Understanding Sources of Economic Resiliency to Hazards:
Modeling the Behavior of Lifeline Service Customers

by Adam Rose and Shu-Yi Liao

Research Objectives

This research refines computable general equilibrium (CGE) modeling for estimating business interruption losses from utilities lifeline disruptions and for estimating the reduction of losses (benefits) from mitigation. The behavioral content of CGE production functions is shown to be able to embody the adaptive behavior of lifeline utility service demand in particular and business operations in general. The individual response types (e.g., conservation, input substitution, import substitution) are linked to specific parameters of these functions. The research also develops algorithms for modifying the parameters on the basis of engineering simulations and empirical data. Also, economic resiliency is defined at the levels of the individual business and of the regional economy as a whole.

Recent studies indicate that utility lifeline supply disruptions can have significant impacts on regional economic activity in the aftermath of an earthquake, other natural disaster, or terrorist attack (see, e.g., Chang et al., 2000a; Bram et al., 2002). Even businesses that incur no physical damage are likely to have to curtail their production if they are cut off from their electricity, natural gas, water, or communication links. Moreover, such disruptions often set off a chain reaction of further production cutbacks among successive rounds of customers and suppliers that spread through the entire regional economy. Surveys following the Loma Prieta and Northridge earthquakes, Hurricane Andrew, and the 1993 Midwest floods indicated that business interruption losses stemming directly or indirectly from lifeline failures rivaled property damage in dollar terms (see Webb et al., 2000).

For many years, input-output (I-O) analysis was the most widely used modeling approach to the subject. Unfortunately, I-O is characterized by a linear and rigid response, almost devoid of behavioral content. In this approach, it is extremely difficult to incorporate input and import substitution or productivity changes (e.g., conservation). In essence, basic I-O analysis provides only an upper-bound estimate of the direct and indirect responses to a supply shortage (see, e.g., Rose et al., 1997). It is applicable to cases where markets are not working properly or where there are

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Previous Summaries

1999-2000:
Chang et al.,
http://mceer.buffalo.edu/publications/resaccom/9900/Chapter1.pdf

1997-1999:
Tierney et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/ch2tiern.pdf

serious constraints to responding to price signals. This approach is not capable of modeling most aspects of the adaptive response, or "resiliency" (e.g., Bruneau et al., 2002) to hazards at either the level of the individual firm or overall regional economy.

A promising alternative is computable general equilibrium (CGE) analysis, which is a behavioral model of producer and consumer responses to price signals in a multimarket context (Rose and Guha, 2003). CGE models are nonlinear and readily incorporate behavioral responses, such as input substitution and conservation, under explicit constraints (Shoven and Whalley, 1992). The problem in this context is that most CGE models are intended for long-run equilibrium analysis (e.g., they are based on generous input and import substitution elasticities, and assume the orderly functioning of markets and a costless adjustment to equilibrium). As such, CGE models without extensive refinements reflect only business as usual considerations and generally lead to overresilient responses. Their results in effect represent a lower-bound estimate of economic impacts.

Work is progressing on improving the CGE methodology for application to supply disruptions of critical inputs in several ways (see also Rose and Liao, 2002). Advances include linking production function parameters to various types of producer adaptations in emergencies, developing algorithms for recalibrating production functions to empirical or simulation data, incorporating realistic supply elasticities to reflect short-run conditions, specifying operational definitions of individual business and regional macroeconomic resiliency, and decomposing partial and general equilibrium responses. We illustrate some of these contributions in a case study of the sectoral and regional adaptive responses and economic impacts of a disruption to the Portland Metropolitan Water System in the aftermath of a major earthquake. As such, our analysis provides a way of further utilizing the extensive empirical and simulation results on business interruption in the aftermath of earthquakes developed by other MCEER researchers (see, e.g., Tierney, 1997; Chang, 2001b).

