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MACROECONOMIC IMPACTS OF CATASTROPHIC EVENTS: THE INFLUENCE OF RESILIENCE

By

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Abstract

As devastating as many recent disasters have been, their economic impacts could have been substantially worse if not for the inherent and adaptive resilience of individual businesses, markets, and the regional macroeconomy (see, e.g., Rose 2006, 2004b; Rose and Liao, 2005). This paper will present recent developments in modeling the impacts of disasters at the micro, meso, and macro levels. This will include such resilience responses as utilizing distributed generation to minimize the risk of centralized electricity supply disruptions, the matching of suppliers without customers with customers without suppliers, and reliance on price signals to allocate scarce resources during a crisis. Results of recent studies will be summarized to measure the relative strength of various types of resilience. The paper will also evaluate the extent to which resilience is eroded by truly catastrophic events.

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Adam Rose*

I. INTRODUCTION

In the past few years, nearly every analysis of the impacts of a catastrophe in the U.S. has highlighted the "resilience" of the economy (see, e.g., Chernick, 2005; FRB, 2005). Resilience is typically used to explain why regional or national economies do not decline as much as might be expected or recover more quickly than predicted. Unfortunately, the term is either poorly defined or defined so broadly as to be meaningless.[1] Is resilience simply a vacuous buzzword, or is it a concept with substance that can provide insight into the impact and recovery from a disaster? Can resilience be quantified? Perhaps most importantly, is resilience a constant, or can it be enhanced?

The purpose of this paper is to address all of these questions. The analysis builds on work by the author and several other researchers in the fields of economics, geography, ecology, natural hazards, engineering, and organizational behavior. I will first discuss the relative strengths and weaknesses of alternative approaches to evaluating the economic impacts of disasters. I will next propose a set of definitions of various aspects of resilience that reconcile diverse perspectives. I will then analyze the definitions and estimated extent of resilience posited in several studies in the aftermath of the September 11 terrorist attack on New York City and of Hurricane Katrina in the New Orleans area. I will also offer an operational measure of resilience and provide estimates of its strength. Finally, I will explore how resilience differs between ordinary disasters and catastrophes.

II. THE STANDARD METHODOLOGIES FOR EVALUATING DISASTER IMPACTS

Two branches of economics are typically applied to estimating the regional or national economic impacts of a disaster. The first is *macroeconomics*, or the study of the workings of the overall economy. This inquiry is often formally approached with the use of econometric models based on extensive time series data. Since their inception, these models have improved from consisting of amorphous aggregates to including basic behavioral considerations and sectoral detail. These models have the capability of forecasting future baseline economic conditions to serve as a reference path for the deviation of economy due to a disaster. They are also consistently estimated and have formal statistical properties.

In comparison to other types of models discussed below, macroeconometric models have relatively stronger capabilities with respect to financial variables, fiscal operations, housing stocks, and real estate markets. Some major drawbacks of macroeconometric models relate to the fact that they are based on time series data, which means they have a bias toward projecting the past, i.e., business as usual behavior. Their consistent (simultaneous equation) estimation also makes it relatively more cumbersome to incorporate modified conditions relating to a disaster.

The second relevant branch of economics is called *impact analysis.* Here, the scope is not as broad nor comprehensive as macroeconomic models, and the emphasis is on a counterfactual experiment ("if then" propositions) rather than a forecasts. In fact, the most prevalently used approach, input-output (I-O) analysis, has been strongly criticized for its over-simplification of the economy. For example, I-O models do not include the explicit workings of markets and prices (or where they do include the latter, the price-quantity interactions are stunted), omit financial variables, and lack behavioral content. At the same time, I-O models have sufficient sectoral detail, are able to capture quantity interdependence (through multipliers), and are inexpensive to construct.

More recently, computable general equilibrium (CGE) models have come to supplant I-O models for impact analysis. CGE models are non-linear, mimic the role of markets and prices, and have behavioral content. At the same time, CGE models to date do not adequately incorporate financial variables, and the standard versions assume the economy is always in equilibrium. In essence, CGE models take the best features of I-O models and overcome most of their limitations (see, e.g., Rose, 1995).[2] Relative to macroeconometric models, however, for both I-O and CGE, it is easier to change key parameters to include considerations relating to disaster situations.

There are some notable differences between both macroeconometric and impact analysis models at the national and regional levels, the latter being arguably the more relevant context for the analysis of most disasters. At the regional level, data are less readily available, so it is relatively harder to construct both types, but especially econometric models. Also, at this level, many key variables (e.g., the money supply, interest rates) can be taken as given. Thus, some of the relative advantage of econometric models wane in this context.

Both of these branches of economics were developed for general purposes such as analyzing economic growth or decline, the entrance or exit of new businesses, or the impacts of public policy decisions. In the context of disasters, I-O models were first used to analyze the economic impacts of military attacks in the 1940s (U.S. Strategic Bombing Survey, 1945), and econometric and CGE models used to analyze the effects of the oil embargo in the 1970s. The first application to natural disasters was the I-O application by Cochrane (1974), followed by more sophisticated I-O applications (see, e.g., Rose et al., 1997; Gordon et al., 2002) CGE analyses (see, e.g., Rose and Liao, 2002), and econometric analyses (see, e.g., Ellson et al., 1984). Recently they have been applied to the analysis of the impacts of terrorist attacks: I-O (Gordon et al., 2005; Haimes et al., 2005), CGE (Rose, 2005; Rose et al., 2006a), econometric (Haughwout, 2005).

