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An Integrated Engineering-Economic Model for Assessing Regional Vulnerability to Natural Disasters

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RESOURCES FOR THE FUTURE

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Abstract

The impact of a tsunami can vary greatly across short distances because of differences in topography, building structures, the concentration of economic activities in the inundation zone, and the economic links beyond the inundation zone. In this study, we take these factors into account in an analysis of a potential tsunami on the west coast of the United States. An integrated engineering-economic model is proposed that uses detailed information on spatial heterogeneities in flood depth and economic activity by connecting engineering estimates of tax-lot physical damages with economic activity at the sector level. The performance of this new approach, in terms of estimated total losses and the distribution of effects across sectors, is compared with two prominent alternatives: engineering-only and economic-only. This study reveals special concerns of overestimation and inaccurate vulnerability assessment by the Federal Emergency Management Agency's Hazus program, which uses an input-output–based framework and lacks spatially explicit estimates of physical damages and economic losses.

Key Words: computable general equilibrium, natural disaster, flood, oceans and coasts, impact assessment, vulnerability, resilience

Contents

1. Introduction **1**

2. Context **4**

3. Integrated Engineering-Economic Model **5**

Engineering Model 5

Engineering-Economic Integration 7

Economic Model 10

4. Results and Discussion **12**

Sensitivity Analysis 14

5. Limitations and Conclusions **15**

References **18**

Tables and Figures **21**

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1. Introduction

This study is concerned with the incorporation of spatial complexity into assessments of regional disaster vulnerability. The context is a tsunami resulting from a Cascadia Subduction Zone earthquake exceeding magnitude 9.0. Coastal communities from northern California to southern Canada have a 40 percent chance of experiencing this level of earthquake in the next 50 years (Goldfinger et al. 2012). A west coast earthquake of this magnitude would affect more than 1000 km of coastline and set off tsunamis similar in their intensity to those caused by the 2011 Tohuku earthquake in Japan. The last large earthquake to strike the region was in January 1700, and one of similar magnitude could happen at any time (Cascadia Region Earthquake Workgroup 2005).

Understanding the potential economic consequences and associated vulnerabilities is critical for guiding investments in predisaster preparedness and planning for postdisaster recovery. Appropriate economic understanding requires detailed information about the structure of local economies but begins with predictions of direct physical damage (Cochrane 1997; Rose et al. 1997). For a given tsunami, the physical damage can vary greatly over short distances because of differences in on- and off-shore topography and infrastructure across developed areas, including the density, size, age, and construction of buildings, roads, and bridges. Predictions of physical damage must take these factors into account (Suppasri et al. 2012; Wiebe and Cox 2014).

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An economic approach, meanwhile, is necessary to translate the physical impact of a tsunami into a monetary value of the damages across sectors. Economic effects can be defined as effects on flows, categorized as direct and indirect (Boisvert 1992; Rose et al. 2007; Okuyama 2008). Direct effects, as defined in this study, are a curtailment in output resulting from a loss in physical capital available to that sector. For example, output in the energy sector will fall when a power plant is destroyed. Indirect effects include disruption of activity in other parts of the economy and other consequent economic adjustments. For example, manufacturing and tourism may suffer indirect losses related to the decline in energy output in addition to their own direct effects. This happened in the 2011 Japanese earthquake, when damage sustained by certain critical auto part suppliers caused a supply chain bottleneck for automobile manufacturers in Japan and countries abroad. Indirect effects also include adjustments in household consumption and firm production due to changes in the economic endowments after the tsunami. These adjustments may create a more resilient system if the supply chain extends outside the affected area (Todo et al. 2015) or if the affected businesses have more redundant connections with suppliers and customers. The existence of diversified networks of supply and demand may create a more resilient system, especially if supply chains extend outside the region (Henriet et al. 2012). These indirect effects can be captured by computable general equilibrium (CGE) models, which capture how shocks reverberate through an economy and influence nearly every sector in some way (Rose and Liao 2005).

To address the regional effect of a tsunami, this study develops a new spatially integrated engineering-economic model that includes an interface between a spatial engineering model and a CGE model. The engineering component starts with the Method of Splitting Tsunami (MOST) model (Wiebe and Cox 2014), a state-of-the-art engineering model for simulating tsunamis, their propagation through the ocean, and the fine-scale spatial distribution of floodwater depth. This information is then fed into empirically derived fragility curves (Suppasri et al. 2012) to generate the tax lot–level probability of major physical damage arising from the tsunami. Using the geographic information system (GIS) from the Environmental Systems Research Institute (ESRI), this tax lot–level probability map is combined with the tax lot–level map of economic activity to generate tax lot–level expected direct economic effects. Finally, the tax lot–level expected direct effects are aggregated into effects by 15 economic sectors and fed into a newly developed, county-level CGE model that is calibrated using a regional social accounting matrix (SAM).

The study thereby addresses two major challenges for the integration of existing engineering and economic models. First, the physical damage with high spatial resolution simulated by engineering models must be converted into economic impact estimates—that is, disruptions in economic production. Second, the economic impact estimates with high spatial resolution need to be aggregated by economic sector. This study contributes to the literature by addressing these issues and integrating the two lines of research.

Improving the interface between engineering and economic approaches is particularly challenging for the tsunami envisioned in this paper because it will affect a large area, including areas linked geographically but not economically as well as areas linked economically but not geographically. Because the physical damage from a tsunami of this type will vary greatly with the spatial heterogeneity in the landscape and built environment, a high level of resolution is required, and this study benefits from the most detailed engineering available (Henriet et al. 2012).

Most disaster impact assessments focus on the damage to particular infrastructure in an urban area, such as water service, transportation centers, or power generators (Rose at al. 1997; Gordon et al. 1998; Cho et al. 2001; Sohn et al. 2004; Rose and Guha 2004; Santos and Haimes 2004; Rose and Liao 2005; Lian and Haimes 2006; Tatano and Tsuchiya 2008; Crowther and Haimes 2010). Rose et al. (1997), for example, assume that the production capacity of all structures is the same as before the earthquake—that is, there are no capacity reductions from damaged factories.

Two post-disaster studies have analyzed the effect of a natural disaster on multiple sectors using reported data (Hallegatte and Ghil 2008; MacKenzie et al. 2012). The Hazus program of the US Federal Emergency Management Agency (FEMA) attempts to predict damages and economic harm due to hypothetical flooding events using the inundated square footage of building stocks at the census block level, assuming building stocks are evenly distributed within the census blocks (FEMA 2012).

This study considers physical damage to a multitude of locations at once. These locations are characterized by different types of economic activity, which are then linked to aggregate outcomes at the county level. It provides a more detailed integration of economic and engineering damage estimates, and it uses a CGE analysis to calculate indirect effects. It focuses on improving estimates of the value of lost production for a medium-run scenario of approximately one to four years.

