The Economic Consequences of Water Utility Disruptions

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The undersigned, appointed by the dean of the Graduate School,

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And hereby certify that, in their opinion, it is worthy of acceptance.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This research produces an economic impact analysis of short duration water utility disruptions to evaluate the consequences of alternative restoration decisions. The study constructs a continuous dynamic disequilibrium demand driven social accounting matrix with supply constraints that incorporates short-run resilience and other strategies employed by businesses, government institutions and households. It is constructed using the IMPLAN database and survey responses of recent water disruption events. The utility of the model is demonstrated by simulating three alternative water service restoration schemes of hypothetical water outages. The results demonstrate that different restoration strategies produce different total output and value added losses. It also shows that, in addition to total valued added losses, time costs, and the additional losses of households and government institutions are important components of total losses and should be considered when comparing restoration strategies. Finally, it highlights the importance of resilience in reducing the overall economic consequences of disruptions. It is expected that this model will help policy makers assess post-alternative recovery and restoration strategies when this type of event occurs. The model can also be used to identify the most critical industries when evaluating precautionary measures and mitigation strategies in order to minimize economic losses.

CHAPTER I: INTRODUCTION

Dependable potable water systems are critical to the performance of regional economies. Small scale, aging infrastructure, limited budgets, and limited expertise combined with simple accidents make small regions more vulnerable to water disruptions than large metropolitan areas. Short duration water disruption events are not evaluated as frequently as major disasters. However, these events often generate significant economic losses especially given their much higher frequency. Economic consequences of water disruption events arise for businesses, government institutions and households. They depend on the degree of resiliency of the community, are highly time dependent and are influenced by the restoration policies and procedures of the service provider. This dissertation develops a dynamic economic impact analysis model of short duration water utility disruptions to evaluate the consequences of alternative restoration decisions.

Household losses have received less attention in studies of economic consequences of water supply disruptions. Most studies of water disruptions have focused on the estimated value of water services and have excluded the induced effects on customers. In this dissertation, the total economic consequences will not only include the direct and indirect effects of businesses but also the induced effects of income changes.

The literature on disasters has also shown that when a water disruption event occurs, firms do not necessarily “shut down” but instead cope by adopting alternative strategies. These resilience strategies are an important aspect of disaster events since they lower the probability of failure and reduce negative consequences. Yet, most studies of disaster events have not adequately accounted for these resilience strategies. Instead they focus only on the business resilience practices and rely on data that do not necessarily provide a complete picture of how short term potable water supply disruptions affect businesses and households. This dissertation includes estimates of resilience and other responses of businesses, government institutions and households based on surveys of respondents recently affected by water disruptions.

Water supply disruptions generate both shocks and constraints in the local economic system. The temporal dynamics of a system in disequilibrium is an important element to consider when assessing economic consequences of water disruption events. This dissertation builds a continuous dynamic social accounting matrix based model that considers both demand and supply constraints. A dynamic disequilibrium model is able to accommodate supply constraints due to water disruption events, and include imbalances and adjustments generated from these constraints in continuous time. Furthermore, it also facilities the inclusion of the dynamic adjustments caused by very short-run resilience and other strategies employed in response to water disruption and as well as indirect effects.

Short duration water utility disruptions are seldom evaluated in detail. It is hoped that this study will shed new insights on the consequences of water utility disruptions on regions when informed restoration policies by utility companies are applied. Ultimately, the model could help policy makers assess post-alternative recovery and restoration strategies when this type of event occurs. It can also be used to identify the industries in which precautionary measures and mitigation strategies can lead to the lowest possible economic losses.

This dissertation is divided into six chapters. Chapter II reviews the research literature related to the economic impact of disaster events and key features of the model are developed. The model is described in chapter III. The analysis of resilience and other strategies employed during water disruptions from surveys of businesses and households recently affected by water utility disruptions is analyzed in chapter IV. The data requirements and the simulation results are presented in chapter V. Summary and conclusions follow in chapter VI.

CHAPTER II: LITERATURE REVIEW

This chapter is a review of studies that have assessed economic consequences of disaster events. The goal of the literature review is to identify relevant factors and methodologies used when analyzing water utility disruption events. Since most of the research in the area of disasters has been limited to large natural hazards or hypothetical terrorist attacks rather than the more common water utility disruption events, the review will cover all types of infrastructure and hazards events. An examination of methodologies used to assess supply constraints in economic consequence models will also be included in this section. The use of continuous time modeling will be a third area reviewed. Methods for modeling resilience found in the literature will also be described in a fourth section. The review in this section leads to the choice of methodology and identifies the most important model features to be included when analyzing short duration water utility disruptions.

2.1. Type of Disruptions

Disruptions take several forms. Physical destruction of facilities, cyber-attacks, introduction of biological agents, chemicals or radioactive materials to a water supply, and release of hazardous chemicals to the environment are examples of human-induced disruptions related to terrorism attacks on water systems (Environmental Law Institute, 2003).