Despite applications to these new areas, each of the modeling approaches discussed above has remained relatively standard. Still, differences in underlying conditions warrant some major changes in these models. For example, in contrast to the single sector focus of opening a new copper mine or closing an automobile plant, the initial stimulus in the case of disasters is typically much more widespread, as it involves extensive destruction of physical capital and human capital as well. A crisis situation warrants reconsideration of the postulate of rational behavior and of equilibrium outcomes.[3] But perhaps the area in most need of refinement is that of *resilience*. It is a contention of this paper that this aspect of disaster impacts cannot be adequately addressed in standard applications of the models at hand.[4] A discussion of modeling advances on this score is presented in Section VI below.

Several researchers have identified major factors that influence economic losses from disasters and how to model them (see, e.g., West and Lenze, 1994; Rose, 2004a). Most of these factors relate to the normal workings of the economy and need not be repeated here. Instead, we take note of three considerations that are often overlooked, all of which have a bearing on resilience.

The first is the importance of flow measures of disaster losses, such as output, income, and employment. For decades, hazard loss estimates were dominated by attention to stock measures, i.e., property damage. However, it is the flow of goods and service from these assets that contributes to well-being.[5] Moreover, these flows include not only direct losses, but rather "higher-order" losses due to multiplier, general equilibrium, or broader macroeconomic effects. The value of a capital asset is the discounted flow of its future earnings, so it may at first appear to be double-counting to include both property damage and business interruption losses. However, in the case of the destruction of the capital asset it is legitimate to include aspects of both. This is because any loss in net earnings while the capital stock is being repaired or replenished represents a lost opportunity to society as a whole. In addition, many flow losses may not even accompany property damage directly, e.g., broad based business shutdowns due to electricity service disruptions caused by terrorist damage to generating stations or transmission lines, when factories themselves are otherwise unscathed.

The second consideration is the limitation of ordinary indicators of macroeconomic performance or of market values. This pertains to the omission of losses of non-priced environmental services, historical and cultural sites, un-priced infrastructure services, un-priced household services, and the economic value of social and psychological disruption. Broadening macroeconomic indicators through the use of enhanced accounting measures, such as "net economic welfare," or more recently, green accounting, are conceptual steps forward in avoiding the understatement of losses. Recent advances have also been made in modeling some other aspects, such as the loss of highway services (Cho et al., 2002) and the value of household time (Rose and Oladosu, 2005).

Third is the difficulty of isolating impacts of disasters from other on-going phenomena in the economy. The often dominating effect of national or regional economic cycles is typically acknowledged. Less frequently acknowledged, however, is the influence of public and private decisions during the course of recovery and reconstruction. Since these do not apply to the estimation of property losses, they have thus often been neglected. However, flow losses are highly sensitive to decisions that are able to mute them on a day to day basis and that can limit the period during which they take place (both being aspects of resilience to be discussed in more detail in the following section). Also relevant is the conceptual issue of whether disaster losses should be measured in gross terms of the economy left to its own devices or in net terms subtracting the influence of insurance payments and outside aid. All too often the latter perspective leads to the conclusion that disasters have minimal economic impacts in the directly affected regional economy, and to the omission of the fact that the geographical transfer of dollars always leaves the nation as a whole worse off.

III. DEFINING ECONOMIC RESILIENCE

I define static *economic resilience* as the ability or capacity of a system to absorb or cushion itself against damage or loss (see also Rose, 2004b). A more general definition that incorporates dynamic considerations, including stability, is the ability of a system to recover from a severe shock to achieve a desired state. I also distinguish two types of resilience in each context:

Inherent--ability under normal circumstances (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).

Adaptive--ability in crisis situations due to ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations, or strengthening the market by providing information to match suppliers with customers).

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 (Hill and Paton, 2005). One company executive recently summarized the situation quite poignantly and in modern business terms: "In short, companies have started to realize that they participate in a greater ecosystem—and that their IT systems are only as resilient as the firms that they rely on to stay in business" (Corcoran, 2003; p. 28). Experience with Y2K, 9/11, natural disasters, and technological/regulatory failures, as well as simulated drills, have sharpened utility industry and business resilience (Eckles, 2003). Similar activities of public agencies have improved community disaster resilience.

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 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. 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.

Of course, markets are likely to be shocked by a major disaster, in an analogous manner to buildings and humans. In this case, we have two alternatives for some or all of the economy: 1) substitute centralized decree or planning, though at a significantly higher cost of administration; 2) bolster the market, such as by improving information flows (e.g., the creation of an information clearinghouse to match customers without suppliers to suppliers without customers). Both approaches are forms of resilience.

