

Defining and Measuring Economic Resilience to Earthquakes

by Adam Rose

Research Objectives

This research provides an in-depth analysis of economic resilience to earthquakes. It fine-tunes the definition to distinguish inherent and adaptive considerations, and it distinguishes the various levels at which resilience is operative. It explicitly links resilience to the behavior of individuals, markets, and the regional macroeconomy, including disequilibrium aspects of each. Finally, it examines the complementarities and tradeoffs between resilience and mitigation. The research is intended to reduce losses from earthquakes by helping to capitalize on and enhance the resilience of business and market operations.

The past decade has witnessed a number of devastating earthquakes in the U.S. and throughout the world. As large as the economic losses from them have been, the outcomes could have been worse had steps not been taken before, during, and after the events. Increasingly the emphasis has shifted to mitigation, or preventative actions taken before an earthquake to reduce loss (see, e.g., Mileti, 1999). Mitigation can reduce the probability and magnitude of the stimulus. It can also reduce our vulnerability. However, even in the absence of mitigation, we have the ability to cushion or reduce loss through *resilience*.

Economic resilience, as defined in this paper, refers to the inherent and adaptive responses to hazards that enable individuals and communities to avoid some potential losses. It can take place at the level of the firm, household, market, or macroeconomy. In contrast to the pre-event character of mitigation, economic resilience emphasizes ingenuity and resourcefulness applied during and after the event. Also, while mitigation often emphasizes new technology (e.g., seismic warning) or institutions (e.g., insurance markets), resilience has greater behavioral emphasis.¹ It focuses on the fact that individuals and organizations do not simply react passively or in a “business as usual manner” in the face of a disaster.

Three difficulties confront researchers in the resilience arena. At the conceptual level, there is the need to identify resilient actions, including those that may seem to violate established norms, such as rational behavior. At the operational level, it may be difficult to model individual, group, and community behavior in a single framework. At the empirical level, it

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Research Team

Adam Rose, Professor,
Department of Geography,
Bo Yang, Graduate
Student, Program in
Energy, Environmental, and
Mineral Economics, Dan
Wei, Graduate Student,
Department of Geography,
Pennsylvania State
University, and Shu Yi Liao,
Assistant Professor, National
Chung Hsing University,
Taiwan

Other MCEER Team Members

Stephanie Chang, School of
Community and Regional
Planning, University of
British Columbia
Masanobu Shinozuka,
Department of Civil and
Environmental Engineering,
University of California,
Irvine
Kathleen Tierney, Natural
Hazards Research and
Applications Information
Center, University of
Colorado, Boulder

Previous Summaries

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is especially difficult to gather data on resilience to specify models.

The purpose of this paper is to summarize progress on all three planes. First, we define several important dimensions of economic resilience. Second, we show how computable general equilibrium (CGE) modeling represents a useful framework for analyzing the behavior of individuals, businesses, and markets. Third, we summarize recent progress in the conceptual and empirical modeling of resilience, including the incorporation of disequilibria and the recalibration of key behavioral parameters on the basis of empirical data. Fourth, we use the results of a case study to illustrate some important issues relating to the subject.

Defining Resilience and its Scope

Basic Definition

We begin by defining static *economic resilience* as the ability or capacity of a system to absorb or cushion against damage or loss (see, e.g., Holling, 1973; Perrings, 2001). A more general definition that incorporates dynamic considerations, including stability, is the

ability of a system to recover from a severe shock.

We distinguish two types of resilience:

- *Inherent* – ability under normal circumstances (e.g., the ability to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals).
- *Adaptive* – ability in crisis situations due to ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations, or strengthening the market by providing information to match suppliers without customers to customers without suppliers).

Resilience emanates both from internal motivation and the stimulus of private or public policy decisions (Mileti, 1999). Also, resilience, as defined in this paper, refers to post-disaster conditions and response, which are distinguished from pre-disaster activities to reduce potential losses through mitigation. The consequences of these two approaches are not mutually exclusive, and below we shed some light on the influence of mitigation on resilience and visa versa.