Results contain useful, practical information for disaster preparedness and local investment policy, and they make important contributions to the analysis of the interface between engineering and economic models. These improvements are documented by a comparison of the results from the integrated engineering-economic model with the results from nonintegrated models, such as Hazus. The integrated model (called Model I) is shown to potentially provide a more accurate economic impact assessment. In particular, the nonintegrated engineering approach (Model II) and the nonintegrated economic approach (Model III) may over- or underestimate total economic effects. The nonintegrated models also incorrectly identify the most vulnerable sectors, which may lead to misallocations of disaster-relief resources and incorrect prioritization of affected industry sectors in the regional disaster resilience plan.

Beyond the coastal hazard example, this study proposes an assessment tool that is applicable to both metro and nonmetropolitan areas. Although both metro and nonmetropolitan economies are exposed to natural disasters, most studies focus on the lifelines available in metro areas (Sohn et al. 2004; Rose and Liao 2005; Rose et al. 2007). The total damage in nonmetropolitan communities may be much less, but a tsunami might inflict more consistent damage in these communities because their economies are usually less diversified and lacking in sufficient resources to cope with large disasters. Moreover, nonmetropolitan communities may be less likely to attract the attention of public media and receive aid for disaster relief.

This study focuses on Clatsop County, a nonmetropolitan county in Oregon, to show how the proposed integrated engineering-economic vulnerability assessment tool is also applicable for nonmetropolitan areas. Thus, this integrated impact assessment tool will demonstrate how to incorporate nonmetropolitan areas into disaster resilience planning.

The rest of the study is arranged as follows. Section 2 describes the context of the case study, including information on the Cascadia Subduction Zone and the characteristics of Clatsop County, Oregon. Section 3 describes the data and procedures of the integrated engineering-economic model. Section 4 compares the economic impact assessments using the nonintegrated and the integrated engineering-economic models. Section 5 concludes the study.

2. Context

Although little known among the general public, the Cascadia Subduction Zone poses an important threat to the coastal communities of western North America. Along the zone, the oceanic Juan de Fuca plate is slipping under the continental North American plate. The sudden displacement of the two oceanic plates will cause a perturbation of the water column from its equilibrium position and create a tsunami. Moment magnitude (Mw) is used to measure the size of plate displacement in terms of energy released. Every unit increase in Mw represents a 31.6-

fold increase in energy. Over the past 10,000 years, full-length zone events have ranged from 8.7 to 9.1 Mw, and the average recurrence interval is 240 years (Goldfinger et al. 2012).

As with many other communities in the Pacific Northwest, much of Clatsop County's economy and community is centered on the coastal margin and thus threatened by a potential tsunami. As of 2010, 96.7 percent of the county's land was rural, and 4.6 percent of its employment was in agriculture, forestry, fishing, hunting, and mining activities. This exceeds the associated average of 3.4 percent for the state level and 1.5 percent for the national level (US Bureau of Census 2014).

Figure 1 displays the location of businesses in Clatsop County; their annual revenues are represented by the size of the dots. The red and blue dots represent businesses inside and outside the inundation zone, respectively. Although only 15 percent of the land area in the county is in the inundation zone, 29 percent of county residents and 46 percent of business activity are located there. Business activities in the county are classified into 15 sectors. In Table 1, output is reported for each of the 15 economic sectors in 2010 along with their rankings. The value of output ranges from $18.67 million for agriculture to $554.71 million for wood manufacturing.

3. Integrated Engineering-Economic Model

The integration of the engineering and economic models is illustrated in Figure 2. The engineering model is first used to estimate the expected physical damages at the tax lot–level caused by a hypothetical tsunami. Second, the two spatially mismatched data—tax lot–level physical damages and point-level business locations—are integrated to estimate expected capital flow disruptions by economic sector. Finally, aggregated capital flow disruptions are fed into a county-level CGE model to assess the total county economic impact after the disaster.

Engineering Model

The engineering model estimates the probability of physical damages in five cities in Clatsop County under tsunamis of three magnitudes. The magnitude of a tsunami is determined by the magnitude of the earthquake that triggers it, which in turn is measured by the distance of the slip of the Juan de Fuca plate beneath the North American plate. Slip distances of 20, 17.5, and 15 meters are considered, which correspond to 9.3, 9.2, and 9.1 Mw earthquakes. To reduce the computational burden, five cities (Astoria, Warrenton, Gearhart, Seaside, and Cannon Beach) in Clatsop County are considered instead of the entire county. These cities account for more than 86 percent of the economic activity within the inundation zone.

The engineering model simulates the probability of physical damage on each tax lot following a two-step procedure, as illustrated by the two shaded boxes in Figure 3. First, a tsunami caused by an earthquake in the Cascadia Subduction Zone is simulated using the Method of Splitting Tsunami (MOST) maintained by the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration. Nested model mesh grids are used to reduce the computation burden. For off-shore regions, the simulation is done at varying degrees of resolution. Once the tsunami reaches the coastline, the resolution is increased to a grid size of 30 m^2. A more detailed description of the numerical model setup can be found in Wiebe and Cox (2014). This model generates the maximum flow depth for each grid, which is the maximum water depth in a particular grid during the flood caused by the tsunami. This is critical for determining the probability of physical damage.

The grid-level (with grid size of 30 m^2) maximum flow depth in Seaside, Clatsop County, is plotted in the first shaded box in the upper left of Figure 3. The colors indicate the maximum flow depth, from shallow (purple) to deep (yellow). Second, the spatial distribution of maximum flow depths is overlaid with the tax lot–level information on building types[1] to calculate the expected probability of major physical damage[2] at the tax-lot level using a fragility curve, which is an empirical stochastic function. The lower-left portion is a map that displays the building type for each tax lot, with green indicating wooden structures and black indicating concrete or steel structures. A sample fragility curve graph in the upper-right portion describes the probability of major physical damage, giving an indicator of physical stress such as flood depth in this case. It also shows how the relationship between damage probability and flood depth depends on the building type. The two S-shaped curves in the graph represent the fragility curves for wood and reinforced concrete structures (Suppasri et al. 2012).

The development of valid fragility curves to estimate physical building damage in general has been a recent advance in the engineering literature. Wiebe and Cox (2014) used the fragility curve of Suppasri et al. (2012), developed from the 2011 Tohoku tsunami, to estimate damage to buildings from a potential tsunami at Seaside, Oregon. In this study, the same methodology is

[1] Tax-lot information on building types is obtained from the Clatsop County Assessment and Taxation Department. Each tax lot is categorized with a three-digit property classification that is used to assign a building type (wooden or concrete/steel).

[2] Major physical damage is defined as occurring when “a window and the larger part of a wall are damaged” (Suppasri et al. 2012).

adopted. Their work is expanded to include more Oregon coastal communities and to link the results to an economic model.

