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Abstract

Policies to mitigate natural hazards and terrorism are facing increasing scrutiny, such as the benefit-cost test. The benefits are the losses that can be avoided by the mitigation actions. For sound policy-making, it is therefore necessary that the various types of losses and major factors affecting them be identified and that metrics be established for their measurement in accordance with economic principles. This paper presents a comprehensive framework for the analysis and measurement of ordinary economic impacts and two categories of impacts that have recently gained the attention of analysts and policy makers, but for which operational definitions are lacking. The first is resilience, which refers to how the economy manages to keep functioning and how quickly it recovers. The second major extension of loss estimation pertains to behavioral and systems linkages. These refer to considerations unique to disasters that cause indirect impacts to be orders of magnitude greater than ordinary indirect effects in cases where risks are amplified, systems are overwhelmed, and resilience is eroded. The framework combines a checklist of types of impacts, consistent definitions, metrics, and strategies for estimation. The framework is serving as a template for loss estimation and benefit-cost analysis by several offices of the U.S. Department of Homeland Security.

KEYWORDS: terrorism, disasters, economic loss estimation, resilience, behavioral impacts

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I. INTRODUCTION

September 11 and Hurricane Katrina were unprecedented disasters. They have spawned a renewed interest in estimating the negative economic consequences (losses) from natural and man-made hazards. Ex post, this helps measure the vulnerability of the U.S. economy to extreme shocks. Ex ante, it is an important input into a benefit-cost analysis of mitigation measures. The benefits are the losses, expressed to the extent possible in dollar terms, that the mitigation is expected to prevent.

It has been the practice in most assessments of losses from disasters to focus on what is often referred to as “direct” impacts, such as property damage, on-site business interruption, or lives lost. Progress has been made in measuring what is typically grouped into a miscellaneous category of “indirect” effects, sometimes referred to as ripple, multiplier, general equilibrium, macroeconomic, or societal impacts. These include off-site business interruption, reductions in property values, and stock market effects, as well as aspects of sociological and environmental effects. The more tangible of these can be traced directly through empirical observation (e.g., surveys), but this is an especially cumbersome process. An alternative approach is to use some form of loss estimation or impact model. Most existing economic models, however, are not up to the task because they are based on data and specifications relating to the normal workings of the economy, rather than crisis situations and the response to them.

Some recent studies have begun to investigate two non-traditional areas of losses from disasters. The first is *resilience*, which mutes the potential negative impacts through various inherent and adaptive adjustments, such as the conservation of scarce inputs and the subsequent rescheduling of lost production at a later date. A survey by Tierney (1997) and simulation modeling by Rose and Lim (2002) indicate that customer losses from electricity lifeline failures following the Northridge Earthquake were reduced by more than 75 percent by such adjustments. The second new area is *extended linkages*, such as the decrease in air travel in the U.S. for nearly twenty-one months following the September 11 attacks. Gordon et al. (2007) estimated that this behavioral response led to economic losses several times the size of more conventional estimates of direct multiplier effects ensuing from property damage and ordinary business interruption.

Traditional loss estimation is no longer adequate to address major man-made and natural disasters. More recent papers have identified an even broader set of potential impacts (see e.g., Blomberg et al., 2004; Frey et al., 2007). However, they have not offered an integrated framework for analysis, nor do they provide insight into how major considerations of resilience or extended linkages can be measured.

This paper develops a comprehensive and integrated framework to analyze and measure ordinary impacts, extended linkages, and resilience associated with disasters. I first summarize special aspects of economic loss estimation applicable to natural and man-made disasters in a manner consistent with benefit-cost analysis. The main focus, however, is on new considerations relating to resilience and behavioral/systems linkages. The contributions of the paper include providing conceptualizations, key definitions, metrics, strategies for estimation, and a summary of applications of the metrics to indicate the prominence of resilience and extended linkages. The loss estimation framework is illustrated for the case of a terrorist attack on a public water system using a radiological device. The example helps explain how the various types of economic losses and major factors affecting them are interrelated.

The approach presented in this paper has served as the organizing framework for the methodological advances in economic consequence estimation in the Bi-Annual Report to the President on dealing with bio-terrorism (DHS, 2008; see also Lee et al., 2008). It is also currently being refined as part of the development of a template for benefit-cost analysis for the General Counsel's Office of the U.S. Department of Homeland Security.

The framework defines the major elements of disaster losses that need to be included in an accurate estimation of economic consequences of major disasters. It explains the two new key areas of resilience and extended linkages, assesses their likely prominence, and shows how they fit into the framework. The paper is intended to acquaint a broad audience with this advanced approach to economic consequence analysis as applied to terrorism and major natural disasters. The paper does not purport that the estimation methods are fully developed for this purpose yet, nor does it provide detailed guidance on how to apply the existing models to actually perform the measurement. It is hoped that by indicating the landscape, future researchers will be able to identify and advance these key areas of inquiry.

II. GENERAL PRINCIPLES OF LOSS ESTIMATION

Below, I discuss important dimensions of the units of measure of economic losses from disasters. The case is made for broad inclusion of impacts and in terms consistent with the requirements of benefit-cost analysis (see, e.g., Boardman et al., 2001).

A. Stocks vs. Flows

One of the fundamental distinctions recognized in economics is between stocks and flows. Stocks refer to a quantity at a single point in time, whereas flows refer to the services or outputs of stocks over time. Property damage represents a decline in stock value and usually leads to a decrease in service flows. *Business interruption* (BI) losses are a measure of this reduction in the flow of goods and services. They stem from damage to plant and equipment or curtailment of a critical input, and represent lost sales revenue in gross terms, or lost personal income in net terms. Recent studies have shown that BI losses rival property damage in magnitude for many disasters. Though property damage estimates have dominated loss reporting until recently, flow measures are superior to stock measures in many ways. First, direct business interruption losses can take place even in the absence of property damage, and hence represent broader coverage of the scope of losses. For example, a factory may be unscathed by a terrorist attack, but may be forced to shut down if its water supply is destroyed or contaminated by terrorists. Another reason flow measures are superior is that they are more consistent with indices of individual well being, such as business profits and consumer satisfaction (utility), or with aggregate measures, such as gross national (or regional) product (see Frey et al., 2007).

B. Time Dimensions

The time dimension of losses must be considered. The typical measure of stock damage (purchase or replacement cost) is invariant to how long the asset is out of service. For example, if the roof of a factory is blown off by a hurricane, there is a tendency to specify the loss in fixed terms, irrespective of whether production is shut down for a week or a year awaiting repairs. Attention to flow losses represents a major shift in the focus of hazard loss estimation—that some types of losses are not a fixed amount but are highly variable depending on the length of the "economic disruption," typically synonymous with the recovery plus reconstruction periods.

This also brings home the point that disaster losses are not simply determined by the strength of the stimulus (coupled with initial vulnerability), but also highly dependent on human ingenuity, will, and resources. As such, flow losses are strongly influenced by behavioral considerations. These include various resilience responses of households, businesses, and government, as well as choices by these decision-makers on the form, pace and financing of recovery and reconstruction.