The concept of resilience emanates from several sources. For

The operational definitions and models produced by this research should be of broad usefulness. Business managers will be better able to assess the inherent role and potential to improve economic resilience to earthquakes. Utility managers will be better able to estimate losses from service disruptions. Emergency planners will be better able to exploit the costless ability of market forces to reallocate scarce resources so as to minimize economic losses from earthquakes.

example, Holling (1973) and other ecologists, as well as Perrings (2001) and other ecological economists, have defined it in terms of the broader concept of sustainability as the capacity to absorb stress and shocks. Tinch (1998) has enumerated several similar measures including: stability, persistence, resistance, non-vulnerability, stochastic return time and resilience. However, Perrings (2001; p. 323) notes: “The property that most closely connects with the idea of sustainability as conservation of opportunity is resilience.”

In disaster research, resilience has been emphasized most by Tierney (1997) in terms of business coping behavior and community response, by Comfort (1999) in terms of nonlinear adaptive response of organizations (broadly defined to include both the public and private sectors), and by Petak (2002) in terms of system performance. Recently, Bruneau et al. (2003; p. 3) have defined *community earthquake resilience* as “the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effectors of further earthquakes.” Further, they divide resilience into three aspects, which correspond to the concepts defined above in an economic context. First is reduced failure probability, which we view as equivalent to mitigation in this paper. Second is reduced consequences from failure, which corresponds to our basic static definition of resilience. Third is reduced time to recovery, which adds a temporal dimension to our

basic definition.² Note that in the infancy of conceptual and especially empirical analysis of economic resilience, we believe it is prudent to pin down fundamental considerations first. Dynamic aspects of resilience, including intertemporal tradeoffs, system “flipping,” irreversibilities, and extreme nonlinearities, are beyond the scope of this paper. In sum, Bruneau et al. (2003) have offered a very broad definition of resilience to cover all actions that reduce losses from hazards, including mitigation and more rapid recovery. These refer to how a community reduces the probability of structural or system failure, in the case of the former, and how quickly it returns to normal in the case of the latter. We have focused on the essence of resilience—the innate aspects of the economic system at all levels to cushion itself against losses in a given period.

Scope

There are several categories of loss from disasters (see, e.g., Rose, 2004). Although property damage has traditionally received the most attention, direct and indirect business interruption losses can be just as prominent (see Tierney, 1997; Webb et al., 2000; Rose and Liao, 2004). Unlike property damage, which refers to structures (buildings, bridges, highways), business interruption refers to human operation of businesses, organizations and institutions. Moreover, unlike the stock measure of property, which incurs its damage during the relatively short period of the disaster stimulus, the flow measure of business interruption takes place for the relatively long

Links to Current Research

This research is part of MCEER's mission of enhancing community resilience to earthquakes. It focuses on how private and public sector decisions influence important dimensions of this issue. It will be tested in an application to the Los Angeles Demonstration Project.

period of recovery. Our analysis will focus on these flow measures, which will also be more useful for dynamic extensions.

Resilience can take place at three levels:

- *Microeconomic* - individual behavior of firms, households, or organizations.
- *Mesoeconomic* - economic sector, individual market, or cooperative group.
- *Macroeconomic* - all individual units and markets combined, though the whole is not simply the sum of its parts, due to interactive effects of an economy.

Examples of individual resilience are well documented in the literature, as are examples of the operation of businesses and organizations (Tierney, 1997; Comfort, 1999). What is often less appreciated by disaster researchers outside economics and closely related disciplines is the inherent resilience of markets. Prices act as the “invisible hand” that can guide resources to their best allocation even in the aftermath of a disaster. Some pricing mechanisms have been established expressly to deal with such a situation, as in the case of non-interruptible service premia that enable customers to estimate the value of a continuous supply of electricity and to pay in advance for receiving priority service during an outage (Rose and Benavides, 1999).