At the macroeconomic level, there are a large number of interdependencies through both price and quantity interactions that influence resilience. That means resilience in one sector can be greatly affected by activities related to or unrelated to resilience in another. This makes resilience all the more difficult to measure and to influence in the desired manner. This includes situations in which the whole is not simply the sum of the parts. An example is offered by Rose and Benavides (1999), where a system of individually structured non-interruptible service premia may not be socially optimal, because individual businesses make decisions on whether to pay the premium on the basis of their own benefits, but ignore benefits to their direct or indirect suppliers and customers.[6]

IV. REVIEW OF ECONOMIC RESILIENCE ASSOCIATED WITH RECENT CATASTROPHES

I now summarize some recent assessments of the macroeconomic impacts of two major catastrophes--terrorist attacks on the World Trade Center and Hurricane Katrina. The focus is primarily on studies that purport to address resilience. Ideally, the analysis of resilience would first include a formal definition, followed by a discussion of ordinary causal factors and relationships that bear on the macro effects, and then on the resilience influences that uniquely mute the effects of these factors. However, the problem in most of these studies is not the lack of conformance with the definition of resilience presented in the previous section but lack of a definition at all. Also, there is a lack of formal analysis of resilience, as well as an absence of testable hypotheses. Moreover, several of the studies identify red herrings as sources of resilience or draw erroneous implications.

The first study reviewed is the edited volume, *Resilient City* (Chernick, 2005). I do not take issue with the overall high quality of the several chapters of this volume, but rather the failings with respect to the book's theme. The impacts of 9/11 on New York City's economy are measured in terms of $50 billion of annual gross city product (GCP) losses by the fourth quarter of 2004, or less than 2% of the City's total economic activity. The overall assessment is that: "There is no question 9/11 was spectacularly successful in disrupting the social and economic fabric of a great city (p. 3)." The Forward to the volume seems to set the tone, i.e., to implicitly define resilience in a nebulous and almost circular fashion by stating that: "By and large the book tells a remarkable story of recovery." Resilience is then gauged in terms of lack of deterioration of the City's competitive position and the ability to absorb firms forced to relocate from their downtown locations. Other characteristics of resilience are related to the strength and flexibility of the economy. However, not faring as well were the City's labor force and tax base.[7]

The study suggests that the major reason for resilience is the presence of agglomeration economies in the City, consistent with studies that have found high density to lead to major productivity increases. The major aspect of agglomeration is related to spillovers of knowledge across industries and occupations. Apparently, a major terrorist attack did not cause a permanent tear in this economic fabric. Similar results were found for cases of external shocks by Glaeser and Shapiro (2002) and Harrigan and

Martin (2002). However, agglomeration economies are difficult to measure, and city size and economic diversification may be poor proxies for measuring the resilience aspect.

The first analysis of Hurricane Katrina reviewed is that of Cashell and Labonte (2005) of the Congressional Research Service (CRS). The authors begin by stating that: "Hurricane Katrina will have substantial and long-term effects on the economies of Southern Louisiana and Mississippi. But, given that those two states account for just 2% of total U.S. Gross Domestic Product, the effects on the national economy will be much less dramatic than the effects on the region" (p.1). The authors then characterize the shock of Hurricane Andrew and 9/11 as previous examples of overall minor intrusions on the national economic scene. Moreover, their emphasis on impacts is in terms of whether these various events effectively halted economic growth, and not just its rate. They also suggest that increased spending of funds flowing into the region following Katrina will offset some of the losses due to the catastrophe. They also curiously state that: "Although damage to the capital stock does not reduce measured GDP, rebuilding increases it" (p. 3). The first part of the passage clearly ignores business interruption losses.

This analysis raises two criticisms relating to the geographic unit of analysis. The first is that the major focus be the economy hardest hit, and that regional economies are distinct entities. Evaluating the overall impact of the shock in relation to the national economy marginalizes the region and trivializes the impact.

The second geographic factor pertains to the misguided implications that regional economies are better off after a disaster because of the inflow of aid and insurance dollars from the outside, and from the dipping into savings internally. This overlooks lost production in the meantime, the likelihood of higher insurance rates affecting business competitiveness thereafter, and the subsequent need to replenish withdrawals from savings. It also fails to acknowledge that for the U.S. as a whole, the interregional transfer of funds may be a boon to the regional economy, but the disaster is always a net loss to the nation.

Another analysis of Katrina is by the Joint Economic Committee Democrats (U.S. Congress, 2005). It is similar to that of the CRS Report in terms of: 1) focusing on impacts on the national economy, 2) emphasizing that the recovery will be a boon to the regional economy, and 3) failing to mention resilience explicitly.

The study quotes the Congressional Budget Office (CBO) analysis of the impacts of Katrina as being about $100 billion and the negative effect on U.S. growth to be 0.5% to 1.0% in the second half of 2005.[8] Again, as in the previous study, this one emphasizes that the region is only a small portion of U.S. economy. There is some assessment of impacts on individual sectors, primarily labor and energy. However, there is no discussion of resilience considerations such as inventories, substitution, and conservation in particular, or human ingenuity in general. At the same time, the study emphasizes positive impacts on the economy during recovery and cites two consulting studies (Economy.com and Macroeconomic Advisors) as predicting positive effects on projected growth of real domestic product beginning during the first half of 2006 and continuing throughout the remainder of the year.

