alerts on both medium-pressure and low-pressure lines. When earthquakes are detected, intelligent gas meters stop the flow of gas supply at each customer location.[39]

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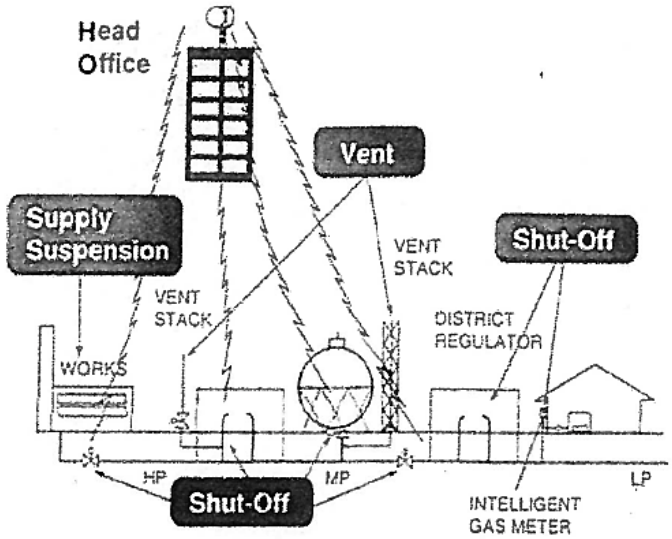
37 Jochen Zschau and Andreas N. Küppers, eds., *Early Warning Systems for Natural Disaster Reduction* (Berlin Heidelberg: Springer-Verlag, 2003).

38 Source: Zschau and Küppers, *Early Warning Systems*.

39 Zschau and Küppers, *Early Warning Systems*.

Figure 6. Tokyo, Japan—Gas Network and Emergency Shutoff from EEW Alerts[40]



The Japan Highway Public Corporation is responsible for transportation applications. One example of how this is implemented is on the expressways. Japanese speed limits are digitally displayed so when an earthquake early warning alert is distributed, the speed limits automatically decrease depending on the expected level of ground motion shaking. As for power, circuit breakers disconnect power lines after detection and turbines cease operation at generating stations. Concerning communications, ShakeAlert only broadcasts through proprietary software issued to persons associated with the scientific community over the public Internet and is significatnly behind the Japanese alert capability, which is automatically distributed over television, radio, mobile phone carriers, cable television, and Internet providers, including Internet of Things devices such as connected printers and display units.[41] The technical challenge domestically lies with the capabilities of the cellular carriers during mass alert distributions.

[40] Source: Zschau and Küppers, *Early Warning Systems*.

[41] Fujinawa and Noda, "Japan's Earthquake."

D. THE NEED IN THE UNITED STATES

The United States is continuously vulnerable to earthquakes. For instance, Alaska regularly experiences seismic events. Additionally, it is home to the second most massive earthquake ever recorded globally when the 9.2 magnitude event in 1964 also triggered a 220-foot high tsunami. California has had its share of significant earthquakes including Fort Tejon in 1857, San Francisco in 1906, San Fernando in 1971, Loma Prieta in 1989, and Northridge in 1994 among others. It is not just the West Coast that experiences these events. For example, the 1886 Charleston earthquake in South Carolina was estimated to be as high as a 7.3 magnitude. The New Madrid Fault zone, covered in more depth in the subsequent chapter, rocked the Midwest in the early 1800s, even temporarily reversing the flow of the Mississippi.[42] Additionally, New York, which experiences at least a 5.0 magnitude quake every 100 years, last experienced an event in 1884.[43] In 2011, a 5.8 magnitude earthquake struck outside Washington DC and "was felt by more people than any other quake in U.S. history, reaching 12 states and several Canadian provinces."[44] Each of these incidents had minimal if any measures in place to mitigate against or warn of the impending impacts, yet today we know earthquakes in these locations are inevitable and that it is probable there could be onein the relatively near future.

Experts argue that the day ShakeAlert goes live, coupled with a sustained educational program, is the day we start on a path toward a more resilient nation. As a result, lives can be saved and billions of dollars in losses can be avoided in preparation for the next catastrophic earthquake. According to a 2017 report from FEMA, the estimated long-term value of building stock losses is USD 6.1 billion annually, 73 percent of which

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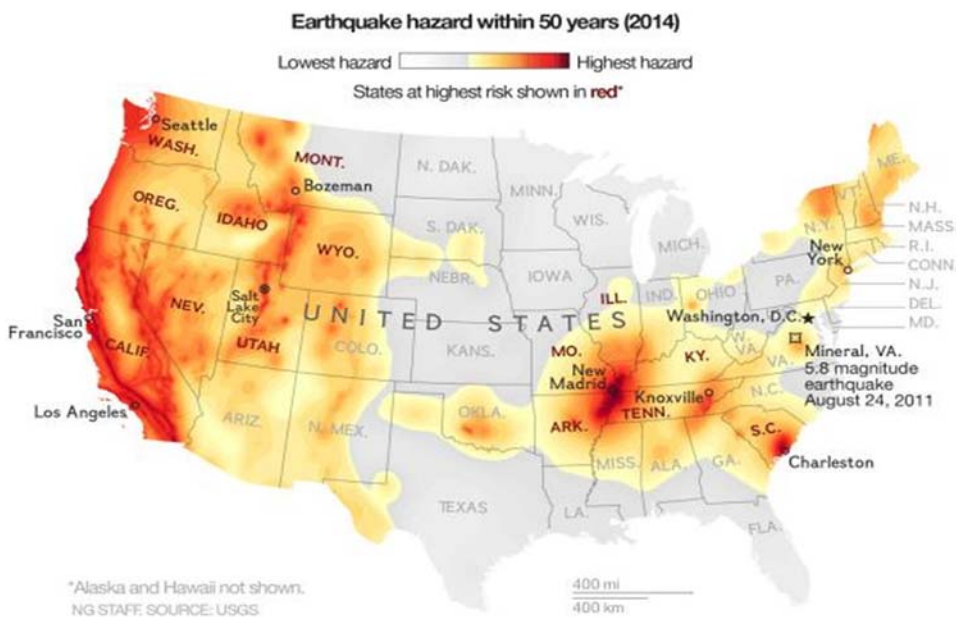
[42] "Earthquake Causes Fluvial Tsunami in Mississippi—February 7, 1812," This Day in History, accessed November 9, 2017, http://www.history.com/this-day-in-history/earthquake-causes-fluvial-tsunami-in-mississippi.

[43] Kathryn Miles, "New York City Is Overdue for a Major Earthquake," *New York Post* (blog), September 9, 2017, http://nypost.com/2017/09/09/new-york-city-is-overdue-for-a-major-earthquake/.

[44] Jason Daley, "What Caused the 2011 D.C. Earthquake?," *Journey to the Center of the Earth* (blog), May 9, 2016, https://www.smithsonianmag.com/smart-news/what-caused-dc-earthquake-2011-180959019/.

is concentrated on the West Coast while the balance spans the remainder of the country.[45] In total the estimated economic losses for all stock and content is USD 59 trillion. However, these estimates do not take into account losses associated with damages to lifelines (e.g., utilities and transportation systems) and other critical facilities, as well as indirect economic losses.[46] Figure 7 illustrates areas of the country for earthquake hazards within 50 years.

Figure 7. USGS Documentation for 2014[47]



Spending more on ShakeAlert now and including sustainable operating costs can be justified. In a 2016 publication in *Seismological Research Letters*, entitled "Benefits and Costs of Earthquake Early Warning," Strauss and Allen determine that "according to FEMA's cost-benefit methodology for hazard mitigation projects, the current value of a

45 Source: Federal Emergency Management Agency, *Hazus® Estimated Annualized Earthquake Losses for the United States* (Washington, DC: Federal Emergency Management Agency, 2017), https://www.fema.gov/media-library/assets/documents/132305.

46 Ibid.

47 Source: Federal Emergency Management Agency, *Hazus® Estimated*.

statistical life in the United States is USD 6.6 million."[48] As such, the benefits outweigh the costs as the earthquake early warning system alone would pay for itself in less than three years and reduce the number of injuries in earthquakes by more than 50 percent because the implementation plan calls for USD 16.1 million per year to operate.[49] For any given year in any specific location, annualized earthquake loss (AEL) measures the estimated long-term average of earthquake losses. According to the Earthquake Engineering Research Institute (EERI), the AEL for the nation is more than USD 10 billion.[50] In other words, numerous reasons justify the necessary expenditures, yet current allocations remain inadequate.

The development of strict building codes and enforcement of seismic standards is supposed to be a predominant output for NEHRP. In February 2016, President Obama signed Executive Order 13717 Establishing a Federal Earthquake Risk Management Standard,[51] which requires any federal agency that owns or leases a building, to comply with seismic standards, set forth by the Interagency Committee on Seismic Safety in Construction (ICSSC). A Government Accountability Office (GAO) report released in August 2016 entitled *Earthquakes: Additional Actions Needed to Identify and Mitigate Risks to Federal Buildings and Implement an Early Warning System*,[52] stated that ICSSC publishes standards for domestic purposes.[53] The report continues by identifying thousands of high-risk buildings, specifically those controlled by the Department of Defense (DOD) and the General Services Administration, which do not meet these standards and thus place thousands of federal employees at risk in the workplace. The report explicitly calls for recommendations to prioritize and implement comprehensive seismic safety measures and to address implementation challenges of the earthquake early warning system. At the state

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48 Jennifer A. Strauss and Richard M. Allen, "Benefits and Costs of Earthquake Early Warning," *Seismological Research Letters* 87, no. 3 (2016): 765–772, https://doi.org/10.1785/0220150149.

49 Ibid.

50 National Research Council, *National Earthquake Resilience*.

51 Exec. Order No. 13717, *Federal Register* 81 (2016), 6405–6410, https://www.federalregister.gov/documents/2016/02/05/2016-02475/establishing-a-federal-earthquake-risk-management-standard.

52 U.S. Government Accountability Office, *Earthquakes*.

53 Ibid.

level, the concern is even more significant. For example, Northern Utah has the highest percentage of unreinforced masonry buildings in the United States, which will increase the damage, destruction, injury, and death in the event of an earthquake along the Wasatch Fault. Local jurisdictions face an even greater challenge. Los Angeles took action in 2015 by passing legislation requiring 15,000 of the cities one million buildings to meet retrofitting standards within "seven years to fix wood apartments and 25 years to fix concrete buildings."[54]

E. POLITICAL SYSTEMS THEORY: EASTON'S INPUT-OUTPUT MODEL

According to Bertalanaffy,

> Modern science is characterized by its ever-increasing specialization, necessitated by the enormous amount of data, the complexity of techniques and of theoretical structures within every field. Thus science is split into innumerable disciplines continually generating new subdisciplines. In consequence, the physicist, the biologist, the psychologist and the social scientist are, so to speak, encapusulated [sic] in their private universes, and it is difficult to get word from one cocoon to the other.[55]

The vignette above by Ludwig von Bertalanffy, a biologist considered one of the founders of general systems theory, is representative of the same challenges faced by NEHRP over the years. When applied to the study of earthquake hazards reduction, the researchers, physical scientists, seismologists, geologists, engineers, programmers, modelers, geophysicists, and specialists have become so immersed in their respective initiatives that they fail to work collaboratively towards common outputs. Political systems theory reached a point of specialization that required a unique and exclusive standpoint regarding the political landscape in the twentieth century.

After World War II, there was a profound shift in political science, and an effort ensued to offer a theoretical framework from which the discipline was to evolve. David Easton, a Canadian-born American political scientist, constructed many of the concepts

[54] Rong-Gong Lin II, Rosanna Xia, and Doug Smith, "Los Angeles Will Have the Nation's Toughest Earthquake Safety Rules," *Los Angeles Times*, October 9, 2015, http://www.latimes.com/local/lanow/la-me-ln-earthquake-retrofit-20151009-story.html.

[55] Ludwig von Bertalanffy, *General System Theory: Foundations, Development, Applications* (New York: George Braziller, 1969).

that remain the backbone of the field today. Easton's original work, *The Political System*, was published in 1953 and "shook the underpinnings of American political science."[56] According to Arnold Rogow, in his 1966 book review on Easton's book in the *Midwest Journal of Political Science*, Easton "called for a reformulation of political theory in the direction of empirical research, greater conceptual rigor, and more precise specification of the variables that enter into political system analysis."[57] Tracy Strong accurately points out in "David Easton: A Reflection of an American Scholar" that he "thought himself to be standing at a kind of turning point of history, a moment of crisis, in which philosophy and science were called to preserve Western values from crumbling."[58] Notwithstanding the crumbling of Western values, what makes his contribution so significant is how it allowed the philosophy of politics to consider a systems analysis approach to government.

Figure 8 is what Easton referred to as his primitive model for approaching the study of political life. Essentially, Easton's theory establishes that a political system, in the case of this thesis that NEHRP, functions based on inputs coming in the form of demands and support, which are converted to outputs, produced as decisions or policies. Based on a systemic feedback loop, the outputs may have a positive or negative impact on the environment, and that in turn can influence inputs. Much of the key terminology from Easton's political systems theory is incorporated throughout this analysis as it is applied to NEHRP in Chapter IV.

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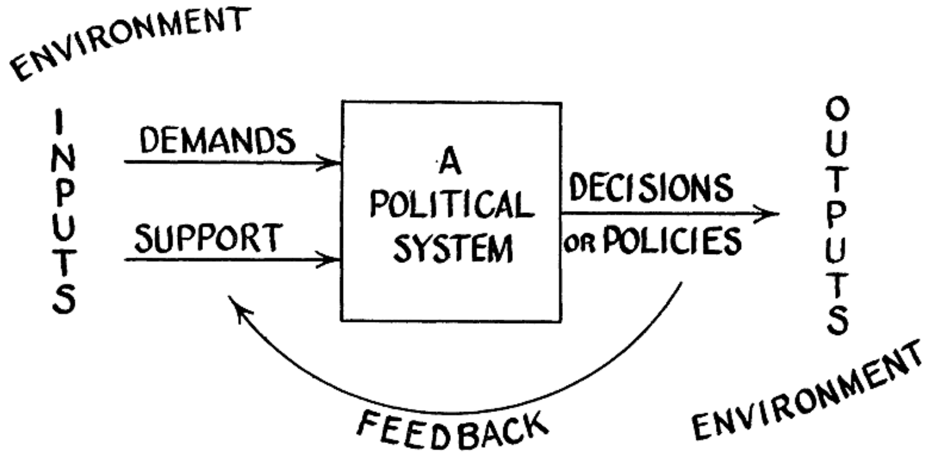
[56] Klonoski, "Book Reviews."

[57] Arnold A. Rogow, "Review of A Framework for Political Analysis: A Systems Analysis of Political Life., David Easton, by David Easton," *Midwest Journal of Political Science* 10, no. 1 (1966): 142–146, https://doi.org/10.2307/2108792.

[58] Tracy B. Strong, "David Easton: Reflections on an American Scholar," *Political Theory* 26, no. 3 (1998): 267–280.

Figure 8. Easton's "Primitive Model" for Approaching the Study of Political Life[59]



In 1965, Easton authored two additional books furthering these constructs: *A Framework for Political Analysis* followed by *A Systems Analysis of Political Life*. The review of the first publication, presented by Wahlke in the *Annals of The American Academy*, describes this work to "include the two essential variables for all and any kinds of political system—the ability to make and execute decisions and the probability that decisions will be accepted as authoritative."[60] Most notably, Easton presents the dynamic response model in the latter publication, and it forms the basis of the input-output conceptual framework. He argues the benefit of the systems approach is that it

> draws us away from a discussion of the way in which a political pie is cut up and how it happens to get cut up…we need a theoretical framework that helps us understand how the very pie itself comes into existence and changes in its basic content or structure.[61]

Michael Crozier defines this approach well in his "Rethinking Systems" article when he stated, "input is good for the democratic vitality of the system and its citizens, ensuring

[59] Adapted from: Easton, *A Systems Analysis of Political Life*.

[60] John C. Wahlke, "David Easton. A Framework for Political Analysis," *The Annals of the American Academy of Political and Social Science* 360, no. 1 (1965): 179–180, https://doi.org/10.1177/000271626536000117.

[61] David Easton, *A Systems Analysis of Political Life* (New York: John Wiley & Sons, Inc., 1965).

binding political decisions that may then be operationalized through the management and delivery of policy back into society."[62]

However, Easton's work is not without its critics. In 1998, Henrik Bang published an article in *Political Theory* called "David Easton's Postmodern Images" in which he valiantly attempts to defend Easton's work and counter critical arguments against his position. The author describes how Easton is "blamed for blinding the researchers to the importance of developing the various discourses of political theory in the context of political science as a formal academic practice."[63] Criticism aside, it remains standard practice today in the teachings of political science that the work of Easton serves as a foundational element when studying the systems of governance and political thoughts, activities, and behavior.

F. LITERATURE REVIEW CONCLUSION

This literature review shows that earthquake early warning systems remain nascent from an operational standpoint. As a result, the shortage of source material indicates a potential absence of data and research in the field. However, as many countries are making investments to develop these systems, the limited literature does show that it is critical to capture the practical application from an operational standpoint and politically, efforts are underway to implement requirements to further resiliency. Furthermore, this review demonstrates how the development of these systems necessitates a framework, defined by particular societal demands and support that produce specific decisions and policies.

