Modeling Regional Economic Resiliency to Earthquakes: A Computable General Equilibrium Analysis of Lifeline Disruptions

by

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ABSTRACT

Business interruption losses from natural hazards and terrorist attacks can be as costly as property damage. They can occur even when no physical damage takes place, as when a business is cut off from one of its utility lifelines. Moreover, such disruptions set off a chain reaction of further production cutbacks among successive rounds of customers and suppliers spreading through the entire regional economy. This paper refines an advanced modeling technique called computable general equilibrium (CGE) analysis to make it suitable for the assessment of the regional economic impacts of lifeline disruptions in the aftermath of a disaster. CGE is the state of the art of regional economic impact analysis but has several weaknesses. We develop a methodology for recalibrating key model parameters in light of empirical data on responses to lifeline disruptions that reflect individual business and regional resiliency. The methodology is applied to analyzing the economic impacts of a disruption to the Portland, Oregon water supply system in the aftermath of an earthquake. Comparison is made between impacts of a business-as-usual scenario and one that reflects the replacement of cast-iron pipe by advanced materials.

KEYWORDS: economic impacts of disasters, business interruption losses, resiliency, computable general equilibrium analysis

1.0 INTRODUCTION

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., 2000). 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 will set off a chain reaction of further production cutbacks among successive rounds of customers and suppliers spreading 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).

Research on this subject has until now been dominated by the application of input-output (I-O) models, which are linear, rigid and characterized by simplistic responses; and by

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mathematical programming models, which omit any behavioral responses to prices and markets (see, e.g., Cole, 1995; Rose et al., 1997). Computable general equilibrium (CGE) analysis would appear to be the superior alternative for the next generation of regional economic impact methodologies. It is comprehensive, non-linear, based on individual behavior in response to market prices, and explicitly incorporates a broad range of constraints (see, e.g., Rose, 2002; Rose and Guha, 2002).

One of the few advantages of I-O over CGE modeling is the clear distinction between direct and indirect impacts in the former. Interdependence is even stronger in the CGE framework because of its price-quantity interconnectedness. Thus, CGE results are typically presented in terms of total impacts only and are difficult to decompose. Another shortcoming of CGE models is the lack of data for estimating the many additional key parameters they require, especially elasticities of substitution.

The methodology in this paper provides an alternative to the usual non-survey "adaptation" approach to CGE model parameter estimation. It utilizes primary data on direct economic losses and a sophisticated computational algorithm to recalibrate sectoral production functions in response to a water lifeline service disruption in the aftermath of a major earthquake. It also measures how resiliency improves when mitigation is implemented in the form of replacing old cast-iron pipe with the latest generation of durable materials. Our modeling advances are inspired by the extensive empirical work on business interruption in the aftermath of earthquakes by Tierney (1997), Chang (2001) and others. Our parameter adjustments are linked to specific real world examples of business resiliency (e.g., conservation, use of back-up supplies and equipment, increased substitutability). The approach also enables us to distinguish between direct and indirect losses in a CGE context. This refinement is important because, while each of these adjustments may be capable of reducing the economic shock to the same minimum direct reduction in output, each has different implications for indirect impacts (see, e.g., Rose and Lin, 1995).

2.0 CGE MODEL ADVANTAGES

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 (Boisvert, 1992; Brookshire and McKee, 1992; Rose and Guha, 2002). CGE models can be finely disagggregated to better distinguish the various degrees of vulnerability to hazards across sectors. The production functions are inclusive of all inputs, not just primary factors as in the case of many other economic models, which facilitates identification of materials shortages. At the same time, CGE models allow for the possibility of input substitution, which mimics real world responses beyond the very short run in minimizing hazard impacts. They also allow for the substitution of imported goods for regionally produced goods. CGE models are non-linear in form, thereby more closely reflecting real world conditions, such as economies of scale and non-linear damage functions. CGE models are more capable of analyzing disjoint change than are model forms based on time series data and which therefore simply extrapolate the past. They can also more readily accommodate engineering data or data based on informed judgment.

Another set of CGE model advantages pertains to the important role of prices and markets. Related to this is explicit consideration of behavioral response, and not just simple optimization but also instances of bounded rationality, applicable to both mitigation and recovery behavior.