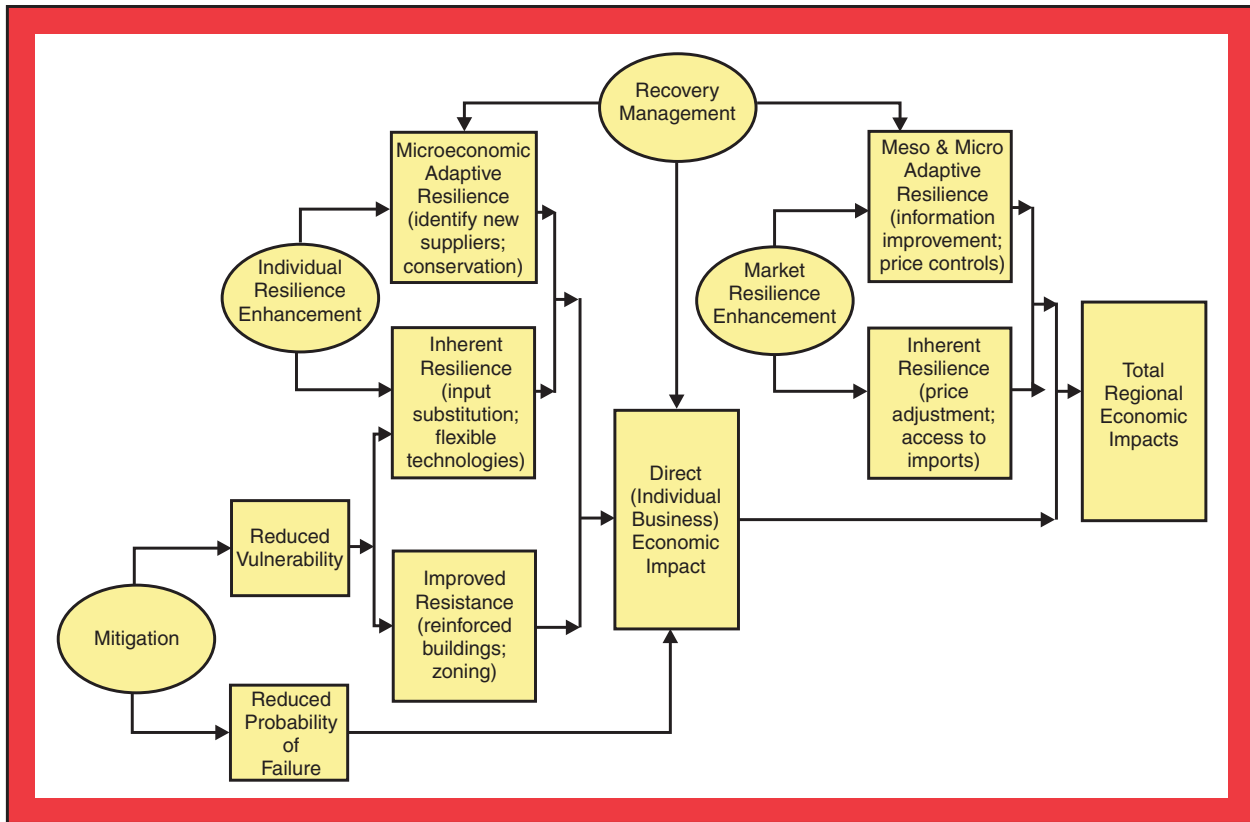
The price mechanism is a relatively costless way of redirecting goods and services. Price increases, though often viewed as “gouging,” serve a useful purpose of reflecting highest value use, even in the broader social setting. Moreover, if the allocation does violate principles of equity (fair-

ness), the market allocations can be adjusted by income or material transfers to the needy.

Of course, markets are likely to be shocked by disasters, in an analogous manner to buildings and humans. In this case, we have two alternatives for some or all of the economy:

- substitute centralized decree or planning, though at a significantly higher cost of administration;
- bolster the market, such as in improving information flows (e.g., the creation of an information clearing house to match customers without suppliers to suppliers without customers).