A good deal of this report is devoted to making a case against large amounts of federal aid to the affected areas, though there is little mention of resilience, which would help make the case that the economy is not as adversely affected as might first be believed. Only a passing reference is made to the effect that: "Although the supply of energy from the Gulf region has been reduced, policy actions and market responses have mitigated the effects of that disruption. . ." (p.1). Instead the analysis emphasizes: "The substantial necessary direct spending on relief and reconstruction should by itself provide considerable short-term stimulus that will cushion the macroeconomic shock from Katrina" (p. 2).

The last analysis of Katrina to be reviewed is that of the Federal Reserve Bank of Atlanta, in whose jurisdiction New Orleans and the other affected parts of the Gulf Coast hit by Katrina reside. In the fourth quarter issue of *Econ South* (FRB, 2005), the President and CEO of the Atlanta Fed offers an editorial entitled, "Witnessing the Resilience of a City and an Economy." Again there is no definition of resilience here nor in the remainder of the quarterly, which is almost entirely devoted to Katrina. Also, Ford evaluates the impact primarily in terms of the effect on national economic growth, though a subsequent section focuses on the region and its individual states. The major sources mentioned in the implicit analysis of resilience focus on those sectors likely to be hardest hit and those that are being positively affected. The only sources of resilience mentioned are those of these "offsetting" sectors and the fact that other ports in the region were able to take up the slack of New Orleans and Biloxi. Interestingly, the rising price of oil is given as a reason for future increased investment in this industry, though little mention is made of the impact of the higher energy prices on the regional or national economy.[9]

V. QUANTIFYING RESILIENCE

In this section, I provide admittedly crude mathematical definitions of resilience at two levels. 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. In terms of actual measurement of resilience, input-output models of disaster impacts capture only quantity interdependence, often referred to as indirect or multiplier effects. Computable general equilibrium models and macroeconometric models capture both price and quantity interaction through the explicit inclusion of market forces (see Rose, 2005).

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:

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

where

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

The major 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. This would be consistent with the context of an I-O model, which is inherently linear. The application of a simple version of this type of model implicitly omits the possibility of resilience.[10] 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.[11]

The measure of *total economic resilience (TER)* to input supply disruptions is the difference between a linear set of general equilibrium effects, which implicitly omits resilience and a non-linear outcome, which incorporates the possibility of resilience. From an operational modeling standpoint this is the difference between linear I-O multiplier and CGE (or other comprehensive, non-linear model) impacts as follows:

$$TRER = \frac{\%?\,TY^m - \%?\,TY}{\%?\,TY^m} = \frac{M\bullet\%?\,DY^m - \%?\,TY}{M\bullet\%?\,DY^m}$$

where

M is the economy-wide input-output multiplier
$\%?\,TY^m$ is the maximum percent change in total output
$\%?\,TY$ is the estimated percent change in total output

Our 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 stage: why an activity level is achieved 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.

VI. MEASURING RESILIENCE

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 inventories. This has long made electricity outages especially problematic, since this 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 losses? Here both individual business and market-related adjustments suggest some muting of general equilibrium effects. Adjustments for lost output of goods and services other than electricity 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.

Table 1 summarizes loss estimates from utility service disruptions and the role of resilience.[12] 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.

A brief summary of the methodologies used in these studies provides some additional insight into the estimates. Primary data collection is typically considered a superior approach to ex-post evaluations, though some underlying conceptual frameworks for the data collection is key to analyzing the intricate workings of resilience.

TABLE 1. SUMMARY OF LOSS ESTIMATES FROM UTILITY SERVICE DISRUPTIONS

Study	Location/ Event	Utility/ Duration	Method or Model	Loss of Utility Services (%)	Direct Output Loss (%)	Total Output Loss from Adjusted Direct (%)	Direct Q Loss/ Loss of Utility Services (%)	Individual Business Resilience (%)	Total Q Loss/ Direct Q Loss (%)	Market Resilience (%)
Tierney (1995)	Los Angeles/ Northridge EQ	Electricity/ 36 hrs	Survey	8.3	1.9[a]	1.9[b]	22.9[b]	77.1	—	—
Rose-Lim (2002)	Los Angeles/ Northridge EQ	Electricity/ 36 hrs	I-O	8.3	0.42[c]	0.6	5.0	95.0	131	79.3
Rose-Guha (2004)	Memphis/ Hypothetical EQ	Electricity/ First week	CGE	44.8	—	2.3[d]	5.1[e]	94.9	—	—
Rose-Liao (2005)	Portland/ Hypothetical EQ	Water/ First week	CGE	50.5	5.7[f, g, h, i]	7.0	11.3	88.7	122	75.6
Rose-Liao (2005)	Portland/ Hypothetical EQ	Water/ First week	CGE	31.0	3.5[f, g, h, j]	5.0	11.4	88.6	143	52.2
Rose et al. (2006a)	Los Angeles/ Hyp Terrorism	Electricity/ Two weeks	CGE	100.0	9.4[g]	13.0	9.4	90.6	138	84.8
Rose et al. (2006b)	Los Angeles/ Hyp Terrorism	Water/ Two Weeks	CGE	100.0	10.2[g]	13.5	10.2	89.8	132	87.2