C. Direct vs. Indirect Impacts

Hazard loss estimation was for many years dominated by engineers, and hence there was an emphasis on (tangible) property damage, as opposed to the operation of businesses or the well being of households. The tendency was to refer to property damage as "direct" impacts and everything else as indirect. This limited perspective is being overcome by more accurate terminology as in the distinction noted above between direct (stock) property damage effects and direct flow (business interruption) effects. As soon as a factory is destroyed, its inability to produce must also be taken into account. The stock/flow distinction is operative for indirect effects as well. Prime examples of indirect property damage are ancillary fires or hazardous material releases from the original terrorist target that affects other businesses. More common, of course, are indirect business interruption losses, stemming from impacts on successive rounds of suppliers and customers (i.e., from suppliers of suppliers and customers of customers). There is also a distinction between direct impacts on people and communities (e.g., those originally contaminated), and indirect impacts on those who suffer some contagion effect.

D. Cost of Mitigation, Response, and Remediation

Losses from terrorism differ from *costs* of terrorism strictly speaking. The former stem from stock damages or flow curtailments and their indirect and extended effects, while the latter also include the direct and indirect value of resources used in mitigation, evacuation, quarantine, and emergency response. In this paper, I use the broader scope of costs. Ideally, a policy-maker would pursue the goal of minimizing the total (joint) costs of terrorism.[1]

The complication here is that mitigation and emergency response almost completely, and evacuation and quarantine in part, involve expenditures that can have stimulating effects on the economy, directly and indirectly. While this is the case, it has to be noted that the funds for these expenditures must come from somewhere. If they emanate from inside the region, it means they have an opportunity cost, i.e., other expenditures must be foregone. Thus, only the net effects should be counted. For a dollar for dollar displacement, this means no impact on economic activity on a direct level.[2] However, different spending streams lead to different multiplier, general equilibrium, and macroeconomic impacts through the relevant interdependencies in the economy. Without a formal model, it is difficult to predict the impacts. The exception is if there is unused

[1] Note that this alternative perspective yields the same result as a benefit-cost analysis, which seeks to maximize the net benefits of mitigation. It simply does not translate avoided losses into benefits, but retains them in the cost side of the ledger and adds them to the costs of mitigation, the sum of which should be minimized.

[2] If resources for these purposes stem from assistance by government or philanthropic organizations outside the region, there will be a net gain to the regional economy. However, there is no net gain to the nation as a whole.

capacity in either or both labor and capital, which means no output is displaced. The former exists if there is a pool of unemployed workers, and the latter if some factories, buses, etc. are standing idle. Explicit data on the case in point is needed to make an accurate estimate.

This section has made the case for not neglecting direct and indirect business interruption losses. These could be measured in gross terms as total sales, or in net terms as personal income or value-added. Additionally, these flows can serve as the basis of the estimation of consumer and producer surplus measures; net benefits are maximized when the sum of these surpluses are maximized (see, e.g., Boardman et al., 2001). Another point of emphasis has been to consider losses *and* costs as broadly as possible.

III. ECONOMIC RESILIENCE

A. Definition

I define static economic resilience as the ability of an entity or system to maintain function (e.g., continue producing) when shocked (see also Rose, 2004b; 2007). It is thus aligned with the fundamental economic problem--efficient allocation of resources, which is exacerbated in the context of disasters. This aspect is interpreted as static because it can be attained without repair and reconstruction activities, which affect not only the current level of economic activity but also its future time path. Another key feature of static economic resilience is that it is primarily a demand-side phenomenon involving users of inputs (customers) rather than producers (suppliers). It pertains to ways to use resources available as effectively as possible. This is in contrast to supply-side considerations, which definitely require the repair or reconstruction of critical inputs.

A more general definition that incorporates dynamic considerations is the speed at which an entity or system recovers from a severe shock to achieve a desired state. This also subsumes the concept of mathematical or system stability because it implies the system is able to bounce back. This version of resilience is relatively more complex because it involves a long-term investment problem associated with repair and reconstruction.

Ability implies a level of attainment will be achieved. Hence, the definition is contextual-the level of function has to be compared to the level that would have existed had the ability been absent. This means a reference point or type of worst case outcome must be established first. Further discussion of this oft-neglected point is provided below.

I also distinguish two other dimensions of resilience. Inherent resilience refers to the ordinary ability to deal with crises (e.g., the ability of individual firms to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals). This is itself a type of resource already in place that can be enhanced prior to a disaster and so that capabilities that are not damaged or eroded can be implemented in the disaster aftermath.

Adaptive resilience in contrast refers to the ability in crisis situations to maintain function on the basis of ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations or strengthening the market by providing information to match suppliers with customers). This corresponds to pushing the efficiency frontier outward.

Resilience emanates both from internal motivation and the stimulus of private or public policy decisions (Mileti, 1999). Also, resilience, as defined in this paper, refers to post-disaster conditions and response (see also Comfort, 1994), which are distinguished from pre-disaster activities to reduce potential losses through mitigation (cf., Bruneau et al., 2003). In disaster research, resilience has been emphasized most by Tierney (1997) in terms of business coping behavior and community response, by Comfort (1999) in terms of non-linear adaptive response of organizations (broadly defined to include both the public and private sectors), and by Petak (2002) in terms of system performance. These concepts have been extended to practice. Disaster recovery and business continuity industries have sprung up that offer specialized services to help firms during various aspects of disasters, especially power outages (see, e.g., Business Continuity Institute, 2002; Salerno, 2003). Key services include the opportunity to outsource communication and information aspects of the business at an alternative site. There is also a growing realization of the broader context of the economic impacts, especially with the new emphasis on supply chain management (Sheffi, 2005).

Resilience can take place at three levels:

Microeconomic--individual behavior of firms, households, or organizations.

Mesoeconomic--economic sector, individual market, or cooperative group.

Macroeconomic--all individual units and markets combined, including interactive effects.

Examples of microeconomic (individual) resilience are well documented in the literature, as are examples relating to the operation of businesses and organizations. What is often less appreciated by disaster researchers outside economics and closely related disciplines is the inherent resilience of markets at the mesoeconomic level. Prices act as the "invisible hand" that can guide resources to their best allocation even in the aftermath of a disaster. Some pricing mechanisms have been established expressly to deal with such a situation, as in the case of non-interruptible service premia that enable customers to estimate the value of a continuous supply of electricity and to pay in advance for receiving priority service during an outage (Chao and Wilson, 1987).

The price mechanism is a relatively costless way of redirecting goods and services. Price increases, though often viewed as gouging, serve a useful purpose of reflecting highest value use, even in the broader social setting (see also Schuler, 2005). Moreover, if the allocation does violate principles of equity (fairness), the market allocations can be adjusted by income or material transfers to the needy.

At the macroeconomic level, there are a large number of interdependencies through both price and quantity interactions that influence resilience. This means resilience in one sector can be greatly affected by activities related to or unrelated to resilience in another.

B. Measuring Resilience

Few operational definitions of resilience have been put forth.[3] Following Rose (2004b; 2007), direct economic resilience refers to the level of the individual firm or industry (micro and meso levels) and corresponds to "partial equilibrium" analysis, or the operation of an entity itself. Total economic resilience refers to the economy as a whole and corresponds to "general equilibrium" or macroeconomic analysis, which includes all of the price and quantity interactions in the economy.

An operational measure of *direct economic resilience (DER)* is the extent to which the estimated direct output reduction deviates from the likely maximum potential reduction given an external shock, such as the curtailment of some or all of a critical input:

$$DER = \frac{\%\Delta DY^m - \%\Delta DY}{\%\Delta DY^m}$$

where

$\%\Delta DY^m$ is the maximum percent change in direct output
$\%\Delta DY$ is the estimated percent change in direct output

[3] Several major, and otherwise excellent, studies have been performed about disasters recently that focus on resilience but fail to rigorously define it anywhere in their pages (see, e.g., Chernick, 2005; FRBA, 2005).