The probability distribution of the tax-lot expected-major-damage map in the lower right of Figure 3 displays a sample of estimated major physical damage probability at tax-lot level, with blue indicating a lower probability of damage, and red, higher. For example, one of the tax lots has a building with a wood structure. MOST predicts a maximum flow depth of three meters on this tax lot. In the map of fragility curve, the solid line, the curve for the wood structures, shows that the corresponding probability of major damage on the tax lot is 0.8. This is the number plotted in the probability distribution of major damage at the tax-lot level in the bottom-right corner in Figure 3.[3]

Engineering-Economic Integration

The integration of the engineering and economic models involves two major steps. The first step is *information integration*, which involves merging economic activities data and simulated physical damages at the tax-lot level to generate expected direct economic losses for each individual business located in the tax lot. The second step is *information aggregation*, which involves combining the expected business-level direct economic losses into sector-level direct economic losses. The aggregated economic effects are then converted into capital flow disruptions to serve as input shocks for the CGE model.

This is one of the first attempts to convert simulated physical damage across an entire disaster zone into economic shocks for a CGE model. Unlike input-output models, which could equate the direct economic effects with output shocks for each sector (Hallegatte and Ghil 2008; MacKenzie et al. 2012; FEMA 2012), outputs in the CGE model are internally determined through agent decisionmaking and general equilibrium processes, and thus the external economic shocks are not imposed through direct shocks to output. Past studies have imposed shocks on particular external input components, such as water and electricity (Rose and Guha 2004; Rose and Liao 2005; Rose et al. 2007). However, this approach addresses the failure of only part of the infrastructure. In our study, capital flows serve as input shocks for the CGE model to assess the total economic consequences because these shocks are an external input in the CGE model and have the closest link with physical damage.

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[3] Readers interested in further details regarding the engineering aspects underlying the development of fragility curves are referred to Suppasri et al. (2012) and Wiebe and Cox (2014).

The capital flow defined in our model includes capital assets purchased over a one-year period to support production activities. By definition, major physical damage involves at least "a window and the larger part of a wall" (Suppasri et al. 2012). Here, for simplicity, major physical damage is assumed to cause a complete interruption in the economic activity inside the building.[4] In other words, major physical damage results in complete loss of capital flow in the building. If the probability of a major physical damage of a building is 50 percent, the expected disruption of capital flow, which equals the probability multiplied by the total capital flow of the business in the building, is only half its capital flow. However, we have no data concerning the capital flows of any business. To figure out the expected disruption in capital flow, the ratio between the sales revenue in the building and the total sales revenue of the sector is first calculated. This ratio is then multiplied by the total capital flow in the economic sector, which is available at county level, to generate the capital flow disruption in the economic sector. This is valid under the assumption that production exhibits a constant return to scale. The direct disruption in the capital flow due to a tsunami created by a 9.2 Mw earthquake is reported in Table 1, by economic sector. It is also assumed that all households are capable of working, implying that there are no shocks to the labor supply. This assumption can be relaxed in future work, but incorporating shocks into the labor supply is beyond the scope of the present study.

For the integration procedure, the expected direct economic effect is defined as the expected loss in the value of output over one year of the accounting period for each business, calculated as the product of the tax lot–level physical damage probability and the volume of sales on the corresponding tax lot. The tax lot–level economic effects are then aggregated by economic sector according to the NAICS code for the business activity at the location. For structures that house multiple businesses, the expected economic effects in different economic sectors are aggregated within their own economic sectors separately. This yields an estimate of the expected direct economic losses of a tsunami in Clatsop County by economic sector, as reported in Table 1. In an input-output analysis, this direct economic effect would be used as the initial shock to the economic system to calculate the multiplying effects. Note that this direct economic effect is much larger than the disruption of capital flow because the latter is only one of the many factor inputs used in production.

[4] In reality, production interruptions due to major physical damage will vary among sectors based on the nature of their operations and the speed at which the damaged capital can be reinstalled. We believe that by incorporating the differentiated interruption and recovery rates across sectors, future applications could improve the accuracy of predicted economic impacts. However, such an effort is beyond the scope of this paper.

Figure 4 demonstrates the two-step process of engineering-economic integration, information integration, and information aggregation, circled in the two gray boxes. In the information integration step (the left gray box), the two upper graphs from left to right show the conversion of point-level spatial data for business activities into tax lot–level data. ESRI (Environmental Systems Research Institute) ArcGIS 9.1 Business Analyst is a database that provides point-level business data by SIC and NAICS industry classifications. The business location data also report the business location, number of employees and total revenue of each business.[5] However, in this data set, the geographical location (given by latitude and longitude) of each business is geocoded using an address-matching method, which is not always accurate in rural areas. In Clatsop County, 39 percent of the businesses that are geocoded by street address are placed in the wrong tax lot, which accounts for the misplacement of 54 percent of sales and 42 percent of employment. To fix this problem, the point-level business location data in Business Analyst were matched with the tax-lot data from the county assessment office by street address.[6] This gives the tax lot–level distribution of economic activity in the county. For each tax lot, the revenue by economic sector (see "Tax lot–level economic activities map" in Figure 4) is multiplied by the corresponding probability of major damage (see "Distribution of major damages at tax-lot level" in Figure 4) to generate the expected direct economic impacts for that tax lot (see "Business-level expected direct economic impacts" in Figure 4). For tax lots with business complexes, only the business with the largest expected loss is plotted in Figure 4.

In the information aggregation step, the business-level expected direct effects are aggregated by NAICS code, as illustrated by the dark line connecting the left graph with the NAICS box below. This generates the sector-level expected direct effects (the rightmost map in Figure 4). Finally, under the assumption of constant returns to scale, the sector-level direct capital flow disruptions are derived and used as input shocks for the CGE model.

[5] The 2010 data for Clatsop County indicate 2,716 businesses, with a total of 20,316 employees. The employment figure is close to the IMPLAN and the Bureau of Economic Analysis estimates of 23,782 and 21,894, respectively.

[6] A MATLAB program has been written to match the street addresses from two data sets using a string comparison considering complexities such as the differences in upper- and lowercase letters and alternative forms of abbreviations. The remaining unmatched businesses are checked individually using Google and Google Maps. Virtually all (99 percent) of the businesses in Clatsop County in the Business Analyst data set are successfully matched with the tax-lot data. The remaining 1 percent of businesses include no significant contributors to either employment or sales.