Finally, CGE models are superior to some other alternatives in modeling the role of lifelines and infrastructure, which include societal necessities such as electricity, water delivery, transportation, and communication. Many of these services are especially vulnerable because they are provided in linear links so that if one is disrupted, so are all downstream extensions. A CGE model can place a valuation on these services, even for public sector outputs that are typically unpriced. This is more than an academic exercise, because "shadow values" might serve as temporary prices to ration these services through the market rather than by administrative decree (Rose and Benavides, 1999).

3.0 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-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 (see, e.g., Perroni and Rutherford, 1993). It can incorporate a range of input substitution possibilities (not just the 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 elasticity is constant for a given tier, but elasticities can vary across tiers). 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). 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. Again, our methodology provides a way of improving the empirical estimates of key elasticities.

3.1 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:

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

$$KLEM = A_2\left(\alpha_2 M^{-\rho_2} + \beta_2 KEL^{-\rho_2}\right)^{-1/\rho_2} \quad (2)$$

$$KEL = A_3\left(\alpha_3 L^{-\rho_3} + \beta_3 KE^{-\rho_3}\right)^{-1/\rho_3} \quad (3)$$

$$KE = A_4\left(\alpha_4 K^{-\rho_4} + \beta_4 E^{-\rho_4}\right)^{-1/\rho_4} \quad (4)$$

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 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
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 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 to water services (1st Tier) and inherent in the overall production function with respect to other inputs (Tiers 2-4).

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, and, in one case, the variables in the sectoral production functions of the CGE model.

3.2 Production Responses to Natural Hazards

Below we summarize types of response to natural hazards, linked to the production function tier and parameters to which each relates and to the recovery/reconstruction stage (time period) to which each is applicable (see Rose and Liao, 2002, for the mathematical derivation of the major production function responses). These responses include:

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), biases 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 it is listed in Table 1 as 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.[2]

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

[2] Actually, an increase in inventory use may be more like response number 5 below because material is actually used and not saved; however, it is listed here because the purchase has been made in an earlier time period (and will likely be replenished in later one).

the earthquake research literature. Sometimes, it has been used to encompass all of the responses noted in Table 1. 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. The presence of this factor is labeled as constant in Table 1; any increase in it over time would mean further technology adjustment and would come under the headings of responses 1 or 7.[3]

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, 1997, 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.[4]

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.

4.0 PORTLAND ECONOMY AND WATER SYSTEM

4.1. The Portland Water System

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 (2001).

4.2 Portland CGE Model

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.

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[3] Note that ATC-25 assumed that the first 5 percent of lifeline service disruption would not result in any loss of output by customers due to various resiliency measures, such as the others noted in Table 1. Hence, there is some ambiguity about the extent to which the ATC-25 importance factor is intended to be limited just to separable production activities as in the definition in this paper.

[4] In a more extensive model involving dispatch decisions in which water or electricity might be rationed by time of day to shave peak production, this adjustment comes into play for firms that cannot switch production to off-hours.

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. Major features of the Portland CGE model are described in Rose and Liao (2002).

4.3 Model Solution Algorithms

Previous research on the application of CGE models to lifeline disruptions (see, e.g., Rose and Guha, 2001) has made use of the basic nonlinear programming features of the General Algebraic Modeling System (GAMS) software (Brooke et al., 1988). However, GAMS was not able to incorporate the range of substitution elasticity values required. We constructed the Portland CGE model using MPSGE, a subsystem of GAMS that facilitates the formulation and analysis of applied general equilibrium models through complementarity programming (Rutherford, 1995), and which allows for a broader range of parameter values and the inclusion of a broader range of constraints (e.g., sectorally differentiated supply availabilities of lifeline services). Basic elasticity of substitution values in the model were based on a careful synthesis of the literature (see Rose and Guha, 2002). Because we are modeling a very short-run response we further modified all input and trade substitution elasticities (except input elasticities pertaining to water as discussed below) so that they were 10% of their initial values.

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 the numerical bisection method, which is a converging root search routine.[5] Given sectoral water availability and the corresponding output reduction rate, the recalibration involves three iterative steps: First, find a lower bound of σ_1. To obtain an initial unadjusted output reduction rate higher than Chang's estimate for all sectors, 0.05 was used as the lower bound for all sectors. Second, find an upper bound of σ_1. Our initial guess of the upper bound of σ_1 was 0.15, which yielded a corresponding output reduction rate lower than Chang's estimate for all sectors. Third, calculate the arithmetic average of the lower and upper bounds of σ_1 and its corresponding output reduction rate. If the output reduction rate is higher (lower) than the direct output loss estimate, then the arithmetic average can be used as the new lower (upper) bound of σ_1 for the next iteration. The iterative procedure is continued until the deviation between the calculated output reduction rate and the empirical direct loss estimate is less than 0.01%. In our model, the routine converged to the recalibrated σ_1 in less than 10 iterations for each sector.