In essence, DER is the percentage avoidance of a maximum economic disruption to a given shock. A major measurement issue is what should be used as the maximum potential disruption. For ordinary disasters, a good starting point is a linear, or proportional, relationship between an input supply shortage and the direct disruption to the firm or industry that uses the input in its production. This maximum could be estimated with the use of an input-output (I-O) model, which is inherently linear, and whose standard application implicitly omits the possibility of resilience.[4] Note that while a linear reference point may appear to be arbitrary or a default choice, it does have an underlying rationale. A linear relationship connotes rigidity, the opposite of the "flexibility" connotation of static resilience defined in this paper. Aspects of non-linearities in the context of an extreme disaster, or a catastrophe, are discussed below.[5]

Analogously, the measure of *total economic resilience (TER)* to input supply disruptions is the difference between a linear set of indirect effects, which implicitly omits resilience, and a non-linear outcome, which incorporates the possibility of resilience. From an operational modeling standpoint this would be the difference between linear I-O multiplier impacts and those obtained from computable general equilibrium or macro econometric models and (CGE).

My definitions of economic resilience have been stated in flow terms in relation to economic output at a given period in time. While the entire time-path of resilience is key to the concept for many analysts, it is important to remember that this time-path is composed of a sequence of steps. Even if "dynamics" are the focal point, it is important to understand the underlying process at each point in time: why the economy functions at a given level and why that level differs from one time period to another. As presented here, resilience helps explain the first aspect, and changes in resilience, along with repair and reconstruction of the capital stock, help explain the second.

To date the only efforts to formally measure economic resilience in the face of disasters pertain to business interruption associated with utility lifeline disruptions. The initial question posed is: Will an X percent loss of electricity result in an X percent direct loss in economic activity for a given firm? The answer is definitely "no" if economic resilience is present. One of the most obvious resilience options for input supply interruptions in general is reliance on

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[4] Resilience can, however, be incorporated into I-O models in the manner of Rose et al. (1997) and Rose and Lim (2002). See the discussion below for the results of the latter study.

[5] The definition presented here (based on Rose 2004b; Rose, 2007) is couched in deterministic terms. Though their definition of resilience (an off-shoot of the broader definition by Bruneau et al., 2003) differs from the one presented here, Chang and Shinozuka (2004) make a major contribution by providing a framework and illustrative example for evaluating economic resilience in probabilistic terms and in relation to performance objectives.

inventories. This works well for water system outages of short duration but has long made electricity outages especially problematic, since the latter product cannot typically be stored. However, the increasing severity of the problem has inspired ingenuity, such as the use of non-interruptible power supplies (capacitors) in computers. Other resilience measures include backup generation, conservation, input substitution, and rescheduling of lost production. In many business enterprises, these measures are adequate to substantially cushion the firm against some losses of a rather short or moderate duration.

Next, the question is extended to: Will a Y percent loss in direct output yield much larger general equilibrium or macro losses? Here both individual business and market-related adjustments suggest some muting of general equilibrium and macroeconomic effects. Adjustments for lost output of goods and services include inventories, conservation, input substitution, import substitution and production rescheduling at the level of the individual firm, and the rationing feature of pricing and re-contracting among suppliers and customers at the level of the market.

Let me now summarize loss estimates from the example of utility service disruptions and the role of resilience. The number of studies is rather sparse, because I have limited inclusion to those studies that used customer lost output as the unit of measure and that have also explicitly or implicitly included indirect (either ordinary multiplier or general equilibrium) effects. Admittedly the examples refer only to an isolated type of shock to an economy, but they provide some important insights into the effectiveness of resilience.

The first major attempt to measure resilience is that of Tierney (1997), who collected responses to a survey questionnaire from more than a thousand firms following the Northridge Earthquake to measure business interruption from the event. In the case of electricity service, for example, the maximum disruption following this event was 8.3% and nearly all electricity service was restored within 24 hours. Tierney's survey results indicated that direct output losses attributable to the electricity outage amounted to only 1.9% of a single day's output in Los Angeles County, indicating DER is 77.1%.

Alternatively, in another study of the Northridge earthquake, Rose and Lim (2002) developed a simple simulation model approach for three resilience options based on considerations relating to overall and time-of-day use of electricity and explicit estimation of production rescheduling after power was restored. They estimated DER of 95%. Although this study did not include the full range of resilience tactics inherent in the Tierney survey, it is likely that production rescheduling would be under-reported by survey respondents because not all businesses connect activities undertaken long after the event with the affects of the disaster.

A study by Rose and Liao (2005) for a hypothetical earthquake in Portland, Oregon, and for water rather than electricity utilities, incorporated engineering simulation estimates of direct output losses into a computable general equilibrium (CGE) model whose key parameters were calibrated to Tierney survey results to account for resilience potential. The simulations indicated a DER of 88.7%.

More recently, Rose et al. (2007a; 2007b) used a similar CGE methodology to perform simulations for hypothetical terrorist attacks on the power and water systems of Los Angeles. They simulated total supply disruptions for the entirety of Los Angeles County for a 2-week period. Their analysis incorporated an extensive set of resilience options and estimated DER at 90.6% for the case of the power outage and 89.8% for the water outage. Market resilience was found to be almost as high. As noted in the following section, the resilience to these targeted attacks is likely to be relatively higher than that for natural hazards. The former are focused on a key aspect of a community's infrastructure in the absence of any other devastation. On the other hand, for natural disasters and more widespread terrorist attacks (e.g., a "dirty bomb"), other aspects of a regional economy are affected. This will reduce the ability to substitute inputs, bring in additional imports, rely on an effectively working market, etc.

The studies by Rose et al. (2007a; 2007b) also compare the relative effectiveness of various resilience responses to water and power outages. Production rescheduling is the most effective option, and this result generalizes to other contexts.[6] On the other hand the results for water storage and alternative sources are region specific e.g., there is little storage in Los Angeles, no major rivers to tap, and groundwater extraction is severely limited by law.

It should be noted, however, that most of the simulation studies performed on this subject come closer to measuring *potential* resilience rather than actual. For one thing, they have not taken into account aspects of bounded rationality (see, e.g., Girgenzer and Selten, 2002), due to factors such as lack of information and stressful decision contexts. At the same time, it should be emphasized that incentives to implement resilience are strong given the immense potential losses that can be avoided and the relative low cost of these options (e.g., much conservation is in fact cost saving and production rescheduling may only require some overtime pay). Also, damage to one utility service provider may lead to a series of cascading failure in others. Finally, the existence of coping measures does not mean they will be optimally used given the likelihood of the situation of

[6] Production rescheduling does have some costs but they are likely to be relatively minor. These include start-up cost and the opportunity cost of deferred production.

bounded rationality, market failures, and extreme uncertainty. At the same time, many analysts on the subject may have not factored in human ingenuity.

IV. BEHAVIORAL AND SYSTEM LINKAGES

A. Definitions

Behavioral and *system linkages* refer to considerations unique to disasters, which are not captured in conventional models and that typically cause indirect impacts to be orders of magnitude greater than ordinary multiplier or general equilibrium effects. One key aspect stems from the "social amplification of risk," where misperceptions, media distortion, increased risk aversion, or increased safety tolerances come in to play (see, e.g., Kasperson et al., 1988; Pidgeon et al., 2003). For example, contamination of the water supply of one city may cause operators of water systems in neighboring cities to shut down until testing has been completed. Even if this action is not taken, the situation may make households and businesses shy away from using tap water and thereby incur various additional cost of substitution or relocation. If a contagious agent is injected into the water system, this may cause people to avoid contact with others, such as withholding their children from school or not going to work.