The role of economic resilience in the extent of economic losses from disasters is summarized in Figure 1, in relation to other major loss reduction strategies—mitigation and recovery management. Both of these strategies can enhance innate economic resilience as defined in this paper, though to date this has not been a major emphasis of either. Mitigation is typically oriented toward reducing the probability of failure and also reducing vulnerability through improved resistance (resistance is defined here as a fixed measure, in contrast to the “bounce-back,” or flexible, nature of resilience). Recovery management is usually oriented toward providing outside assistance to businesses and households affected by disaster, and to reducing recovery time. The former aspect of recovery is not consistent with resilience because resilience emphasizes the self-reliance of communities in terms of the broader concept of sustainability (Mileti, 1999). The latter, however, will be a key



■ Figure 1. Role of Economic Resilience in Economic Losses from Disasters

to extending the concept of economic resilience presented in this paper to include more dynamic elements.³

Computable General Equilibrium Modeling Refinements

Computable General Equilibrium (CGE) analysis is the state-of-the-art in regional economic modeling, especially for impact and policy analysis. It is defined as a multi-market simulation model based on the simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource

constraints (see, e.g., Shoven and Whalley, 1992). The CGE formulation incorporates many of the best features of other popular model forms, but without many of their limitations (Rose, 1995).

The basic CGE model represents an excellent framework for analyzing natural hazard impacts and policy responses (Brookshire and McKee, 1992; Rose and Guha, 2004). CGE modeling encompasses all the elements in the scope of analysis presented in the previous section. In fact, it is the only economic modeling approach to incorporate micro, meso, and macro levels (see Rose, 2004, for a discussion in the context of disaster impact analysis).

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Business Responses to Hazards in a CGE Context

The production side of the CGE model developed by the author and his research team is composed of a standard, multi-layered, or multi-tiered, constant elasticity of substitution (CES) production function for each sector. The production function is normally applied to aggregate categories of major inputs of capital, labor, energy, and materials, with sub-aggregates possible for each (e.g., the energy aggregate is often decomposed by fuel type—electricity, oil, gas, and coal). In most prior CGE models, water has been omitted or incorporated as one of the materials (intermediate goods producing) sectors. In our illustration, we explicitly separate water as a major aggregate in the top tier of the production function so that we can analyze the impacts of a water service disruption.

This production function represents a type of hierarchical, or sequential, decision-making process. For a given level of output, the firm’s manager first chooses the optimal combination of capital and energy. He/she next juxtaposes that combination to labor to determine the optimal choice of inputs in the third tier, etc. In the top tier, input decisions are made regarding water in terms of the various ways it can be provided (the reader is referred to last year’s *Research Accomplishments* report for the mathematical specification of the production function).

Inherent resiliency is embodied in the basic production function for individual businesses and in the combination of producers, consumers, and markets (includ-

ing interaction effects) for the economy as a whole. Adaptive resilience is captured by changes in the parameters. For example, an increase in the productivity term for water would reflect conservation, while an increase in the substitution elasticity would reflect increased substitution possibilities between utility water service and other inputs (such as bottled water). In the aftermath of a disaster, people behave in a more urgent manner and are more likely to call forth ingenuity. For example, for short periods, maintenance can be skipped, water fountains can be turned off, water can be reused, etc. Also, in general, inefficient practices can come to light and new opportunities can be initiated. There is an extensive literature suggesting that managers can become more clever in emergency situations. There is additional literature, now very prominent in the energy and environmental fields, indicating a much greater range of conservation opportunities when one looks at the production process from a holistic standpoint (see, e.g., Porter and van der Linde, 1995).

Economy-Wide Responses and Disequilibria

As noted above, the market system is inherently resilient to shocks and can be bolstered by various policies. All of this can best be modeled in a CGE framework. However, an inherent shortcoming of CGE is its equilibrium emphasis. Following a major disaster, a sustained period of disequilibrium is likely to ensue. Fortunately, several refinements of CGE modeling by the

author and others have moved to overcome this limitation. These disequilibria are typically related to closure rules, or account balance conditions.