While source literature about system models for societal analysis exist, no continuous inquiries concerning the impacts of earthquake early warning systems have been undertaken to improve performance and usability. Accepting trillions in future losses, earthquake engineering is an area the United States has yet to apply in addition to our standards of life safety. The next phase is to move beyond the science and focus on the

[62] Michael P. Crozier, "Rethinking Systems: Configurations of Politics and Policy in Contemporary Governance," *Administration & Society* 42, no. 5 (2010): 504–525, https://doi.org/10.1177/0095399710377443.

[63] Henrik P. Bang, "David Easton's Postmodern Images," *Political Theory* 26, no. 3 (1998): 281–316, https://doi.org/10.1177/0090591798026003002.

application, much like Japan has done. In that environment, ground motion is the input, and it dynamically changes the strength and performance of structures. Easton's theory allows us to provide a framework to analyze NEHRP in Chapter IV to identify how best to move into this area of seismic application, but first we need to understand what the U.S. strategy has been toward catastrophic earthquakes. This is discussed in the next chapter.

III. U.S. STRATEGY TOWARD CATASTROPHIC EARTHQUAKES

> Politically speaking, it's always easier to shell out money for a disaster that has already happened, with clearly identifiable victims, than to invest money in protecting against something that may or may not happen in the future.
>
> — James Surowiecki, Disaster Economics, *The New Yorker*

The United States has a long history of earthquakes that have resulted in devastating losses of life, property, and the economy. An overview of the following areas provide the necessary background before we apply Easton's model of systems theory tos the U.S. strategy: (1) the most significant catastrophic earthquake environments, (2) the application of NEHRP to date, and (3) a summary of ShakeAlert, our earthquake early warning system currently under development.

A. CATASTROPHIC EARTHQUAKE ENVIRONMENTS

Four regions in the United States have a high probability of catastrophic earthquakes. The question is when will they occur. The federal government coordinates with state and local jurisdictions in preparation for these expected incidents. Unfortunately, preparedness efforts predominately focus on response requirements and lack any substantial coordination concerning long-term recovery or significant investment in mitigation measures. These are precisely the mission areas where ShakeAlert could serve as the proper output benefiting society and the environment.

1. Cascadia Subduction Zone—Northwest

Kathryn Schulz won the Pulitzer Prize for Feature Writing and a National Magazine Award after her 2015 story in *The New Yorker* called, "The Really Big One"[64] went viral. The story portrayed the realities of the consequences of a Cascadia subduction zone

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[64] Kathryn Shulz, "The Really Big One," *The New Yorker*, July 20, 2015, https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

earthquake that many Americans were not familiar with. Experts warn that the Cascadia subduction zone is arguably the most dangerous situation because it results in not only a horrific earthquake but also a devastating tsunami with global implications. The last major Cascadia earthquake occurred in 1700, and the science shows that a recurrence happens on average every 243 years, leaving us about 74 years overdue.[65]

FEMA conducted a four-day exercise in 2016 called Cascadia Rising in conjunction with local, state and federal partners. Several planning assumptions included eight million people in the impact zone, no electricity or fuel for weeks if not months, limited supply chain capability including food and water, significant damages to infrastructure and transportation systems, including no access to water or sewer systems for months, if not years. An area for improvement identified related to "life-saving and life-sustaining public messaging was limited in scope and effectiveness and did not evolve to reflect the changing conditions within the impacted area."[66] Public messaging about the initial earthquake as well as multiple days of subsequent aftershocks are potential opportunities for ShakeAlert to assist with response and recovery efforts.

2. New Madrid Fault Zone—Midwest

A sequence of catastrophic earthquakes occurred along the New Madrid fault zone between December 1811 and February 1812, all above 7.0 magnitude. The area of strong shaking associated with these shocks was "two to three times as large as that of the 1964 Alaska earthquake and 10 times as large as that of the 1906 San Francisco earthquake."[67] The immediate impact areas included eight states, beginning in Arkansas and cascading through neighboring Mississippi, Alabama, Tennessee, Kentucky, Missouri, and Illinois. Experts believe that within the next 50 years, there is a 25–40 percent chance of a 6.0 magnitude or greater earthquake in this area.[68]

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[65] Ibid.

[66] Federal Emergency Management Agency, *Cascadia Rising 2016*.

[67] Susan E. Hough, "Cataloging the 1811–1812 New Madrid, Central U.S., Earthquake Sequence," *Seismological Research Letters* 80, no. 6 (2009): 1045–1053, https://doi.org/10.1785/gssrl.80.6.1045.

[68] A. D. Frankel et al., "USGS National Seismic Hazard Maps," *Earthquake Spectra* 16, no. 1 (2000): 19.

In 2011, FEMA conducted a national level exercise (NLE) based on the New Madrid catastrophic earthquake scenario. NLEs are congressionally mandated because of the Post-Katrina Emergency Management Reform Act of 2006 and require participation from senior officials at the federal level. As per the FEMA after-action report (AAR), an area for improvement captured pertained to the whole community, or using Easton's terms, the *total environment*, in that

> although the enormous potential of the private sector was on display in NLE 11, there was a lack of formal mechanisms by which their resources and information were integrated into the incident support system. This lack of formal mechanisms also affected the use of social media and highlighted gaps in processes for integrating information gathered from social media into the response.[69]

The Central United States Earthquake Consortium (CUSEC) is the regional partnership of stakeholders that comprise the New Madrid seismic zone. CUSEC produced its AAR based on the NLE 11 exercise and specifically outlined a recommended course of action for the consortium that it

> CUSEC will coordinate research into how GIS, social networks, and other emerging technologies can be used to enhance recognition, warning, and post-event information sharing so that all local, state, federal, and private-sector partners share a common operating picture. CUSEC will also provide decision makers at all levels with accurate, seamless communication and information needed to make life-saving and emergency response decisions.[70]

These findings demonstrate all aspects of Easton's model from recognizing the inputs associated with all stakeholders, including the private to the political system that is the decision makers and how they convert those inputs into outputs. In this case, outputs consist of capabilities associated with warning and information sharing to make life-saving decisions that allocate value for society.

[69] Federal Emergency Management Agency, *National Level Exercise 2011 (NLE 11) Functional Exercise Final After Action Report* (Washington, DC: Federal Emergency Management Agency, 2011). https://asdwasecurity.files.wordpress.com/2012/04/nle-11-aar-final_v022812.pdf.

[70] Central United States Earthquake Consortium, *CUSEC After Action Report* (Memphis, TN: Central United States Earthquake Consortium 2012), http://cusec.org/cusec-new-madrid-catastrophic-planning-project-after-action-report-now-available/, 45.

3. San Andreas Fault—California

The infamous San Andreas Fault has three segments running approximately 750 miles through California. This thesis emphasizes the southern segment, which begins near the Salton Sea, passes north through Los Angeles and ends in Monterey County. FEMA and the State of California Governor's Office of Emergency Services released the Southern California Catastrophic Earthquake Plan in 2010 is based on the "Great Shakeout Scenario" prepared by Dr. Lucy Jones and team. Under that scenario, a 7.8 magnitude earthquake is predicted to "cause about 1800 deaths and USD 213 billion of economic losses."[71]

The impacts associated with the ShakeOut scenario are devastating for the entire country. The extra costs to the economy are based on a number of critical consequences of the earthquake that ShakeAlert can help prevent, or at least minimize to some extent. For example, due to the loss of fire suppression capability from damaged water systems, the senario predicts 1600 fires will erupt and destroy hundreds of blocks or roughly 133,000 homes and USD 65 billion in property loss, and doubling the loss of life to 3600. It also predicts over 140,000 hazardous materials incidents will occur, and more than 300,000 buildings will have significant damages. The senario forcasts upwards of 100,000 landslides, causing cascading road and railroad disruption. In adiditon, it estimates there will be more than eight million mental health cases for distress or disorders from the earthquake crippling the healthcare system, this outside of injuries.[72] Finally, it forecasts disruption to the Ports of Los Angeles and Long Beach, which account for 40 percent of all domestic imports, would run upwards of USD 1 billion a day in loss of goods.[73]

[71] Lucile M. Jones et al., *The ShakeOut Scenario* (Reston, VA: US Geological Survey, 2008), https://pubs.usgs.gov/of/2008/1150/.

[72] "Catastrophic Planning," CALOES, accessed November 13, 2017, http://www.caloes.ca.gov/for-businesses-organizations/plan-prepare/catastrophic-planning.

[73] Chris Kirkham et al., "If the West Coast Ports Shut Down, Who Wins and Who Loses?," *Los Angeles Times*, February 13, 2015, http://www.latimes.com/business/la-fi-port-economics-20150214-story.html.

4. Wasatch Fault Zone—Utah

The Wasatch Fault zone is divided into 10 segments and is located predominately in the state of Utah and extends into southern Idaho. About 80 percent of Utah's population lives in this zone as it straddles the mountain range beginning in the city of Nephi, then running along to Provo, right through downtown Salt Lake City, proceeding north to Ogden, Brigham City and beyond. Utah has experienced 16 earthquakes greater than 5.5[74] magnitude since 1847, and studies have indicated a prior history of earthquakes greater than 6.5 magnitude.

In 2015, with support from FEMA, EERI published a report capturing the hazards and loss estimates for a 7.0 magnitude earthquake on the Salt Lake City segment of the fault zone.[75] The report established timelines for each of the zone's 10 segments, based on last known "big one," for events and projections moving forward. Put simply, any one of the fault zone segments is at or has surpassed the expected timeframe for another rupture to occur. There is a 57 percent probability that this region will experience at least one 6.0 magnitude or greater earthquake and a 43 percent probability of at least one 6.75 magnitude or greater earthquake in the next 50 years.[76]

B. NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

During the 1970s, scientists around the world began formulating different methodologies around the concept of earthquake prediction. The 1971 San Fernando earthquake has been referred to as a "watershed" event as public decision makers in California, concerned about the social disruption from a prediction announcement, created the California Earthquake Prediction Evaluation Council (CEPEC)[77] in 1975. The charge

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[74] Federal Emergency Management Agency, *Wasatch Range Catastrophic Earthquake Response Plan*, Ver. 2.0 (Washington, DC: Federal Emergency Management Agency, 2012, https://www.hsdl.org/?abstract&did=784739.

[75] EERI Utah Chapter, *Scenario for a Magnitude 7.0 Earthquake*.

[76] Working Group on Utah Earthquake Probabilities, *Earthquake Probabilities for the Wasatch Front Region in Utah, Idaho, and Wyoming* (Salt Lake City, UT: Utah Geological Survey, 2016), https://ussc.utah.gov/pages/view.php?ref=1283.

[77] C. Kisslinger and Tsuneji Rikitake, eds., *Practical Approaches to Earthquake Prediction and Warning* (New York: Springer, 1985).

of CEPEC is to establish communication protocols between the scientific community and those responsible for public safety, with warnings to be communicated first through the governor's office and then to local officials.[78]

Other devestating earthquakes during the 1970s around the world caused widespread damages in several countries. Most significant was the 1976 magnitude 7.8 earthquake in Tangshan, China, which killed at least 242,000 people, with some estimates as high as 700,000.[79] As a result, the California congressional delegation introduced federal legislation to support seismic studies, and in turn, Congress passed the National Earthquake Hazards Reduction Act (Public Law 95-124)[80] in 1977. This established NEHRP and provided ongoing funding for earthquake research in the United States.

The four federal agencies responsible for NEHRP (NIST, FEMA, NSF, and USGS) "have distinct roles and responsibilities that are mutually supportive."[81] Each agency's contribution to NEHRP is intended to improve the "basic understanding of earthquakes and their effects on people and infrastructure through interdisciplinary research involving engineering, natural sciences, and social, economic, and decision sciences."[82] Figure 9 is the closest representation as to how these agencies interact and how the flow of effects from the environments found in Easton's model would correlate to NEHRP outputs.

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[78] Daniel Sarewitz, Roger A. Pielke, Jr., and Radford Byerly, Jr., eds., *Prediction: Science, Decision Making, and the Future of Nature* (Boulder, CO: Center for Science and Technology Policy Research, 2000), http://sciencepolicy.colorado.edu/publications/special/prediction/toc.html.

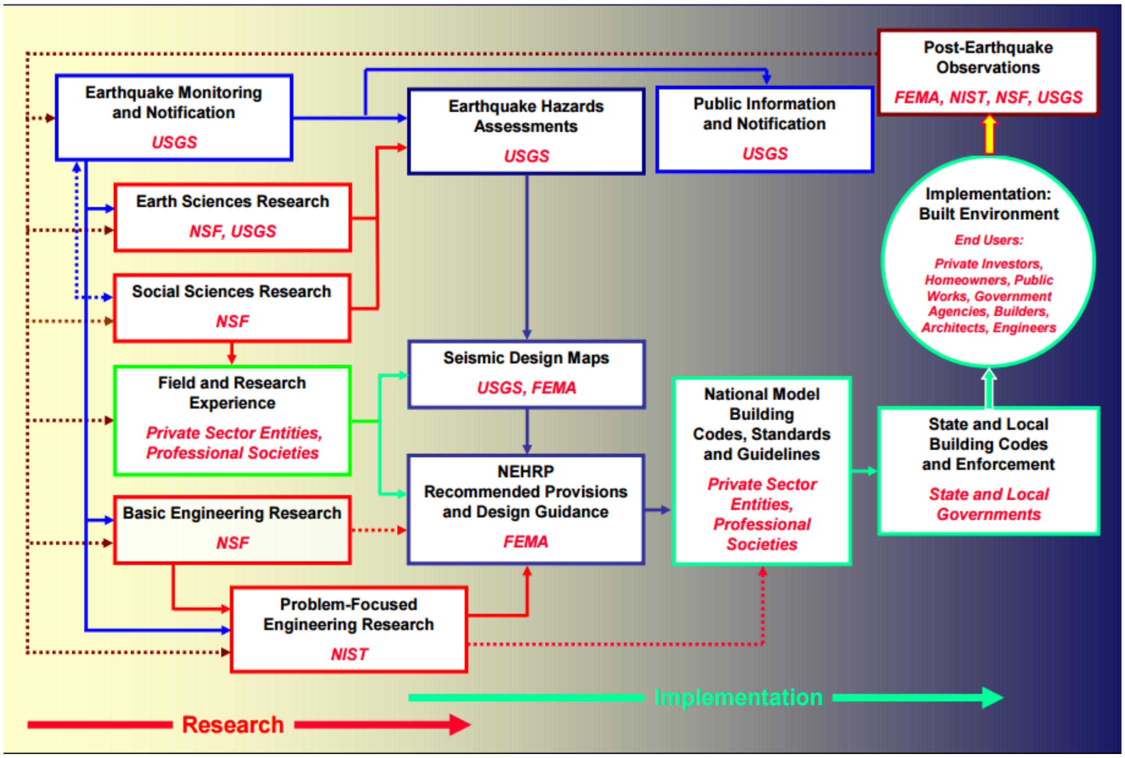
[79] Theodore S. Glickman, *Acts of God and Acts of Man: Recent Trends in Natural Disasters and Major Industrial Accidents* (Collingdale, PA: Diane Publishing 1993).

[80] "91 Stat. 1098—Earthquake Hazards Reduction Act," U.S. Government Printing Agency, accessed January 2, 2017, https://www.gpo.gov/fdsys/granule/STATUTE-91/STATUTE-91-Pg1098/content-detail.html.

[81] NEHRP, *Annual Report* (2014).

[82] Folger, *National Earthquake Hazards*.

Figure 9. NEHRP Agency Research and Implementation Workflow[83]



Since its inception, NEHRP has undergone several congressional revisions. After an amendment in 1980, which incorporated the newly established FEMA as the lead agency, two signficant reauthorizations have occurred. In 1990, Congress refocused the program from prediction to hazard reduction. This happened because of the scientific community, which felt early on that the prediction of earthquakes was possible, ultimately realized that this might never be achievable. Instead, NEHRP shifted focus toward mitigating the risks of earthquakes to people, property, and the environment. In 2004, a second reauthorization transferred the lead agency responsibilities from FEMA to NIST and introduced a new governance structure. These federal agencies and governance bodies continue to support ShakeAlert but only as an inconsequential component of their respective research and mission areas.