Responses to Hazards in a CGE Context

The production side of the CGE model used in this paper is composed of a multi-layered, or multi-

The methods and applications from this research should be of broad usefulness. Utility managers can better identify their customers' needs. They can also better evaluate the benefits of mitigation efforts. Businesses can better evaluate their adaptive responses to lifeline disruptions. Emergency planners and high level government officials can evaluate alternative strategies for minimizing regional economic losses due to lifeline service disruptions.

tiered, constant elasticity of substitution (CES) production function for each sector. The CES has several advantages over more basic forms such as the Leontief (linear) or Cobb-Douglas (simple multiplicative) functions. It can incorporate a range of input substitution possibilities (not just the extreme zero and unitary values of the aforementioned functions). The multiple tiers allow for the use of different substitution elasticities for different pairs of inputs. The CES 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). Water is usually omitted or incorporated as one of the materials (intermediate goods producing) sectors. 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. For an application of this approach to electricity lifeline disruptions, the reader is referred to Rose et al., 2003.

CES Production Function

Our constant elasticity of substitution (CES) production function has the following nested form for five aggregate inputs capital, labor, energy, materials, and water:

$$Y = A_1\left(\alpha_1 A_{1W}\, W^{-\rho_1} + \beta_1\, KLEM^{-\rho_1}\right)^{-1/\rho_1}$$

1st Tier (1a)

$$KLEM = A_2\left(\alpha_2\, M^{-\rho_2} + \beta_2\, KEL^{-\rho_2}\right)^{-1/\rho_2}$$

2nd Tier (1b)

$$KEL = A_3\left(\alpha_3\, L^{-\rho_3} + \beta_3\, KE^{-\rho_3}\right)^{-1/\rho_3}$$

3rd Tier (1c)

$$KE = A_4\left(\alpha_4\, K^{-\rho_4} + \beta_4\, E^{-\rho_4}\right)^{-1/\rho_4}$$

4th Tier (1d)

where A_i is the factor-neutral technology parameter, $A_i > 0$; A_{1W} is the water-specific technology parameter; α_i, β_i are the factor shares, $0 \le \alpha_i\, \beta_i \le 1$; σ_i is the constant elasticity of substitution, $\sigma_i = \frac{1}{1+\rho_i}$; Y is output; K, L, E, M, W are individual capital, labor, energy, material and water aggregates; $KLEM$ is the capital, labor, energy, and material combination; KEL is the capital, energy and labor combination; and KE is the capital and energy combination.

The fixed coefficient production function of an I-O model would yield 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 define *individual business (or sectoral) resiliency* as the difference between the fixed coefficient (proportional) result and the flexible input (disproportional) result, and which is attributable both to the various response mechanisms related directly to water services (1st Tier) and inherent in the overall production function with respect to other inputs (Tiers 2-4).

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Collaborative Partners

Los Angeles Department of Water and Power

Portland Bureau of Water Works

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 rather than from emergency situations. Hence, it is necessary to explicitly incorporate the resiliency responses below into the analysis. This is accomplished here by altering the parameters in the sectoral production functions of the CGE model.

Production Responses to Natural Hazards

1. **Conservation of Water.** This response can be implemented immediately and continued through the long-run, i.e., be incorporated into the production process on a permanent basis. One of the silver linings of disasters is that they force businesses to reconsider their use of resources, and often not just at the margin for a single input but also holistically (as noted in item 7 below). The parameter changes for this response in the case of water pertain to the technology trend variable in the first tier of the production function specified above. More generally, in each tier of the production function, the productivity term, A_i, is specified as covering all inputs, i.e., factor neutral. Adjustment of the productivity term for an individual factor, such as the A_{1W} term in equation (1a), orients the productivity improvement in the direction of that factor.

2. **Conservation of Other Inputs**. This is analogous to water conservation and can be applied to any of the tiers. However, it can often take on more permanence than water conservation, which is a dire necessity in many cases, and is constant over the applicable period rather than decreasing. Examples would include a reduction in number of trucks or maintenance personnel. One other adjustment option can be thought of as a sub-case—an increase in the use of non-water inventories, though only through the very short run.