It is now possible to operate a CGE model in situations where demand need not always equal supply in the following cases:

1. The labor market, which allows for unemployment
2. The government budget, which allows for deficit spending
3. Trade, which allows for import/export imbalances
4. Goods and services, which allows for explicit shortages

The last of these advances bears some elaboration. Ordinarily, any gap between supply and demand is resolved by a change in price. However, it is possible in CGE modeling to fix the price of a commodity and have the supply constrained, so that potential demand exceeds actual demand. This refinement is facilitated by the development of new software that uses a complementarity programming approach, thereby allowing for some “slack” in the system, and hence disequilibrium. For example, in the study to be discussed below, we were able to limit the supply of water to each sector. Ordinarily this would increase the price of water, but this is unrealistic given the fact that water is not priced in an ordinary market but rather under the administrative authority of a public service agency. We therefore fixed the price of water as well, essentially modeling it as a disequilibrium market. The slack is taken up by a reduction in the profit margin in the water sector.

Closely related are the many ad hoc adjustments and tempo-

rary equilibria that ensue after a disaster, many of which can be incorporated through further refinement of the CGE model. Examples identified by West and Lenze (1994) include additions to the labor market in the form of outside government and NGO volunteers, by Cochrane (1997) include households dipping deep into savings or increasing their borrowing to fund repairs, and by Rose and Lim (2002) include businesses recapturing lost production through overtime work at a later date.

Empirical Specification

CGE models used for hazard analysis are likely to yield estimates of business disruptions for some if not all sectors of an economy that differ significantly from the direct loss estimates provided by empirical studies. This is because production function parameters are not typically based on solid data, or, even where they are, the data stem from ordinary operating experience (inherent resilience only) rather than from emergency situations. Hence, it is necessary to explicitly incorporate adaptive resilience responses into the analysis.

Rose and Liao (2004) have recently developed a methodology for altering the behavioral parameters in the sectoral production functions of the CGE model based on an optimizing routine and solutions utilizing both analytical and numerical methods. Empirical or simulation model estimates of direct output changes, emanating from an input supply disruption, are used to recalibrate productivity and substitution elasticity param-

eters of the CES production function. When the initial parameters are accurate for business as usual contexts, we say they embody “inherent” resilience. The difference between these original and the recalibrated parameters would then reflect “adaptive” resilience. Unfortunately, accurate initial parameters are rarely available, so that in such cases, while the recalibration encompasses both types of resilience, the overall effect cannot yet be accurately decomposed into its two components. Still, the method is sufficiently general to be able to do so when better parameter data become available.

Illustration

Portland Water System and Economy

The Portland (Oregon) Bureau of Water Works (PBWW) is a rate-financed, City-owned utility that serves 840,000 people in portions of the Portland Metro Area (including businesses responsible for 98% and 72% of sales in Multnomah County and Washington County, respectively). In 1999, PBWW water sales amounted to 39 billion gallons. The largest customers are major manufacturing companies, the Portland City Bureau of Parks and Recreation, and several hospitals.

The PBWW transmission and distribution is comprised of nearly 2000 kilometers of pipelines, 29 pump stations, and 69 major storage tanks. About 70% of the system still consists of cast iron pipes, even though the agency began installing ductile iron in the 1960s. Additional information on

the PBWW, and its earthquake vulnerability and mitigation costs, can be found in Chang et al. (2002).

We constructed a CGE model of the portion of Portland Metropolitan Area economy that overlaps with the Portland Bureau of Water Works (PBWW) Service Area (Rose and Liao, 2004). The main data upon which the empirical model is based are the 1998 IMPLAN Social Accounting Matrix (SAM) and Input-Output Table for Multnomah County and Washington County (MIG, 2000). It is divided into several partitions that reveal the structure of the regional economy, including the industry, commodity, factor income, household, government, capital, and trade accounts.⁴

Water Disruption Simulations

Chang et al. (2002) performed simulations for alternative combinations of earthquake types, calendar years, and mitigation options, using several sophisticated geological and engineering models. Each case was subject to 100 Monte Carlo simulations. These simulations were used to estimate direct losses in sectoral output, factoring in resilience but without any specification of the type of resilience response. We adapted the results of a questionnaire survey by Tierney (1997) for the Northridge earthquake to assume that water conservation and substitutability were likely to be the primary ways that customers implemented adaptive resilience (see Rose and Liao, 2004).