Natural disruptions of water supplies include hydrological events (floods, landslides, avalanches, storms, hurricanes), geological events (earthquakes, volcanic eruptions and tsunamis), and meteorological events (droughts, extreme temperatures, floods, and windstorms) (Guha-Sapir et al., 2004).

Some water disruptions are intentionally caused by the utility company in order to protect the water supply, to allow maintenance, and during periods of stress due to high demand (Memphis Light Gas and Water, 2011). Another type of disruption is that due to the interdependence among categories of infrastructure such as electrical outages that negatively impact water distribution systems. Finally, some disruptions are caused by providers of services to water utility companies (such as vendors of water treatment chemicals) (Chicago Metropolitan Area Critical Infrastructure Protection Program, 2000).

Distinguishing the type of disruptions is a necessary step in the assessment of economic consequences. Chang et al. (2002) point out that the type of disruption determines the manner and extent of the ensuing economic disruption. For example, the direct costs of both natural disasters and bioterrorism include casualties, illnesses, contamination, and business interruption; property damage is expected to be large in the case of most natural disasters but minimal in bio-terrorism events (Lee et al., 2008).

Not all disruptions generate disasters. Okuyama and Chang (2004 , p.2) point out that disasters only result “when the physical event intersects with vulnerable built and socio-economic environments.” Earthquakes or tornados that do not affect inhabited areas are examples of incidents that do not generate disasters.

2.2. Issues in Assessing Costs

Significant progress has been made in understanding the economic consequences of disasters. Still, there is no consensus on the type of losses to include when assessing total losses from disaster events. Gall et al. (2009) and NRC (2006, 2012) distinguish direct from indirect losses, where direct losses include damages to structural and non-structural property and indirect losses include other than property damages such as business interruption losses. Rose and Linn (2002), Rose (2009b) and HAZUS-HM by FEMA (2010a) add to these direct and indirect losses, *direct* and *indirect effects*. From this broader perspective, loss estimates could be highly variable (Gall et al., 2009) and subject to double-counting (Rose & Lim, 2002; Rose, 2009b).

2.2.1. Measures of Losses

Property damage estimates are insufficient to assess total losses from disaster events. Losses from disaster events are time dependent, occur even in the absence of damages to property, and depend on the resiliency of the system and on the repair and reconstruction activities (Rose, 2009b; Rose et al., 2011).

It is important to distinguish between stock and flow measure to avoid double-counting. Property damage (a stock) leads to a decrease in the flow of goods and services due to business interruption (Rose, 2009b). Both the cost of repair and the loss of net revenues are actual costs. However, the reduced value of assets due to the reduced net revenues should not be included.

In the literature on disaster, flow measures typically reported include business interruption losses, impact on wages and salaries and profits, transportation costs, remediation activities and their opportunity costs, utility revenue loss, household interruption losses and fatalities. Stocks measures are usually related to property value losses, and damage of structural and non-structural property.

2.2.1.1. Business Interruption Losses

Researchers have used several methods to estimate business interruption losses from disasters. Total output loss has been the most common indicator of business interruption loss. Three methods have been most commonly used.

The first method involves estimating lost working days (Gordon et al., 1998; Cheng et al., 2006) or job losses (Lee et al., 2008) which are transformed into output losses using the employment/output ratio.

The second results from property damage. Specifically, property damage is transformed into 100 minus percentage of capacity remaining and this is multiplied by the baseline total output to obtain an estimate of total output losses (Cole et al., 1993; Bockarjova, 2007; Steenge & Bočkarjova, 2007). Output losses have also been estimated by calculating the product of the total output per square foot of structure (an assumption) and the square feet of building damage (Jones et al., 2008; Rose et al.,

2011) . Another mechanism has been to use a loss of function that associates structural damages with total output losses (Cho et al., 2000; Gordon et al., 2004; Jones et al., 2008; U.S. Federal Emergency Management Agency, 2010b, c; Rose et al., 2011; U.S. Federal Emergency Management Agency, 2011).

The third method estimates lifeline[2] disruptions by estimating the percentage of service available and multiplying this by the baseline output (Rose et al., 1997; Bay Area Economic Forum, 2002; Chang et al., 2002; Chang, 2003; Chang & Seligson, 2003; Chang & Shinozuka, 2004; Shinozuka & Chang, 2004; Brozovic et al., 2007; Chang et al., 2008; Chang & Chamberlin, n.d.).

2.2.1.2. Other Flow Measures

Other related losses include measuring the impact on wages and salaries from additional number of staff hours (Okuyama et al., 2004) and on profits (Harrington et al., 1991).

Estimates of transportation related costs depend on the type of infrastructure affected and the type of disaster studied. For example, the destruction of transportation infrastructure leads to increased commuter costs. In the case of ex-post analyses of actual events, these costs are usually estimated using surveys (e.g. Gordon et al., 1998; Livernois, 2001). Studies of hypothetical events have used transport network models to

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[2] MCEER(2010) defines lifelines as systems and facilities that provide critical services for the community. Lifelines include communication, electric power, liquid fuel, natural gas, transportation (airports, highways, ports, rail and transit), water, and wastewater.

predict the required changes in traffic behavior (Cho et al., 2000; Gordon et al., 2004; Jones et al., 2008; Porter et al., 2011).