[a] Survey response incorporates various undefined direct resilience practices.
[b] Explicitly includes only direct effects, though it is likely that some indirect effects are included.
[c] Resilience adjustments limited to time-of-day use, importance factor, and production rescheduling.
[d] Model not able to incorporate very short-run elasticities; hence, flexibility of response is exaggerated.
[e] Numerator is total output loss, since direct and indirect output losses could not be distinguished in this model.
[f] Does not include production rescheduling.
[g] Production rescheduling (recapture) factors from Rose-Lim (2002) were applied to study results.
[h] In addition to production rescheduling, the remaining resilience is attributed to conservation and input substitution for water, though other factors are implicitly present.
[i] Prior to any mitigation.
[j] After mitigation.

Various ad hoc adjustments have been suggested for incorporating resilience into I-O models with respect to increased reliance on imports (see, e.g., Cochrane, 1997) and for other types of resilience (see Rose and Lim, 2002). This typically involves changing I-O coefficients according to a demand-supply balancing algorithm or use of side equations (e.g., production rescheduling can readily be separated from other types of resilience in ordinary disasters and its effects represented as additive to those of other resilience types).

A stronger theoretical foundation is possible in the context of CGE models. My associates and I have utilized nested constant elasticity of substitution (CES) production functions to represent the hierarchy of decisions business managers make in ordinary circumstances and crises (with the possibility of different rationality postulates for each context). Parameters of these production functions can be linked to individual types of resilience, most notably inherent and adaptive input substitution, import substitution, and conservation. Rose and Liao (2005) and Rose et al. (2006a; 2006b) illustrate this approach. A cornerstone of the analyses is an optimizing algorithm for utilizing survey and simulation data to recalibrate ordinary CGE parameters for crisis situations, i.e., formally factoring in resilience associated with key parameters of the model. Other types of resilience such as inventories are incorporated through the relaxation of resource constraints, and market resilience is analyzed by comparison of flexible-pricing results with fixed-price or linear model results.

The first study in Table 1 is that of Tierney (1997), who collected responses to a survey questionnaire from more than a thousand firms following the Northridge Earthquake. Note that maximum electricity service disruption following this event was 8.3 percent, and that 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 percent of a single day's output in Los Angeles County as interpreted by Rose and Lim (2002) from the Tierney data.

A study by Rose and Lim (2002) of the aftermath of the Northridge Earthquake used a simple simulation model of three resilience options to estimate adjusted direct output losses at 0.42 percent and used an I-O model to estimate total region-wide losses of 0.55 percent. Although this study did not include the full range of resilience tactics as was inherent in the Tierney study, it is also likely that in the Tierney study the effects of production rescheduling would be under-reported because not all businesses connect activities undertaken long after the event with the affects of the disaster. This helps explain the relatively higher level of resilience in the analysis by Rose and Lim.

A CGE analysis by Rose and Guha (2004) of the impacts of a hypothetical New Madrid Earthquake on the Memphis, Tennessee economy indicated that a 44.8 percent loss of utility services would result in only a 2.3 percent loss of regional output. However, this model did not explicitly include many resilience options and was constrained by computational limitations from reducing major parameters, such as elasticities of substitution, to levels that reflected a very short-run crisis situation.

A study by Rose and Liao (2004) for a hypothetical earthquake in Portland, Oregon, and for water rather than electricity utilities, incorporated engineering simulation estimates of direct output losses into a CGE model. The first simulation, which represented a business-as-usual scenario, indicated that a 50.5 percent loss of utility services would result in a 33.7 percent direct output loss, factoring in some resilience measures. Further adjustment for production rescheduling reduces this to 5.7 percent. A second simulation, representing the case of $200 million capital expenditure initiative of replacing cast-iron pipes with modern materials, indicated that a 31percent loss of utility services would result in a 3.5 percent loss of direct output in the region. Direct resilience declined following mitigation (direct output losses as a proportion of utility outage levels increased), because mitigation reduces initial loss of service and hence ironically narrows the range of resilience options that can be brought into play.

More recently, Rose et al. (2006a; 2006b) performed 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 found direct resilience to be over 90 percent for the case of the power outage and slightly less than 90 percent 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.

Individual business, or direct, resilience is presented in column 9 of Table 1. This measure is simply the complement of the figure in column 8 (the column 8 figure subtracted from 100 percent). The results of the several studies, using several alternative methods, indicate that individual business resilience is quite high and that results of analyses that included this factor would be between 77 percent and 95 percent lower than for analyses that neglected it (e.g., a purely linear model).[13]

General equilibrium effects are presented in Column 10 and indicate a moderate increase over direct (partial equilibrium) effects, ranging from 122 percent to 143 percent. The I-O model of the Rose-Lim (2002) study did not allow for ordinary multiplier effects, because of the assumed adequacy of inventories for goods other than electricity for the 36-hour outage period, and thus considered only "bottleneck effects" (see also Cochrane, 1997). Interestingly, the first simulation by Rose and Liao (2005) yielded general equilibrium effects on the order of 22 percent of direct effects, and the second simulation yielded general equilibrium effects 43 percent as great as direct effects. This means that mitigation not only lowered direct business resilience but also made the regional economy as a whole less resilient, thus offsetting some of this strategy's benefits.