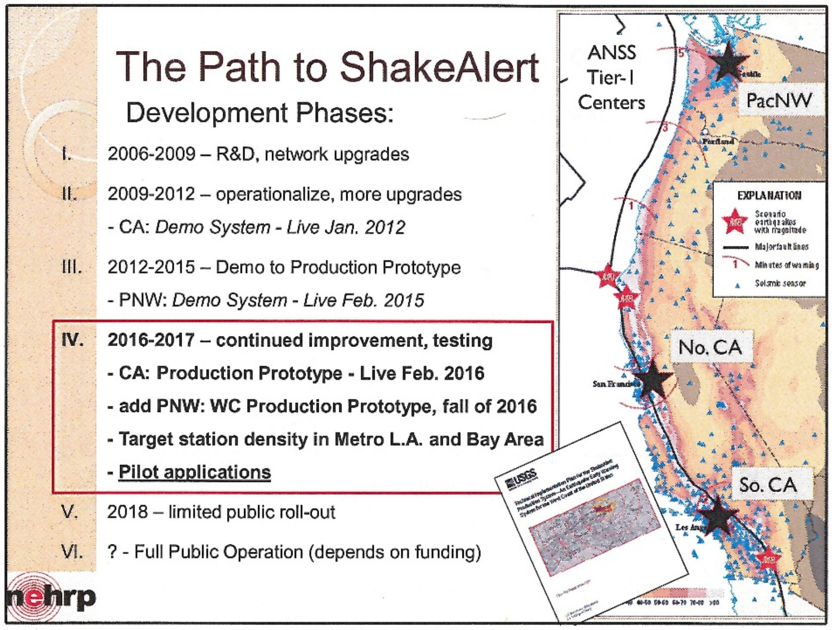
[83] Source: Jack Hayes, "National Earthquake Hazards Reduction Program, Program Overview" (presented to National Science and Technology Council Subcommittee on Disaster Reduction, November 2009), http://www.nehrp.gov/pdf/ppt_sdr.pdf.

C. SHAKEALERT: EARTHQUAKE EARLY WARNING IN THE UNITED STATES

Efforts have been underway since 2006 to develop ShakeAlert in California. Beginning with establishing the sensor network infrastructure, it was not until 2009 that the system became operational in a test environment. It took another three years before a demonstration prototype came online and yet four more years passed before it officially reached a production prototype for testing in California and the Pacific northwest in the fall of 2016. The most recent legislation calls for a limited public roll-out in 2018; however, USGS is not entirely sure what that will entail nor have it secured funding for the remaining sensor installations required to complete the build-out. According to a 2017 *CBS 8* news story, "California needs about 1100 of the seismic stations…Currently, the state only has about half that number."[84] Figure 10 provides a progression for ShakeAlert development thus far.

[84] "California Earthquake Early Warning System Still Years Away," *CBS 8*, last updated November 10, 2017, http://www.cbs8.com/story/36817856/california-earthquake-early-warning-system-still-years-away.

Figure 10. Progression of ShakeAlert Development[85]



ShakeAlert is a front detection system dependent on the Advanced National Seismic System (ANSS). The density of the seismic network is supplemented by the Global Seismic Network (GSN) stations and additional station nodes in targeted fault locations on the West Coast. As defined by its 2017–2027 strategic plan, the ANSS

> is a cooperative effort to collect and analyze seismic and geodetic data on earthquakes, issue timely and reliable notifications of their occurrence and impacts, and provide data for earthquake research and the hazard and risk assessments that are the foundation for creating an earthquake-resilient nation.[86]

Meanwhile, the GSN "is a permanent digital network of state-of-the-art seismological and geophysical sensors connected by a telecommunications network, serving as a multi-use

[85] Source: Bill Leith, "U.S. Geological Survey Update" (presented at meeting of Advisory Committee for Earthquake Hazards Reduction, Boulder, CO, November 2016), http://www.nehrp.gov/pdf/ACEHRNov2016_USGS.pdf.

[86] U.S. Geological Survey, *Advanced National Seismic System—Current Status, Development Opportunities, and Priorities for 2017–2027* (Circular 1429) (Reston, VA: U.S. Geological Survey, 2017), http://pubs.er.usgs.gov/publication/cir1429.

scientific facility and societal resource for monitoring, research, and education."[87] However, USGS has limited success in supporting ShakeAlert, which it claims is due in large part to budgetary restrictions and the inability over the past 40 years to implement and sustain baseline equipment requirements of the GSN and the ANSS.[88] Both of these platforms, which are core components for a successful activation of ShakeAlert in the United States, are today considered incomplete and insufficiently maintained.

To address the shortage of station density, comprehensive research, and system implementation, the USGS formally established a partnership with the state of California, creating the California Integrated Seismic Network to complement the ANSS. In 2013, California State Senator Alex Padilla introduced Senate Bill 135[89] mandating the implementation an earthquake early warning system for California. As identified in the California Earthquake Early Warning System charter,[90] California law states,

> the California Governor's Office of Emergency Services will, in collaboration with the California Institute of Technology, the California Geological Survey, the University of California, USGS, the Alfred E. Alquist Seismic Safety Commission, and other stakeholders, develop a comprehensive statewide earthquake early warning system in California through a public-private partnership.[91]

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87 "GSN—Global Seismographic Network," U.S. Geological Survey, accessed November 9, 2017, https://earthquake.usgs.gov/monitoring/gsn/.

88 U.S. Geological Survey, *An Assessment of Seismic Monitoring in the United States; Requirement for an Advanced National Seismic System* (Circular 1188) (Reston, VA: U.S. Geological Survey, 1999), http://pubs.er.usgs.gov/publication/cir1188.

89 "SB-135 Earthquake Early Warning System," California Legislative Information, accessed November 19, 2016, http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB135.

90 California Seismic Safety Commission, *California Earthquake Early Warning System: Project Charter* (Sacramento, CA: California Seismic Safety Commission, 2014), http://www.seismic.ca.gov/pdf.files/CEEWS%20Project%20Charter%202-21-14%20(2).pdf, 1.

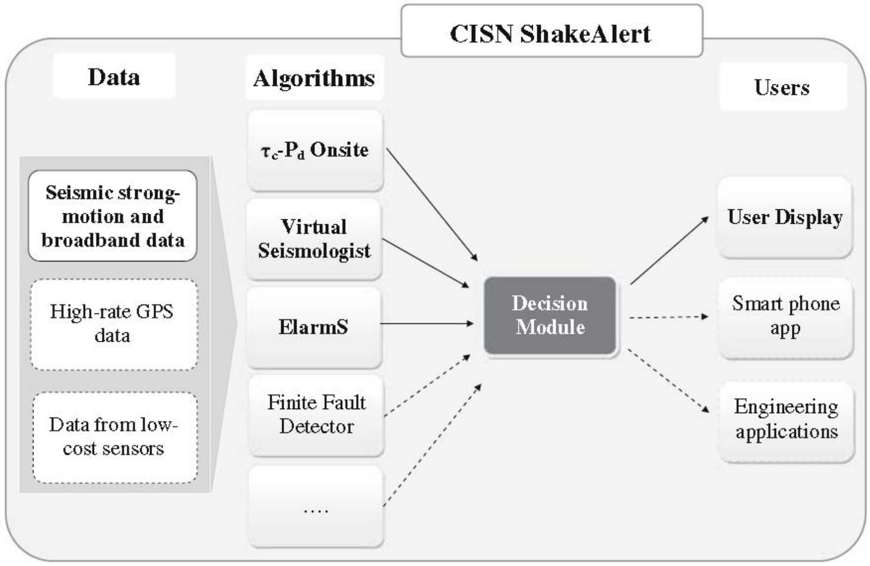
91 "SB-494 Emergency Services: Seismic Safety and Earthquake-Related Programs," California Legislative Information, accessed November 19, 2016, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB494.

As identified in the Advanced Technologies in Earth Sciences 2014 report entitled *Early Warning for Geological Disasters*,[92] ShakeAlert demonstrates the most advanced collaboration to date with the integration of a decision module algorithm called "Virtual Seismologist." This effort provides a real-time code component to the algorithm in development by the Swiss Seismological Service at ETH Zürich, with support from ETH, USGS, and from European project Seismic Early Warning for Europe, Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation, and Strategies and Tools for Real-Time Earthquake Risk Reduction.[93] Figure 11 depicts how these algorithms process data sources through the decision module and produce outputs for specific users. Although there is much promise with this module, station augmentation and further data are necessary to improve false detections, reduce interference from noise signals, and generate faster and more reliable estimates.

[92] Robert Anderson, "Early Warning for Geological Disasters: Scientific Methods and Current Practice," *Environmental & Engineering Geoscience* 20, no. 4 (2014): 404, doi:10.2113/gseegeosci.20.4.404.

[93] Ibid.

Figure 11. How ShakeAlert Processes Earthquake Alerts[94]



Real-time estimates of earthquake source and ground-motion parameters are determined by three algorithms and the decision module combines them to provide a unified ShakeAlert.

California has taken steps with its recent legislation to support ShakeAlert by appropriating supplemental funding for the sensor network and requiring a public education component. However, this is a one-time allocation, and research suggests only a sustained investment ensures adoption and integration. The primary challenge NEHRP agencies face is funding. To date, USD 120 million has been spent on ShakeAlert, and USGS projects that the project needs that another USD 38.3 million to complete the West Coast implementation, with additional annual maintenance and operations cost of USD 16.1 million.[95] As shown in Figure 12, at the current rate of development, these step increases contributing to the build-out eventually merge with the operating and maintenance costs, resulting in a completed system approximated for sometime around 2025.[96] It is important to note that the last reauthorization technically expired in 2009, yet

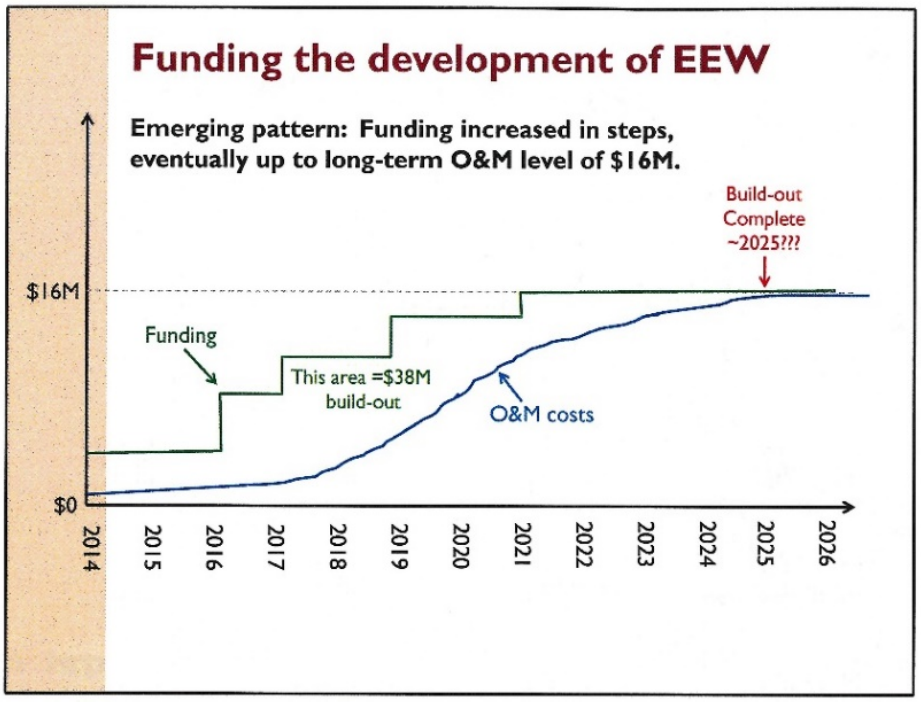
[94] Source: D. D. Givens et al., *Technical Implementation Plan for the ShakeAlert Production System—An Earthquake Early Warning System for the West Coast of the United States* (Open File Report No. 2014-1097) (Menlo Park, CA: U.S Geological Survey, Earthquake Science Center, 2014), https://pubs.usgs.gov/of/2014/1097/pdf/ofr2014-1097.pdf.

[95] Givens et al., *Technical Implementation Plan*.

[96] Leith, "U.S. Geological Survey Update."

Congress has continued to appropriate annual funding to support NEHRP in each subsequent fiscal year. Furthermore, this development timeline is only for the West Coast implementation and does not take into consideration the deficiencies with station density attributed to the ANSS.

Figure 12. Funding EEW Development [97]

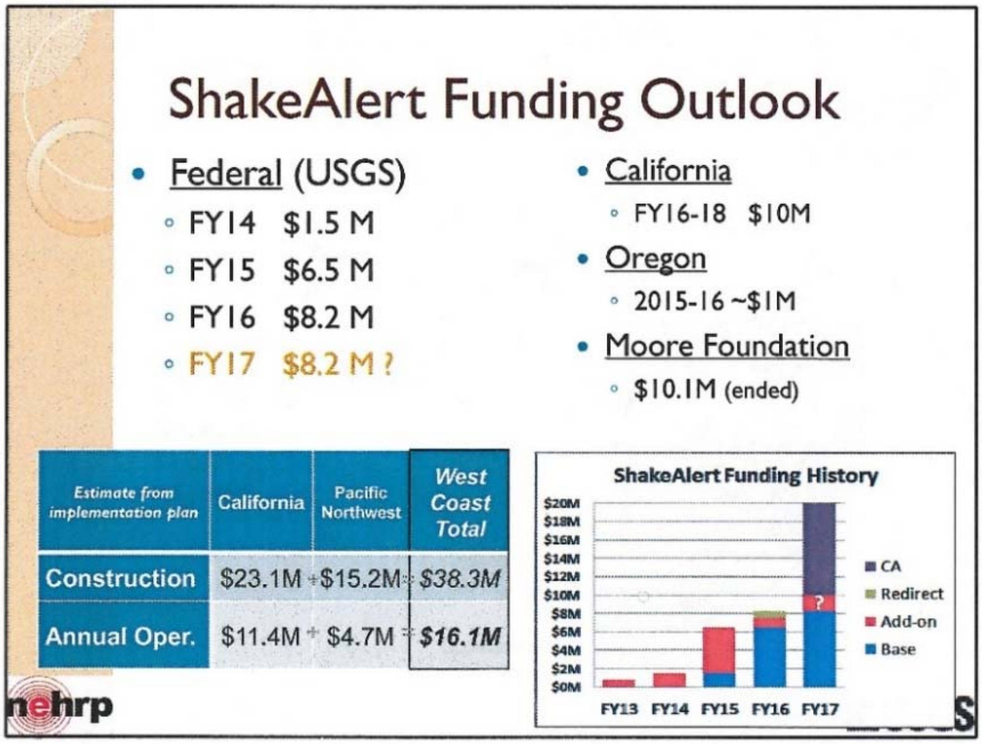


As depicted in Figure 13, funding for what many consider the most significant deliverable of NEHRP, ShakeAlert, remains a piecemeal effort. Isolated budget "carve-outs" in conjunction with inconsistent government and philanthropic contributions have served as funding mechanisms, with no strategic or sustained sourcing solutions identified. For example, USGS provided USD 7.8 million (or 13 percent) of its 2016 annual allocation towards ShakeAlert, and the state of California and the Gordon and Betty Moore Foundation have provided total funds of USD 10 million each to date.[98]

[97] Source: Leith, "U.S. Geological Survey Update," slide 12.

[98] Robert Sanders, "State Budgets $10 Million for Earthquake Early Warning," *Berkeley News*, June 30, 2016, http://news.berkeley.edu/2016/06/30/state-budgets-10-million-for-earthquake-early-warning/.

Figure 13. Overview of ShakeAlert Funding Outlook[99]



For distributing warnings, ShakeAlert is currently piloting a desktop application, and an Android mobile application is forthcoming. However, operational capability includes the integration of sending alerts through the FEMA Integrated Public Alert and Warning System (IPAWS), which broadcasts to cell phones in the form of wireless emergency alerts and through traditional media on radio and TV as part of the Emergency Alert System. Further future vehicles for dissemination of warnings include social media, National Oceanic and Atmospheric Administration (NOAA) weather radios, and the ability for the private sector to automatically receive and distribute alerts through existing communication channels.

D. STRATEGY IN THE UNITED STATES CONCLUSION

This chapter reviewed the four regions in the country with the highest probability of catastrophic earthquakes, explored what NEHRP entails, and studied ShakeAlert, the

[99] Source: Leith, "U.S. Geological Survey Update," slide 3.

United States earthquake early warning system in development today in California. A systems analysis approach to ShakeAlert is also valuable based on the collective inputs from the international seismic community. Easton's framework for the extrasocietal environment offers insights about how structures respond and what lessons have been learned. Although there is cooperation between the United States and Switzerland using the Virtual Seismologist algorithm, a broader effort to establish a collaborative framework among all international earthquake early warning systems has the potential to provide critical analyses and development opportunities. The next chapter analyzes NEHRP by applying Easton's model for political systems theory to understand ShakeAlert as an output of the conversion process.

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IV. SYSTEMS ANALYSIS: NATIONAL EARTHQUAKE HAZARDS REDUCTION

I don't make jokes. I just watch the government and report the facts.