3. **Increased Substitutability of Other Inputs for Water System Deliveries.** This response would be exemplified primarily by purchasing water from other sources (by the bottle or truckload), or by moving to another location where less water is needed.

4. **Back-up Supplies.** This response is often implemented in the immediate aftermath of an earthquake in the short-run. It includes adjustments that incur costs, such as the digging of wells, and rather costless measures, such as collecting rainfall or using riverine water. The costless alternatives can be modeled in a manner similar to conservation and the cost-incurring ones similar to substitution. The use of water inventories (stored water) is best addressed as discussed above. As with the inventory item discussed above, there is some flexibility in how costs are considered temporally.

5. **Water Importance**. This response requires more explanation because of the widespread use of the term "importance" in its broadest sense in the earthquake research literature. Sometimes, it has been used to encompass all other

responses. In ATC-25 (1991), utility lifeline importance was quantified as the percentage change in a sector's output that would result from a one percent change in input availability. If water were used everywhere in the production process and no resiliency measures were possible, a one percent decrease in water would lead to a one percent decrease in output, or an importance factor of 1.0 (the same as the I-O fixed coefficient production function). The existence of various responses lowers the importance factor, which had a value as low as .30 for the Transportation and Warehouse sector in ATC-25. Here we go to the opposite extreme in the use of the term as the percentage of production activities in a given sector that do not require water to operate. Thus, it refers to the inherent resiliency of a production process in the absence of any explicit adjustment.

6. Time-of-Day Usage. This is a passive response that pertains to hours during which the business is closed, and hence where loss of water has no effect on output (see, e.g., Rose and Lim, 2002, for an example of how this adjustment greatly reduced loss estimates from electricity disruptions in the aftermath of the Northridge earthquake). It is listed here for the sake of comprehensiveness.

7. Change in Technology. This refers to long run (permanent) changes in the overall process, such as replacing open systems, which do not recycle water, with closed systems. It may require the reformulation of the entire production function.

Portland Water System and Economy

The Portland 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. Construction of the PBWW dates back to 1894. 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, its maintenance and earthquake mitigation costs, and its earthquake vulnerability can be found in Chang (2001b).

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. 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.

Links to Current Research

Los Angeles Lifeline Demonstration Report

NSF Project on Infrastructure User Costs on Seismic Risk Management

> ***"Our analysis provides a way of further utilizing the extensive empirical and simulation results on business interruption in the aftermath of earthquakes developed by other MCEER researchers"***

The SAM industry accounts contain 20 sectors, with the Water & Sanitary Services separated from other utility services in order to pinpoint economic impacts of water supply disruptions in the aftermath of an earthquake. The Total Gross Output of the Portland Metro economy in 1998 is \$71.2 billion, including \$42.1 billion in interindustry transactions and \$29.1 billion of total value-added. The total domestic commodity supply and exports of the Portland Metro Area in 1998 are \$43.3 billion and \$27.9 billion, respectively, implying the region is moderately self-sufficient. This is further evidenced by the trade accounts. The net domestic trading surplus is about \$3.4 billion and the net foreign trading deficit is about \$5.2 billion.

Simulating the Response to Natural Hazards

The Portland Area is characterized by moderate seismic activity stemming from the ocean floor Cascadian Subduction Zone and a series of shallow crustal faults. Two damaging earthquakes have taken place in the past 40 years measuring M5.5 and M5.6. However, large subduction earthquakes as great as M9.0 have taken place as recently as 1700 (see Wong et al., 2000).

Chang (2001b) simulated the effects of three alternative mitigation measures (no action, cast-iron pipe replacement, and tank/pump upgrade). The analysis was undertaken in the context of a life-cycle cost model that factored in not only the cost of mitigation over time and its ability to reduce system vulnerability through the year 2050, but also the savings of ordinary maintenance costs.