Our simulations are based on an engineering fragility analysis of the Portland water utility system and the direct loss estimation simula-

tions of Chang et al. (2002) described above. Although Chang’s engineering vulnerability and direct loss simulations involve many scenarios relating to alternative earthquake magnitudes, outage durations, and resilience responses, this paper focuses on a subset of scenarios characterized by:

- One earthquake type (Bolton crustal fault) of magnitude 6.1
- Impacts in the Year 2000
- Scenarios for Business as Usual (No Mitigation) and Pipe Replacement (Mitigation)
- Outages of varying lengths from 3 to 9 weeks

We focused on the first characteristic because it represented the “most likely” case, and on the latter three to keep the number of simulations manageable.

Resilience in the Absence of Mitigation

The results of our simulations for the Business as Usual Scenario (no mitigation) are presented in the first column of Table 1. Note that the duration of this outage is projected to be four weeks, but the table summarizes the situation for the maximum disruption, which takes place during the first week.

Unmitigated sectoral water disruptions are estimated by Chang to average 50.5 percent of pre-earthquake levels. However, direct output losses are estimated to be only 33.7 percent, because they incorporate direct sectoral resilience to water service outages. Our measure of *direct regional economic resilience (DRER)* is the extent to which the estimated direct output reduction deviated from the likely (fixed-coefficient) maximum, which is equivalent to

■ **Table 1.** Economic Resilience to a Water Service Disruption in the Portland Metro Area (percentage)

	Pre-Mitigation	Post-Mitigation
Direct Water Outage	50.5	31.0
Direct Output Reduction	33.7	21.3
Indirect Output Reduction	7.3	9.2
Total Output Reduction	41.0	30.5
Direct Economic Resilience	33.0	31.3
Total Economic Resilience	60.4	48.2

the percentage water input disruption in our linear approach to baseline estimation:

$$DRER = \frac{\% \Delta DQ^m - \% \Delta DQ}{\% \Delta DQ^m} \quad (1)$$

where $\% \Delta DQ^m$ is the maximum percent change in direct output and $\% \Delta DQ$ is the estimated percent change in direct output.

The measure of *DRER* is 33.3 percent in this scenario $[(50.5 - 33.7) \div 50.5]$.⁵

Our estimates of the indirect (net general equilibrium) and total regional (gross general equilibrium) economic impacts of the water lifeline disruption are presented in Rows 3 and 4 of Table 1. Overall, they yield only a 7.3 percent indirect reduction in regional gross output and a 41.0 percent total reduction in regional gross output for the first week. The former represents \$99.9 million and the latter \$561 million of lost sales.

Some interesting aspects of indirect output losses bear further discussion. First, they are only about 22 percent the size of direct output losses. In the context of an input-output (I-O) model, this would be a multiplier of only about 1.22. The Portland Metro economy-wide I-O multiplier is significantly larger

“This paper has presented major conceptual, operational, and policy analysis advances in evaluating individual and regional economic resilience to earthquakes.”

than this, but the CGE model incorporates many other factors that mute the uni-directional and linear nature of the pure interdependence effect of the I-O model. For example, the CGE model is able to capture price changes for intermediate goods from cost and demand pressures, various substitutions aside from those relating to water, and various income, substitution and spending considerations on the consumer side.