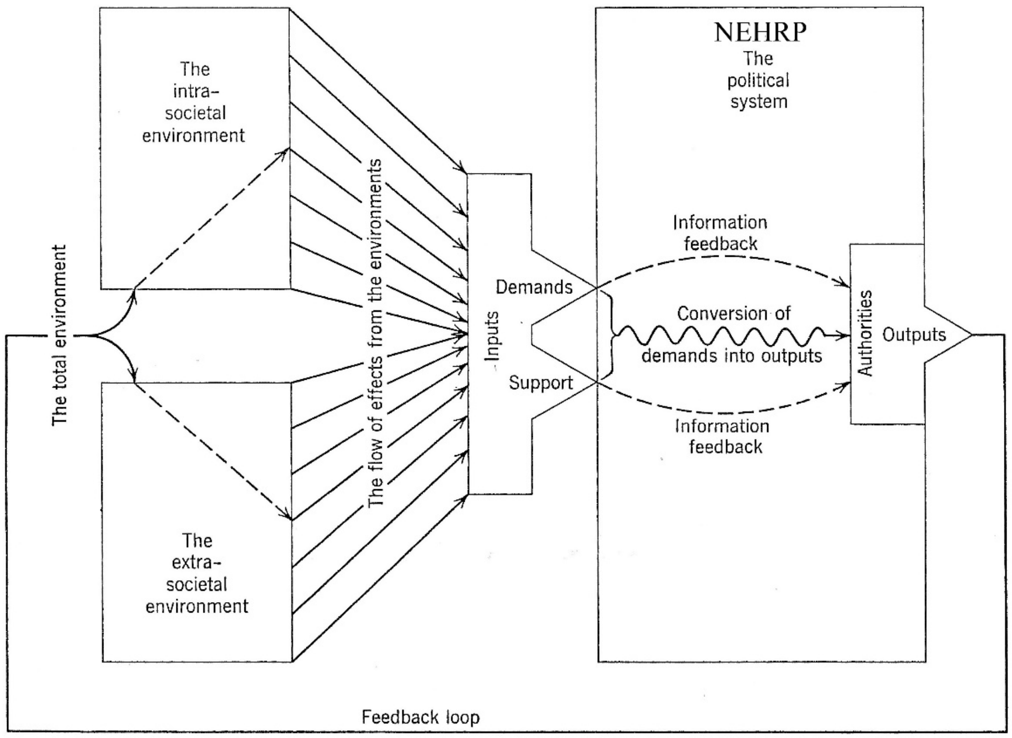
— Will Rogers, May 1933 Radio Broadcast in Washington, D.C.

To advance the implementation of ShakeAlert in the United States, it is necessary to understand the broader context of who is responsible for the system and under what requirements it operates. Thus far, Chapters I and II provided research in the form of a literature review to understand earthquake early warning systems, the behavioral conditions they institute, and a methodology for analysis using David Easton's political systems theory. Chapter III covered the United States strategy for catastrophic earthquakes: discussing the concerns about catastrophic earthquake environments, providing an overview about federal legislation authorizing NEHRP, and addressing ShakeAlert, which is currently in development to reduce the impacts from earthquake hazards through advanced warnings. Chapter IV explores the mechanics and the processes within this complex political system using Easton's dynamic response model for systems analysis to determine if the necessary elements are in place to achieve its intended function.

A. DYNAMIC RESPONSE MODEL OF A POLITICAL SYSTEM

Previous chapters have identified some challenges with NEHRP over the course of the program's history. These include but are not necessarily limited to funding mechanisms, coordination difficulties, agency budgetary procedures, and different agency priorities. The following sections analyze NEHRP in an adapted version of the dynamic response model developed by Easton, which he theorized as applying to any political system. The primary components of the model are the inputs, authorities, outputs, and systemic feedback loop. This adapted version for NEHRP is illustrated in Figure 14:

Figure 14. NEHRP Dynamic Response Model[100]



B. INPUTS: DEMANDS AND SUPPORT

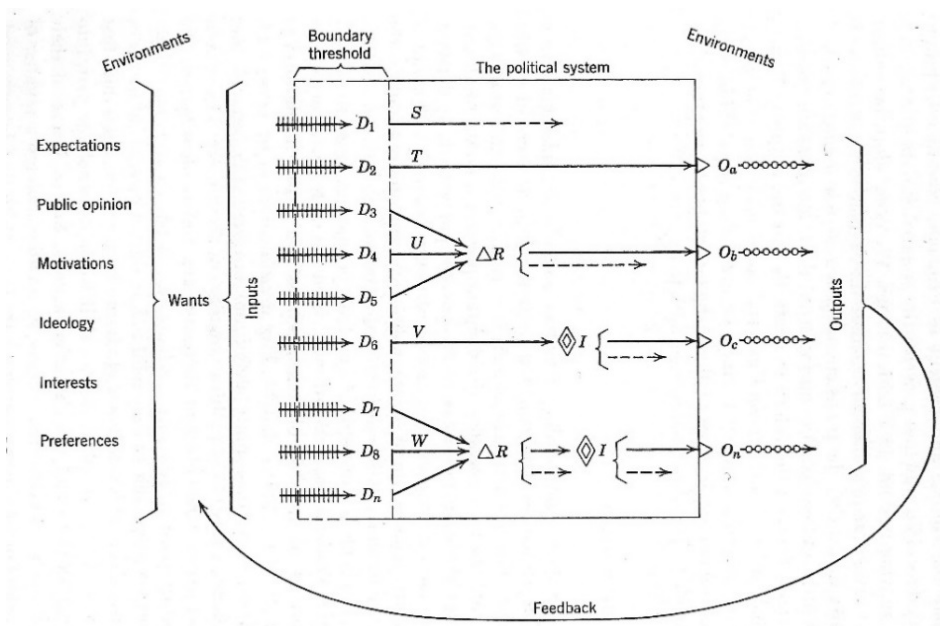
Easton describes inputs as being in the form of *support* and *demands*. Support is categorized as either overt or covert and contributes "to the promotion of goals, ideas, institutions, actions, or persons" whereby its total input is a "measure of the intensity of individual feelings and behavior together with the number of individuals involved."[101] Support is represented by the cultural characteristics for earthquake early warning support between Japan and the United States, for example. Due to the frequency of earthquake impacts on society and the collective sentiments of its members, Japan has a high degree of supportive actions for the development and implementation of its earthquake warning system. In contrast, members of the U.S. population experience infrequent earthquakes of significant ground motion and therefore individual feelings for the necessity of a system do not result in a combined effect of its members to create overt support.

[100] Adapted from: Easton, A Systems Analysis of Political Life, 30.

[101] Easton, A Systems Analysis of Political Life.

Easton defines demands as "an expression of opinion that an authoritative allocation with regard to a particular subject matter should or should not be made by those responsible for doing so."[102] Demands must come direct and explicit form and should not be confused with *wants*. Wants are first generated outside of the political system as part of the total environment and then flow into the system through either the *intrasocietal* or *extrasocietal environments*. These may include expectations, opinions, motivations, ideologies, interests, and statements of preferences. Figure 15 illustrates the process of conversion associated with wants into demands whereby they are shaped into a priority ranking and can be consolidated or reduced. Once within the political system, these demands undergo a second conversion process, turning from demands into issues and then into outputs.

Figure 15. Demand Flow Patterns[103]



Wants are converted to demands (D), managed based on type (S through W), reduced as necessary (R) into issues (I), and ultimately into outputs (O)

[102] Ibid.

[103] Source: Easton, *A Systems Analysis of Political Life*.

The corresponding wants for NEHRP include the expectation that authorities will protect society from natural disasters or public opinion that assumes because other countries have earthquake early warning systems, then the United States should have one as well. Motivations for ShakeAlert could be because people sympathize with others they see in distress during disasters or the ideology of a government performing its civic duty and providing services. Interests could be projected subjectively or objectively; however, unless they rise to the level of authoritative action, they merely that—an interest not necessarily a demand. Finally, wishes and desires as preferences do not constitute a call to action itself, absent any verbal or formal request to act.

The process of how communities convert wants of avoiding risk into actionable demands illustrates this flow pattern in Easton's model. The ability to measure seismic risk across the country is critical to how states and local communities plan for hazards. Decisions based on risk calculations determine what critical infrastructure projects, "such as road and bridge networks, rail systems, potable and wastewater systems, voice and data communications, and the power grid will be funded and prioritized."[104] Concurrently, these calculations also provide insights about potential direct economic losses from an incident such as structural and nonstructural building costs, content damages, and business inventory and interruption losses. Furthermore, indirect economic losses are also delineated, such as impacts to the agricultural, industrial, manufacturing, transportation, and utility sectors. Ultimately, these assessments inform the authorities about development strategies for land use and built environments at all levels of government.

As research and science continue to identify the hazards associated with seismic risk, there is a natural tendency to increase the scope of the program. While all states have some potential for earthquakes, "42 of the 50 states have a reasonable chance of experiencing damaging ground shaking from an earthquake within 50 years (the typical

[104] *Subcommittee on Research and Technology Hearing—A Review of the National Earthquake Hazards Reduction Program, Committee on Science, Space, and Technology, Hearing Charter* (113th Cong.) (2014), https://science.house.gov/legislation/hearings/subcommittee-research-and-technology-hearing-review-national-earthquake-hazards.

lifetime of a building)."[105] Scientists also conclude "16 of those states have a relatively high likelihood of experiencing damaging ground shaking. These states have historically experienced earthquakes with a magnitude 6 or greater."[106]

Earthquakes are not simply the result of natural conditions but do in fact include human-made causes. For example, an area where these studies have recently expanded and pose new challenges for NEHRP is induced seismicity. Typically caused by drilling operations, the process of hydraulic fracturing, commonly referred to as "fracking," is a well stimulation technique that injects high-pressure liquid deep underground for resource extraction to the surface. In 2013, ACEHR called for studies of induced seismicity, particularly in the central and eastern United States as it relates to oil and gas exploration and production as well as the increase in deep-well injections and disposal of oilfield brines, produced water, and flow-back water from hydraulic fracturing activities.[107] During 2016, a series of concerning earthquake events led to the suspension of several well operations and led to the state of Oklahoma regulators to develop a fracking plan. This example and others like it widen the aperture to potential newcomers to the total environment. Through the application of Easton's theory as a framework to NEHRP, this increases the management of additional inputs, which require conversion from wants into demands, applying further stresses on the system for prioritizing outputs.

With the continuous expansion of stakeholders involved with seismic risk, it is critical to incorporate *support* appropriately through the flow of effects within the intrasocietal and extrasocietal environments. Easton refers to stresses on a political system that can jeopardize support for that environment and "where such support threatens to fall below a minimal level, regardless of the cause, the system must either provide mechanisms

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[105] "USGS Updates National Seismic Hazard Maps: Sixteen States Deemed 'High Risk' in Latest Revision," Building Design + Construction, July 30, 2014, https://www.bdcnetwork.com/usgs-updates-national-seismic-hazard-maps.

[106] Jessica Robertson and Mark Petersen, "New Insight on the Nation's Earthquake Hazards," *Science Features* (blog), last updated July 17, 2014, https://www.usgs.gov/blogs/features/usgs_top_story/new-insight-on-the-nations-earthquake-hazards/.

[107] Folger, *National Earthquake Hazards*.

to revive the flagging support or its day are numbered."[108] As an example, according to the Director of the Illinois Emergency Management Agency, Jonathon Monken, in his 2013 testimony during a hearing before the Subcommittee on Research and Technology Committee on Science, Space, and Technology of the House of Representatives regarding NEHRP:

> This program absolutely deserves to be a legislative priority and balance should be restored in terms of how the program is governed and funded. While emergency management plays a significant role in earthquake preparation, response, and mitigation, only 1 of the 15 members of the NEHRP Advisory Committee actually comes from the emergency management profession.[109]

Although contributing to some extent as a member of the intrasocietal environment, the emergency management community will significantly increase its contributions of inputs when ShakeAlert launches. If the proper implementation of this output extends value to emergency management communities, and in turn society, then the systemic feedback loops will be productive. Absent this value, stress will occur, and NEHRP will lose support. ShakeAlert is the intended output that serves this community and the feedback from this stakeholder group has undoubtedly been voiced as support, politically and otherwise, warranting the demand.

C. NHERP POLITICAL SYSTEM: THE AUTHORITIES

Authorities include members of a system who "engage in the daily affairs of a political system; they must be recognized…as having the responsibility for these matters; and their actions must be accepted as binding…as long as they act within the limits of their roles."[110] The authorities comprising this system are the ICC, ACEHR, and the four agencies responsible for the implementation of NEHRP. Figure 16 is an adaptation of Easton's model for this thesis applied to the NEHRP political system and depicts the recognized authorities in relation to the total environment. Their respective societal

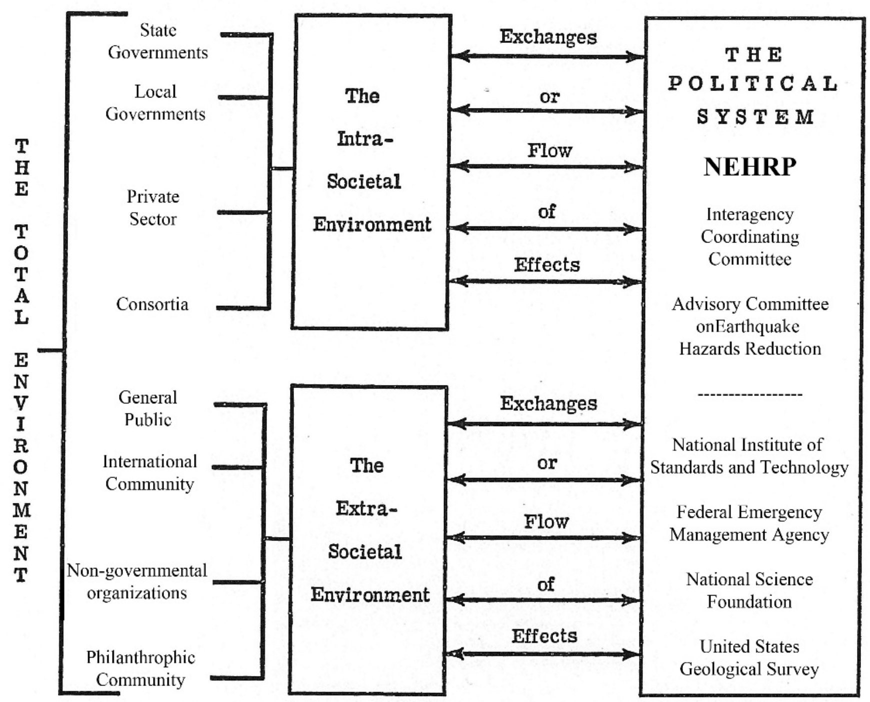
[108] David Easton, *A Framework for Political Analysis* (Englewood Cliffs, NJ: Prentice-Hall, 1965).

[109] *Subcommittee on Research and Technology Hearing*.

[110] Easton, *A Systems Analysis of Political Life*.

environments and corresponding contributors illustrate the exchanges or flow of effects to the authorities.

Figure 16. NEHRP: The Total Environment[111]



NEHRP made an effort to establish a system for the program to remain legitimate and align with the demands outlined by Congress. In 2005, NEHRP published the *Interim Report on NEHRP Performance Measures* in attempt to prescribe a methodology for tracking goals and objectives for the agencies.[112] In part, this was driven by the requirements of the OMB to provide documentation pertaining to the Government

[111] Adapted from: Easton, *A Framework for Political Analysis*, 75.

[112] National Earthquake Hazards Reduction Program [NEHRP], *Interim Report on NEHRP Performance Measures* (Washington, DC: National Earthquake Hazards Reduction Program, 2005), http://nehrp.gov/pdf/interim_report_2005.pdf.

Performance and Records Act of 1993[113] and the Program Assessment Rating Tool.[114] The subcommittee that developed this methodology recommended an evaluation system to measure performance and ensure continuity with the strategic goals and objectives of NEHRP. Figure 17 demonstrates how the authorities structured the workflow associated with the responsible agencies.

Figure 17. NEHRP Research-to-Practice Pipeline[115]

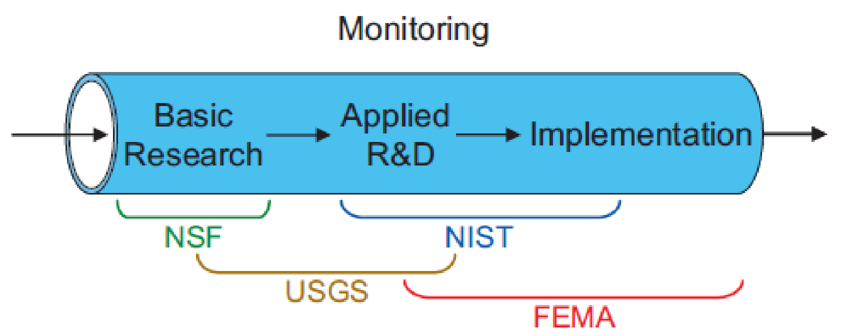


Figure 3: NEHRP Research-to-Practice Pipeline

This analysis shows that this level of strategic planning and coordination for transparency and accountability remains as the most prominent level of effort to date for NEHRP. With that said, the 2005 interim report also noted the corresponding challenges in that each agency's "missions and programs differed, their performance goals, measures, targets and timeframes differed."[116] It is important to note that per Public Law 108-360, the 2004 Reauthorization of NEHRP, the ICC is required to meet "not less than 3 times a year at the call of the Director…shall oversee the planning, management and coordination

[113] "S.20—Government Performance and Results Act of 1993," Congress, accessed October 15, 2017, https://www.congress.gov/bill/103rd-congress/senate-bill/20.

[114] U.S. Government Accountability Office, *Program Evaluation: OMB's PART Reviews Increased Agencies' Attention to Improving Evidence of Program Results* (GAO-06-67) (Washington, DC: U.S. Government Accountability Office, 2005), https://www.gao.gov/products/GAO-06-67.

[115] Source: NEHRP, *Interim Report*, I-5.