Chang (2001b) 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 an amorphous amount of resiliency. Based on the work by ATC (1991) and Tierney (1997), resiliency is defined by Chang as "the remaining percentage of output that an industry can still produce in the event of total water outage." Sectoral resiliency measures range from a low of 21 percent for Health Services to a high of 49 percent for Transportation and for Communications and Utilities. Note that the definition of resiliency we provided above is a generalization of Chang's definition to cases where the water outage is not a total one. Note also that the ATC definition assumes a linear relationship, but that non-linear relationships are likely to be more realistic. Our methodology can be used to estimate non-linear relationships between water service disruptions and output reduction and hence represents a non-linear measure of resiliency.

The recalibration of the water productivity parameter (A_W) was solved analytically. However, the recalibration of the elasticity of substitution (σ_1) between water (W) and the capital, energy, labor, and material aggregate ($KELM$) could only be undertaken with a numerical solution, in this case uses the numerical bisection method, which is a converging root search routine. In our analysis, we simulate water conservation and water substitutability with equal 50-50 weights based on survey results for the Northridge earthquake by Tierney (1997).

Water Disruption Simulation Results

Simulations were conducted of the regional economic impact of an earthquake-induced water supply disruption in the Portland Metro Area. Although Chang's engineering vulnerability and direct loss simulations involve many scenarios relating to alternative earthquake magnitudes, outage durations, and resiliency responses, our analysis focuses on a subset of scenarios characterized by:

1. One earthquake type (Bolton crustal fault) of magnitude 6.1.
2. Impacts in the Year 2000.
3. Scenarios for Business as Usual (No Mitigation) and Cast-Iron Pipe Replacement.
4. Outages of varying lengths from 3 to 9 weeks.
5. Four resiliency responses grouped into water conservation and increased substitutability.

We focused on the first characteristic because it represented the "most likely" case, and on characteristics 2-4 to keep the number of simulations manageable.

Note, one other important dimension of our simulations, which relates to pricing of water delivery. Ordinarily, CGE simulations allow prices to fluctuate freely in response to changing supply and demand conditions. However, two features of this situation warrant simulations with fixed water prices. The first is the fact that businesses often resist raising their prices in the aftermath of a natural disaster for reasons of altruistic community concern and to avoid the image of price gouging. Second, the PBWW is not a typical enterprise with fluctuating prices, but rather one in which rates are adjusted only periodically in the context of open public hearings.

No Pre-Event Mitigation; Post-Event Water Conservation and Increased Substitution

We used our recalibration algorithms to explicitly incorporate resiliency adjustments into our model accordingly for water conservation and increased substitutability. In our first simulation, unmitigated sectoral water disruptions sum to a 50.5 %. Our initial reference point of total direct (partial equilibrium) output losses equaling 49.1 % are estimated by our model before any resiliency adjustment. Chang's estimates of direct output losses, amounting to only 33.7 % because they reflect direct sectoral resiliency to water service outages. One measure of direct regional resiliency would be the extent to which the actual direct output reduction deviated from the likely (fixed-coefficient) maximum, which is equivalent to the %age water input disruption. The measure would be 33.3 % in this scenario [(50.5-33.7) ÷ 50.5].

Our estimates of the indirect (net general equilibrium) effects are 7.3 % reduction in regional gross output and a 41.0 % total (gross general equilibrium) reduction in regional gross output for the week. The former represents $99.9 million ($5,197 x 1/52 million) and the latter $561 million. Chang (2001b) assumes that restoration takes place within four weeks in a straight-line manner, so the total loss in economic output for the Region is estimated to be $1,122 million.

Indirect losses for the first case are only about 22 % the size of direct losses. In the context of I-O, this would be a multiplier of only about 1.22. The Portland Metro economy-wide output multiplier is significantly larger 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, it 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. A measure of overall regional economic resiliency to earthquake disruptions of Water Service would be the difference between the total fixed coefficient I-O multiplier and the CGE impacts. The weighted average Type II output multiplier for the Portland Economy is 1.9, or a 90 % increase over direct effects. Thus the regional economic resiliency measure in this case would be 54.4 % [(90-41) ÷ 90].