While I have stressed the importance of including general equilibrium effects, it is equally likely that they might be overestimated, especially if a linear model is used. The extent of this problem can better be appreciated by examining *market* resilience, which is based on factors such as the ability of price changes to guide resource reallocation, changes in interregional trade, etc. It is measured as the percentage deviation between an analysis that takes the workings of the market into account and one that does not. Some aspects of market resilience can, however, be taken into account in a linear model like I-O analysis, as in the work of Cochrane (1997), Rose et al. (1997), and Rose and Lim (2002). In the former case, the solution algorithm allows for market resilience by changing the pattern of imports and exports, while in the latter two it includes an assumption that customers without suppliers will find new suppliers without customers in a type of "re-contracting" arrangement. Indirect effects in both of these approaches are thus limited to "bottleneck" effects, where one sector is so extensively disrupted that it limits the "smoothing" effects on supply and demand throughout the economy. Otherwise, if the standard I-O formulation is used, multiplier effects (as a proxy for general equilibrium effects) can be quite large. In the studies listed in Table 1, the LA County multiplier is about 2.5 and the Portland Metropolitan area multiplier is 1.9. Column 11 represents a measure of market (net general equilibrium) resilience as a percentage deviation from the purely linear results based on these multiplier values. However, even with the overestimation resulting from a standard I-O model, direct resilience appears to be the more dominant of the two effects.

Two limitations of our definition of resilience and its measurement should be noted. First, I have used a common denominator of economic output to define resilience. Although I have not done so in my own research, and neither has anyone else, I have indicated how the standard measures of gross output, gross regional product, and value added can be extended to include the value of un-priced or under-priced goods and services as well. Still, the single measure while being additive, reasonably comprehensive, and readily measurable, tends to obscure specific elements of an economy, such as its relative competitiveness or equity.

Second, most of the simulation studies performed on this subject come closer to measuring <u>potential</u> resilience rather than actual. For one thing, they fail to take into account factors beyond the disruption of utility services. A terrorist attack targeted at the electricity system will likely leave factories and shops unscathed, but an earthquake will not, thereby making it less than automatic to reschedule production (see the more extensive discussion below). Also, the existence of coping measures does not mean they will be optimally used given the likelihood of the situation of bounded rationality and market failures. At the same time, all analysts on the subject may have underestimated human ingenuity. Overall, however, the estimates of resilience presented in Table 1 are likely biased toward the high side.

VII. CONTEXTUAL INSIGHTS INTO RESILIENCE

Additional insight into resilience can be gained by examining the context in which it operates and how changes in this context affect the concept. By context, we refer to internal and external conditions affecting a phenomenon. The former includes characteristics of businesses, such as size, age, inherent flexibility of production process, skills of management and workers, and location. Pertinent characteristics at other levels would be a business's connection to the supply chain, competitiveness of its market, etc. The external context refers to the frequency, magnitude, and duration of the external shock, interdependence of the market system, and inflow of external funds (both insurance and aid).

Here we examine how resilience changes in relation to two of the external factors: duration and severity of the disaster. More specifically, we examine the time trend and the effectiveness of different resilience responses and how effectiveness at a given point in time and over a period of time differs between an ordinary disaster and a catastrophe.[14]

Table 2 summarizes a set of individual business resilience actions in relation to a water service disruption for the sake of illustration. Column 1 lists the type of action, while column 2 provides a concrete example. Column 3 lists the current effectiveness based on a study by Rose et al. (2006b).[15] The conclusion from this study is that most types of resilience reduce potential losses by only a few percentage points each. The major exception is production rescheduling, which ranges from 30-99 percent in terms of potential loss reduction capability depending on the sector (see FEMA, 2004; Rose and Lim, 2002). "Resource importance" refers to the proportion of business operation that can continue without water. ATC (1991) estimates that this ranges from zero to 85 percent depending on sector.

The effectiveness of the various options over time is presented in column 4. By definition, inherent substitution is constant, since any improvement in it is assigned to the adaptive version, which increases with learning, as well as with availability of substitutes. The situation for import substitution is analogous. Adaptive responses, on the other hand are likely to increase with learning and managerial and market efforts, such as re-contracting. Inventories (e.g., stored water in small containers or large tanks) is the most limited option for most businesses because it is a fixed amount that is not readily continued (replenished) over time; in fact it is characterized by depletion. Resource importance is likely to be rather constant except if technological change takes place. Ironically, the most potent resilience option, production rescheduling, decreases over time, as firms near their productive capacity limits or lose market share permanently.