The computational procedure we have developed to improve model accuracy also generates an additional dividend of enabling us to decompose loss estimates. Our estimation of indirect losses involves the following procedure:

1. Extract the sectoral production functions from the CGE model and adjust parameters and variables in them one at a time to match empirical direct loss estimates.

2. Reinsert the recalibrated sectoral production functions into the CGE model, reduce input supply to a level consistent with empirical estimates, and compute total regional losses.

3. Subtract direct losses from total losses to determine indirect losses.

[5] Other parameters, such as A_W, can be solved analytically (see Rose and Liao, 2002).

5.0. SIMULATING THE RESPONSE TO NATURAL HAZARDS

5.1 Earthquake Parameters

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).

Although PBWW service has not been disrupted by earthquakes, a recent study by EQE (1999) found that operators of the system consider it vulnerable. The study also identified mitigation measures that might help meet the System's safety performance standards desired by stakeholders.

Chang (2001) 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. In the analysis below, we will confine our attention to the Year 2000. Also, we will focus on the direct and indirect effects of system disruptions before and after mitigation (through cast-iron pipe replacement by the latest generation of advanced materials) and will leave to another paper our analysis of the regional impacts of implementing the mitigation measures.[6]

5.2 Empirical Measurement of Resiliency

Chang (2001) 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 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 analysis below can be used to estimate non-linear relationships between water service disruptions and output reduction and hence represents a non-linear measure of resiliency.

6.0 WATER DISRUPTION SIMULATION RESULTS

Simulations were conducted of the regional economic impact of an earthquake-induced water supply disruption in the Portland Metro Area. The analysis is based on the simulation of the systems analysis of the Portland water utility system and the direct loss estimation simulations of Chang (2001) described above. Although Chang's engineering vulnerability and direct loss simulations involve many scenarios relating to alternative earthquake magnitudes, outage durations, and resiliency responses, this paper 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.

[6] Chang (2001) estimates the cost of tank pump upgrades as only $2.1 million, but that of pipe replacement as $380 million.

5. Resiliency responses involving only the substitution of other inputs for water services.

We focused on the first characteristic because it represented the "most likely" case and characteristics 2-4 to keep the number of simulations manageable. We confined ourselves to the characteristic 5 because we have not yet fully developed the methodology to implement changes in other parameters.

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.

6.1. No Pre-Event Mitigation; Post-Event Water Substitution

The results of our simulations for the Business as Usual Scenario (no mitigation) are presented in Table 1. Note that the duration of this outage is projected to be 4 weeks, but the table summarizes the situation for the maximum disruption, which takes place during the first week. Results for the total outage period are summarized more briefly below.

The sector labels on the left-hand side of Table 1 refer to the economic producing units of the Portland CGE model, and direct water disruption for each sector is presented in column 2. In 2000, for example, unmitigated sectoral water disruptions sum to a 50.5 percent. As discussed further below, negative indirect effects on sectors such as Construction are so great as to reduce water demand significantly below the post-earthquake availability levels. Baseline output is presented in Column 3 and reflects the relative prominence of sectors in Portland Metro economy; it also serves as a reference point for our impact simulations. Note that the Water sector (11) gross output represents only 0.44 percent of the regional economy.

Column 4 of Table 1 presents the direct output losses equaling 49.1 percent that are estimated in our model before any resiliency adjustment. Chang's estimates of direct output losses amounting to only 33.7 percent, which incorporate the extent of resiliency, are presented in Column 5.[7] Our direct loss estimates are based on input substitution elasticities of 0.05 presented in the next to the last column in Table 1. Note that our direct loss estimates exceed those of Chang in every sector because ours omit all resiliency options except normal input substitution (and at very low levels). The final column shows the elasticities necessary to incorporate resiliency measures for our model results to be consistent with the Chang estimates (these range from a low increase of 36 percent in Sector 18 to a high increase of 130 percent in Sector 11 itself).