[116] NEHRP, *Annual Report* (2014).

of the Program…develop a strategic plan…and transmit an annual report."[117] However, the ICC has met only once in at least the last three years,[118] the last strategic plan was for 2008–2013, it has failed to produce a subsequent plan, and the last annual report was published in 2014. This lack of aptitude in managing NEHRP incapacitates the environments that foster the necessary demands, based on want conversion and feedback to produce exchanges or flow of effects into the NEHRP political system. To try and assess why this breakdown is occurring, it is necessary to examine how each agency is functioning in its current role.

1. National Institute of Science and Technology

With the 2004 NEHRP reauthorization, the lead agency responsible for the overall program transitioned from FEMA to NIST. In support of developing tools, such as performance-based seismic engineering, NIST primarily works on problem-focused research. NIST is responsible for publishing technical briefs that serve as aids in the efficient transfer of research into practice to reduce losses resulting from earthquakes.[119] These can include studies on subjects such as reinforced masonry, braced frames, load systems, and concrete diaphragms. The National Research Council recommended in 2011 that NIST should develop guidelines for earthquake-resilient lifelines systems for deliverables such as "manuals of practice and model codes for seismic design and retrofit of buildings, lifelines, bridges, and coastal structures."[120] However, the study did cite that this task was not achievable without substantial increases to existing funding levels.[121] NIST continues to receive the least amount of funding annually from NEHRP

[117] National Earthquake Hazards Reduction Program Reauthorization, Pub. Law No. 108-360 (2004), https://www.hsdl.org/?abstract&did=29333.

[118] Hayes, "NEHRP: Program Overview" (2016).

[119] "Prof. Ben Schafer Co-Authors New Seismic Design Technical Brief Based on American Iron and Steel Institute Standard," Johns Hopkins, November 18, 2016, https://engineering.jhu.edu /civil/2016/11/18/prof-ben-schafer-co-authors-new-seismic-design-technical-brief-based-american-iron-steel-institute-standard/.

[120] National Research Council, *National Earthquake Resilience*.

[121] Ibid.

appropriations, approximately USD 4 million of the total USD 128 million average allocations each of the past five years.[122]

2. Federal Emergency Management Agency

FEMA receives the second lowest amount of NEHRP funding with approximately USD 8 million of the annual appropriation.[123] The agency must provide three core functions in promotion, mitigation and response efforts. Promotion includes outreach, education, and training about seismic safety, public awareness, and planning initiatives. Mitigation covers building codes and standards, critical infrastructure and lifeline systems and grant opportunities for states to leverage. Education and training entail programmatic delivery of earthquake hazard courses and the promotion of building practices and educational materials for national distribution. Furthermore, response efforts involve adequate capabilities to support state and local governments in the event of an earthquake disaster and successfully transition into long-term recovery.

Concerning the appropriate role for federal, state, and local governments in an earthquake hazards reduction preparedness strategy, it is essential to recognize the statutory responsibilities of each party as they stand today. Ultimately, disasters are local, and the responsibility for preparedness lies with the whole community. The state and the federal governments serve as support mechanisms when an earthquake has overwhelmed a local jurisdiction, and it has exhausted all of its resources. For this reason alone, the local governments must ensure adequate planning for and mitigation against disasters, and that they have the proper resources to deal with disasters. Local hazard mitigation plans accomplish this by identifying gaps and vulnerabilities, which lead to local investment, training, and exercises, and as a result, prepares a community to be able to respond and recover effectively.[124]

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[122] Hayes, "NEHRP: Program Overview" (2016), slide 5; NEHRP, *Annual Report* (2014), 12.

[123] Ibid.

[124] Christine Becker, "Disaster Recovery: A Local Government Responsibility," Alliance for Innovation, November 6, 2012, http://transformgov.org/en/Article/102674/Disaster_Recovery__A_Local_Government_Responsibility.

Prior to fiscal year (FY) 2013, FEMA disseminated funding support for earthquake hazards reduction through the State Assistance Program. However, after a legal determination of 44 Code of Federal Regulations, Parts 361.4[125]–361.5,[126] beginning in the fourth year of funding and future years of the direct cooperative agreements, each state or territory had to match any FEMA funding with a direct cash match contribution, which is one dollar of state or territorial funding for every one dollar provided to it. Unfortunately, this funding has disappeared because less than half of the states could meet the match.[127] Director of the Illinois Emergency Management Agency, Monken, furthered the argument by stating,

> The need for coordination between all levels of government has never been greater, and yet the program continues to lag behind at the federal level because of FEMA's NEHRP office being buried and fragmented within the agency.[128]

By removing the funding mechanism at the state level, the efforts of local governments to plan, train, and exercise for this unique hazard have been decimated, leaving local communities unprepared to manage the consequences of these disasters.

As a result, FEMA pursues an alternative approach by distributing funds to NEHRP's earthquake consortia and partners. Organizations receiving FEMA support now include four regional earthquake consortia: Cascadia Region Earthquake Workgroup , CUSEC, Northeast States Emergency Consortium, the Western States Seismic Policy

[125] Matching Contributions, 44 C.R.F., § 361.4, (2002), https://www.gpo.gov/fdsys/pkg/CFR-2002-title44-vol1/pdf/CFR-2002-title44-vol1-sec361-4.pdf.

[126] Criteria for Program Assistance, Matching Contributions, and Return of Program Assistance Funds, 44 C.R.F., §361.5 (2002), https://www.gpo.gov/fdsys/pkg/CFR-2002-title44-vol1/pdf/CFR-2002-title44-vol1-sec361-5.pdf.

[127] National Earthquake Hazards Reduction Program, *Effectiveness of the National Earthquake Hazards Reduction Program* (Washington, DC: National Earthquake Hazards Reduction Program, 2015), http://nehrp.gov/pdf/2015ACEHRReportFinal.pdf.

[128] *Subcommittee on Research and Technology Hearing*.

Council, and four partners: EERI, Federal Alliance for Safe Homes, Inc., Outreach Process Partners, LLC, and Southern California Earthquake Center.[129]

To confirm Monken's point about the "office being buried and fragmented within the agency," FEMA embeds responsibility for managing NEHRP within its Federal Insurance and Mitigation Administration, Risk Reduction Division, Building Science Branch. FEMA headquarters allocates eight positions at along with a part-time staff representative from each of the 10 FEMA regional offices.[130] However, a number of those positions have been frozen, lost due to agency reductions, or are currently vacant.[131] This only furthers the concern about capability and increases the agency's vulnerability for program support from the total environment. Lastly, FEMA plays no role in the development of ShakeAlert.

3. United States Geological Survey

The USGS is the largest recipient of NEHRP funding on an annual basis, averaging USD 61 million per year over the last six years.[132] The agency handles extensive earth sciences research, but its primary responsibility within NEHRP starts with earthquake monitoring and notification. The agency operates the National Earthquake Information Center and works internationally for the exchange of earthquake information. USGS is also accountable for the development and maintenance of the ANSS and the production of seismic-hazard maps for research and practitioner purposes. Figure 18 represents the FY16 budgetary allocations.

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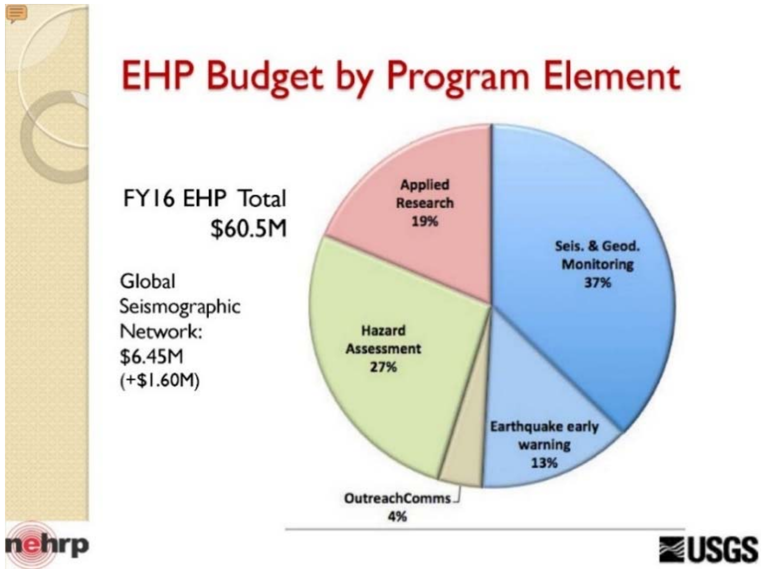
[129] Federal Emergency Management Agency, *The FEMA National Earthquake Hazards Reduction Program Accomplishments Report* (Washington, DC: Federal Emergency Management Agency, 2014), https://www.fema.gov/media-library-data/1445956390866-521590815d20178f79eba957fa0a7b44/NEHRP_Report_FY2014.pdf.

[130] *Subcommittee on Research and Technology Hearing*.

[131] Edward M. Laatsch, "NEHRP ACEHR Meeting FEMA Update" (presented at meeting of Advisory Committee for Earthquake Hazards Reduction, Boulder, CO, November 2016), http://www.nehrp.gov/pdf/ACEHRNov2016_FEMA.pdf.

[132] William Leith, "USGS Update for ACEHR" (presented at Advisory Committee on for Earthquake Hazards Reduction, Gaithersburg, MD, March 2016), http://www.nehrp.gov/pdf/ACEHRMar2016_USGS.pdf, slide 5.

Figure 18. USGS Earthquake Hazards Program Budget by Element[133]



As for its governance role, the USGS implemented internal measures establishing the National Earthquake Prediction Evaluation Council (NEPEC), comparable to CEPEC mentioned earlier. It is the responsibility of NEPEC to provide advice and recommendations to the USGS director about forecasts to support warnings of impending geological disasters; however, protocols on a national level have yet to be established.[134] This output has significant ramifications on many levels and has a direct correlation to ShakeAlert.

With the FY17 funding request, an understanding of how inputs are flowing through the decision conversion process to produce outputs regarding the USGS Earthquake Hazards Program budget would be beneficial. According to the NEHRP FY14 report, at year's end, 93 percent of planned equipment upgrades for the entire GSN were completed yet GSN was allocated USD 8.4 million and USD 13.3 million in FY15 and FY16, respectively.[135] However, Figure 19, presented by USGS at the 2016 NEHRP

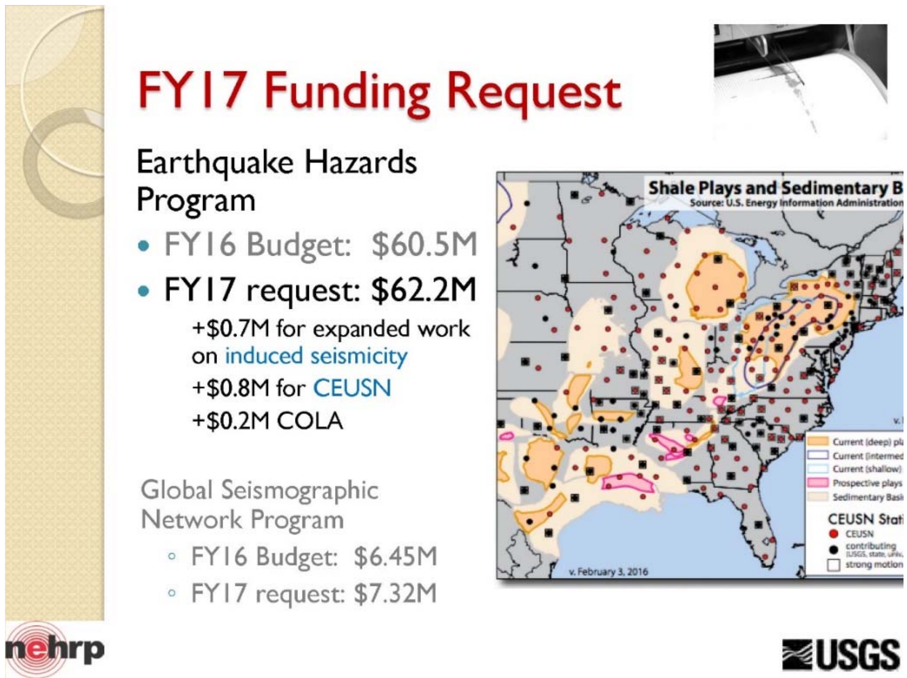
[133] Source: Leith, "USGS Update for ACEHR," slide 6.

[134] National Research Council, *National Earthquake Resilience*.

[135] NEHRP, *Annual Report* (2014), 11–12.

annual meeting, recognizes USD 6.45 million in FY16 and a request for FY17 of USD 7.32 million.[136]

Figure 19. FY17 Earthquake Hazards Program Funding Request[137]



Aside from the discrepancy in the allocated amounts, a feedback the intrasocietal environment could raise a concern as to what additional costs are required at such a significant amount to finalize the outstanding seven percent of equipment. Furthermore, what is the trajectory of spending requirements moving forward? Perhaps most importantly, who decides that this particular expenditure is a higher priority than ShakeAlert, or other outputs for that matter? Could that allocation be absorbed elsewhere? The systems analysis could not identify a clear association of internal USGS decisions corresponding to NEHRP goals.

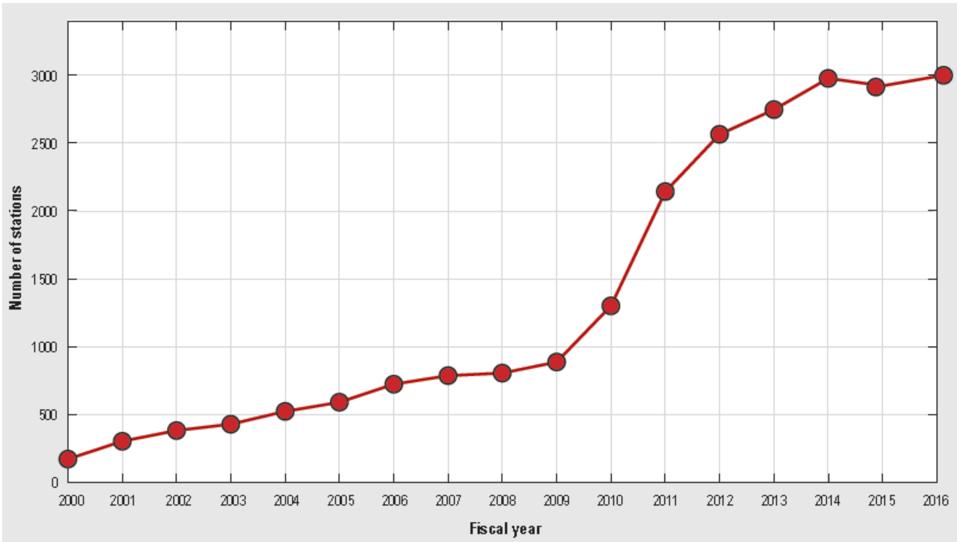
Figure 20 shows a chart of the progression of seismic station installations for the ANSS. As described in the recently released 2017–2027 strategic plan in USGS Circular

136 Leith, "U.S. Geological Survey Update," slide 6.

137 Source: Leith, "U.S. Geological Survey Update," slide 6.

1429,[138] without the influx of funding in 2010–2012 from the American Recovery and Reinvestment Act, the target of 7000 stations identified in the 1999 strategic plan in USGS Circular 1188,[139] would be even further behind schedule.

Figure 20. Growth of the ANSS Seismic System Stations[140]



The inputs based on Easton's support can be raised here. If an agency specifies a target in its 1999 strategic plan to accomplish a specific number of stations, and 17 years later, it has significantly missed its objective, where were the management and feedback loop opportunities to capture this deficiency? More importantly, has an analysis of the intrasocietal or extrasocietal environments been entertained to look at how new technologies over the years could have either decreased costs or presented alternative solutions to advance or expedite delivery?

4. National Science Foundation

Operating as an individual federal agency, the NSF supports research and education across all fields of science and engineering. With an overall FY16 budget of USD 7.5

[138] U.S. Geological Survey, *Advanced National Seismic System*.

[139] U.S. Geological Survey, *An Assessment of Seismic Monitoring*.

[140] Source: U.S. Geological Survey, *Advanced National Seismic System*.

billion, NSF funding allocations reached all 50 states through grants to nearly 2,000 colleges, universities, and other institutions.[141] Approximately USD 54 million annually is allocated to the NSF through NEHRP appropriations for its continued research to improve safety through building performance, lifeline, and structural stability in partnership with private sector entities and professional societies.[142]

Through this funding, the NSF develops and archives most research and literature from science and technology departments within academia in support of earthquake hazards reduction, but its work is limited in terms of applied science. Much of the 2005–2014 NSF funding allocation has gone towards the management of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES),[143] which is a collection of 14 experimental equipment sites for testing design and construction practices to mitigate earthquake damage. Furthermore, NSF invests heavily in a cyberinfrastructure collaboration hub to connect the sites, and it is in the process of migrating to a platform called the Natural Hazards Engineering Research Infrastructure (NHERI). The challenge with academia is that there is no specific charge to conduct research or studies with regard to a NEHRP output aside from the principal goal of earthquake hazards reduction. Except for a small few, most universities associated with this earthquake funding do not express interest in earthquake early warning research or are not required to pursue it. Instead, they are developing initiatives on a project-by-project basis with minimal oversight or integration with the overarching goals of NEHRP. Most of their efforts instead gear toward geological sciences, for studies regarding mitigation or engineering purposes, such as building codes and standards.