TABLE 2. EVALUATION OF INDIVIDUAL BUSINESS RESILIENCE ACTIONS

Action	Example	Ordinary Effectiveness	Effectiveness Time Trend	Potential Effectiveness	Effectiveness in Catastrophe
Inherent Resource Substitution	bottled water for piped water	minor	constant[a]	limited by cost	lowered because substitutes less available
Adaptive Resource Substitution	drilling new water wells	minor to moderate[b]	increases w/ learning	increases w/ planning	lowered by limited substitution options
Inherent Import Substitution	importing bottled water	minor	constant[a]	limited by cost	lowered if transport network damaged
Adaptive Import Substitution	importing trucked water	moderate	increases w/ re-contracting	increases w/ planning	lowered if transport network damaged
Adaptive Conservation	using less water by recycling	minor to moderate[b]	increases w/ learning[c]	increases w/ technology	weakened by property damage
Resource Inventories	using stored water	minor	decreasing	limited by capacity	weakened by property damage
Resource Importance	portion of operation not requiring water	moderate to large[b]	constant	increases w/ technology	unlikely to be affected
Production Rescheduling	making up lost production afterward	moderate to immense[b]	decreases w/ length of disruption	improvements unlikely	weakened by property damage[d]

[a]Increases are associated with the *adaptive* version of this action.
[b]Depends significantly on sector.
[c]Draconian measures are likely to be sustainable for only short periods, however.
[d]Also weakened by decreased availability of other inputs and cancellation of customer orders.

Column 5 provides a summary of potential effects in the context of ordinary disasters. Inherent capabilities are limited by definition, though it is possible to enhance them before the event ("capacity building"). This is also the case for inventories by increasing storage capacity. Conservation and resource importance can be increased after the shock through improvements in technology. Production rescheduling is likely to defy improvement, e.g., it is not worthwhile to increase productive capacity to make up lost production if this additional capacity is needed only sporadically.

Catastrophes can have major effects on resilience. Their sheer magnitude and associated duration are likely to challenge not only individual businesses but the economy as a whole, e.g., multiple failures in the provision of infrastructure. They may also reduce decision-making capability by reducing information flows or creating stress and trauma.

Several of these factors directly or indirectly affect resilience options. In the case of inherent substitution, a catastrophe, because it is relatively more widespread, is likely to reduce the availability of substitutes. This is also likely to be the case for adaptive substitution. Both inherent and adaptive import substitution are highly vulnerable to damage to the transportation system. Adaptive conservation is weakened by property damage. Resource inventories are also likely to be weakened by damage to structures and containers. Resource importance is unlikely to be affected in any other than a random way. Production rescheduling is also weakened by property damage, as well as by decreased availability of needed inputs and cancellation of customer orders (loss of market share).

Overall, the brief analysis here indicates that catastrophes are likely to lower resilience significantly. This will stem from a combination of damage to physical aspects of the business enterprise, as well as damage to the remainder of the economy on which it is dependent. Catastrophes will also weaken decision-making ability.

In relation to some concepts mentioned earlier, we point out another important feature of the time dimension of disasters. Dovers and Handmer (1992) emphasize a major distinction between natural ecosystems and society--the latter's greater ability to anticipate and learn. These features are key to adaptive capacity. They are operable not only during the course of a single event, but also over multiple and disparate events. For example, the rush of companies in Los Angeles to buy back-up electricity generators after the Northridge earthquake in 1994, and after the rolling blackouts (caused by poorly designed deregulation) in 2000-21, makes them less vulnerable to the possibility of a terrorist attack on the electric power system.

One other consideration that is critical in the context of catastrophes is the baseline from which we measure resilience. Earlier, I used a linear damage function as this reference point, but it is likely there are complexities and interactions that make damages exponential in the context of catastrophes (i.e., an X% loss of a critical input will yield a loss of output larger than X%). At the extreme there are irreversibilities or "flips" that can lead to a state of decay in an eco-system (see, e.g., Perrings, 2001), which are applicable to human catastrophes as well. These various factors make resilience all the more important, while at the same time posing an even greater challenge to its effectiveness. Note, however, that a total absence of static resilience would result in only a linear reduction in economic activity. The damage states exceeding the linear outcome would appear to be related to aspects of dynamic resilience in reverse--decay versus rebuilding.

VII. CONCLUSION

In this paper, I have endeavored to develop a formal approach to analyzing economic resilience to extreme events. This has included explaining and illustrating definitions of the concept, offering metrics by which to gauge it, identifying the limitations of recent studies to explicitly address it, summarizing other studies that have formally tried to measure it, and discussing ways that resilience might differ between ordinary disasters and catastrophes. This paper has focused on two of several possible dimensions of economic resilience. One intent is to inspire additional research on more formal analyses of the broader scope of this important topic. Without more formal analyses, it will be impossible to accurately assess the potential of resilience in reducing economic losses from disasters.

Resilience has several attractive features. It is an extension of many of the best qualities of the human spirit, an indication of human ingenuity, and a way to hone our survival skills. In many cases, resilience represents a low cost way (e.g., conservation, production, rescheduling, and use of market signals) to reduce losses from disasters. However, major catastrophes may really challenge resilience. Estimates of high levels of resilience for disasters such as the Northridge Earthquake or 9/11 may not be applicable to widespread devastation such as left by Hurricane Katrina. An accurate assessment of the cost and potential of resilience for each context is needed to accurately factor this set of tactics into an overall risk reduction strategy.