At the systems level, this refers to interdependence and cascading failures. The most prevalent example is damage to an electricity system that causes failures in communication systems and in water systems that do not have sufficient backup generators to do the pumping. The water system outage can also, in turn, lead to reduced effectiveness of the fire protection system in cases of major conflagrations or just the threat of them (e.g., high-rise office buildings have to shut down when water systems are disrupted because of the limited vertical range of hook and ladder fire trucks). In extensive emergencies, the social fabric may be torn as well.

Part of the problem stems from systems being overwhelmed, as in the levy and dike system in New Orleans in the aftermath of Katrina. Clearly such conditions are more likely with a widespread calamity than in the case of a targeted attack. However, some forms of terrorism, especially repeated ones, can lead to panic and a general social malaise that affects not only human well being directly but the economy as well. Others, such as a "dirty bomb" or radionuclide contamination of the water system, can kill large percentages of a population, leading to ghost towns that may not recover because of fear of lingering contamination or stigma (as in the case of the area around Chernobyl) or depressed economic conditions prior to the catastrophe (as in the case of Homestead, Florida in relation to a non-terrorist event like Hurricane Andrew).

Overlaps between resilience and behavioral/system linkage effects exist. Positive behavioral responses, such as heroism and resourcefulness, are associated with the former, while extreme negative reactions, such as panic or avoidance behavior, typically dominate the latter. It would appear that there are important non-linearities and threshold effects at work here, as when an individual "snaps" or "mass hysteria" breaks out. The same is true with infrastructure systems in the case where their capacity and even their resilience are overwhelmed.

B. Measuring Extended Linkages

Progress on formalizing the analysis of extended linkage lags that of formalizing resilience for several reasons. In the case of resilience, there is a common objective—how best to utilize the resources available in a crisis. Moreover, this is likely done in the context of rational behavior. Overall, even considering the ingenuity involved, resilience operates "within the box" of maximum impacts. An indication of the amenability of resilience to analysis is indicated by the work of Rose and Liao (2005), where resilience options are linked to key parameters of an economic production function, and Rose and Oladosu (2007), where they are linked to parameters of the household production function.[7] *Behavioral linkages* on the other hand involve aspects of less rational behavior. In the aftermath of the 9/11 attacks, which made use of commercial aircraft as weapons, passenger demand for air travel plummeted. Of course, there was an increased risk associated with such activity, but it was unlikely to have been so large as to justify a 50 percent drop in commercial airline travel and the return to base levels only after nearly two years (see Gordon et al., 2007). Analysts have referred to this as a "fear factor." It is also likely to arise in other contexts. For example, if the water system of one city is contaminated by a radiological device, suspicions are likely to be significant in neighboring cities. Terrorist can "spread" the damage significantly by just the threat or even a hint of more widespread activity. Many other examples exist, such as fear of eating contaminated food, visiting iconic sites, or working in industries relatively more likely to be terrorist targets (ports, chemical factories, etc.).

We refer to these situations as *extended linkages* because they go beyond the economy affected or the normal reaction to the event. For example, several studies of the decision to install counter-measures to shoulder mounted rocket launchers limited the analysis of potential avoided damages to a selected number

[7] For example, conservation is reflected in the productivity term of the production function and input substitution is associated with the elasticity of substitution parameters.

of destroyed aircraft, associated loss of life, and ordinary multiplier effects. Clearly, consideration of extended linkages was warranted.

The key issue here is to assess the fear factor, and it is more difficult to measure and predict irrational behavior than rational behavior. One practical approach is to adapt data from case studies, either actual experiences or simulations, and transfer them to the case in point.[8] Unfortunately, this approach offers few analytical insights and is based on more tenuous data than other approaches noted below.

A much more ambitious strategy to formulate an analytical framework, collect necessary data, and develop an operational model is being spearheaded by Burns et al. (2007; see also Burns and Slovic, 2006). It is based on the concept of the social amplification of risk and shows how risk perceptions, media attention, hazard characteristics, rumor, first responder actions, and private citizen-government trust interact in a dynamic setting (see also Burns et al., 1993). Longitudinal surveys and laboratory experiments are used to collect the necessary data to calibrate the model. A systems dynamics framework (Sterman, 2000) integrates the various behavioral and structural features of the problem. The system contains positive loops of actions and delays that amplify behavior and negative ones that dampen it. Models such as this offer a way to measure (and predict) such events as the anthrax scare in the aftermath of the September 11 attack.

With respect to economic impacts in particular, Rose and Asay are developing a special module of the systems dynamic model (Burns et al., 2007). This is a modified (CGE) model, with household and producer decisions undertaken in context of “bounded rationality” (see, e.g., Conlisk, 1996; Kahnemann, 2004). The behavioral postulate is changed from one of simple optimization to one that includes alternative objective functions, explicit constraints on decisions, heuristics, changes in risk aversion, extreme uncertainty, myopia, and inability to process information or to process it correctly. Model parameters would be based on new data collections especially designed around a broader set of economic behavior. Overall, it is important to note that behavioral linkages emanate from direct economic effects, though they are often ancillary to the terrorist attack in both time (e.g., post-event evacuation or quarantine) and space (e.g., neighboring locations defined broadly to include an entire country or continent in extreme cases).

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[8] This approach has been formalized as *benefit transfer*, where benefit, in this case, refers to avoided damages (see e.g., Brookshire and Neill, 1992; Smith, 2002). Formalization refers to choice of data to transfer and to modifications needed to render the data more appropriate to a different context (location, population, etc.).

With respect to *system linkages*, numerous studies have examined infrastructure cascading failures (e.g., power systems on a geographic basis) and compound events (e.g., hurricanes/floods linked to dams/levy failure). Ordinary input-output analysis can be very effective in capturing standard interdependencies (see, e.g., Santos and Haimes, 2004; Haimes et al., 2005; Rose, 2005). In these cases the linkages are more tangible and, in all but the worst disasters, more bounded. For example, the compound event of hurricane, initial flooding, levy failure, and more severe flooding in New Orleans last year was not surprising, but the unraveling of the social structure and policy response failure at all government levels was.

In addition to case studies, systems linkages can be modeled by various types of systems analyses to predict their potential impact in a probabilistic manner (see, e.g., Chang and Shinozuka, 2004). However, it behooves the analyst to think outside the box to the broader realm of potential extended linkages over space, time, and societal component.

The operative measure of behavioral linkages might be a type of multiplier, whereby the total economic impact of the link is divided by the estimate of more ordinary impacts, including ordinary multiplier, general equilibrium, and/or macro impacts, but also including resilience associated with them. Fear of eating contaminated meat will cause a partially offsetting shift to chicken and fish. Shutdowns of factories for fear of contaminated water supplies can be offset by working extra shifts or using excess capacity at a later date in most sectors.

A similar measure applicable to systems linkages is possible, though the choice of the base is arbitrary. Some might choose to include only the total economic impacts associated with the first system in the denominator, while alternatively one could include the total economic impacts of all system components that are likely to fail beyond some probability threshold in the denominator. Of course, resilience adjustments should be made for systems linkages of as well.