NSF uses its NEHRP allocations with minimal connectivity back to the requirements of the program. ACEHR recommended in the 2017 report for the NSF to identify

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[141] "About NSF—Overview," National Science Foundation," accessed October 15, 2017, https://www.nsf.gov/about/.

[142] Ibid.

[143] "NEES Overview," NEES Hub, accessed April 29, 2017, https://nees.org/about/overview.

> how current NEHRP-related investments contribute to NEHRP strategic goals and plans…devise a reporting and information-sharing approach...fund a workshop or other forum on past and future opportunities….more fully engage NEHRP partner agencies….foster the translation of research accomplishments into demonstrable advances of earthquake resilience.[144]

ACEHR is essentially stating that there is no clear identification of what NSF is doing will their NEHRP funding allocations, and they struggle to align outputs with strategic goals.

D. OUTPUTS: DECISIONS AND POLICIES

Outputs "represent a method for linking up what happens within a system to the environment through the unique behavior related to the authoritative allocation of values."[145] In the analysis of the model to NEHRP, ShakeAlert is representative of an output of the system. Other outputs include other solutions, such as ANSS, GSN, technical briefs, building codes, training, exercises, and so forth. Collectively, these represent the decisions and policies that NEHRP has allocated through its authority as what it considers to be of value for society. For a system to persist as Eason describes, these outputs need to

> …meet the existing or anticipated demands of the members of a system. They will do this either by modifying environmental or intrasystem conditions so that the original circumstances that gave rise to the demands no longer exist, or they may take steps to create this impression in the minds of the members, even though it in fact nothing other than the image has been changed. Failing this, the authorities through the outputs may coerce the members into continuing to support a system even though no efforts are made to satisfy the demands.[146]

ShakeAlert is dangerously close to operating in this space. Absent any significant growth of station density and implementation strides with communication capabilities for distributing alerts, the authorities may soon find themselves as failing to convince society that progress is being made and thus not satisfying their demands.

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[144] Advisory Committee on Earthquake Hazards Reduction [ACEHR], *Effectiveness of the National Earthquake Hazards Reduction Program* (Washington, DC: Advisory Committee on Earthquake Hazards Reduction, 2017), http://nehrp.gov/pdf/11Sept2017_Final_ACEHRReport%20pg11%20fixed.pdf.

[145] Easton, *A Framework for Political Analysis*.

[146] Ibid.

Easton's model identifies one method that could enhance the support for ShakeAlert, incorporating additional stakeholders that could contribute toward the effort. Within the original act of Public Law 95-124, under §5 of 42 U.S. Code 7704, the NEHRP initially called for participation from USGS, NSF, DOD, Department of Housing and Urban Development, National Aeronautics and Space Administration (NASA), NOAA, National Bureau of Standards, Energy Research and Development Administration, Nuclear Regulatory Commission (NRC), and the National Fire Prevention and Control Administration.[147] Congress subsequently merged the National Bureau of Standards and the Energy Research and Development Administration into NIST. Also, the disaster mission under the Department of Housing and Urban Development, along with the National Fire Prevention and Control Administration transitioned, in 1979 with the establishment of FEMA.

Surprisingly, DOD, NASA, NOAA, and the NRC do not play a role today in NEHRP in terms of converting demand into outputs as recognized authorities. Overall, the charge of NEHRP remains mostly unaffected and assigned to the same four agencies to "advance our knowledge of earthquake causes and effects and to develop and promulgate measures to reduce their impacts."[148] In the meantime, NEHRP struggles to define a clear strategy with measurable outputs and faces challenges in demonstrating the effectiveness of its activities. This has caused concern for participating agencies about the support for and sustainability of NEHRP to persist as a federally funded priority.

Other indirect funding issues will affect USGS and NSF in the immediate future and may reduce their ability to meet their NEHRP responsibilities due to significant upcoming challenges for the agencies. For instance, the primary USGS offices responsible for NEHRP, currently located in Menlo Park, California, will be relocating to the NASA Ames Research Center in Moffett Field, California. Although many are optimistic this new operating environment's potential for new relationships and opportunities, USGS has no funding sources identified for the move. Moreover, numbers of current staff, who have vast

[147] "S.126—An Act to Reduce the Hazards of Earthquakes, and for Other Purposes," Congress, accessed October 15, 2016, https://www.congress.gov/bill/95th-congress/senate-bill/126/all-actions.

[148] National Research Council, *National Earthquake Resilience*.

institutional knowledge, are diminishing because of retirements. At the same time, the agency is having difficulty in recruiting new talent. Similarly, NSF has acknowledged staffing concerns at the annual ACEHR meeting and is completing its relocation from Arlington to Alexandria, Virginia in 2017.

In looking at the big picture, only one study commissioned by NEHRP has considered the cost estimates of what it would involve to get many of the NEHRP initiatives operational and to identify sustainment-funding requirements.[149] The proposed plan, conducted by EERI in 2003, underwent further review in 2011 by the National Research Council. According to the council,

> The cost of the plan was estimated at $358 million per year for the first 5 years of a 20-year program of funding for activities within the NEHRP agencies. The total estimate for the 20-year plan, including capital investments, was $6.54 billion, with the expectation that funds would ramp up at a 15 percent annual rate over the first 5-year period of the Plan[150]

Comparing these figures to congressional appropriations thus far exposes a glaring gap between federal funding support and what is required to achieve realistic programmatic goals.

Some might argue that building seismic networks, establishing guidelines, and ensuring program sustainability should be the stress-free part. The most significant challenge is the ongoing education for earthquake preparedness. Education requires a consistent and broad campaign to include messaging, training, and exercises at all levels of government, including the private sector and the general public. This must be accomplished in all jurisdictions, across all cultures, and among all generations, continuously over time. At the local level, this includes preparedness measures pre-incident as well as a shared understanding for requirements post-incident, including but not limited to safety assessors, inspectors, and overall damage assessment requirements.

[149] Earthquake Engineering Research Institute, *Securing Society against Catastrophic Earthquake Losses: A Research and Outreach Plan in Earthquake Engineering* (Oakland, CA: Earthquake Engineering Research Institute, 2003), http://eeri.org/wp-content/uploads/store/Free%20PDF%20Downloads/securing_society.pdf.

[150] National Research Council, *National Earthquake Resilience*, 210.

Comprehensive research is lacking concerning the psychological impacts of warnings from ShakeAlert and the social science associated with notifications. Further assessments about community development and resiliency should capture the economic shifts that could occur from warnings as well as how long-term recovery unfolds post-incident. This list could be exhaustive, but we have not been afforded the opportunity to explore many questions because the fundamental components of the research have yet to be implemented.

Only after proper funding has finally supported the physical buildout of these seismic systems and the educational efforts have taken root can we then explore the adoption challenge that remains as the accurate measure of ShakeAlert effectiveness. Not until we can evaluate a significant number of case studies based on general public utilization will we be able to determine the extent to which this output will save lives, property, and the environment. At a point in time, when the private sector has incorporated system automation within critical infrastructure facilities, work processes integration, and internal communications protocols as routine, is where those efforts will demonstrate the value-added for industry. From a public sector perspective, the policies that remain outstanding regarding authority and responsibility for public dissemination of messaging remain elusive and untested. Lastly, from a financial sector standpoint, incentivizing insurance companies, homeowners, businesses, and capital markets to participate in the development process to buy down the risks associated with earthquake hazards can only be accomplished through a collective approach.

Presenting a case for NEHRP outputs that allocate value for society would include innovation and adaptability for emerging technologies. ACEHR appropriately outlines this in its 2017 biennial assessment to the ICC whereby recommends pursuing new opportunities with geosciences, engineering, and social sciences.[151] One example of a promising trend is probabilistic mapping. However, advances in computer modeling do not come without controversy. In a 2012 publication, authors Peresan and Panza bluntly state that "such a posteriori changes to a model are an example of "Texas sharpshooting," in which one shoots at the barn and then draws bull's-eyes around the bullet holes. They

[151] ACEHR, *Effectiveness of the National Earthquake* (2017).

amount to closing the barn door after the horse is gone."[152] In a May 2014 publication, authors Wang and Rogers take a firm stance on the time aspect of earthquake forecasting and its utility. In the article titled, "Earthquake Preparedness Should Not Fluctuate on a Daily or Weekly Basis," they present their position that

> Society's best strategy against the consequence of earthquakes is to focus on making the built environment earthquake resistant. Practical methods to minimize the consequences of ground shaking, such as sending early warning signals after the initiation of a rupture, can play important supporting roles…(1) In mitigating seismic risk, the goal is to let people stay in their buildings without fear and without getting hurt, not to tell people when to escape from their buildings. (2) Forecast of seismic hazard should be made over decades and centuries, so that society knows how to strengthen the built environment within economic constraints. (3) Except for aftershocks, the scientific community has no authoritative role to play in providing forecasts over days and weeks.[153]

As is the case with the introduction of many new technologies, arguments within the scientific community over the value and application will persist. The challenge for NEHRP is to take into consideration the appropriate balance of research, science, practical implementation, and sustainment of ShakeAlert while at the same time prioritizing this solution with other program objectives.

E. INTRASOCIETAL ENVIRONMENT: ENTERPRISE FEEDBACK

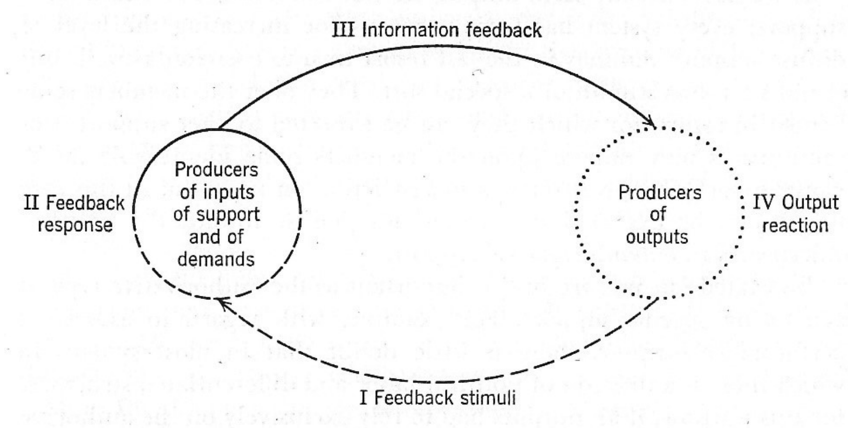
The intrasocietal environment is adapted and defined as the "enterprise environment," which includes state and local governments, the private sector, and the consortia around the country who are responsible for regional seismic planning initiatives. Each of these stakeholders plays an instrumental role in the systemic feedback loop. ShakeAlert presents a unique opportunity for the intrasocietal environment to play an integral role in the development and implementation of this output. Figure 21 outlines the four phases of the systemic feedback loop as it provides information from producers of

[152] Antonella Peresan and Giuliano F. Panza, "Improving Earthquake Hazard Assessments in Italy: An Alternative to 'Texas Sharpshooting,'" *Eos, Transactions American Geophysical Union* 93, no. 51 (2012): 538, https://doi.org/10.1029/2012EO510009.

[153] Kelin Wang and Garry C. Rogers, "Earthquake Preparedness Should Not Fluctuate on a Daily or Weekly Basis," *Seismological Research Letters* 85, no. 3 (2014): 569–571, https://doi.org/10.1785/0220130195.

inputs to create output reaction, and in turn, stimuli that become response mechanisms for future support and demands.

Figure 21. The Four Phases of the Systemic Feedback Loop[154]

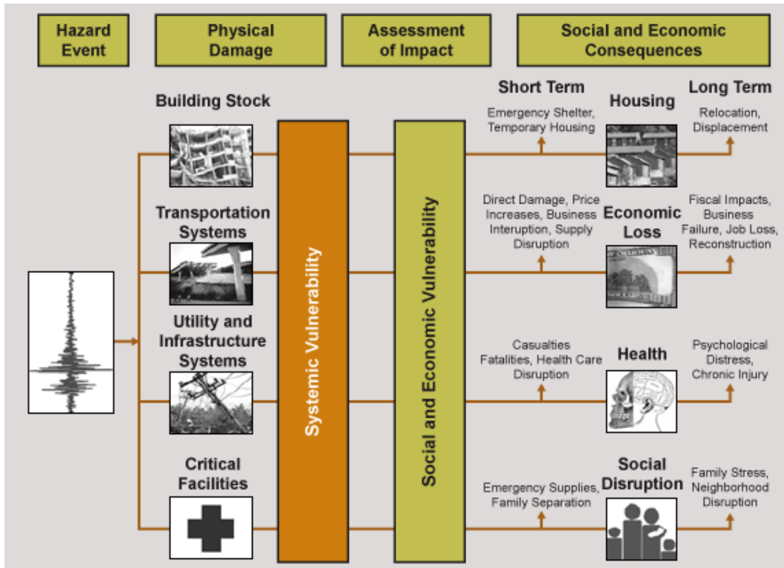


As occurred in Japan, the ability for the private sector to lead the way with system utility is exemplary of this systemic feedback loop efficiently working. As industry stakeholders defines how to best integrate solutions within their operating environments, this promotes an increase in value by reducing risk and protecting their assets, equipment, resources, personnel, and ultimately their customers.

Although it is hard to quantify because there is minimal historical data, the opportunities to decrease damages depend on the various applications of ShakeAlert in the public and private sectors. Figure 22 depicts where seismic vulnerabilities are in the physical and socioeconomic environments.

[154] Source: Easton, *A Systems Analysis of Political Life*, 381.

Figure 22. Evaluating Seismic Vulnerability and Losses Considering Both Physical and Socioeconomic Aspects[155]



Here are a few opportunities for development:[156]

- Fire station doors can automatically open to prevent from jamming.
- Heavy equipment such as trains and port facilities can stop in safe positions.
- Pipeline valves can be shut automatically, preventing spills.
- School children can drop, cover, and hold on.
- Crowds in theaters and stadiums can be forewarned and given instructions to prevent panic.
- Before aftershocks, rescue workers will have alerts for their safety.
- Elevators will stop at the nearest floor and open doors, so occupants are not trapped.
- Notifications will inform people to move away from hazards and protect themselves.
- Financial institutions can suspend or transfer critical data transfers to save vital data.

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[155] Source: "Overview," Syner-G, accessed April 29, 2017, http://www.vce.at/SYNER-G/files/project/proj-overview.html.

[156] Strauss and Allen, "Benefits and Costs of Earthquake."

- Hospitals can stop emergency and elective surgeries.
- Airports can divert inbound aircraft away from runways.
- Provide additional time to evacuate from low-lying coastal areas from a tsunami.[157]

Dr. Richard Allen outlined an example of effective earthquake early warning system implementation along with proper mitigation measures in a 2011 *Scientific American* story. He writes:

> In 2003 two earthquakes near Sendai, Japan, caused more than $15 million in losses to the OKI semiconductor manufacturing plant because of fire, equipment damage and loss of productivity. The plant had to be shut down for periods of 17 and 13 days, respectively, following the quakes. The company then spent $600,000 to retrofit the factory and to install a warning system. In two similar earthquakes since, the factory suffered only $200,000 in losses and 4.5 and 3.5 days of downtime.[158]

This example demonstrates the benefit of solutions to Easton's intrasocietal and extrasocietal environments. The inherent challenge with these solutions though, along with the potential for many others, is the requirement for a significant level of effort to educate and subsequently, design, analyze, test, and deploy. NEHRP should capitalize on many of these opportunities utilizing systems theory and the input-output model.

F. EXTRASOCIETAL ENVIRONMENT: CONSUMER FEEDBACK

For the adaptive purposes of this thesis, the extrasocietal environment is referred to as the consumer environment. The extrasocietal, or "consumer environment," includes the general public, the international community, nongovernmental organizations, and the philanthropic community. Much like the enterprise environment, each of these consumers plays an instrumental role in the systemic feedback loop yet each group follows its own

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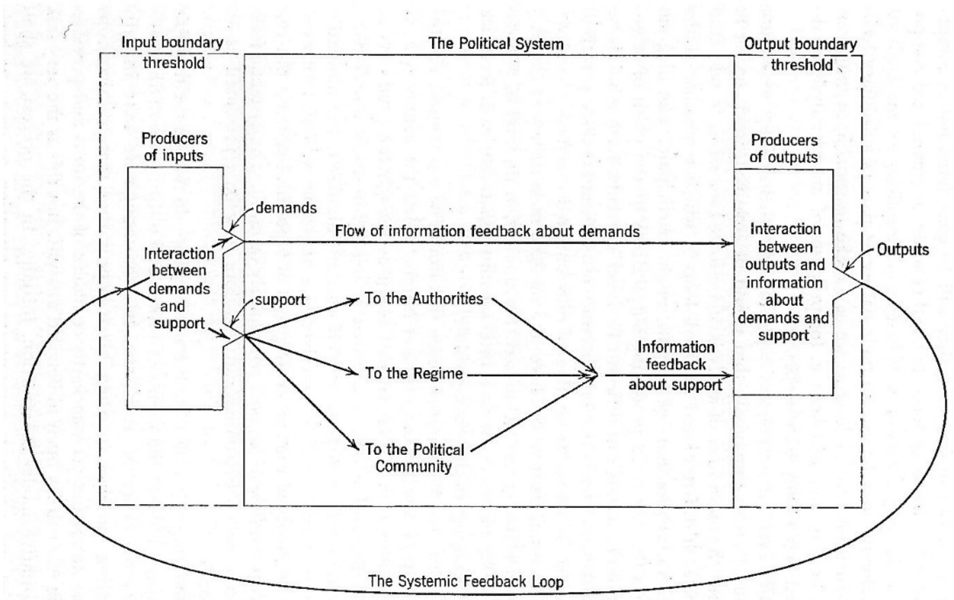
[157] "Earthquake Early Warning System," City of Los Angeles, accessed October 15, 2016, https://web.archive.org/web/20161228172833/www.catastrophicplanning.org/eew/ (original site discontinued). Material was created by the author in a report entitled *Action Project Report* that can be provided upon request: https://web.archive.org/web/20161228172833/www.catastrophicplanning.org/eew/Action%20Project-Oct9.pdf.