Economic Model

The CGE model, calibrated using the economic transaction data in IMPLAN (2011), is similar to standard approaches, such as Hosoe et al. (2010). However, it is newly developed and simpler than other contemporary regional CGE models, such as Reimer et al. (2015). Only the major assumptions are highlighted below, with a corresponding schematic in Figure 5. The production technology, specified in Equation (1), is composed of a constant elasticity of substitution (CES) function for each sector. This is consistent with firms that can vary input use according to price, supply, and demand conditions, a major factor in the ability of the local economy to recover after a coastal disaster. The degree of input substitution can be adjusted to simulate short- and long-run effects. The specification is the following:

1) $$Z_j = A_j^X \left[\alpha_{i,j}^X (X_{i,j})^{\rho_j^X} + \alpha_j^L (L_j)^{\rho_j^X} + \alpha_j^K (K_j)^{\rho_j^X} \right]^{1/\rho_j^X}$$

where Z_j is sector j's output; A_j is the production technology parameter; $X_{i,j}, L_j$ and K_j are, respectively, the intermediate input, labor input, and capital input of sector j; $\alpha_{i,j}^X$, α_j^L, and α_j^K are production share parameters, where $0 \leq \alpha_{i,j}^X, \alpha_j^L, \alpha_j^K \leq 1$; and ρ_j^X is the input substitution elasticity, which is set equal to –4 for all the sectors to reflect moderate elasticity of input substitution in the short run.

The local demand for goods can come from domestic production as well as imports from the rest of the world, combined using the CES function shown in Equation (2):

2) $$Q_j = A_j^Q \left[\delta_j^M (M_j)^{\rho_j^Q} + \delta_j^D (D_j)^{\rho_j^Q} \right]^{1/\rho_j^Q}$$

where Q_j is total county demand for a composite good consisting of goods produced domestically in the county and imports from the rest of the world; A_j^Q is a normalizing parameter; δ_j^M and δ_j^D are composite goods share parameters, where $0 \leq \delta_j^M$ and $\delta_j^D \leq 1$; M_j is total imports; and D_j is demand for local production. The elasticity of import substitution ρ_j^Q is set equal to 0.5, which is between commonly estimated long-run and short-run elasticities of import substitution (McDaniel and Balistreri 2003).

Profit-maximizing producers sell their output either locally or outside the region according to the CES function:

3) $$Z_j = A_j^E \left[\gamma_j^E (E_j)^{\rho_j^E} + \gamma_j^D (D_j)^{\rho_j^E} \right]^{1/\rho_j^E}$$

where A_j^E is the normalizing parameter of sector *j*; γ_j^E and γ_j^D are export and local share parameters of sector j, where $0 \leq \gamma_j^E$ and $\gamma_j^D \leq 1$; E_j is the total export of sector *j*'s good; and ρ_j^E is the elasticity of export substitution set equal to 0.5, based on McDaniel and Balistreri (2003). Because Clatsop County is considered a small open economy, prices are exogenously determined.

Households maximize Cobb-Douglas utility as represented in Equation (4):

$$\max_{X_i^H} U^H = \prod_i (X_i^H)^{\alpha_i^H}$$

4) $$\text{subject to} \sum_i P_i^Q X_i^H = \sum_i P_i^L L_i + \sum_i P_i^K K_i - S^H - T^H$$

where U^H is utility, X_i^H is household consumption of good i, α_i^H is a share parameter, P_i^Q is the price of good i, P_i^L is the wage rate (common to all sectors), P_i^K is the price of capital (common to all sectors), S^H is household saving, and T^H is household income tax.

The government purchases goods from each sector following a fixed proportion of overall spending, as in the SAM. The government receives revenue from taxing the industry sectors and households. After putting aside a fixed proportion for savings, it spends the remaining revenue on government purchases, as calibrated with the 2010 baseline data. Savings from households and government are assumed to be absorbed from a virtual investment agent. The agent then invests all the savings from the economy into each sector with a constant proportion.

To close the model, the following market-clearing conditions are imposed. First, the total demand, which is the sum of household consumption, government purchases, investment, and intermediate input supplies, equals the total supply of the composite good, which is the sum of imports and domestic output. Second, the sum of the values of factor inputs (labor and capital) equals the total value of endowments of the factor goods (labor and capital).

The parameters of the CGE model are calibrated to be consistent with a 2010 IMPLAN SAM, newly developed for Clatsop County and reported in the Reviewer Appendix. The regional SAM delineates the county's economy into 15 business activities and contains information on input-output relations, the supply and demand of labor and capital, household consumption, government spending, and investment and trade accounts.

4. Results and Discussion

The main results are in Table 1. The first column lists the 15 economic sectors used in the analysis. The next two columns report the outputs of those sectors and rank the sectors according to their output values. All the estimated economic effects are based on a scenario of a tsunami created by a 9.2 Mw earthquake (equivalent to 17.5 meters of plate slip). The results from the integrated model (Model I) are reported in columns four to six in Table 1. Agriculture, which is generally inland from the coast and thus out of reach of the tsunami, has the smallest total loss, at $0.41 million. For the same reason, the wood manufacturing sector has the next-to-smallest total loss, $1.76 million, even though at $554.71 million it is the largest sector by value in timber-dependent Clatsop County. Finance and real estate have the largest loss in absolute terms, a total of $111.70 million from a base of $513.41 million. Tourism has the largest loss in proportional terms, with a total of 32.8 percent, or $111.10 million, from a base of $338.65 million. This suggests that economic effect is not proportional to the economic size of a sector. It is important to incorporate the spatial heterogeneity in the distributions of both physical damage and economic activities.

To illustrate the importance of integrating the engineering and economic models, the results from the two nonintegrated models are also reported in Table 1 and then compared in Figure 2. Model II applies only the engineering model in this paper, while Model III uses only the economic model. In Model II, it is assumed that the tax lot–level probability of major physical damages is available for the estimation of economic loss. If the spatially disaggregated data on economic activities are also accessible, an obvious estimate for the economic loss would be the expected output loss in buildings with major physical damage—that is, multiplying the probability damage with the sales revenue in those buildings. This is one of the most common approaches of applying disaster shocks for supply-side input-output models, such as Hazus (FEMA 2012). The estimated losses by sector and their rankings are reported in columns seven and eight in Table 1. These estimated effects correspond to the concept of “direct economic losses” in the literature.

A comparison shows that the integrated model (I) predicts an economic effect far less than the estimated direct economic effect in the nonintegrated, engineering-only model (II). The estimated economic loss from Model I is $564.95 million, which is 24 percent less than the estimated loss of $743.39 million in Model II. Although this may seem counterintuitive, it actually highlights the resilience of the economic system. The estimated economic effect from Model I is smaller because businesses and consumers reoptimize with the shock. The direct effect is partially offset by adaptive behavior among businesses and households, specifically through substitution of labor for capital in production and consumption of different sets of goods in the household consumption basket. For instance, the finance and real estate sector has a $111.70 million loss under Model I, and a $184.95 million loss under Model II. Given that the sector output is $513.41 million before the tsunami, Model II predicts a 36.0 percent loss while Model I predicts only a 21.8 percent loss, suggesting that the local economy is capable of mitigating one-third of the direct economic effects in this sector through the voluntary adaptive behaviors among businesses and households.