Our estimates of the indirect and total regional economic impacts of the water lifeline disruption are presented in Columns 7 and 8. Overall, they yield a 10.7 percent indirect reduction in regional gross output and a 44.4 percent total reduction in regional gross output for the week. The former represents $586 million and the latter $2,431 million. Chang (2001) assumes that restoration takes place in a straight-line manner, so the total loss in economic output for the Region is estimated to be $4,862 million. Moreover, for an actual earthquake, damage to other utilities and buildings would likely lead to losses much greater than this, though care needs to be taken to avoid double-counting losses to the same

[7] One measure of resiliency would be the extent to which the actual direct output reduction deviated from the likely (fixed-coefficient) maximum, which is equivalent to the percentage water input disruption. The measure would be 33.3 percent in this scenario [(50.5-33.7) ÷ 50.5].

business from several sources (see Chang et al., 1996).

Some interesting aspects of general equilibrium (indirect) losses for the first case are indicated by Table 1. First, they are only about 32 percent the size of direct losses. In the context of an input-output model, this would be a multiplier of only about 1.32. 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. The sector suffering the largest indirect decline is Construction (a leading indicator of economic activity); however, if post-earthquake recovery and reconstruction were to be factored in, the Construction decline would be offset significantly. In addition, several sectors are characterized by positive or minimally negative indirect effects, most notably basic necessities, such as Food Processing and Health Services.

6.2 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 presented in Table 2. We realize this scenario is somewhat unrealistic because it accelerates the replacement of cast-iron pipes at an unrealistic pace but believe this provides a useful illustration of the potential advantages of mitigation. Note also that the results represent a lower bound of the gains in this type of mitigation in future years, since pipe replacement would be even more valuable as the current system deteriorates, thereby incurring increasingly higher ordinary maintenance cost and likely greater earthquake vulnerability.

In this second Scenario, the direct water outage is reduced from 50.5 percent to 31.0 percent (see column 2 of Table 2). Our initial estimates of direct output losses are 30.7 percent, compared to Chang's empirical estimates of 21.3 percent.[8] The substitution elasticity adjustments needed for the model to replicate the Chang direct loss estimates are presented in the final column of Table 2. They are lower than the corresponding water input changes in each sector because the direct output losses are projected to be lower in each.

Interestingly, our estimate of general equilibrium ("indirect") losses in Scenario 2 is 11.2 percent, which is a 52.6 percent greater than direct losses. Moreover, not only is the percentage increase over direct losses higher in Scenario 2 than in Scenario 1 but the absolute level is as well. The latter is quite surprising at first glance. It would seem to 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 non-linear. Secondly, we should not forget that we have changed parameters (with respect to water substitution), so even in an I-O context multipliers would differ (though only slightly given the small size of our parameter changes, which would correspond to the coefficient changes that would be utilized in an I-O model). The major explanation of the relatively higher percentage of general equilibrium effects in Scenario 2 is due to the difference in the sectoral mix of direct water disruptions in relation to Scenario 1. This changes relative prices, and the model, despite its relatively low substitution elasticities, is quite responsive. For example, sectors 3, 5, and 7 all incur indirect effects greater than direct ones, and these sectors, as well as 6, 12, 16, and 20, incur greater indirect

[8] The resiliency index defined in endnote 7 is 31.3 percent in this case. Resiliency would seem to decrease from the 33.3 percent of Scenario 1, but this is likely due to the fact that resiliency opportunities decrease as the size of the disruption decreases (and vice versa, though some threshold may exist for especially large disruptions that overwhelm the resiliency capabilities). Note also that 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) ÷ 50.5].

losses in Scenario 2 than in Scenario 1, despite lower direct losses in the former.

Overall, Scenario 2 is estimated to incur a 32.5 percent 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 $1,800 million. Chang (2001) 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 $2,700 million, for an overall reduction from business as usual of 44.5 percent. We now decompose this improvement into its various constituents. The greatest contribution of cast-iron pipe mitigation is the reduction in restoration (-24.4 of the -44.5 percent) time, followed closely by the decrease in direct losses (-21 percent). Indirect losses (0.8 percent) are beyond the control of policymakers, and, although they undercut the effectiveness of this mitigation alternative in this case, their influence is minimal. Moreover, in most cases they are likely to be reinforcing.[9]

7.0. CONCLUSION

This paper has presented major methodological advances in computable general equilibrium modeling for application to estimating the regional economic impacts of earthquakes and other disasters. First, we have provided an operational methodology for recalibrating model parameters in light of empirical estimates of production losses due to a lifeline supply disruption. Second, the methodology enables the analyst to decompose loss estimates into direct and indirect components. Our application to a disruption of water services of the Portland Metro economy showed that indirect economic losses can vary substantially according to the overall level and sectoral mix of water shortages.