V. OVERALL FRAMEWORK

An overview of the analytical framework is presented in Figure 1. It presents the main categories of the linkages, with more details provided for a specific example in Figure 2 below. Although this paper is intended to be generally applicable to all natural and man-made disasters, most of the examples will focus on a terrorist attack on a public water system using a radiological device. A brief summary of the results is presented at the end of this section.

As noted above, the framework is intended primarily to estimate the avoided losses of a disaster or terrorist attack as part of a benefit-cost analysis, as might be used to evaluate mitigation measures such as airport passenger screening, "hardening of infrastructure," or miscommunication efforts. This evaluation would require an estimation of the situation (level of economic activity) without the protective measure and an estimation of the situation with its implementation. It is always difficult to perform the first estimate (the baseline or reference case) because of inherent problems in predicting the future. However, discussion of these considerations is beyond the scope of this paper. Instead, we take a more pragmatic approach focusing on the difference between the counterfactual and baseline. The framework for analysis below focuses on this difference.[9]

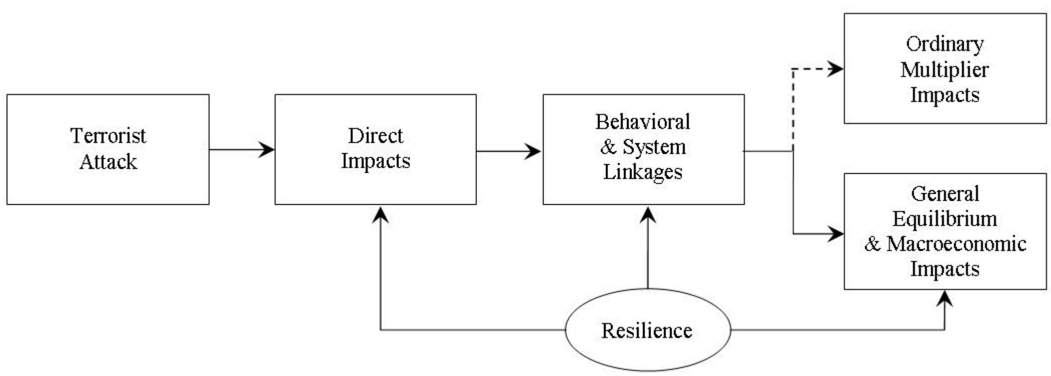

Figure 1. Framework for Modeling Total Economic Impacts of Extreme Events

Additionally, a number of alternative models can be used to estimate both the baseline and "impacted" situation. Discussions of the best choice of alternative models from among the categories of input-output, computable general equilibrium, mathematical programming, agent-based, and macroeconometric, is also beyond the scope of the paper (the reader is referred to Rose, 2004a). We simply note here several desirable qualities of the model choice, such as the ability to control for extenuating circumstances, incorporate behavioral considerations, and account for non-linearities.

[9] In the ex ante case discussed above, it is common practice to assume extenuating circumstances, such as trends, business cycles, and politics, are held constant. The application is more difficult for the case of ex post analyses. There, one must actually account for the influence of these extenuating circumstances in order to accurately estimate the impact of the disaster.

In Figure 1, a terrorist attack leads to a general category of direct impacts (e.g., property damage, business interruption, fatalities). This in turn sets off a set of behavioral linkages (e.g., fear factors, avoidance of contact) and system linkages (e.g., interdependencies among types of infrastructure). Often the next step is to evaluate indirect effects in terms of ordinary multipliers, as with an input-output model. However, a more comprehensive assessment of "indirect" impacts would consider general equilibrium and macroeconomic effects. The former relate primarily to price and quantity interactions, as well as various types of macroeconomic impacts relating to financial markets, international competitiveness, and fiscal conditions (see, e.g., Frey et al., 2007). As noted in an earlier section, resilience can have the effect of muting losses at each of the three linkage stages. Individual businesses and households can conserve or import goods in short supply, emergency plans in place can mute the "fear factor," and redundancies can stymie cascading infrastructure failures. The workings of the price system and adaptive measures to re-establish markets can improve the allocation of resources so that maximum efficiency can be attained for the resources remaining that were targeted, as well as all of society's resources in general.

More details are presented in Figure 2 for the case of a hypothetical radiological attack on a municipal water system (described in more detail below). In the left-hand margin of Figure 2, various stages, or linkages, of the analysis are listed. Across the top margin, the level of analysis is distinguished, beginning with the water system itself and extending through to the macro level. Note also that the figure distinguishes impacts on businesses and households, as well as including linkages and impacts relating to decontamination/remediation and reconstruction/resettlement.

The flow of events in Figure 2 begins with the "radionuclide attack" in the upper left-hand corner, which results in an actual water system contamination. However, as expressed by the dashed line in the figure, suspected water system contamination may cause a shut-down of water services or "do not drink/use" edicts in neighboring areas. Both the real and imagined contamination will lead to direct business interruption losses, with the suspected water system contamination working through the "fear factor." However, only actual water system contamination will result in deaths and injuries, which will then translate into lower effective demand for goods and services, i.e., increased business interruption (BI). Direct effects then cause changes in supply and demand through markets, with prices changing to achieve new equilibria (indirect BI). Evacuation and relocation can help reduce the number of deaths and injuries, but, at the same time, this results in an increase in BI as well. In fact, massive evacuations can result in larger BI than would be suffered from an actual event. In these instances policymakers place a higher premium on saving lives than on