Although overall losses under Model I are less than that of Model II, this does not hold for all sectors. For example, the health, agriculture, and public sectors sustain heavier losses under Model I than under Model II. This is because the mitigation of the direct effect requires relocation of resources across sectors. Given the limited amount of economic resources available in the local economy, the increase in the resources allocated to some sectors must eventually come from a decrease in the resources in other sectors.

Model III uses only the economic component of this paper. Because it is not integrated with the engineering model, the probability distribution of major physical damage and the expected damage distribution across sectors, as shown in Figure 2, are not available for the simulation of economic losses. However, the predicted flood damage based on total inundated floor space of the building stock in the region is available from the Hazus model (FEMA 2012). Even though Hazus does not provide the sectoral distribution of the economic effects, it is possible to generate a rough estimate under the assumption that economic activities are evenly distributed within the inundation zone. To facilitate the comparison, the total capital flow disruption used in Model I is allocated into the 15 economic sectors according to the relative size of the sectors in the inundation zone. For instance, if a sector accounts for half of the economic activities in the inundation zone, half of the total capital flow disruption is apportioned into that sector. For this reason, Model III has a different "loss in capital flow" column in Table 1.

Results from Model III are reported in the rightmost columns of Table 1. Compared with Model I, Model III underestimates the overall economic loss by 4 percent, or $24 million (–$540.96 versus –$564.96 million), even though the total direct economic losses are designed to be the same for two models. If the actual Hazus model were used, the direct economic effects would be derived from the average inundated square footage of building stocks at the census block level, which would generate even less accurate predictions.

Moreover, the economic losses in Model I are distributed differently than in Model III. This is reflected in both the different estimated losses and the ranking in the two models. For policy discussion, Model III is unable to correctly identify the economic sectors most vulnerable to a tsunami. For example, it underestimates the total economic loss in tourism by 43 percent and therefore falsely ranks this as the fourth rather than the second most vulnerable sector. The large difference in the simulated effects arises because tourism-related businesses are usually located in places that are more vulnerable to damage caused by tsunamis.

The loss estimates for the forestry and wood manufacturing sectors by Model III are five times greater than those of the integrated model (–$11.11 million versus –$1.76 million). Although has a significant number of wood manufacturing businesses are located in the disaster-affected area, the expected direct physical damage is much smaller after the spatial distribution of economic activities is overlaid with the physical extent of the natural disaster. The risk of physical damage to the wood manufacturing facilities is lower than average because of their location in less flood-prone areas and stronger building structures.

Greater accuracy could be achieved by taking into account the local supply lines to the seafood processing sector in addition to physical damage to structures. For example, when a tsunami destroys most fishing boats and ports, local fishermen will be unable to supply the seafood processors, and important food transportation lines may also be interrupted.

In summary, the county economy is moderately resilient to natural disasters, at least when measured as the sum of net losses (–$564.95 million) relative to value of regional output ($3,714.01 million). Through voluntary adaptations and adjustments among businesses and households, the local economy can make up for almost one-quarter of the direct economic loss.

Sensitivity Analysis

Comparison of the integrated model (I) with the nonintegrated models (II and III) provides a form of sensitivity analysis. To further investigate the sensitivity of the favored model's results, different assumptions about the production input elasticity and import-export elasticity are considered relative to Model I. The results are summarized in Table 2. In general, changes in import and export elasticities have limited effects on the total economic losses, which range from 2 percent less ($554.01 million) to 2 percent more ($574.91 million) than the baseline measure of $564.95 million.

By contrast, assumptions about the input elasticity have a larger effect. In the case of no input substitution (Leontief production function), the total economic effect is a decrease of $966.63 million instead of $564.95 million, an increase of 70 percent over the baseline. The Leontief approach is somewhat reflective of the simulated economic impact from an input-output model. When technological or behavioral responses are disallowed, the severity of damages is overstated.

Another potentially sensitive assumption is the size of the earthquake being considered. The economic effects of tsunamis generated by two additional hypothetical earthquakes with +0.1 and –0.1 moment magnitudes (Mw) from the base 9.2 Mw scenario are simulated, which correspond to a doubling or halving of the released energy, respectively (see Table 3). The results show that the total economic effect increases monotonically with the strength of the tsunami. However, under the 9.3 Mw scenario, the ordering of the total effect across sectors changes slightly. Wood manufacturing is no longer next to last in terms of amount of damage; that designation falls to seafood manufacturing. However, the percentages of change are quite different among the sectors, with absolute values of change ranging from 2 to 62 percent. Some of these differences have to do with the divergence in initial baseline values (of loss), but it is likely that these differences are driven in part by the more intensive and extensive damage inflicted by the larger tsunami. Although the amount of physical damage and economic effect does not always scale up uniformly, there are strong correlations between direct capital flow disruptions and total economic losses for each sector when comparing across scenarios; this provides additional confidence in the robustness of the model.

5. Limitations and Conclusions

This research studies the consequences of a potential tsunami for a coastal county in Oregon, but the method is applicable to other forms of natural disasters. In this study, an integrated engineering-economic model is proposed to assess the vulnerability of a regional economic system to a tsunami. The proposed model, which combines the best features of recent engineering and economic models, is intended to improve the accuracy of vulnerability assessment. High-resolution predictions of physical damage from an engineering model are linked to county-level losses suffered by 15 economic sectors using fragility curves and tax lot–level economic activity data. This generates spatially explicit estimates of direct economic effect after a hypothetical tsunami. A CGE model developed from detailed input-output and related data is then used to generate the indirect damage to the county economy.

Because this integrated model considers the heterogeneous distribution of direct damage across space and across economic sectors, it can potentially provide a more accurate economic impact assessment than nonintegrated models, such as FEMA’s Hazus model, where direct damages are assumed to be evenly distributed within the inundation zone. In this case study, the integrated model shows that ignoring heterogeneity across space and economic sectors can lead to significant over- or underestimation of the economic losses in various sectors.

There are a number of specific observations regarding the case study that are important to emphasize. One is that the local economy is surprisingly resilient. It is able to mitigate almost one-quarter of the direct economic effects through voluntary adaptations among businesses and households. This observation ties in with the CGE model, where physical damage is transferred through loss of capital flow instead of output, and businesses and consumers are allowed to respond and reoptimize with the shock. Another interesting finding is that some very large sectors suffer very little damage, while some small sectors have proportionately much higher damage. Revealing the unexpected vulnerability of certain sectors is one of the reasons that the integrated analysis is important. Without the approach developed in this article, the most vulnerable sectors are more likely to be misidentified. For instance, the integrated engineering-economic model reveals that the economic effect in tourism is underestimated by 43 percent compared with the nonintegrated engineering model, which incorrectly identifies tourism as the fourth rather than the second most vulnerable sector. The nonintegrated economic model, meanwhile, identifies it as fourth.

Another finding is that the economic effects may not scale up in a linear fashion with the size of the tsunami and underlying earthquake. There are at least two reasons for this, one physical and one economic. First, physiographic characteristics of the setting (e.g., topography) may cause large discrete changes in losses to physical capital. And second, not all sectors are equal; some are tied much more directly to the rest of the economy.