Remediation activities are another type of flow observed during disruption events. In addition to service restoration undertaken by the provider of the service remediation activities include provision of bottled water (Livernois, 2001), hospitalization, decontamination support activities (Lee et al., 2008), and household displacement and public shelter needs (Chang et al., 2008; U.S. Environmental Protection Agency, 2010b; U.S. Federal Emergency Management Agency, 2010a).

To fully account for the costs of service disruptions, possible increases in the subsequent price of the service or taxes are typically included. Most of the studies reviewed here consider remediation expenditures, often as positive benefits to the local economy, but two studies considered the opportunity costs of remediation. Lee et al. (2008) assumed that post-disaster remediation costs were paid by the government but were financed by households (through taxes) which adds to the indirect costs. In the WHEAT model, the Environmental Protection Agency (2010b) assumes that costs of repairs to the water supply infrastructure would be paid for by households through increases of water rates.

Studies of utility revenue losses for water disruption events are found in life-cycle cost models (Chang, 2003; Chang & Seligson, 2003), in cost-benefit analyses (implemented in URAMP by Huyck et al., 2003; Seligson et al., 2003) and in the WHEAT model (U.S. Environmental Protection Agency, 2010b).

Some studies have estimated the cost of household service interruption losses due to water disruptions using constant elasticity demand curves to obtain willingness to pay measures to avoid water supply disruptions (Harrington et al., 1991; Bay Area Economic Forum, 2002; Brozovic et al., 2007; Aubuchon & Morley, 2012). A complementary approach has been used to obtain estimates of averting behavior and other household expenditures during water contamination events (Harrington et al., 1991; Abdalla et al., 1992; Collins & Steinback, 1993; Laughland et al., 1993; Livernois, 2001).

Estimates of the cost of lost lives vary because of complications and ambiguities involved in monetizing life. Some studies predict the number of casualties using the HPAC[3] program or by estimating the value of loss of life based on other empirical studies (Lee et al., 2008). Another approach has been to simply predict the number of injuries and fatalities without placing an economic value on the losses as is done by the Environmental Protection Agency (2010b) in the Water Health and Economic Analysis Tool (WHEAT) or what the Federal Emergency Management Agency (2010a) has implemented in HAZUS-MH Earthquake model. At the federal level, the cost of lost lives has been a relevant factor in the measurement of benefits and cost of regulations for preventative measures. It represents a measure of "willingness to pay for reductions in only small risks of premature death"(U.S. Office of Management and Budget, 2003).

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[3] The Hazard Prediction Assessment Capacity (HPAC) is an atmospheric dispersion modeling tool developed by the Defense Special Weapons Agency (DSWA), and later the Defense Threat Reduction Agency (DTRA) for military operations.

Among the agencies which have defined “official” guidelines of value of statistical life (VSL) base estimates and adjustments are the Environmental Protection Agency (U.S. Environmental Protection Agency, 2000, 2010a) and the Department of Transportation (2008, 2011).

2.2.1.3. Stock measures

Property value loss is another aspect of costs considered when assessing the impact of disruption events. Livernois (2001) is an example of a study that measures household property value losses using a hedonic price regression.

Studies of structural damage have used hazard loss estimation tools such as EPEDAT (Cho et al., 2000; Gordon et al., 2004; Shinozuka & Chang, 2004; Chang et al., 2008; Chang & Chamberlin, n.d.), US Quake (Chang & Seligson, 2003), HAZUS-MH (Jones et al., 2008; Porter et al., 2011; Rose et al., 2011), LIFELINE-E (Chang et al., 2002). The identification of damages is performed by overlaying the system (e.g. the infrastructure system, or GIS map layer that covers a region) with a damage map layer that identifies hazard losses.

Another method is to assume specific damages to specific components of the network (Bay Area Economic Forum, 2002; U.S. Environmental Protection Agency, 2010b).

2.2.2. Restoration of the Service

Restoration decisions are influenced by the prioritization guidelines of the service providers. Their goals are often based on considerations other than the efficient allocation of resources. Rose et al. (2007a),Tabucchi et al. (2008) and the Bay Area Economic Forum (2002) affirm that priorities of the service providers are to maintain health and safety of the region's households. Other priorities mentioned by Tabucchi et al. (2008) include efficient utilization of restoration crews based on technical (e.g. employing sequential steps to avoid overreacting) and/or cost-engineering considerations (e.g. giving priority to stations that can reestablish services as fast or as inexpensively as possible). These types of goals could lead to greater than necessary economic losses (Rose et al., 1997).

Inclusion of restoration activities is accomplished through the use of repair progress functions (Chang et al., 2002; Chang, 2003; Chang & Seligson, 2003), restoration curves (HAZUS-MH models and Jones et al., 2008; Porter et al., 2011) or by expert judgment (Cheng et al., 2006). Restoration costs are either estimated from surveys (Livernois, 2001) or from simulation models (URAMP by Seligson et al., 2003; WHEAT by the U.S. Environmental Protection Agency, 2010b).