[158] Richard Allen, "Seconds before the Big One: Progress in Earthquake Alarms," *Scientific American*, March 11, 2011, https://www.scientificamerican.com/article/tsunami-seconds-before-the-big-one/.

unique flow of information. Consumer feedback, in Figure 23 as is depicted by Easton, passes through the domain of three entities.

Figure 23. The Systemic Feedback Loop[159]



We have already analyzed the authorities but need to consider two additional variables. The first is the regime or the "sets of constraints on political interaction in all system…broken into three components: values (goals and principles), norms, and structure of authority."[160] The second is the political community, which refers to "that aspect of a political system that consists of its members seen as a group of persons bound together by a political division of labor." [161] How this correlates to NEHRP is representative of the four responsible agencies, their relations to one another, and the commitment to their respective agency.

On the one hand, the primary allocation of funding lies with that of research and science. As was described earlier, the analysis shows a degree of struggle between the

159 Source: Easton, *A Systems Analysis of Political Life*.

160 Easton, *A Systems Analysis of Political Life*.

161 Ibid.

scientists and the practitioners. Regimes have evolved over the years with these sub allocations fueling the development of microenvironments within the authorities. Fostering an internal understanding to protect the functionality of these environments and not lose support at the expense new demands or investing in alternative outputs. ShakeAlert appears to have fallen victim to this circumstance. The question has yet to be presented to NEHRP, nor has anyone volunteered why only USD 8.2 million, or just 13 percent, of the USGS earthquake hazards program allocation goes to ShakeAlert. Who has made that determination that it is not a priority above and beyond other output expenditures? Furthermore, if ShakeAlert was initiated in 2006 and garnered political support publically by congressional representatives and state legislatures, then how can the system not even be mentioned once in the NEHRP 2009–2013 strategic plan?[162]

Regarding the political community, the analysis shows that a clear preference to support science by prioritizing funding for research laboratories and academic groups over practical application. Congruently, each responsible agency also caters to the needs and expectations of its parent agency. NSF is the most representative of this concern. The political community and regime that comprise NSF were able to convert the support for this intrasocietal environment from NEES into NHERI, which will support earthquake research but has expanded its research to include research related to windstorms.[163] This begs the question, how do windstorms relate to earthquakes? NSF agency priorities fail to demonstrate how the funding allocations correlate directly to earthquake outputs of NEHRP goals and solutions. Furthermore, with an average annual budget of approximately USD 7.5 billion, it is difficult to understand how only USD 54 million is dedicated to earthquake research and the intrasocietal environment cannot reprioritize its efforts to contribute, at least to address the immediate need, of solving the funding gap that ShakeAlert requires to launch.

[162] National Earthquake Hazards Reduction Program, *Strategic Plan for the National Earthquake Hazards Reduction Program Fiscal Years 2009–2013* (Washington, DC: National Earthquake Hazards Reduction Program, 2008), http://nehrp.gov/pdf/strategic_plan_2008.pdf.

[163] Jay M. Pauschke, "Update National Science Foundation" (presented at Advisory Committee on for Earthquake Hazards Reduction, Gaithersburg, MD, March 2016), http://www.nehrp.gov/pdf/ACEHRMar2016_NSF.pdf.

Easton speaks of specific demands of a political system based on this internal and external feedback.[164] One example of such feedback is the presumption that during catastrophic earthquakes (or any disaster for that matter) government has taken into account the possibility of such an event occurring, shaped policies, and executed solutions. Authorities are recognised as legitimate based on the premise that their policies are for the benefit of society and that their decisions are in anticipation of specific behaviors constructed upon the interests and well being of societal members. To that end, it is essential to diagnose in history how societies have responded to earthquakes for NEHRP to convert these inputs into proper outputs.

In 2010, Professors Hamilton Bean and Dennis Mileti published a report analyzing the perceptions of public warnings during large-scale disasters. They concluded there are three myths when issuing timely and efficient warnings that cost lives during disasters.[165] The first myth is that people will panic. A JMA study after the 2011 Tohoku earthquake showed, however, that as many as 85 percent of respondents felt the most significant value was understanding the situation immediately and preparing for the appropriate action in mind.[166] The report recognized that 50 percent of the respondents felt the alerts provided a feeling of safety and mental preparation as well as the having the ability to protect themselves.[167]

The second myth is that warnings must be short. Bean and Mileti accurately described the concept as seeming counterintuitive, whereby

> short messages actually slow down public action-taking because they create an "information starved" public. People at risk want to know as much as they can about pending events for which warnings are issued…Short

[164] Easton, *A Framework for Political Analysis*.

[165] Hamilton Bean and Dennis S. Mileti, *RCPGP Warning System Integration Research Project Final Report* (Baltimore, MD: National Consortium for the Study of Terrorism and Responses to Terrorism, 2010), http://www.start.umd.edu/publication/rcpgp-warning-system-integration-research-project-final-report.

[166] Miho Ohara and Atsushi Tanaka, "Study on the Changes in People's Consciousness Regarding the Earthquake Early Warning before and after the Great East Japan Earthquake—Analysis Based on Regular Disaster Information Survey Results," *Journal of Disaster Research* 8, no. sp (September 2013): 792–801, https://doi.org/10.20965/jdr.2013.p0792.

[167] Fujinawa and Noda, "Japan's Earthquake."

> warnings that do not tell the public everything they need to hear spark people at risk on a search for more information before they take protective action.[168]

According to the same study, 80 percent of those who received the warnings were prompted to act. However, Fujinawa and Noda provide further analysis, demonstrating the need for continuous education because only 61 percent took action after the warning, 17 percent tried without success, and 22 percent took no action.[169]

The third myth relates to crying wolf. The JMA report addressed the concern that false alarm warnings result in an unwillingness to respond to future warnings, but it also argues that inaction decreases when public education campaigns do not immediately follow false alarms, which angers local governments because its costs money to meet this obligation.[170] The JMA report did cite that 10 percent of respondents considered the system useless.[171] Fujinawa and Noda present further analysis by reviewing improvement requests toward system effectiveness that increased demands for further ubiquity and accuracy of warnings.[172] Finally, Ohara and Tanaka emphasized that 85.6 percent of respondents want warnings despite the possibility of the system missing a warning.[173]

Societies are willing to pay for earthquake early warning systems. A 2007 article titled "Estimating Willingness to Pay for Hypothetical Earthquake Early Warning Systems" emphasizes that those surveyed were willing to pay the equivalent of USD 38 per month to use a hypothetical earthquake early warning system.[174] Using the contingent valuation method to evaluate the benefits of an earthquake early warning system, authors Asgary, Levy, and Mehregan found that the more educated the respondents were and more

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[168] Hamilton Bean, *RCPGP Warning System Integration Research Project Final Report* (College Park, MD: START, 2010), http://www.start.umd.edu/publication/rcpgp-warning-system-integration-research-project-final-report, 35.

[169] Fujinawa and Noda, "Japan's Earthquake."

[170] Bean, *RCPGP Warning System*, 35.

[171] Fujinawa and Noda, "Japan's Earthquake."

[172] Ibid.

[173] Ohara and Atsushi Tanaka, "Study on the Changes."

[174] Asgary, Levy, and Mehregan, "Estimating Willingness," 316.

children they had, the more they were willing to pay. Based on this data, they suggest that policymakers and technology firms can utilize this information when debating optimal investments.[175] Although the validation through their investigation was limited, it does reveal a potential model for system implementation to offset a lack of funding by introducing a pay for service scheme that might be attractive to the private sector. Others may argue that preparedness behaviors increase if there is a cost associated with providing preventative measures to the end user.

Easton's model also identifies a specific input that he refers to as "support." He expresses various elements that comprise the concept of support, however, as it relates to behavioral outcomes, the idea that members of society have to some extent experienced earthquake early warning, garners an ongoing support for the authoritative efforts underway.[176] This is demonstrated by analyzing the available research on earthquake survivor responses to alerts that come predominantly from studies in Japan, Mexico, and other countries, such as China and Taiwan, that are quickly advancing their systems. The Center for Integrated Disaster Information Research at the University of Tokyo published a report in 2013 based on survey results that it conducts annually. Two particular findings demonstrate the value of training and education: The "recognition rate" identifies persons who knew about alerts and "reception experience rate" is those who received an alert.[177] Since the 2011 earthquake, almost 80 percent of the respondents know what the alerts are for, an increase of approximately 18 percent since the last survey. At the same time, persons who experienced an earthquake alert had increased nearly 28 percent. These surges could result in increased effectiveness of individual action given advanced training and education.

[175] Ibid.

[176] Easton, *The Political System*.

[177] Ohara and Tanaka, "Study on the Changes."

Table 2. Support for Alerts Based on Actual Experiences[178]

	Before 2011 Earthquake	After December 2011
Recognition Rate	**61.3%**	**79.3%**
Reception Experience Rate	**27%**	**54.9%**

The reports also capture the social benefits of earthquake early warning. More than 75 percent of respondents found the alerts useful, and many requested additional functionality, including automation such as turning on TVs and radios to receive alerts, intensity information, and instructions for proper behaviors. Of particular concern, Ohara and Tanaka indicate that the "interest in behaviors when receiving EEWs [alerts] need be enhanced by means of training and materials of EEWs in regions to which EEW have rarely been issued so far and where the reception experience rate will fluctuate at a low level."[179] This analysis demonstrates the need to ensure the appropriate levels of funding beyond just system development to include public education and training.

Japan has recognized many successes based on the outputs from its earthquake implementation strategy. After the launch of the Japanese earthquake early warning system in 2007, it broadcast 11 warnings over the subsequent 18 months. According to Allen, Gasparini, and Kamigaichi, the JMA relies on private providers and home seismometers among other methods to disseminate the warnings. In their research, they identify how 500 of these devices are located in schools and students complete three drills per year. They explain, "In the first drill, students are warned when the drill will occur; in the second, they know the week during which it will occur, and the third can be at any time."[180] These exercises as described by Allen, Gasparini, and Kamigaichi, along with regular training videos, have resulted in students' ability to get in safe areas under their desks in no more than five seconds with an audible warning.[181]

[178] Adapted from: Ohara and Tanaka, "Study on the Changes."

[179] Ohara and Tanaka, "Study on the Changes."

[180] Allen et al., "The Status of Earthquake," 688.

[181] Ibid.

Conversely, Mexico has experienced several setbacks with its implementation strategy. Mexico's earthquake early warning system, called the Sistema de Alerta Sismica (SAS), is the longest running operational in the world.[182] In his 2009 performance evaluation based on 18 years of historical data, Gerardo Suarez concluded that the SAS accuracy rate was significantly low. Furthermore, SAS lacks an integrated plan with state and federal governments and provides minimal if any education to numerous stakeholders. What is intriguing about the report is that it also included a survey of users and provides an evaluation of on the social impact of SAS along with agency measures. This data is critical to understand other how earthquake early warning systems determine the effectiveness of their implementations. This is an area where there is entirely no literature to date due to the absence of any long-term fully operational systems. Therefore, case studies are difficult to generate, reinforcing the need for a conceptual framework for interconnected systems compiling data for comprehensive analysis. Nonetheless, absent and prevalent successes that demonstrate the value of any system, the feedback loop as Easton defines it fails to increase the support required for it to be recognized as legitimate or necessary to persist.[183]

The research shows how support for these systems and the demand for performance can generate feedback and influence public policy. Bang describes this conversion process, suggesting that

> the practical task of behavioralists, on these positivist images appears solely to be one of providing public decision makers reliable technical knowledge of how to remove "dysfunctions" and "anomalies," which pose a threat to developing and sustaining social and political order.[184]

For the United States, there is great concern for the validity of ShakeAlert to be consistent and to minimize false alarms. Yes, it is true that specific behaviors can be dependent upon culture or geographic environment, but there is not enough conclusive evidence to

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[182] Gerardo Suárez, David Novelo, and Elizabeth Mansilla, "Performance Evaluation of the Seismic Alert System (SAS) in Mexico City: A Seismological and a Social Perspective," *Seismological Research Letters* 80, no. 5 (2009): 707–716, doi:10.1785/gssrl.80.5.707.

[183] Easton, *A Systems Analysis of Political Life*.

[184] Bang, "David Easton's Postmodern Images."

officially state that human behavior and reaction to earthquake early warning alerts from ShakeAlert in the United States will vary from that of Japan or Mexico. The very nature of behavior to an earthquake itself is unlike any other, and although expectations will always remain high for system performance, the limited evidence appears to demand something versus nothing and inaccuracy over nonexistence.

G. SYSTEMS ANALYSIS CONCLUSION

In this chapter, Easton's dynamic response model provided a framework to understand how NEHRP decisions are processed within this complex political system. The goal of the analysis was to determine if the necessary elements are in place for NEHRP to achieve its intended function. An analysis of each step in the model allowed for an examination of the inputs, authorities, outputs, and environmental feedback. The analysis concludes that today's model is not working and investment decisions do not reflect stakeholder priorities.

The following interpretations from the analysis of NEHRP suggests reasons why ShakeAlert is not a priority output and remains far from implementation. First, each of the authorities for NEHRP sees its respective earthquake programs as a minor part of its agency. With all due respect to those representatives managing NEHRP, they lack the rank and influence within their agency to promote the earthquake program enough to increase funding allocations. For the inputs to affect the decision process, these representatives cannot stop at the boundary; they have to add value to leadership within their agencies and show the program as a significant, necessary priority to fund.

Second, each agency underfunds its earthquake programs, which in turn marginalizes the ability for NEHRP to invest adequately in outputs, including ShakeAlert. As an example, Table 3 outlines the percentage of the overall budget dedicated to each agency's earthquake distributions for NEHRP.

Table 3. FY16 Total Agency Budgets versus NEHRP Allocations[185]

FEMA	NIST	NSF	USGS
14,169,074,000	954,000,000	7,564,000,000	1,085,000,000
8,500,000	5,200,000	54,200,000	67,000,000
0.06%	0.55%	0.72%	6.18%
7,348,000,000	*FEMA Annual Disaster Relief Fund (DRF)*		
6,821,074,000	*FEMA Budget Less DRF*		
0.12%			

These funds represent the fiscal year 2017 allocations but are consistent historically for NEHRP. USGS by far allocates the most, just over six percent of its annual budget, whereas each of the other responsible agencies contribute less than one percent. The one caveat is FEMA, which as noted is appropriated USD 7.4 billion annually for the Disaster Relief Fund.[186] However, even when calculated separately from the budget, the contribution is still inconsequential at 0.12 percent. In comparison, Japan spends the equivalent of one billion annually on earth science, the equivalent of USGS alone.

Third, the reality is that the United States has had a relatively quiet 40 years of seismic activity since the establishment of NEHRP. Aside from the 1989 Loma Prieta and 1994 Northridge earthquakes (63 and 57 lives lost respectively), there has been no significant seismic event to capture enough to increase attention for NEHRP.[187] Of the 40

[185] Adapted from: U.S. Department of Homeland Security [DHS], *Budget-in-Brief Fiscal Year 2017* (Washington, DC: U.S. Department of Homeland Security, 2016), https://www.dhs.gov/sites/default/files/publications/FY2017_BIB-MASTER.pdf; Will Thomas, "Final FY17 Appropriations: National Institute of Standards and Technology," *FYI Bulletin*, no. 59 (May 2017), https://www.aip.org/fyi/2017/final-fy17-appropriations-national-institute-standards-and-technology; Alexis Wolfe, "Final FY17 Appropriations: U.S. Geological Survey," *FYI Bulletin*, no. 63 (May 2017), https://www.aip.org/fyi/2017/final-fy17-appropriations-us-geological-survey; Alexis Wolfe, "Final FY17 Appropriations: National Science Foundation," *FYI Bulletin*, no. 55 (May 2017), https://www.aip.org/fyi/2017/final-fy17-appropriations-national-science-foundation.

[186] DHS, *Budget-in-Brief Fiscal Year 2017*.