Although the emphasis of most policy-makers since 9/11 has been on mitigation, we must realize that we cannot always prevent catastrophes before they happen. In those cases where they do occur, resilience is a most valuable second line of defense.

ENDNOTES

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[1] For example, Chernick (2005) does not define resilience, nor is the term even included in the index of the collection of papers he edited. This and several other recent studies appear to be using the term in the vernacular and appear to be unaware of three decades of formal refinement of the term in several different disciplines.

[2] Hybrids of the I-O and econometric models are available, including the "conjoined" model developed by Hewings and his associates (see, e.g., Hewings et al., 2002) and the more integrated regional econometric modeling framework developed by Treyz (REMI, 2006), which is also touted as having CGE features.

[3] My research has attempted to rectify some of these issues by, for example, incorporating disequilibria into a CGE model. The next phase of my research will explore broadening the range of the behavioral responses through the use of bounded rationality.

[4] There is some disagreement about whether the random element of natural hazards or terrorist attacks makes a difference in their modeling. It should be emphasized that the models discussed above need not be able to predict where the damage will occur (they only need to be supplemented by models able to do so). Also, damage is not as random as one might first imagine, since terrorist attacks are often targeted for maximum damage. Moreover, mitigation action, such as building codes and flood plain management, reduce the randomness of the impacts of natural hazards. Finally, the models discussed in this section are also currently being used to predict terrorist targets (those that are likely to result in the greatest direct and indirect economic losses) to help in allocating funds to protect potential targets.

[5] Formal "welfare" measures of the impacts, typically approximating consumer surplus losses, are also related to flow measures.

[6] As in many other fields, some researchers on the subject of resilience have re-invented the wheel narrowly in their own discipline, rather than looking carefully for precedents or at the big picture. Ecologists have pioneered a useful, broad definition of resilience relating to the survival of complex systems. Holling (1973; p.17) is typically cited as the first to have defined *resilience,* his definition being "the ability of systems to absorb changes . . .and still persist." He sometimes refers to it as "buffer capacity."

It would appear that some analysts, such as Mileti (1999) and Bruneau et al. (2003), have envisioned a goal of a community that is able to take many steps to minimize its vulnerability to hazards. Resilience has become a convenient term to characterize all of these possibilities including mitigation. However, this broad usage is inconsistent with the etomology of the term in general (*resilio*, meaning rebounding), its use in ecology, and its use in other areas of hazards research. Ideally, another term can be found to modify this ideal community, so that the term "resilience" can be applied to the sub-set of characteristics to which it is well suited.

It is also important to distinguish the concept of resilience and related terms. For example, Holling (1973; p. 17) defines *stability* as "the ability of a system to return to equilibrium after a temporary disturbance." This definition is often put forth as the essence of resilience or at least a special dimension. However, it is clear that resilience and stability are distinct. As Handmer and Dovers (1996) point out, a stable system may not fluctuate significantly, but a resilient system may undergo significant fluctuation and return to a new (and, implicitly, an improved) equilibrium rather than the old one.

[7] Interestingly, while New York City's economy received a positive characterization as "resilient," two companion volumes, also sponsored by the Russell Sage Foundation, concluded that other dimensions did not perform as well.

These include a volume entitled *Wounded City,* which indicates that vulnerable neighborhoods and workers were disproportionally adversely affected, and *Contentious City*, which characterizes post-recovery politics as byzantine.

[8] These results are similar to those presented by Cashell and Labonte, as well as those of several brokerage houses and consulting firms.

[9] Cashell and Labonte (2005) note that the last four recessions were accompanied by sharply rising oil prices. A case could be made that at least two of them were in fact caused by these higher prices.

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

[11] Note that the definition presented here (based on Rose 2004b) is couched in deterministic terms. Though their definition of resilience (an off-shoot of the 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.

[12] Nearly all studies of power outages exclude resilience (see, e.g., Caves et al., 1992; Lave et al., 2006), except for those that use a resilience response as a proxy value of service continuity, as in the case of back-up generators (see, e.g., Bental and Ravid, 1986).

[13] It should be noted that the various studies listed in Table 1 are not entirely independent. For example, Rose and Liao used some of the Tierney survey findings on resilience to recalibrate their production function parameters. In addition the same production rescheduling (recapture) factors used in the Rose and Lim study were applied to all of the other study results by Rose and associates. It should be kept in mind, however, that these are only a few of several considerations that influence the numerical value of the results.

[14]Note two considerations. First, duration and magnitude are not independent. Larger magnitude events are likely to have longer durations (duration here is defined from an economic standpoint as not simply being the period of ground shaking or flood waters, but rather the subsequent period during which the business, market, or economy as a whole has not recovered). Second, we offer no specific definition of the threshold at which a disaster becomes a catastrophe. We simply point to clear-cut examples that we have in mind, such as Hurricane Katrina, Indian Ocean Tsunami, and World Trade Center attacks.

[15]See also Rose et al. (2006a) for a counterpart assessment of electricity service disruptions.

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