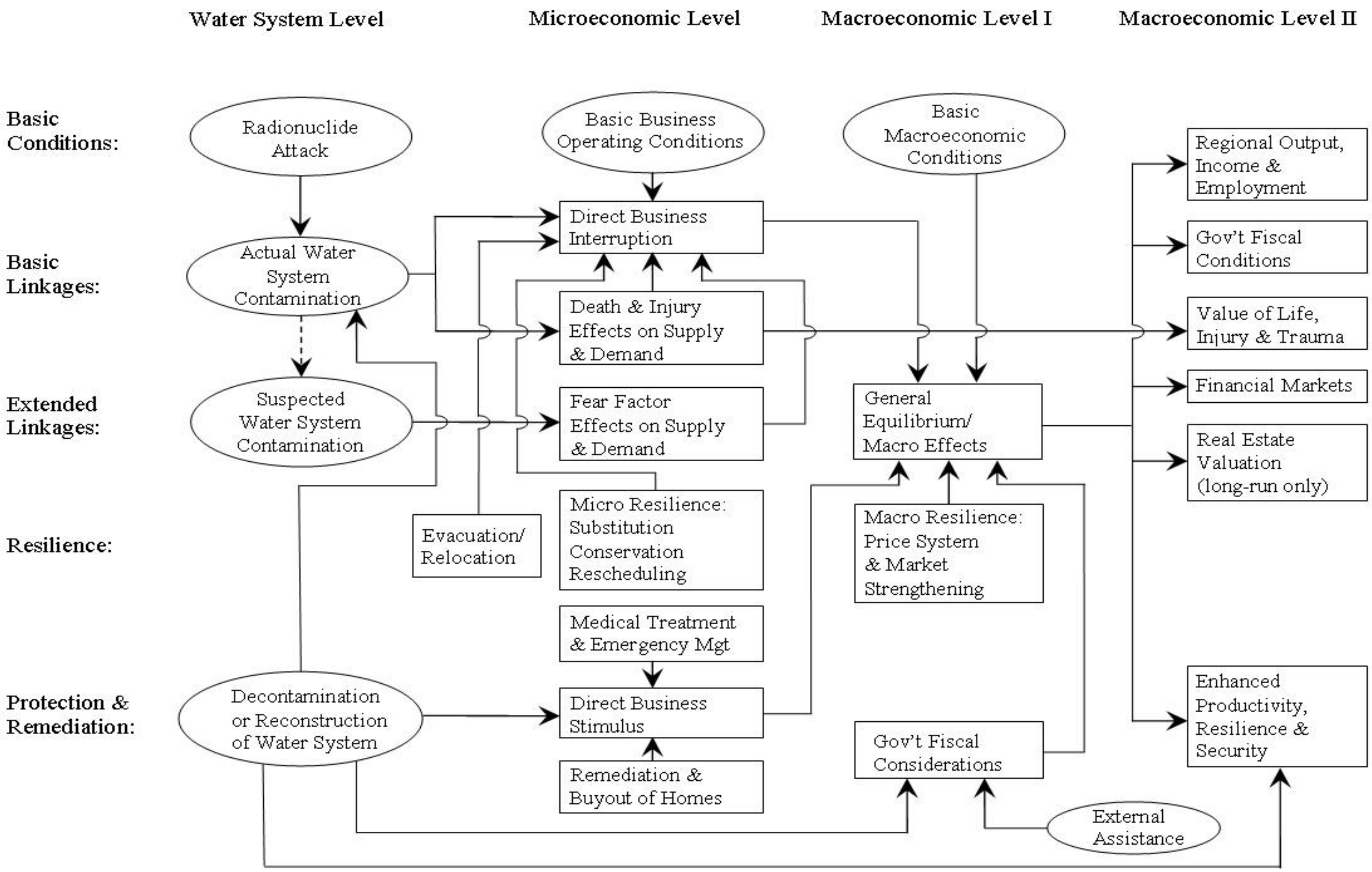

Figure 2. Estimating the Total Economic Impacts of a Radiological Attack on a Municipal Water System

business activity. Note that resilience influences many of the aforementioned linkages. Microeconomic options for resilience include input/import substitution, conservation, use of inventories and rescheduling of activities (both production and household activities that relate to well being).

At Macroeconomic Level I, the direct business interruption and direct business stimulus are injected into the broader economy subject to resource constraints to capture price and quantity interactions in multiple markets. At this initial macro level, resilience relates to the rationing role of prices for goods, such as water, in short supply, as well as general signaling of relative scarcity of resources and goods for the economy as a whole.

Another layer added in Figure 2 that is not explicit in Figure 1 is protection and remediation. Here, decontamination and reconstruction of the water system decreases the damaging agent and thus stunts the business interruption. In addition, decontamination or reconstruction of businesses and remediation or buyout of homes both could stimulate economic activity at the direct level. However, they typically siphon off resources from other activities, and this combination of effects comes together at the general equilibrium level, such that the positive stimulus might be more than offset by the diversion of the necessary resources from normal (and often more productive) economic activities. Also coming into play at this level is the role of external assistance and its effect on government fiscal operations. Massive expenditures on security, either warranted or affected by the "fear factor," would also represent an extended linkage.

The final perspective in Figure 2 is referred to as Macroeconomic Level II, which provides details of the overall outcome. Note, however, that these details are not additive. The bottom line macroeconomic indicator would relate to the total production in the economy, stated in terms of gross output (total sales) or some net measure such as gross regional product, value-added, or income. Employment is also listed, since, it contains broader aspects of the "human condition." Other details would include the government sector fiscal position (the extent to which the government incurs a deficit or finds other ways to finance the situation, and the effects of the disaster on its ability to borrow). This would also relate to matters of external aid and reduced tax payments from a deterioration of the tax base, both stock (property) and flow (sales). This final column also includes the value of death, injury, and trauma to the population.

With respect to more extended linkages, the analysis would ideally evaluate changes in real estate values, though it would include only those that continue in the long run. It would also evaluate impacts on financial markets. This would include factors such as the interest rate, which would have a major bearing on micro decisions (housing sales), fiscal considerations (government's ability to borrow), and other macro variables (money supply, exchange rates, etc.).

Finally, the last column includes aspects of enhanced productivity, resilience, and security. Many of these stem from explicit policies, investments and experience, such as reconstruction and enhanced protection of the water supply, learning by businesses and households on how to cope with terrorist attacks, and heightened security.

So as not to clutter the diagram, we have not included various non-market impacts, such as damaged ecosystems from contaminated water. This could also include a dollar value estimate of reductions in household well being, apart from medical considerations, such as the value of household time to boil water, increased cost of purchasing alternative sources of water, and other activities to cope with the problem.

I briefly summarize the results of the application of major portions of the framework to provide an illustration of the relative prominence of various components of economic losses. One aspect of the study analyzed the system-wide damage from the placement of a radionuclide device in the water system of a small city with a population of 100,000. Total losses were estimated to be about $100 billion, of which more than half were due to loss of life. Direct business interruption was the next major impact factor, contributing $15 billion to the total. General equilibrium impacts were rather small in this context due to a combination of the limited interindustry linkages in a small city. However, total business interruption was reduced by more than 50 percent by resilience, thus serving as a much larger influence on a downside than general equilibrium effects on the upside. The fear factor was estimated at less than $1 billion because detection of any contamination in neighboring jurisdictions could be undertaken relatively rapidly. However, if all water systems in the U.S. had to be shut down for a day or two for testing, the consequences would exceed 100 billion due to this consideration, even after accounting for resilience. Note also that remediation and mitigation costs are relatively high, with estimates of the former being an upper-bound of $8.4 billion and the latter being $9.8 billion. These results reinforce those presented in Sections III and IV regarding the potential relative prominence of resilience and extended linkages.

VI. POLICY AND RESEARCH IMPLICATIONS

The proposed framework would be useful to those analysts and policy-makers at several levels of government and in the private sector charged with reducing risks from terrorism, other man-made hazards, and natural disasters. A measure of the economic consequences is indispensable to evaluating these risks. One must first identify the major types of consequences. Often there is a tendency to consider only on-site impacts, but this neglects ordinary indirect (multiplier, general equilibrium, or macroeconomic) impacts. Moreover, it ignores ramifications far from the site due to the "social amplification" of the risk. Although more difficult to measure, these effects can increase ordinary losses by more than an order of magnitude. Even rough estimates may be better than omitting them altogether.

The prominence of behavioral linkages suggests that efforts to accurately convey risk to the public are key to avoiding the exacerbation of losses. This is important for both government agencies and the media. It requires diligence in making sure the terrorist threat has not spread from the original target. No doubt, some policies, such as more stringent airport screening, are as important in minimizing the fear factor as they are to mitigating the terrorist threat in the first place. Awareness of system linkages is likely to result in greater efforts to reduce infrastructure interdependencies and thus prevent cascading failures.

Resilience also has a major effect on economic consequences but in the opposite direction. Resilience is novel in the benefit-cost calculus for disaster risk reduction for two reasons. First, although it would be preferable to be able to mitigate such disasters, i.e., prevent them from happening in the first place or to reduce their force, this is impossible, or far too costly. Resilience thus represents our best second line of defense. Also, while both mitigation and resilience can reduce losses, many resilience options are relatively more cost-effective. Conservation typically more than pays for itself, backup systems incur relatively low cost, and production rescheduling is relatively inexpensive.