Our measure of *total regional economic resilience (TRER)* to earthquake disruptions of water services is the difference between the total fixed coefficient I-O multiplier and the CGE impacts:

$$\begin{aligned} TRER &= \frac{\% \Delta TQ^m - \% \Delta TQ}{\% \Delta TQ^m} \\ &= \frac{M \bullet \% \Delta DQ^m - \% \Delta TQ}{M \bullet \% \Delta DQ^m} \end{aligned} \quad (2)$$

where M is the economy-wide average Type II input-output multiplier; $\% \Delta TQ^m$ is the maximum percent change in total output; and $\% \Delta TQ$ is the estimated percent change in total output.

The weighted average Type II output multiplier for the Portland Economy is 1.9, or a 90 percent increase over direct effects. Thus, $TRER$ in this case is 60.4 percent $\{[(1.9)(50.5) - 41] \div [(1.9)(50.5)]\}$.

Resilience in the Aftermath of Mitigation

The results of the scenario of an M6.1 crustal fault earthquake but with cast-iron pipe replacement are also presented in the second column of Table 1. In this second scenario, the direct water outage is reduced from 50.5 percent to 31.0 percent. Chang estimates direct output losses to be 21.3 percent. The $DRER$ index is 31.3 percent in this case $[(31-21.3) \div 31]$. Direct resilience thus decreases a bit from the 33.3 percent of Scenario 1, and this is likely due to the fact that resilience opportunities decrease as the size of the direct disruption decreases. Note also that *direct mitigation effectiveness*, with respect to the difference in direct water losses between the two scenarios, could be measured by a similar index and would equal 38.6 percent $[(50.5-31.0) \div 50.5]$.

The parameter recalibrations needed for the model to replicate the Chang direct loss estimates are lower than the corresponding parameter values in our initial simulation, because the direct output losses are projected to be lower in each sector following mitigation. Note that this seemingly counter-intuitive result has a valid explanation – because water disruptions are smaller after mitigation, there is less need and less room to maneuver (fewer opportunities for adaptive resilience). Mitigation lowers direct losses, but there is a partially offsetting effect from lowering adaptive capability.⁶

Interestingly, our estimate of “indirect” losses in Scenario 2 is 9.2 percent, which is 43.2 percent the size of direct losses. Thus, the percentage increase over direct losses is higher in Scenario 2 than in Scenario 1, as is the absolute level (not shown). This appears surprising at first glance. It would be an impossibility, for example, in the context of an I-O model (where multiplier values are the same at all scales). However, our CGE model is nonlinear. Secondly, we have changed parameters (with respect to water substitution), so, even in an I-O context, multipliers would differ (though likely only slightly given the small size of our parameter changes, which would correspond to coefficient changes in an I-O model). One explanation for the relatively higher percentage of general equilibrium effects in Scenario 2 is the fact that water substitution and productivity term parameters are lower than in Scenario 1, meaning that not only is the direct response less flexible, but so is the indirect response relating to water. Another explanation is the difference in the sectoral mix of direct water disruptions in relation to Scenario 1. This changes relative prices, and the model responds accordingly.

The discussion above can be summarized and quantified in the *TRER* for the post-mitigation case, which is 48.2 percent $\{[(1.9)(31) - 30.5] \div [(1.9)(31)]\}$. The difference between *TRER* and *DRER* is a measure of *indirect regional economic resilience (IRER)*, which is relatively lower in the post-mitigation case.⁷

Overall, the *DRER* is higher than *IRER* in both scenarios. This suggests that the overall resilience of

individual businesses is greater than the overall resilience of markets in the Portland economy.

Conclusion

This paper has presented major conceptual, operational, and policy analysis advances in evaluating individual and regional economic resilience to earthquakes. We provided an operational, though relatively narrow, definition of resilience and couched it in terms of economic theory. We then summarized a methodology for incorporating disequilibria and recalibrating CGE model parameters in light of empirical estimates of production losses due to a lifeline supply disruption. Our application to a disruption of water services in the Portland Metro economy showed how indirect (pure general equilibrium) economic losses vary according to the overall level and sectoral mix of water shortages, the extent of pre-event mitigation, and post-event inherent and adaptive resilience. It also identified some major complementarities and tradeoffs between mitigation and resilience. Our methodology can be adapted to other applications of CGE models for response to other types of disasters, including terrorist attacks on economic targets.