Several limitations in the study can be addressed in the future. For example, damage to structures from the shaking of the earthquake was not considered. The wood manufacturing industry has the smallest proportional total losses according to the study, for instance, but this assumes that the transportation infrastructure outside the tsunami zone is still available. Since it may not be, this study’s estimates are likely to underestimate the severity of the damage.

In future studies, the integrated engineering-economic model can be improved in two respects. First, in addition to the heterogeneity of direct damage among sectors in the inundation zone, businesses of the same sector inside and outside the inundation zone usually have a different transaction matrix because of the often uneven distribution of population and economic activity between the coast and inland. The county-level model assumes the same business transaction matrix within the county for sectors inside and outside the inundation zone. However, when estimating the economic effect of a tsunami, failing to account for the differences in economic interdependencies between coastal and inland regions leads to an inaccurate assessment of the regional economic effect. Thus, a subcounty, multiregional CGE model could potentially improve the accuracy of the economic impact assessment. It is worth exploring under what conditions the subcounty and county-level economic models provide significantly different impact assessments.

Another limitation of the study is that it provides deterministic point estimates of losses. Although the estimates appear robust to alternative assumptions, as revealed through sensitivity analysis, an improvement would be to use Monte Carlo simulation methods to estimate the risks of economic loss for a potential tsunami.

Other aspects of a natural disaster could be considered, such as insurance coverage for individuals and local population dynamics following the tsunami, including effects on jobs and wages. The analysis could also consider the postdisaster recovery effort, including the inflow of federal and state funds.

Such limitations are necessarily left for future research. It is noted, however, that in some cases, it may be very difficult to obtain relevant data, in which case the analysis must depend more extensively on assumptions about future possibilities than we have done in this study. It is hoped that the integrated engineering-economic model proposed here proves useful for other researchers working on models of regional disaster resilience vulnerability and planning.

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Tables and Figures

Table 1. Economic Loss Assessment for Tsunami Created by 9.2 Mw Earthquake ($ million)

Sector	*Current economy*		*Model I (integrated engineering-economic)*			*Model II (engineering only)*		*Model III(economic only)*		
	Output	*Rank*	*Loss in capital flow*	*Estimated impacts*	*Rank*	*Estimated impacts*	*Rank*	*Loss in capital flow*	*Estimated impacts*	*Rank*
Finance, real estate	513.41	2	-7.25	-111.70	1	-184.95	1	-4.34	-80.03	1
Tourism	338.65	5	-21.16	-111.10	2	-179.51	2	-10.88	-63.33	4
Education	271.39	7	-50.39	-80.69	3	-105.37	3	-37.46	-63.60	3
Public	442.77	3	-24.47	-55.86	4	-54.19	5	-30.84	-64.92	2
Energy, construction	237.43	8	-3.04	-47.55	5	-45.32	6	-2.82	-45.19	7
Trade	312.24	6	-4.13	-44.19	6	-55.35	4	-5.10	-50.35	6
Health	360.13	4	-1.35	-37.41	7	-24.95	8	-4.40	-55.70	5
Business services	207.56	9	-6.62	-27.12	8	-31.01	7	-10.13	-36.73	8
Other services	147.98	10	-1.67	-14.98	9	-15.34	10	-1.62	-14.47	10
Information	52.50	14	-3.51	-13.10	10	-21.90	9	-1.94	-8.51	13
Other manufacturing	102.09	11	-3.55	-10.63	11	-14.20	11	-4.91	-14.14	11
Transportation	58.89	13	-0.80	-6.22	12	-7.08	12	-1.15	-8.17	14
Fishing, seafood manufacturing	95.58	12	-0.70	-2.23	13	-2.54	13	-8.99	-19.83	9
Forestry, wood manufacturing	554.71	1	-0.36	-1.76	14	-1.59	14	-3.42	-11.11	12
Agriculture	18.67	15	-0.01	-0.41	15	-0.10	15	-1.00	-4.87	15
Total	3714.01		-129.01	-564.95		-743.39		-129.01	-540.96	

Table 2. Sensitivity Snalysis of Production and Trade Flexibility of Response under 9.2 Mw Earthquake ($ million)

	Production input elasticity of substitution			*Import/export elasticity of substitution*		
	No flexibility of response (Leontief function)	*Baseline (elasticity = 0.5)*	*High flexibility of response (elasticity = 0.999)*	*Low flexibility of response (elasticity = -9)*	*Baseline (elasticity = 0.5)*	*High flexibility of response (elasticity = 0.999)*
Total economic effect	-966.63	-564.95	-376.33	-574.91	-564.95	-554.01
Regional GDP	2747.37	3149.06	3337.67	3139.10	3149.06	3159.99
Aggregate import value	724.96	858.54	898.24	848.01	858.54	871.29
Aggregate export value	929.67	1066.18	1105.90	1055.65	1066.18	1078.93

Table 3. Sensitivity Analysis of Tsunamis of Different Magnitudes (Mw)

	Tsunami caused by 9.3 Mw earthquake			*Tsunami caused by 9.1 Mw earthquake*		
Sector	*Loss in capital flow*	*Estimated impacts*	*Rank*	*Loss in capital flow*	*Estimated impacts*	*Rank*
Finance, real estate	-7.94	-121.40	1	-6.21	-95.13	1
Tourism	-21.84	-115.40	2	-17.99	-93.71	2
Education	-51.36	-82.97	3	-45.99	-72.78	3
Public	-27.54	-61.86	4	-16.04	-39.88	5
Energy, construction	-3.33	-51.32	5	-2.59	-40.33	4
Trade	-4.63	-48.59	6	-3.59	-37.90	6
Health	-1.48	-40.20	7	-1.15	-31.59	7
Business services	-7.46	-30.05	8	-5.35	-22.22	8
Other services	-1.73	-15.81	9	-1.53	-13.04	9
Information	-3.63	-13.66	10	-3.15	-11.57	10
Other manufacturing	-3.96	-11.80	11	-3.28	-9.71	11
Transportation	-0.81	-6.44	12	-0.75	-5.68	12
Fishing, seafood manufacturing	-0.74	-2.37	14	-0.65	-2.00	13
Forestry, wood manufacturing	-0.56	-2.38	13	-0.03	-0.67	14
Agriculture	-0.02	-0.44	15	-0.01	-0.34	15
Total	-137.01	-604.69		-108.32	-476.55	

Note: Values are in millions of dollars.