Thus, benefit-cost analysis needs to be broadened to consider both mitigation (pre-event options) and resilience (post-event options) simultaneously.[10] It is likely that, given the neglect of resilience, future decisions might tilt more toward this category of loss reduction options. At the same time, two important distinctions should be made with respect to the type of loss. First, reduction of BI losses before or after the event can be viewed as equivalent in the aggregate. However, the distribution of these losses will differ according to whether mitigation or resilience is employed. Second, the equivalence breaks down for the reduction of loss of life and injury. For these losses, mitigation is the superior alternative.

At present, several parts of DHS have or are making use of this framework. A streamlined version, including direct and indirect BI environmental impacts, as well as some aspects of resilience, were part of the framework for evaluating FEMA mitigation programs over the period 1993 -2003 (Rose, et al., 2007). The DHS National Preparedness and Plans Directorate is

[10] Note that although resilience is implemented after the disaster, it can be enhanced prior to it by various investments in storage facilities, inventories, backup systems, production system flexibility, and emergency planning.

charged with evaluating the consequences of a wide range of terrorist attacks against many different kinds of target. This group has expressed an interest in how resilience and behavioral systems linkages can be modeled and incorporated into consequence analysis. The ChemBio Division of the DHS Science and Technology Directorate carries out a bi-annual Bioterrorism Risk Assessment that evaluates the threat, vulnerability and consequences of several types of attacks. In its 2008 report, this group attempted to take into account behavioral reactions to biological terrorist attacks, as well as several types of resilience. This group has expressed strong interest in refinements to take into account social and psychological impacts of terrorist attacks as well. The DHS General Council's Office recently sponsored a workshop that focused in part on developing a comprehensive framework for estimating regulatory program benefits (avoided losses). The DHS Policy Office, particularly its Private Sector Office is also interested in how to model and quantify the impacts of terrorist attacks and natural disasters.[11]

A major purpose of this paper is to draw the attention of the research community to new areas of economic consequence analysis. Debates persist over the best impact model to use (input-output, computable general equilibrium, macroeconometric), but this choice is likely to vary the estimates by no more than 50 percent. Resilience and behavioral linkages, however, can result in ten-fold differences in loss estimates.

On resilience, more research is needed primarily on the empirical side. This might begin with a better assessment of the difference between potential resilience and actual practice. The identification of obstacles to implementation is key to overcoming them. This should be followed up by analyses of policy instruments to promote resilience (see, e.g., Smith et al., 2008). Research is also needed on the most effective way of implementing resilience, just as research has long been undertaken in evaluating this issue in the case of mitigation. Should it be the public or private sector, or some combination of the two? It is important to identify areas of overlap and moral hazard to avoid wasteful spending. Other issues relate to sharing arrangements for critical supplies among sectors, households and government. Cooperation here is likely to lower costs.

The market is an excellent source of resilience. When markets are intact after a disaster, prices provide signals as to the value of scarce resources. Research is needed on how best to restore and maintain markets. Models that can distinguish legitimate price increases associated with increased scarcity from

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[11] One caveat is that some DHS regulatory economists hold the view that it is only legitimate to incorporate direct impacts into cost-benefit analysis, because of concern about double-counting and shifts in economic activity. However, this view is pertinent to ordinary indirect effects but should not apply to direct effects of resilience or behavioral linkages.

price increases that merely represent gouging can be useful to emergency management officials in monitoring the workings of the economy.

The biggest gap in the framework relates to behavioral linkages. More research is needed on how risk perceptions are formed and how they are affected over time by the type of disaster, media and government reporting, social interactions, and background conditions relating to location and socioeconomic characteristics. Further study is needed to evaluate the accuracy of the characterizations of government and the media reporting of events. Acknowledgement of limitations and accuracy or the existence of biases can then serve as a first step in remedying the source of the problem. The remaining sources relate to human nature and how to quell irrational fears. This is important to both the citizenry's peace of mind and to their pocketbook.

Finally, there is a need to improve the interface between the various components of the overall framework. This includes making models more compatible and being able to factor in interactive effects across all loss types.

VII. CONCLUSION

Until recently, disaster loss estimation has been confined to the consideration of property damage, loss of life, direct business interruption and ordinary multiplier effects. Several analysts, however, have identified ways in which losses are both muted and exacerbated. They have appended some estimates of these broader phenomena to their estimates in an ad hoc and partial fashion.

This paper provides a comprehensive and consistent framework that practitioners can use to perform disaster loss estimation. The case is made for grounding the framework in the principles of benefit-cost analysis. Operational definitions of resilience and extended linkages are provided that can be used to measure their effects. The prominence of these two aspects of economic losses is illuminated by summarizing recent studies that employ these metrics. The framework is presented in schematic form and illustrated with a hypothetical example of a radionuclide attack on an urban water system. The paper identifies the important interconnections between various pieces of the loss estimation puzzle and how they fit together.

Progress in these new areas of loss estimation has been uneven. Much further empirical work is needed on how resilience can be enhanced and eroded, including the cost-effectiveness of the various options to promote the former and to prevent the latter. Fundamental conceptual work is still needed on behavioral linkages, and empirical estimation presents a great challenge as well.

REFERENCES

Baker, M., Jr., Inc. 2008. "Municipal Water Distribution System Security Study: Recommendations for Science and Technology Investments," Final Report to the U.S. Department of Homeland Security, Washington, DC

Becker, G. S. and Y. Rubinstein. 2004. "Fear and the Response to Terrorism: An Economic Analysis," Unpublished manuscript, University of Chicago and Tel-Aviv University.

Boardman, A., D. Greenberg, A. Vining, and D. Weimer. 2001. *Cost-Benefit Analysis: Concepts and Practice* (2nd ed). Upper Saddle River, NJ: Prentice Hall.

Bruneau, M., S. Chang, R. Eguchi, G. Lee, T. O'Rourke, A. Reinhorn, M. Shinozuka, K. Tierney, W. Wallace, and D. von Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance Seismic Resilience of Communities," *Earthquake Spectra* 19: 733-52.

Burns, W. and P. Slovic. 2008. "Public Response to a Terrorist Strike," *Risk Analysis*, forthcoming.

Burns, W., P. Slovic, A. Rose, and G. Asay. 2007. "Modeling Community Response and Economic Impacts of Risk Amplification Following a Terrorist Strike," Research proposal submitted to the National Science Foundation, February 2007.

Burns, W., P. Slovic, R. Kasperson, J.X. Kasperson, O. Renn, and E. Scrinvas. 1993. "Incorporating Structural Models into Research on the Social Application of Risk: Implications for Theory Construction and Decision Making," *Risk Analysis* 13: 611-23.

Business Continuity Institute. 2002. Good Practice in Business Continuity Management, *Continuity* 6(4): 2.

Chang, S. and M. Shinozuka. 2004. "Measuring and Improving the Disaster Resilience of Communities," *Earthquake Spectra* 20: 739-55.

Chao, H. and R. Wilson. 1987. "Priority Service: Price Income Investment and Market Organization," *American Economic Review* 77: 899-916.

Chernick, H. (ed.). 2005. *Resilient City: The Economic Impact of 9/11*. New York: Russell Sage Foundation.

Conlisk, J. 1996. "Why Bounded Rationality?" *Journal of Economic Literature* 34: 669-700.

Comfort, L. 1994. "Risk and Resilience: Inter-Organizational Learning Following the Northridge Earthquake of 17 January 1994." *Journal of Contingencies and Crisis Management* 2(3): 157-70.