Overall, our results appear to be reasonable for the economy as a whole, for individual sectors, and for individual impact stages (direct and indirect). We have, however, modeled only one resiliency measure, albeit one of the most important ones—increased substitutability of other inputs for water utility services. As discussed earlier, different types of resiliency responses would generate different types of indirect impacts. However, only a full simulation will provide a definitive conclusion.

[9] Note that we also simulated cases (not shown) in which water prices were allowed to fluctuate in response to changing conditions of supply and demand. Interestingly, despite a 33 percent increase in water prices in this variant of Scenario 2 the overall results were similar, though indirect effect losses did decrease from 11.2 percent to 10.5 percent, or lower than the 10.7 percent of the Business as Usual Scenario. The reason for this improvement is that resources are allocated more efficiently when prices are not fixed, though the price increase will be especially burdensome to marginal businesses and low income consumers. This points out one of the important equity-efficiency tradeoffs in the mitigation of natural hazards impacts. Mitigation is often just associated with pre-event activities, but it also pertains to post-earthquake responses, such as reducing restoration times or modifying pricing, both of which can have the effect of reducing overall losses or losses to various stakeholders (see also Rose et al., 1997; Shinozuka et al., 1998).

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TABLE 1. ECONOMIC IMPACTS OF WATER SERVICE DISRUPTIONS IN THE PORTLAND METRO AREA, 2000: NO MITIGATION
(fixed water service price)

Sector	Water Input			Output	Output Change From Water Outage				Elasticity (σ)	
	Baseline (million $)	Direct Disruption	Total Unused	Baseline (million $)	Our Direct w/o Adjust[a]	Chang's Direct	Indirect	Total[b]	Without Adjustment	With Adjustment
1. Agriculture	0.9	-48.0%	-48.4%	297.4	-46.0%	-33.7%	-1.8%	-35.5%	0.050	0.074
2. Mining	0.0	-48.6%	-48.9%	57.7	-46.7%	-26.5%	-11.5%	-38.0%	0.050	0.078
3. Construction	8.4	-51.5%	-60.0%	5160.4	-49.5%	-27.8%	-31.1%	-59.0%	0.050	0.089
4. Food Products	3.1	-49.9%	-50.0%	1862.7	-48.0%	-33.5%	1.8%	-31.7%	0.050	0.077
5. Manufacturing	27.8	-54.5%	-59.1%	16509.7	-52.5%	-36.2%	-21.7%	-57.9%	0.050	0.083
6. Petroleum	0.4	-54.5%	-54.8%	127.7	-52.5%	-36.2%	-16.7%	-52.9%	0.050	0.083
7. Transportation	27.8	-47.8%	-48.0%	3210.3	-45.9%	-24.3%	-20.7%	-45.0%	0.050	0.098
8. Communication	1.2	-48.0%	-48.5%	1453.1	-46.1%	-25.0%	-8.1%	-33.0%	0.050	0.083
9. Electric Utilities	2.4	-48.0%	-48.1%	1992.8	-46.1%	-25.0%	-4.8%	-29.7%	0.050	0.085
10. Gas Distribution	0.1	-48.0%	-48.5%	570.7	-46.1%	-25.0%	-0.5%	-25.5%	0.050	0.078
11. Water & Sanitary Services	4.9	-48.0%	-53.5%	315.4	-46.2%	-25.0%	-13.5%	-38.5%	0.050	0.115
12. Wholesale Trade	12.3	-51.8%	-51.9%	7122.6	-49.8%	-33.1%	-13.3%	-46.4%	0.050	0.083
13. Retail Trade	14.1	-50.9%	-50.9%	4994.2	-48.9%	-36.1%	2.7%	-33.4%	0.050	0.078
14. F.I.R.E.	32.5	-48.9%	-49.0%	10158.0	-46.9%	-36.4%	2.4%	-33.9%	0.050	0.073
15. Personal Services	9.1	-50.9%	-50.9%	1521.1	-48.9%	-35.0%	-0.3%	-35.4%	0.050	0.082
16. Business & Prof. Services	13.7	-51.2%	-50.9%	7971.4	-49.2%	-34.6%	-8.0%	-42.6%	0.050	0.078
17. Entertainment Services	1.5	-50.0%	-50.3%	459.6	-48.0%	-34.6%	-1.1%	-35.7%	0.050	0.077
18. Health Services	7.5	-52.7%	-52.9%	3006.9	-50.7%	-42.5%	12.2%	-30.2%	0.050	0.068
19. Education Services	0.8	-51.9%	-51.9%	587.3	-49.9%	-36.3%	4.0%	-32.3%	0.050	0.075
20. Other Services	9.6	-49.3%	-49.3%	3981.2	-47.4%	-34.0%	-10.3%	-44.3%	0.050	0.077
Total	178.2	-50.5%	-51.0%	71188.9	-49.1%	-33.7%	-10.7%	-44.4%		

[a]From partial equilibrium analysis.
[b]Following CGE simulation.