Figure 1. Business Activity Inside and Outside Inundation Zone, Clatsop County, Oregon

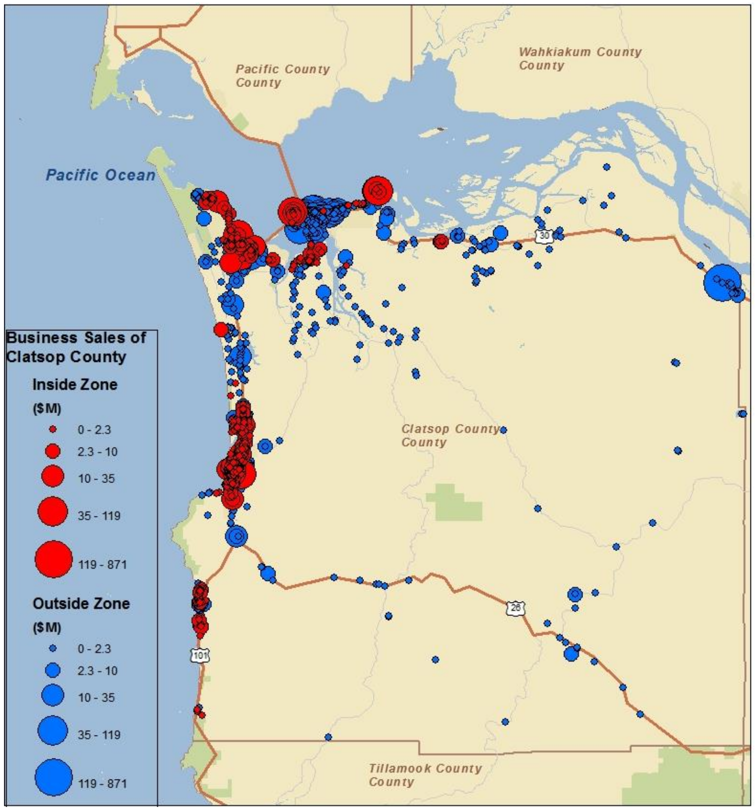

Figure 2. Flow Chart of Integrated Engineering-Economic Model

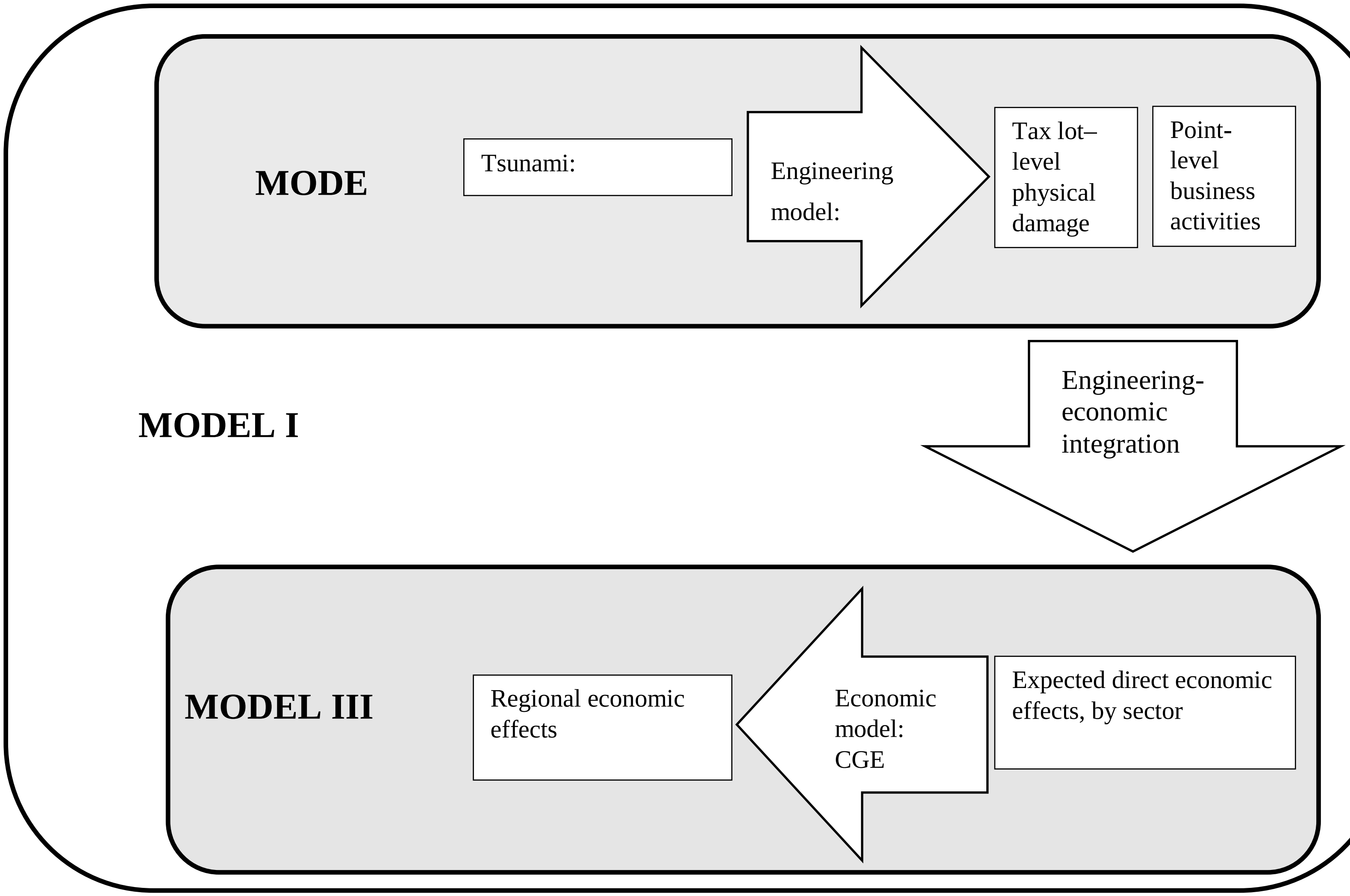