2.2.3. Changed Behavior

Behavioral attitudes from social amplification of risk (e.g. afraid to flight) are considered in a study that assesses the consequences of terrorist attacks (Lee et al., 2008). Other behavioral attitudes arise from sympathetic behavior of mutual support to others in earthquake events (Okuyama et al., 2004). The inclusion of these behavioral attitudes has typically been through changes in consumer consumption patterns. A third type of behavioral attitudes includes resilience, which will be reviewed in section 2.5.

2.2.4. Modeling Dimensions

Time is relevant in these analyses because of the dynamic behavior of damages and the changes that occur when the damages are repaired. Time appears in several forms in the studies reviewed—the time involved in rebuilding infrastructure (HAZUS-MH, URAMP, Hwang et al., 1998; Bay Area Economic Forum, 2002; Chang et al., 2002; Chang & Shinozuka, 2004; Shinozuka & Chang, 2004; Chang et al., 2008; Jones et al., 2008; Porter et al., 2011; Chang & Chamberlin, n.d.), time as a factor in the life cycle costs of equipment (Chang, 2003; Chang & Seligson, 2003), time as an argument in the present value of costs and benefits (URAMP by Huyck et al., 2003; Seligson et al., 2003), time involved in production delays, business closures and/or transportation delays (Cole, 1998; Okuyama et al., 2004), dynamic aspects of resilience (Haimes et al., 2005a; Haimes et al., 2005b) and in time series econometric models (French et al., 2010; Xiao, 2011).

Space is another relevant dimension especially because of the likelihood that neighboring areas will be affected by the changing demands of the local businesses (and the utility water company) (Lee et al., 2008). The spatial dimension involves the location and network characteristics of infrastructure damages (Chang et al., 2002; Chang, 2003; Cheng et al., 2006), neighborhood effects (Lee et al., 2008), interregional economic flows and relationships (Okuyama et al., 2004), spatial distribution of direct, indirect and induced effects (Gordon et al., 1998; Cho et al., 2000; Gordon et al., 2004), and effects on transportation related costs such as increased commuting, travel and freight costs (Cho et al., 2000; Gordon et al., 2004).

The analysis of risk and uncertainty usually requires stochastic simulations using a method such as Monte Carlo. This approach is frequently used in studies that performed hazard analysis and in a few studies that estimated direct businesses losses (e.g. Chang et al., 2002). Ex-post studies of actual events frequently do not deal with the issue of risk since the event being study has already occurred.

2.2.5. Methods Used

Ex-post estimates of total economic costs of actual disaster events often use data collected from surveys (Harrington et al., 1991; Gordon et al., 1998; Livernois, 2001).

System flow programs and spatial data and analyses have frequently been used to identify industries and/or regions potentially susceptible to disruptions. These results are then transformed into measures of direct economic losses (Chang et al., 2002; Chang & Seligson, 2003; Chang & Shinozuka, 2004; Shinozuka & Chang, 2004; Cheng et al., 2006; Chang et al., 2008; Chang & Chamberlin, n.d.).

Business map layers overlaid with a damage map layer from hazard loss estimation tools such as HAZUS-MH, EPADAT or URAMP are a third method (Cho et al., 2000; Huyck et al., 2003; Gordon et al., 2004; Bockarjova, 2007; Porter et al., 2011; Rose et al., 2011).

Estimates of direct plus indirect economic consequences commonly employ static input-output models. The tool’s simplicity, its ability to reflect interdependencies between industries and the ease with which it can be adapted to include other non-economic aspects seems to be the most compelling reasons for the tool’s popularity (Okuyama, 2007). Researchers have devised ways to combine input-output analysis with GIS and spatial tools (Gordon et al., 1998; Cho et al., 2000; Gordon et al., 2004; Bockarjova, 2007), system flow programs (Rose et al., 1997) and hazard models such as HAZUS-MH (Jones et al., 2008; U.S. Federal Emergency Management Agency, 2010a, b, c; Rose et al., 2011). However, static input-output models have limitations such as linearity, its rigid structure with respect to input and import substitutions, and its lack of explicit resource constraints and responses to price changes (Rose, 2004b; Okuyama, 2007). Social Accounting Matrices (SAM) and input-output models are similar and share many of their weaknesses. However, these models generate considerably information regarding impacts across different socio-economic agents, activities and institutions (Okuyama, 2007).

To overcome limitations of the input-output models, static Computable General Equilibrium (CGE) models have sometimes been built and used (Rose & Guha, 2004;

Rose & Liao, 2005; Rose et al., 2007a, b; Porter et al., 2011; Rose et al., 2011; Rose et al., 2012). However, these models produce long-run equilibrium projections (Rose & Liao, 2005), assume optimizing behavior and require significantly more data (Okuyama, 2007). Rose and Liao (2005) contend that CGE models underestimate economic impacts due to their overly flexible adjustment features. For these reasons, results from input-output models are considered upper bound estimates in contrast with results from CGE models which are generally considered lower bounds (Okuyama, 2007).