TABLE 2. ECONOMIC IMPACTS OF WATER SERVICE DISRUPTIONS IN THE PORTLAND METRO AREA, 2000: PIPE REPLACEMENT
(fixed water service price)

Sector	Water Input: Baseline (million $)	Water Input: Direct Disruption	Water Input: Total Unused	Output: Baseline (million $)	Output Change From Water Outage: Our Direct w/o Adjust[a]	Output Change From Water Outage: Chang's Direct	Output Change From Water Outage: Indirect	Output Change From Water Outage: Total[b]	Elasticity(σ): Without Adjustment	Elasticity(σ): With Adjustment
1. Agriculture	0.9	-30.9%	-30.8%	297.4	-29.5%	-21.4%	2.2%	-19.1%	0.050	0.064
2. Mining	0.0	-30.2%	-37.1%	57.7	-28.8%	-16.4%	-3.5%	-19.9%	0.050	0.065
3. Construction	8.4	-32.7%	-52.1%	5160.4	-31.2%	-17.8%	-36.9%	-54.6%	0.050	0.071
4. Food Products	3.1	-30.2%	-30.1%	1862.7	-28.8%	-20.5%	8.6%	-11.9%	0.050	0.063
5. Manufacturing	27.8	-35.3%	-52.0%	16509.7	-33.7%	-23.8%	-27.6%	-51.3%	0.050	0.067
6. Petroleum	0.4	-35.3%	-45.2%	127.7	-33.7%	-23.8%	-21.4%	-45.1%	0.050	0.067
7. Transportation	27.8	-24.5%	-32.1%	3210.3	-23.3%	-13.4%	-19.8%	-33.2%	0.050	0.070
8. Communication	1.2	-28.3%	-28.0%	1453.1	-27.0%	-14.8%	-2.8%	-17.6%	0.050	0.066
9. Electric Utilities	2.4	-28.3%	-29.0%	1992.8	-27.0%	-14.8%	2.1%	-12.7%	0.050	0.068
10. Gas Distribution	0.1	-28.3%	-28.3%	570.7	-27.0%	-14.8%	7.1%	-7.7%	0.050	0.064
11. Water & Sanitary Services	4.9	-28.3%	-44.2%	315.4	-27.1%	-14.8%	-5.0%	-19.8%	0.050	0.086
12. Wholesale Trade	12.3	-31.9%	-38.0%	7122.6	-30.4%	-20.7%	-16.4%	-37.1%	0.050	0.066
13. Retail Trade	14.1	-33.5%	-33.9%	4994.2	-32.0%	-23.5%	6.7%	-16.8%	0.050	0.066
14. F.I.R.E.	32.5	-29.8%	-30.0%	10158.0	-28.4%	-22.2%	5.4%	-16.7%	0.050	0.062
15. Personal Services	9.1	-32.4%	-31.9%	1521.1	-31.0%	-22.3%	3.6%	-18.7%	0.050	0.067
16. Business & Prof. Services	13.7	-32.0%	-31.9%	7971.4	-30.5%	-21.8%	-8.2%	-30.0%	0.050	0.064
17. Entertainment Services	1.5	-31.6%	-31.8%	459.6	-30.1%	-21.8%	2.8%	-18.9%	0.050	0.065
18. Health Services	7.5	-34.9%	-34.8%	3006.9	-33.3%	-28.0%	18.9%	-9.2%	0.050	0.060
19. Education Services	0.8	-35.0%	-35.1%	587.3	-33.4%	-24.1%	12.8%	-11.3%	0.050	0.065
20. Other Services	9.6	-30.7%	-33.4%	3981.2	-29.3%	-21.1%	-14.4%	-35.5%	0.050	0.064
Total	178.2	-31.0%	-36.5%	71188.9	-30.7%	-21.3%	-11.2%	-32.5%		

[a]From partial equilibrium analysis.
[b]Following CGE simulation.