Figure 3. Flow Chart of Engineering Model

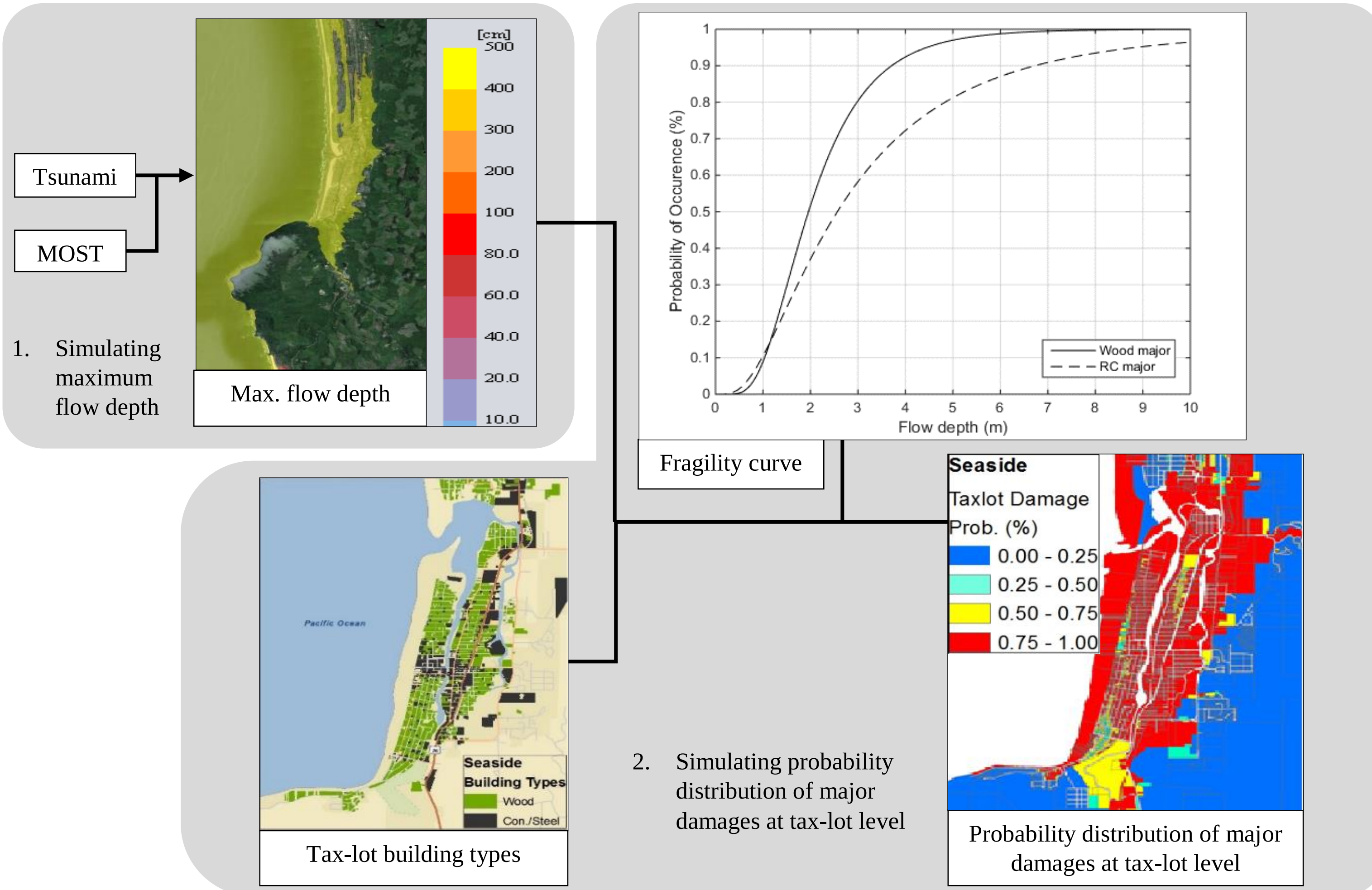

Figure 4. Flow Chart of Engineering-Economic Integration

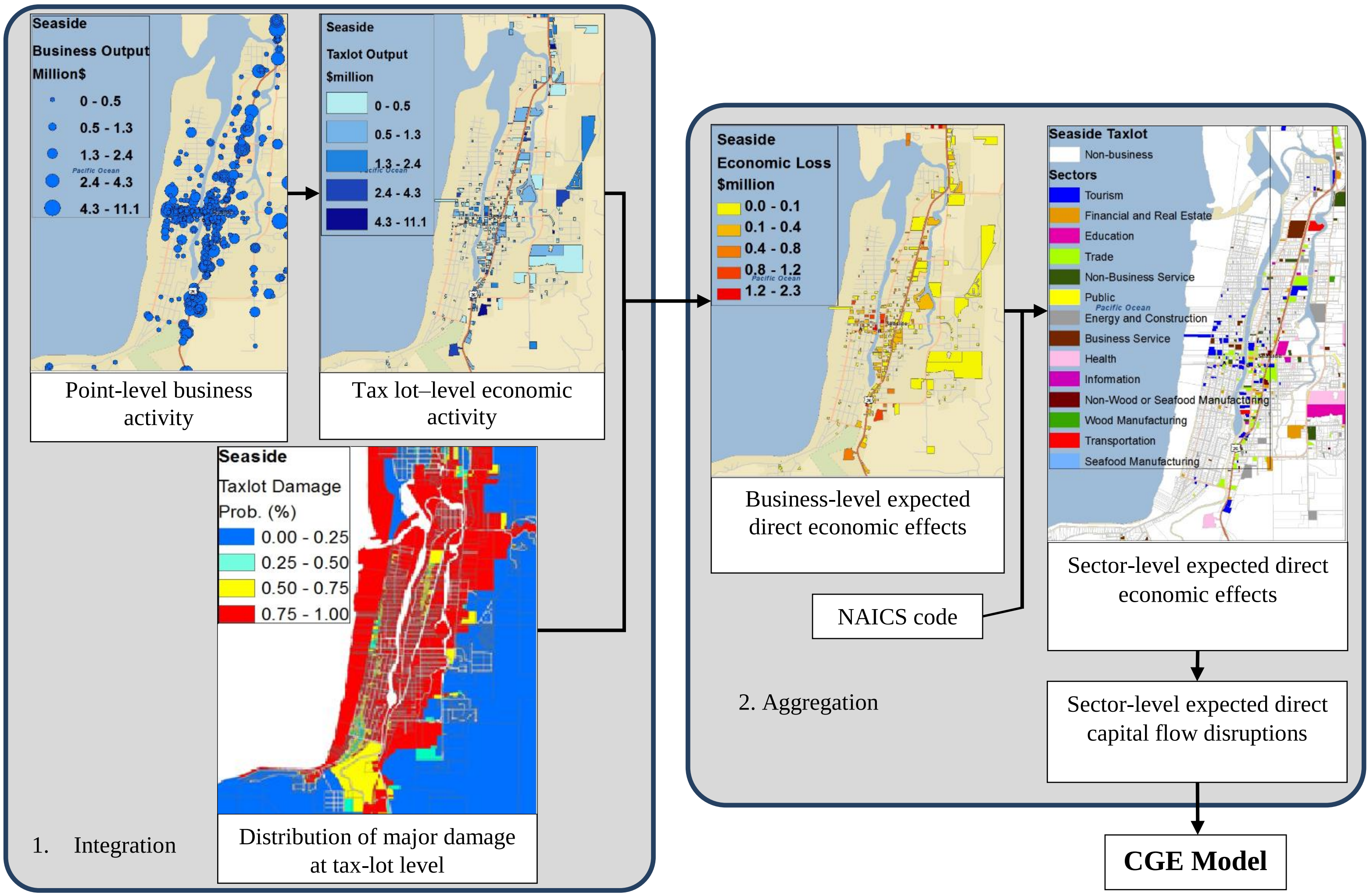

Figure 5. Flowchart of County CGE Model