Finally, econometric models are also used to assess economic impacts (French et al., 2010; Xiao, 2011). In contrast to the previous models mentioned, econometric models can be evaluated statistically, can provide stochastic estimates, can accommodation dynamic processes, and have more forecasting capabilities (Okuyama, 2007). However, these models require large data sets and do not allow the analyst to distinguish direct, indirect or/and higher-order effects (Rose, 2004b).

2.2.6. Purpose of the Analysis

Economic impact analysis tends to be very specific to a particular infrastructure (e.g. the consequences of a disaster on water system serviceability) and/or disaster (e.g. the consequences of an earthquake). The economic models reviewed use loss estimation models (e.g. Brozovic et al., 2007), survey analysis (e.g. Livernois, 2001), input-output models (e.g. Lee et al., 2008), combined input-output with transportation models (e.g. Gordon et al., 2004), social accounting matrices (e.g. Cole, 1998) or computable general equilibrium models (e.g. Rose & Liao, 2005). In the majority of these cases, these models do not estimate the direct cost of the disaster (e.g. the physical damage) but instead take the results from other studies or use results from surveys. For example Rose & Guha (2004) use Chang (2003) results to estimate the economic consequences of electric power disruptions. The aim of these studies was to assess the impact of mitigation strategies (e.g. Rose & Liao, 2005) or to demonstrate an economic scenario (e.g. Bay Area Economic Forum, 2002).

Another type of analysis is designed to evaluate the effectiveness of alternative mitigation strategies in order to improve system performance. Performance goals range from assessing serviceability[4] (e.g. Hwang et al., 1998), or reducing direct industry losses (e.g. Chang, 2003) to improving community resilience (e.g. Chang et al., 2008).

A third category of analyses are those that aim to perform risk assessment analysis. These studies usually combine some type of priority setting mechanism that considers threats, vulnerabilities and consequences in order to obtain a composite risk factor. This risk factor value is then used to prioritize the protection of infrastructure or particular assets within the infrastructure. Quantification of these risk factors is usually based on a combination of subjective estimations (in the case of vulnerability estimates) and more objective tools to assess economic consequences. For example, the WHEAT tool from the Environmental Protection Agency (2010b) is compatible with the

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[4] The most common serviceability indicators in the water system are flow, pressure and percentage of unmet demand (before and after the distortion).

RAMCAP[5] methodology. These tools are supplemented with remediation strategies to reduce risk.

2.3. Supply Constraints

Studies that have employed input-output models to assess the direct and indirect economic consequences of disasters are predominantly demand-driven and inherently static. Using this approach, estimates of economic consequences are obtained by estimating direct consequences as changes in final demand (e.g. the WHEAT model developed by the U.S. Environmental Protection Agency, 2010b) or by converting the gross output changes into final demand changes using the inverse input-output multipliers (e.g. Rose et al., 1997; Gordon et al., 1998). A weakness of this approach is that it assumes that the linkages between industries have not been affected by the water disruption and that the economic impacts are consequences of demand changes only. Models that have corrected this weakness have introduced “output” or “capacity” constraints with rebalancing algorithms to reestablish the balance between supply and demand in static models. Examples of this kind of work include the HAZUS-MH model by FEMA (2010a) and the adaptive input-output model by Hallegate (2008).

Models known as mixed endogenous/exogenous static input-output models impose output constraints by exogenizing the constrained industry and endogenizing the final demand of that industry (Miller & Blair, 2009). This permits the model to avoid

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[5] The RAMCAP stands for The Risk Analysis and Management for Critical Asset Protection tool.

the overestimation of backward linked effects. Examples includes the work of Johnson & Kulshreshtha (1982), Davis & Salkin (1984)[6], Petkovich & Ching (1978) and the more recent work of Steinback (2004) and Breisinger et al. (2009). While this technique has merit, its application can, in some cases, predict negative outputs.

2.4. Continuous Time Modeling

The dynamic nature of the impact of disasters on the economy has been analyzed using the sequential inter-industry model (SIM) developed by Romanoff & Levine (1986) and adapted to model disaster events by Okuyama et al. (2002; 2004). A problem with this approach is that it treats time as discrete units which could lead to a number of modeling inflexibilities (Donaghy et al., 2007).

Continuous time models better manage the mismatch between the time intervals involved in water disruption events (days and hours) and the typical observation interval of the data used for modeling purposes (months and years) (Donaghy et al., 2007). Other advantages of continuous models include the use of disequilibrium adjustment processes, the ability to incorporate distributed lags, the use of differential instead of difference equations and the better treatment of stock and flow relationships (Gandolfo, 1993; Wymer, 1993).

Examples of the redefinition of input-output models into continuous time include the work of Johnson (1979, 1983; 1985; 1986, 1993) and Donaghy (2007).

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[6] Only the supply constraints derived from the purchase coefficients described by these authors corresponds to demand-driven supply-constrained models.