The measurement of resilience is important because it enables us to evaluate an important strategy for reducing economic losses from earthquakes. Failure to incorporate resilience in loss estimation will result in inflated assessments of business interruption from earthquakes. Failure to include resilience in policy-making will result in missed opportunities to further reduce losses.

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Endnotes

¹ There is growing awareness of the behavioral aspects of the implementation of mitigation. For example, even promising new technology and policies may incur obstacles to its implementation and use (see, e.g., Alesch and Petak, 2001).

² Recently, Chang and Shinozuka (2004) have operationalized a portion of this framework to examine the effects of mitigation, based on engineering performance standards for a water system, on basic measures of technological, organizational, and economic resilience. Their work differs from the presentation in this paper in terms of the definition of economic resilience overall, more in-depth analysis of the concept here, and our inclusion of region-wide economic losses.

³ We briefly note the relationship between resilience and two other concepts. *Preparedness* refers to steps taken before a disaster to subsequently reduce losses. Some of these actions, such as the building up of inventories, improve the capacity of inherent resilience, while others, such as the establishment of an improved communication network, increase adaptive resilience capacity. Preparedness typically focuses on ways of enhancing resilience before the event, while resilience emphasizes the reduction of economic losses due to an earthquake during and after the ground shaking (i.e., the benefits of reduced losses). Moreover, not all preparedness affects innate resilience (e.g., that which is pure mitigation), and not all resilience stems from preparedness (e.g., innate human ingenuity and the natural self-adjusting feature of markets). Note also that resilience differs from the concept of adaptation. *Adaptation* consists of two components: an active effect to reduce losses after an event has taken place (e.g., migration) and a passive absorption (“suffering”) of the loss. Our concept of adaptive resilience overlaps with the first component.

⁴ The computational procedure we have developed to improve model accuracy also generates an additional dividend of enabling us to decompose loss estimates into direct (partial equilibrium) and indirect (total general minus partial equilibrium) effects. While the I-O model automatically makes this distinction, our methodology to decompose the two categories of effects is a necessary advance in CGE modeling to do so.

⁵ The fixed coefficient production function of an I-O model yields an upper-bound estimate of direct output losses from water input disruption, where the percentage loss of the former would be equal to the percentage loss for the latter. All other types of production functions would yield percentage output losses lower than the percentage decrease in water availability because of substitution possibilities. We measure *direct individual business (or sectoral) resilience (DIBR)* as the difference between the fixed coefficient (proportional) result and the flexible input (disproportional) result, which is attributable both to the various response mechanisms related to water services (1st Tier) and inherent in the overall production function with respect to other inputs (Tiers 2-4). *DRER* is simply the weighted average of *DIBR* for all businesses in the region.

Note that our choice of a linear reference base for resiliency estimation is reasonable but still somewhat arbitrary pending more empirical work. There are

instances in which the maximum potential loss is greater than a proportional impact (i.e., a situation in which an X% loss of water results in greater than an X% loss of output). However, our general loss estimation and resilience modeling methodologies are sufficiently general to accommodate these definitional changes.

⁶ This reduction in resilience is more than offset by the beneficial effect of mitigation in reducing recovery time (Chang et al., 2002), but it is a negative side effect of mitigation just the same and may dominate the recovery time benefit in other cases.

⁷ Note that we have not been able to distinguish between inherent and adaptive resilience in the sectoral (summed to direct regional) case because of limitations of accuracy of our initial elasticity estimate. It would appear that *TRER* includes only inherent resiliency, since we have not included any explicit adaptive considerations. However, our assumption of return to equilibrium (in all markets except water, labor, and the government budget) in a period of only 3-4 weeks invokes some implicit adaptive responses (such as improved information flows). In fact, the 3-4 week adjustment is greatly optimistic, such that our *TRER* estimates contain a significant upward bias.

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