[187] NOAA National Centers for Environmental Information Significant Earthquake Database (California+Loma Prieta+ 1989), accessed October 15, 2017, https://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1; NOAA National Centers for Environmental Information Significant Earthquake Database (California+Northridge+1994), accessed October 15, 2017, https://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1;

most significant earthquake earthquakes aside from these two since the inception of NEHRP in 1977, 21 lives were lost in total.[188]

Fourth, considering countries around the world that have moved forward with earthquake early warning system investments, two immediate observations become apparent. First, as discussed earlier, they experienced a significant seismic event costing thousands of lives in the process. Second, each of those nations faces a tremendous seismic threat in its capital. Even though Washington, DC did experience the 2011 earthquake, it is not seen as a daily possibility and does not draw the attention of politicians who appropriate funding to NEHRP authorities. Because they do not live in an environment with no-notice events, such as earthquakes, they lack the emotional connection to the threat.

The final interpretation of the analysis relates to ownership. Because no single agency owns natural hazards, there is no homebase for an earthquake program. The result is the inability to promote the issue at the highest level. Perhaps it is time for the United States to consider a separate department to deal solely with natural hazards, much like the Japanese Meteorological Agency. In his book *The Age of the Unthinkable*, Joshua Ramo eluded to such a concept by establishing a Department of Resilience, recognizing:

> …a major commitment to fostering real resilience would in turn elevate ideas…to a new level of importance…that touches everyone in the country prepares us to better deal with the unknown…resilience expands the virtue of slow-variable policies beyond their traditional domains.[189]

This could be an evolution of NEHRP from a program to a dedicated department comprised of agencies and divisions that are currently spread across multiple environments. By consolidating USGS, FEMA, NOAA, and perhaps portions of other agencies into a new Department of Resilience, we could properly focus the outputs for natural hazards research with the applied science and engineering.

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[188] "Earthquake Lists, Maps, and Statistics," U.S. Geological Survey, accessed November 29, 2017, https://earthquake.usgs.gov/earthquakes/browse/.

[189] Joshua Cooper Ramo, *The Age of the Unthinkable: Why the New World Disorder Constantly Surprises Us and What to Do about It* (New York: Back Bay Books, 2010).

V. CONCLUSION

> The earthquake is inevitable, but the disaster is not, the disaster is what the earthquake does to human structures. We change those human structures, we can eliminate the disaster.
>
> — Lucy Jones, "An Earthquake is Going to Hit L.A. Then What?" *CNN*

The United States is extremely vulnerable to catastrophic earthquakes. Congress created the National Earthquake Hazards Reduction Act in 1977, funding four federal agencies to reduce the national risk from these natural disasters and address our vulnerabilities. Over the past 40 years, the science of earthquake studies has transformed from a focus on prediction to hazard reduction. The scientific community felt early on that prediction was promising, but it came to the realization that this may never be achievable. Instead, it has shifted focus to the risks to people, property, and the environment. Researchers have developed numerous solutions or are in the process of completing solutions, such as seismic networks, building codes and standards, forecasting and warning systems, and many others, to assist all levels of government and the private sector.

As NEHRP has evolved, so to have the concepts surrounding what capabilities it can and should address. The demarcation between science and research working in concert with practical application remains elusive. These distinctions, along with arguable funding allocations, have led to a strategic inflection point in determining what inputs best guide NEHRP and ultimately what outputs best save lives, communities, property, and the environment for future earthquakes. With adequate funding and an integrated, strategic vision for the completion and sustainability of ANSS, earthquake hazard reduction can be improved and put the nation on a path toward earthquake resiliency, ensuring sustainability of the economy and communities.

In recent years, new technologies have focused on earthquake early warning have led to the development of ShakeAlert that provides real-time notifications of impending impacts before shaking occurs. Furthermore, with the newfound phenomena of induced seismicity impacting communities as oil and gas exploration expands, the scope of NEHRP increases while current funding levels remain constant. However, absent a synchronized, strategic vision as to what the scientific community requires and what specific outputs to achieve, each agency focuses on internal goals and objectives while research and implementation efforts remain extemporized and uncoordinated.

The research question asked was how can the United States increase the nation's resilience to catastrophic earthquakes? This analysis shows that Congress created NEHRP to provide that very solution. It has evolved in a manner that continues to generate significant outputs yet falls short of facilitating a shared mission to maximize national resilience. We then asked the question, why has the United States not fully implemented an earthquake early warning system? To answer this question, we used David Easton's input-output model to provide a systems analysis of a political system. We applied that model to NEHRP to gain a more comprehensive understanding of ShakeAlert. The analysis demonstrates that NHERP fails to adopt innovative approaches and has a fundamental inability to shift funding towards priorities for resilience.

Lastly, we asked, could a systems analysis approach add value toward the reduction of earthquake hazards and increase the nation's resilience? In short, yes, this approach does assist in understanding how to align strategies with outputs however it is not the single solution. What became apparent in this analysis is that although one can apply many variables to try to maximize the mechanics of the conversion of demands to outputs, Easton's concepts of the total environment warrants their own need for analysis. Establishing an artificial boundary around NEHRP does help to provide clarity for the internal situation, but the reality is there are many other factors well outside this system that influence the behaviors of the authorities that seem well beyond their purview.

The only way for the United States to prepare for the consequences of catastrophic earthquakes is through greater collaboration and commitment. This research demonstrates that the current methodologies of NEHRP are insufficient to meet the goals for ShakeAlert and to adapt to the speed of technological change. By addressing the challenges for funding, education, and adoption, a comprehensive reauthorization with significant expansion would adequately restructure NEHRP to best advance seismic research and science and launch ShakeAlert. Restructuring the contributions of all levels of government, including the private sector, will optimize the governance and policy requirements. In turn, this will also safeguard the sustainability of ShakeAlert by ingratiating the operational systems into the cultures of government, industry and the general public. Perhaps most importantly, the implementation of ShakeAlert will help prepare the people, businesses, infrastructure, economies, and communities hopefully before the next significant earthquake impacts the United States. The reality is that the authorities must set their differences aside and prioritize their efforts to make ShakeAlert happen as soon as possible. If the next Big One happens, and ShakeAlert is not yet operational, the court of public opinion will revolt, knowing that there had been a solution and the government failed to implement it to protect society and the economic viability of the country at such a nominal cost.

A. AUTHORITATIVE ALLOCATION OF EARTHQUAKE VALUES FOR SOCIETY

Using Easton's systems analysis approach to the political system and applying his input-output model to NEHRP has allowed us to understand the mechanics of how this particular political system functions and arrives at the solutions it sets out to achieve. Undoubtedly, David Easton's mark on history will be his contributions to political science and the concept of the political system as being the authoritative allocation of values for a society. In narrowing the focus of values, much like Easton did when refining general systems theory to political systems theory, this analysis results in a comparable recommendation for NEHRP to use a systems approach and facilitate the authoritative allocation of earthquake values for society. By focusing this macrosolution to the NEHRP strategy, a solution like ShakeAlert become a higher priority and authorities will expedite its implementation for society because its value toward earthquake resilience in relation to programmatic goals is so significant.

On September 11, 2017, ACEHR submitted its biennial assessment of the effectiveness of NEHRP to the chair of ICC. In that report, the Advisory Committee provides an expectation of the authority of NEHRP to allocate values for a society based on earthquake resilience by stating,

> There remains a pressing need to build the research infrastructure to improve our social, behavioral, and economic understanding of: the societal roots of risk with an emphasis on the social, cultural, political, and economic practices that facilitate risk creation; barriers and facilitators for the diffusion of risk reduction practices among public and private entities; behavioral and economic incentives and other considerations for public and private sector decisions about improving resilience.[190]

NEHRP as a political system has two recognized oversight bodies and four primary responsible agencies. They have the authority required to convert demands into outputs. With an established program entering its fortieth anniversary since its legislative establishment, it has legitimacy. Due to a small number of boundary thresholds, they have the autonomy to select from a range of alternative strategies and the capacity to transform themselves as necessary. They have set goals and standard practices within the structure of their internal organization. Finally, NEHRP is capable of evaluating what is happening in the total environment and can take action to institute necessary changes. Each of these variables described by Easton is all that a political system requires to sustain itself and provide a continuous level of value for society. However, if NEHRP does not capitalize on outputs such as ShakeAlert, even if it is a perceived value, or if the total environment finds NEHRP at fault with any one of these other variables, not requiring a combination thereof, then its political system can be in jeopardy.

B. A SYSTEMS APPROACH TO EARTHQUAKE RESILIENCE

Accordingly to the last NEHRP annual report, its goals are three-fold:

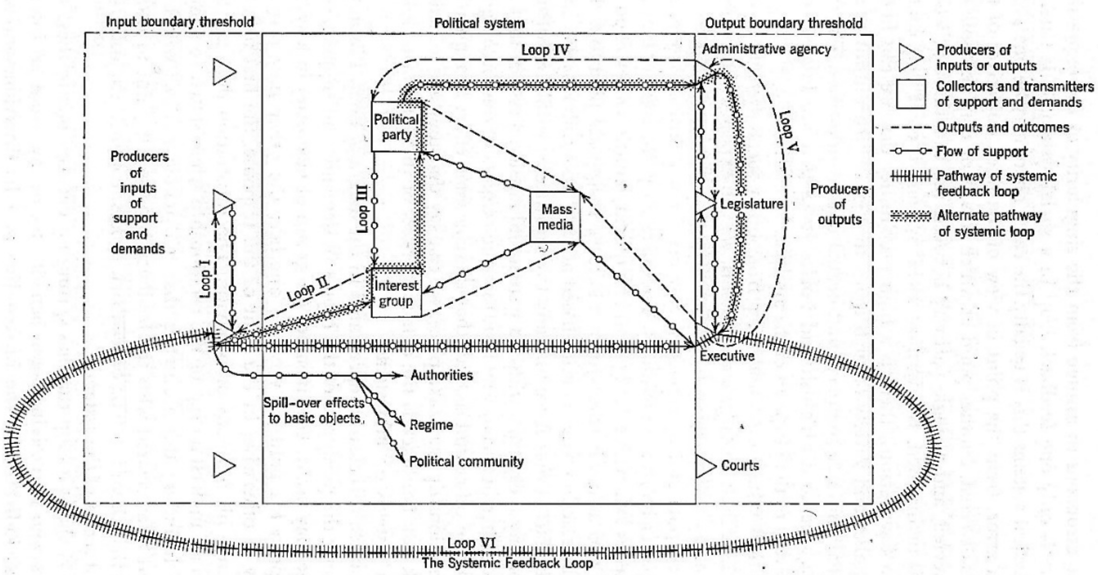
- (Goal A) improve understanding of earthquake processes and impacts,
- (Goal B) develop cost-effective measures to reduce earthquake impacts on individuals, the built environment, and society at large and,
- (Goal C) improve the earthquake resilience of communities nationwide.[191]

[190] ACEHR*, Effectiveness of the National Earthquake* (2017).

[191] NEHRP, *Annual Report* (2014).

In the analysis of these goals against the outputs for ShakeAlert, there is a direct correlation to each goal. However, ShakeAlert continues to receive minimal support and prioritization by NEHRP agencies. This thesis has provided a systems approach to analyze how the authorities that represent the program convert demands into outputs and noted areas of concern as well as opportunities for advancement. In this last diagram, Figure 24 provides a snapshot of what Easton referenced as a functional political system with multiple feedback loops.

Figure 24. Multiple Feedback Loops of a Political System[192]



This thesis recommends a future application include instituting similar components to ensure the legitimacy and persistence of the program. This model allows producers of the inputs to voice their demands through interest groups, political parties, and mass media, while at the same time ensuring that the authorities can concentrate their efforts related to outputs to be in line with executive, administrative, and legislative audiences effectively. This systems approach would allow ShakeAlert to move through these pathways in a manner that produces the requirements for it to be completed and brought online through

192 Source: Easton, *A Systems Analysis of Political Life*.

stakeholder empowerment and shared ownership. With that said, the analysis also cautions that if NEHRP continues and when ShakeAlert launches nationally, four main strategies must remain prevalent and will require sustained support: (1) to ensure a streamlined integration between the public and private sector, (2) requiring a sustained education of the public, (3) allowing for the adaptability to integrate technological advancements, and (4) requiring ongoing social impact analysis from false alarms to intermittent warnings. Utilizing the model for political systems theory allows for a path forward regarding legitimacy and persistence of ShakeAlert as an approach to earthquake resilience.

C. FUTURE RESEARCH CONSIDERATIONS

There are two noteworthy studies that use Easton's model of the political system. In 1969, Chester Rogers of Western Michigan University used Easton's model to test several hypotheses to explain outputs from municipalities in the United States and their corresponding policies based on environmental conditions in the "Environment, System and Output: The Consideration of a Model."[193] Then in 1972, Richard Trilling of Duke University presented the "Easton's Concept of Effective Support: Two Formal Models,"[194] which includes a mathematical expression to outline an interpretation of political questions empirically. These studies could serve as an empirical study for applying Easton's approach of NEHRP based on a formulaic systems analysis and would present a comprehensive method for prioritizing outputs and possibly justifying ShakeAlert as a top concern in more detail.

Programmatically, three immediate efforts for consideration and future research from this analysis are as follows. First, based on Executive Order 13717, those agencies identified as having facilities requiring compliance with seismic standards are to provide a report to OMB on their progress in February 2018.[195] A future consideration would be to

[193] Chester B. Rogers, "Environment, System and Output: The Consideration of a Model," *Social Forces* 48, no. 1 (1969): 72–87, https://doi.org/10.1093/sf/48.1.72.

[194] Richard J. Trilling, "Easton's Concept of Effective Support: Two Formal Models," *Comparative Political Studies* 4, no. 4 (1972): 491–507, https://doi.org/10.1177/001041407200400406.

[195] Exec. Order No. 13717.

monitor the findings of those submissions and how NEHRP can play a role in the execution of those standards and what actions are necessary to move forward.

Second, as a component of the 2004 reauthorization, within subsection (2) Department of Homeland Security, Federal Emergency Management Agency, part (A) it states,

> (vi) shall develop, coordinate, and execute the National Response Plan when required following an earthquake, and support the development of specific State and local plans for each high risk area to ensure the availability of adequate emergency medical resources, search and rescue personnel and equipment, and emergency broadcast capability;

In 2008, DHS released *The National Response Framework* (NRF), which implements the new requirements and terminology of Presidential Policy Directive 8.[196] The NRF superseded the *National Response Plan*. If Congress presents a future reauthorization, it would be advantageous to update this particular language but further introduce the concept of integrating the *National Disaster Recovery Framework* (NDRF) as a required input to help guide the performance measures of NEHRP. An analysis potentially based on Easton's model would help establish fundamental core capabilities that would drive the delivery of solutions tailored to meet the NDRF's recovery support functions.[197]

Third, ACEHR has term limits with its sitting members and in 2018 many of those positions, including that of the chair, will be vacated, and new members will be selected. A future consideration would be to research what skillsets would be best suited for those positions based on the outputs, and future priorities are for NEHRP and the implementation of ShakeAlert. Also, with new leadership taking hold as the new administration settles in, the principles that comprise the ICC will also be taking the reins. If and when a 2018 ICC

[196] Federal Emergency Management Agency, *National Response Framework*, 3rd ed. (Washington, DC: Federal Emergency Management Agency, 2016), http://www.fema.gov/media-library/assets/documents/117791.

[197] Federal Emergency Management Agency, *National Disaster Recovery Framework* (Washington, DC: Federal Emergency Management Agency, 2017), https://www.fema.gov/national-disaster-recovery-framework.

meeting is held, that would be an opportunity to research what changes will be adopted and how they apply systematically using the model.

Three considerations for future research are more of an operational nature. First, considering that NEHRP was established well before 9/11 and the creation of the DHS, it would be of interest to see how a change in NEHRP leadership would impact the outputs if the responsibilities that currently reside with FEMA were elevated to DHS. The immediate consideration for analysis would be to study how the intrasocietal environment would benefit, specifically the private sector, due to the working relationships between DHS and its responsibilities for critical infrastructure nationally. Each of the operational systems discussed in Japan, as well as many others, fall within the 16 sectors that make up the DHS Office of Infrastructure Protection within the National Protection and Programs Directorate. Furthermore, the DHS Science and Technology Directorate is the research and development arm that regularly works with state and local officials and could support ShakeAlert itself.

Second, one of the most critical components to a successful rollout of ShakeAlert is going to be the reliance on the communications networks and integrated technology strategies. The cell carriers have been working with the Federal Communications Commission and FEMA on the implementation of IPAWS. As mentioned earlier, this system serves as the nation’s federal alert and warning system and much work is yet to be done to ensure that the timeliness of ShakeAlert warnings are distributed efficiently as seconds matter. There are some considerations worth researching within this realm that range from the type of messages sent, what format, to what devices, how long should they be, how far from the event, and so on. Many unanswered questions remain as to the specifics of ShakeAlert warnings.

Third, the most critical operational component will be the feedback loop associated with warnings to the general public. How people are going to receive warnings is the first distribution challenge. However, a future research consideration that will require in-depth analysis builds on the information that was presented earlier on behavioral analysis of alerts to recipients in Japan. ShakeAlert will require a far-reaching analysis to determine things such as how loud should messages be, with what tone and volume should distributions occur, what should they say, in what language, what continuing information needs to be provided, should recipients be able to respond or is the communication just one way, etc. All these questions remain unknown and future research is certainly warranted.

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