Despite their differences in terms of formulations (e.g. modeling the rate of change in the rate of production versus the rate of change in the growth rate of production, respectively), the variables modeled (production, consumption and investment activities versus production, employment and income, respectively) and the methods used (numerical methods versus continuous econometric estimates, respectively), these studies demonstrate the capacity and advantages involved in reformulating input-output models as continuous time disequilibrium adjustment processes.

System dynamics is a type of continuous time modeling that employs numerical methods to generate approximate solutions. In system dynamics, the system is modeled in terms of stocks and flows, decision functions and information channels (Forrester, 1961). Stocks represent states; and flows, rates. Stocks and flows are connected through feedbacks relationships. In particular, stocks accumulate over time according to rates of flows and indicate the state of the system over time. Decisions regarding control variables alter the rates of the flows which ultimately affect the stocks (Sterman, 2000). Decision makers are bounded-rational and their decisions rules are determined by heuristic rules (Radzicki & Sterman, 1993; Sterman, 2000). Finally, since the stocks accumulate the historical flows, the state of the stocks allow the system to incorporate delays, to temporarily decouple rates of flows, and to induce possible disequilibrium dynamics in the system (Sterman, 2000).

System dynamics principles are grounded in control theory and nonlinear dynamics (Sterman, 2000). Mathematical representations of stocks and flows and their relationships are expressed in terms of integrals and differential equations. Since these structures include non-linear and discontinuous relations, the solutions of these models are commonly found using numerical methods. Numerical simulation software of this type includes Vensim[7] and Stella[8] programs.

Applications of system dynamics to examine the consequences of alternative policies on real world problems include industrial, economic, social and environmental systems. Examples include integrated assessment models such as those developed by the Millennium Institute (Bassi, 2006; Millenium Institute, 2012), Forrester (1971), Meadows (2004). System dynamics has also been used to improve the understanding of classical theories as demonstrated in the work of Wheat (2007) and Mashayekhi et al. (2006). System dynamics models of the US macroeconomy include the work of Forrester (1993), Forrester N. (1982) and Senge (1978).

In the area of regional economics, system dynamics has been used to address several issues surrounding input-output systems. Braden (1981, 1983), Diehl (1985, 1986), and Amsyari (1992) have used system dynamics to demonstrate the role of inventories, delays and/or damping coefficients. More recently, the work of Beyeler & Brown (2004) has addressed the effects of inventories, delays and production constrains on interdependency infrastructures. The effects of uncertainty on inventory controls

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[7] VENSIM is a system dynamics software produced by Ventana System Inc. Available at http://www.vensim.com/.

[8] STELLA is a system dynamics software especially designed for multidisciplinary group model building (http://www.iseesystems.com/).

have been captured in the representation of the SIM into system dynamics by Okuyama (2002). Bryden et al.(2010) constructed an input-output model that combined population dynamics and other agriculture and rural relationships in system dynamics to demonstrate the consequences of agriculture policies in European regions.

2.5. Resilience

Resilience is derived from the Latin word “resilíre” that means to spring back or rebound (Dictonary.com, 2011). There is a consensus of the relevance of resilience to ameliorate the impacts of disaster events. However, there is no unique definition.

Table 2.1 shows selected definitions of resilience from the literature of disasters. Definitions of resilience are a function of the object of analysis (e.g. system, business, community or infrastructure), the disruption (natural hazard, human made, economic downturns), the attributes characteristics included (preparation, mitigation, response, recovery, adaptation, learning, etc.) and the purpose use (to evaluate mitigation, to security and resilience, to improve response). Despite the various definitions, resilience approaches can be categorized as traditional or contemporary.

Table 2.1: Selected Resilience Definitions

Author	Object of Analysis/Disruption	Type of Approach	Definition
Gilbert (2010)	General / Natural and Human Made Disasters	Traditional	The ability to minimize the costs of a disaster, to return to a state as good as or better than the *status quo* ante, and to do so in the shortest feasible time.
Chang et al. (2002)	Industry/Earthquakes	Traditional	The ability of business to withstand temporary lifeline disruptions.

Kajitani & Tatano (2009)	Industry/Earthquakes	Traditional	The ability to reduce losses under external unpredictable disturbances such as natural disasters.
Rose (2009b)	Economy/Natural and Human Made Disasters	Traditional	Static: ability of the system or entities to maintain function when impacted by a disaster event. Dynamic: the speed at which the system recover quickly when impacted by a disaster event.
Haimes et al. (2005b)	Economy /Terrorist Attack	Traditional	The recovery rate of the industry sectors to a terrorist attack.
Klein et al.(2003)	General/ Natural and Human Made Disasters	Contemporary	A system characterized with the following possible attributes: 1) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction and 2) The degree to which the system is capable of self-organized.
Norris et al.(2008)	Community/ Natural and Human Made Disasters	Contemporary	The process that links a set of networked adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance.
Cutter et al. (2008)	Community/ Natural and Human Made Disasters	Contemporary	The ability of a social system to respond and recover from disasters and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the social system to re-organize, change, and learn in response to a threat.
CARRI (2011a, b)	Community/ Natural and Human Made Disasters -Economic Downturns-Pandemics	Contemporary	The capability of a community to anticipate risk, limit impacts and recovery rapidly through survival, adaptation, evolution and growth in the face of a turbulent change.
Carlson et al.(2012)	Infrastructure/ Natural and Human Made Disasters	Contemporary	The ability of an entity –asset, organization, community, region to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance.
Renschler et al. (2010a, b)	Community/ Natural and Human Made Disasters	Contemporary	The capability to sustain a level of functionality
The White House (2013)	Infrastructure/ Natural and Human Made Disasters	Contemporary	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from deliberate attacks, accidents, or naturally occurring threats or incidents.
U.S. Homeland Security (2008)	General/ Natural and Human Made Disasters	Contemporary	The ability to resist, absorb, recover from or successfully adapt to adversity or a change.