Comfort, L. 1999. *Shared Risk: Complex Seismic Response.* New York: Pergamon.

Federal Emergency Management Agency (FEMA). 2004. *Earthquake Loss Estimation Methodology (HAZUS).* Washington, DC: National Institute of Building Sciences.

Federal Reserve Bank of Atlanta (FRBA). 2005. *Econ South* 7(4): 1-33.

Freudenburg, W. R., C. L. Coleman, J. Gonzales and C. Hegeland. 1996. “Media Coverage of Hazardous Events-Analyzing the Assumptions,” *Risk Analysis* 16: 31-42.

Gigerenzer, G., and R. Selten (eds.). 2002. *Bounded Rationality: The Adaptive Toolbox.* Cambridge: MIT Press.

Gordon, P., H. Richardson, J. Moore, II, J. Park and S. Kim. 2007. "Economic Impacts of a Terrorist Attack on the U.S. Commercial Aviation System," *Risk Analysis* 27(3): 505-12.

Gordon, P., J. Moore, II, J. Park and H. Richardson. 2008. "Impacts of Closing the U.S. Borders," in *Global Business and Terrorism*, Cheltenham, UK: Edward Elgar, forthcoming.

Haimes, Y., B. Horowitz, J. Lambert, J. Santos, C. Lian, and K. Crowther. 2005. “Inoperability Input-Output Model for Interdependent Infrastructure Sectors. I: Theory and Methodology,” *Journal of Infrastructure Systems* 1 (2): 67-79.

Haughwout, A. 2005. “Evidence from Real Estate Markets of the Long Term Impact of 9/11 on the New York City Economy,” in H. Chernick (ed.), *Resilient City*. New York: Russell Sage Foundation.

Kahneman, D. 2003. “Maps of Bounded Rationality: A Perspective on Intuitive Judgment and Choice,” *American Economic Review* 9(5): 1449-75.

Kasperson, J. X., R. E. Kasperson, N. Pidgeon, and P. Slovic. 2003. “The Social Amplification of Risk: Assessing Fifteen Years of Research and Theory,” in N. Pidgeon et al. (eds.), *The Social Amplification of Risk.*

Klein, R., R. Nicholls, and F. Thomalla. 2003. “Resilience to Natural Hazards: How Useful is This Concept?” *Environmental Hazards* 5: 35-45.

Kunreuther, H. and G. Heal. 2003. "Interdependent Security," *Journal of Risk and Uncertainty, Special Issue on Terrorist Risks* 26: 231-49.

Lee, B., P. Gordon, J. E. Moore, II, and H. Richardson. (2008) "Simulating the Economic Impacts of a Hypothetical Bio-Terrorist Attack: A Sports Stadium Case," *Journal of Homeland Security and Emergency Management* 5, Article 39.

Mileti, D. 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States.* Washington, DC: Joseph Henry Press.

National Research Council. 1999. *The Impacts of Natural Disasters: A Framework for Loss Estimation.* Washington, DC: National Academy of Sciences Press.

Pidgeon, N., R.E. Kasperson, and P. Slovic. (eds.). 2003. *The Social Amplification of Risk*. Cambridge: Cambridge University Press.

Rose, A. 2004a. "Economic Principles, Issues, and Research Priorities of Natural Hazard Loss Estimation," in Y. Okuyama and S. Chang (eds.), *Modeling of Spatial Economic Impacts of Natural Hazards*, Heidelberg: Springer, pp. 13-36.

Rose, A. 2004b. "Defining and Measuring Economic Resilience to Disasters," *Disaster Prevention and Management* 13: 307-14.

Rose, A. 2005. "Analyzing Terrorist Threats to the Economy: A Computable General Equilibrium Approach," in H. Richardson, P. Gordon, and J. Moore, II (eds.), *Economic Impacts of Terrorist Attacks*, Cheltenham, UK: Edward Elgar, pp. 196-217.

Rose, A. 2007. "Economic Resilience to Natural and Man-made Disasters: Multidisciplinary Origins and Contextual Dimensions," *Environmental Hazards: Human and Social Dimensions* 7: 383-98.

Rose, A. and S. Liao. 2005. "Modeling Resilience to Disasters: Computable General Equilibrium Analysis of a Water Service Disruption," *Journal of Regional Science* 45 (1): 75-112.

Rose, A. and D. Lim. 2002. "Business Interruption Losses from Natural Hazards: Conceptual and Methodology Issues in the Case of the Northridge Earthquake," *Environmental Hazards: Human and Social Dimensions* 4: 1-14.

Rose, A. and G. Oladosu. 2008. “Regional Economic Impacts of Terrorist Attacks Disrupting Household Use of Utility Lifelines: A Computable General Disequilibrium Analysis,” Center for Risk and Economic Analysis of Terrorism Events, University of Southern California, Los Angeles, CA.

Rose, A., G. Oladosu, and S. Liao. 2007a. “Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout,” *Risk Analysis* 27(3): 513-31.

Rose, A., G. Oladosu, and S. Liao. 2007b. “Regional Economic Impacts of a Terrorist Attack on the Water System of Los Angeles: A Computable General Disequilibrium Analysis,” in H. Richardson, P. Gordon, and J. Moore, II (eds.), *Economic Costs and Consequences of a Terrorist Attack*, Cheltenham. UK: Edward Elgar.

Rose, A., G. Asay, D. Wei, and B. Leung. 2008. "Economic Impacts of Shutting Down the U.S. Borders in Response to a Security or Health Threat," in H. Richardson, P. Gordon and J. Moore (eds.) *Global Business and Terrorism*, Cheltenham, UK: Edward Elgar, forthcoming.

Rose, A. et al. 2007. “Benefit-Cost Analysis of FEMA Hazard Mitigation Grants,” *Natural Hazards Review*, 8(4): 97-111.

Salerno, C. 2003. “Powered Up When the Lights Go Out,” *Continuity Insights: Strategies to Assure Integrity, Availability and Security* 1(6): 23-28.

Schuler, R. E. 2006. “Two-sided Electricity Markets: Self-Healing Systems,” in H. Richardson, P. Gordon, J. Moore, II (eds.), *Economic Impacts of Terrorist Attacks*, Cheltenham, UK: Edward Elgar.

Shaw Environmental, Inc. 2006. *Radionuclide Contamination: Cost Estimates for Radionuclide Attack Scenarios.*

Sheffi, Y. 2007. *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage.* Cambridge, MA: MIT Press.

Slovic, P., M. Layman, N. Kraus, J. Flynn, J. Chalmers, and G. Gesell. 1991. “Perceived Risk, Stigma, and Potential Economic Impacts of a High-Level Nuclear Waste Repository in Nevada,” *Risk Analysis* 11: 683-96.

Smith, V. K., C. Mansfield, and A. Strong. 2008. "Can the Economic Value of Security be Measured?" Department of Economics, Arizona State University, Phoenix, AZ.

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Boston, MA: McGraw-Hill.

Tierney, K. 1997. "Impacts of Recent Disasters on Businesses: The 1993 Midwest Floods and the 1994 Northridge Earthquake," in B. Jones (ed.), *Economic Consequences of Earthquakes: Preparing for the Unexpected*, Buffalo, NY: National Center for Earthquake Engineering Research.

U.S. Department of Homeland Security. 2008. *Bioterrorism Risk Assessment: Report to the President*, Washington, DC.

Vale, L. and T. Campanella. 2005. The Resilient City: How Modern Cities Recover from Disaster. New York: Oxford.