Pre-Event Pipe Replacement and Post-Event Water Substitution

The results of the scenario of an M6.1 crustal fault earthquake but with cast-iron pipe replacement are based on a reduction of the direct water outage from 50.5 % to 31.0 %. Our initial estimates of direct output losses are 30.7 %, compared to Chang's empirical estimates of 21.3 %. The parameter adjustments needed for the model to replicate the Chang direct loss estimates are lower than the corresponding parameter changes in each sector of the previous case because the direct output losses are projected to be lower in each. Our estimate of indirect losses in Scenario 2 is 9.2 %, which is a 43.2 % the size of direct losses.

Overall, Scenario 2 is estimated to incur a 30.5 % loss in gross output in the Portland Metro economy in the Year 2000 during the first week of water service disruption. In dollar terms, this translates into $418 million. However, Chang (2001b) estimates the system can be restored to full service within three weeks in this case, so, again assuming a linear restoration path, total output loss is $627 million. This is lower than the total economic loss associated with the "No Mitigation" simulation because it reflects both the reduction in loss for the initial disruption period (first week) but also a reduction in the time during which losses take place (from 4 to 3 weeks).

Table 1 decomposes the effects of the cast-iron pipe replacement strategy in the context of water conservation and increased substitutability responses. It indicates that the greatest contribution is from this strategy's reduction in direct losses (30.4 % of the 43.6 % overall reduction in losses for the total outage period). The reduction in loss due to decreased outage time is 13.1 %. The pure mitigation strategy actually increases the indirect losses by 4.8 %, but this is more than offset by the reduced outage time during which these effects

■ Table 1. Decomposition of Gains from Mitigation in Reducing Total Regional Losses from Portland Water Service Disruptions

	Level ($\$10^6$)	Percent Reduction
Total Business as Usual Scenario Loss	$1,112	--
Pipe Replacement Loss Reduction Decomposition	-485	-43.6
Change in direct loss (pure mitigation)[a]	-338	-30.4
Change in direct loss (reduced outage time)[b]	-146	-13.1
Change in indirect loss (pure mitigation)[a]	52	4.8
Change in indirect loss (reduced outage time)[b]	-63	-5.7
Index number error term	30	2.7

[a] Loss for a 4-week restoration period.

[b] Loss for a 3-week restoration period

take place. Note, however, that indirect losses are beyond the control of policymakers, and that this may pose a problem in dealing with the effects of various strategies. Fortunately, although it undercuts the cost-effectiveness of the mitigation alternative in this case, the unwanted increase in indirect effects is relatively small. Moreover the qualitative results in this case should not be generalized, because it is possible that, in other cases, indirect effects will be reduced, thereby reinforcing the mitigation effort.

Conclusion

We emphasize that, although we contribute significant advances to CGE modeling of the economic impacts of natural and other types of disasters, we have not remedied all of the problems. We assume that the economy adjusts to a new equilibrium, but we do not incorporate disequilibrium phenomena, except for holding utility lifeline service prices constant. We incorporate mitigation and adaptation costs but not other transition costs (e.g., labor relocation). Still, we believe the use of CGE modeling is legitimate in this case and significantly improves the accuracy of economic loss estimates. With respect to equilibrium adjustment considerations, earthquake ground-shaking may last only thirty seconds, but the time horizon we model includes the extended period of pre-event preparation, as well as the weeks to full recovery of lifeline services and rescheduling of production directly or indirectly interrupted. We compress the period of further general equilibrium adjustments to this time period without loss of generality. The analysis assumes that suppliers without customers and customers without suppliers can be matched during this short period. In fact, emergency management officials are investigating prospects for establishing an information clearinghouse to help expedite such adjustments. Essentially, we utilize a stylized period of analysis that strikes a balance between realism, manageability, and approximations of CGE modeling.

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