2.5.1. Traditional Approaches

Traditional definitions associate resilience with the capacity or ability to maintain its function, to recover (quickly) or bounce back when impacted by misfortune, stress or difficulty (Merriam-Webster.com, n.d.; Oxford Dictionaries, n.d.). In this approach, resilience is commonly described as an after-disaster response and as an outcome. This interpretation is also referred to static resilience. When resilience is associated with quick or rapid recovery attributes, it acquires dynamic interpretation. Traditional approaches to resilience definitions have facilitated the inclusion of resilience in economic impact assessment models (or economic loss models), since it lowers the probability of failure and reduces negative consequences (Chang et al., 2002; Rose, 2009b). Chang et al.(2002), Kajitani & Tatano (2009) give examples of industrial resilience definitions while Haimes et al.(2005b) and Rose (2009a) provide economic resilience interpretations.

2.5.1.1. Industrial Resilience

Chang et al.(2002) and Kajitani & Tatano (2009) link industry resilience to static attributes. Chang et al.(2002) define resilience as the ability of businesses to withstand temporary lifeline disruptions. Kajitani & Tatano (2009) associate resilience with the ability to reduce loss. These authors obtain specific industrial resilience factors using business surveys. These resilience factors have been used to adjust assessments of economic losses from lifeline outages in earthquakes.

Chang et al. (2002) developed the overall business direct sectoral resilience indicator which is the percentage of businesses in a sector that did not close. Other examples of the use of this approach include Chang & Seligson (2003) and Shinozuka & Chang (2004). Examples of studies with similar interpretations include the work of the Bay Area Economic Forum (2002) and Brozovic et al. (2007).

Unlike Chang's applications, Kajitani & Tatano (2009) consider multiple simultaneous lifeline outages and account for the impacts that backups, alternative lifeline resources and production rescheduling have on industrial resilience.

2.5.1.2. Economic Resilience

Rose (2009a) defines economic resilience as the ability of the system or entities to maintain function and recover quickly when impacted by a disaster event. This approach treats resilience as a post-event response that emerges from the inherent and adaptive resilience as a mechanism to cope and adapt when facing disasters. Inherent resilience refers to the ordinary ability that is already in place to deal with crisis while adaptive resilience are strategies adopted during crisis situations using ingenuity or extra effort and are focused on pushing the efficiency frontier outwards (Rose, 2007, 2009b).

Resilience responses occur at three economic levels: microeconomic, through individual behavior (e.g. conservation, substitution, rescheduling, storage); mesoeconomic, including the economic sector and individual markets (e.g. prices); and macroeconomic, including the aggregation of individual units and markets (e.g. prices and quantity interactions) (Rose, 2007, 2009b). Resilience options are eroded with time and their effectiveness depends on the type of disaster event[9].

Table 2.2 provides example of business resilience responses to water outages that occur at the micro level. These strategies can be both inherent and adaptive although there are exceptions. For example, Rose indicates that while conservation is more a adaptive strategy, substitution of pipe water is more a inherent strategy (Rose, 2009a). Rose asserts that while most researchers have focused on measuring individual micro resilience strategies, most fail to recognize the resilience effects of prices and quantities that occurrs at macro and meso levels (Rose, 2007, 2009b).

Table 2.2: Examples of Micro Resilience Responses to Water Outages

Resilience Options	Examples
Conservation	• Using less water by recycling. • Decreasing use of air conditioning. • Reduction in the number of personnel.
Substitution	• Drilling new water wells or collecting rainfall. • Purchasing bottled water or truckled water. • Using capital, labor or materials instead of water.
Inventories of water	• Using stored water from small containers or large tanks.
Resource importance	• Suspending activities not requiring water[1].
Production rescheduling	• Making up lost production afterward.

Note: [1]Rose & Liao (2005) refers to resource importance as identifying activities in one's business that do not require the resource (e.g. water) and suspending these activities during disaster events.
Source: Rose & Liao (2005), Rose et al.(2007b)

Rose (2009b) also points out that many of these resilience strategies that occur at the micro, meso and macro levels are more cost-effective than mitigation strategies.

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[9] For example, backup supplies are only available until these are totally consumed. Also, rescheduling production could be an option available during terrorist attacks but not under flood if electricity lifeline system is destroyed (Rose, 2009a).

In particular, mitigation can limit the range of responses and thus erode economic resilience (Rose, 2004a; Rose & Liao, 2005)[10]. However, inherent resilience options can be enhanced; e.g. by increasing access to resilience options and increasing flexibility in the production or in markets (Rose, 2009a).

Rose suggests some quantitative measures of static and dynamic, and direct and total economic resilience. These measures compare the maximum percentage change in direct output to the current percent change in direct output. These measures have been evaluated in several subsequent studies of the impact of mitigation on economic resilience (Rose & Guha, 2004; Rose & Liao, 2005; Rose & Oladosu, 2007; Rose et al., 2007a, b). The total static economic resilience from Rose & Liao (2005) measure was applied by the Environmental Protection Agency (2010b) to adjust the direct and indirect economic consequences of water utility disrutpions in the WHEAT tool.

Despite the progress made in quantifying economic resilience, most of these methods focus on estimates of static economic resilience from businesses. These studies have simulated the effects of specific business resilience behaviors in lifeline disruption events (e.g. conservation, input substitution, prioritization, or production rescheduling) by changing key behavioral parameters in static Computable General Equilibrium (CGE) models. Rose has also incorporated business resilience strategies

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[10] For example, mitigation during the pre-event will reduce initial loss of service when disruption event but narrows the range of resilience options that individuals and businesses could have employed (Rose & Liao, 2005).

(resource importance and production rescheduling) into input-output models (IO). Table 2.3 provides examples of static business resilience strategies included in Rose studies.

Table 2.3: Economic Business Resilience Responses

Authors	Conservation	Substitution	Inventories	Resource importance	Production rescheduling
Rose & Lim (2002): electricity outage from earthquake (IO)				x	x
Rose & Guha(2004): electricity outage from earthquake (CGE)	x	x			
Rose & Liao (2005): water outages from earthquake (CGE)	x	x			
Rose et al. (2007a): electricity outage from terrorist attack (CGE)	x	x		x	x
Rose et al. (2007b): water outage from terrorist attack (CGE)	x	x	x	x	x
Rose et al.(2011): multiple infrastructure disruptions from earthquakes (IO)				x	x
Porter et al.(2011): multiple infrastructure disruption from storm (CGE)		x		x	x

Dynamic economic resilience features have been included in the inoperability input-output approach (IIM) developed by Haimes et al. (2005b). Inoperability is defined as the inability of a system to perform its intended functions and expressed as the percentage of production that is affected relative to the desired level (Haimes et al., 2005b). In this approach dynamic resilience is defined as the adjustment rate of production in the case of a falling demand or the recovery rate in the case of a terrorist attack (Haimes et al., 2005b). Unlike Rose's economic resilience, the IIM resilience can be enhanced by risk mitigation strategies (Haimes et al., 2005b). Applications include the work of Haimes et al. (2005a), Haimes et al. (2005b), Lian & Haimes (2006), Santos (2006) and Barker & Santos (2010a, b).

Household resilience options are seldom considered. This is a controversial area. Rose & Oladosu (2007) argue that household resilience responses are an equally important element in economic impact analyses of disaster events. In contrast, Brozovic et al (2007) contend that the concept of resilience is not useful when estimating household losses since it does not produce estimates of monetary losses. Evidence from actual water contamination events suggest that household resilience responses exist and are important elements when estimating economic consequences of water disruption events. Examples of household resilience responses in water contamination events include water conservation, decontamination of water, substitution and use of backup supplies.

2.5.2. Contemporary Approaches

In contemporary approaches, resilience is defined as a process and/or as an outcome, and it is a before and after disaster response. It is also frequently considered a place-based approach since it identifies local community assets as capacities to be used when facing disasters.

The before and after disaster responses relate to resilience with multiple attributes including the four stages of emergency management response (preparation, mitigation, response and recovery), adaptive capacities, self-organizing capacity and/or learning attributes. These attributes have associated resilience definitions with static and dynamic characteristics. Unlike many traditional approaches to resilience, contemporary approaches emphasize the role of coordination and collaboration into a whole community approach to build more resilient systems. Most of these approaches aim to build community resilience to all hazards.

Contemporary approaches to resilience definitions have received considerable attention in the research and policy arena. It has served as a framework for developing tools that help to build community resilience and for constructing community resilience index measures. In the policy arena, contemporary approaches to resilience have been used as a mechanism for building capacity of nations and communities to prepare and respond to disasters.

Contemporary approaches to resilience define resilience as an outcome, a process or as an outcome and a process. Examples include the work of Bruneau et al.(2003), Norris et al. (2008), and Klein et al. (2003) and Cutter et al. (2008), respectively. Contemporary approaches that have produced tools to build community resilience include the Community and Regional Resilience Institute (2011a). Renschler et al. (2010a, b) and Petit (2013) develop resilience index measures to assess community and critical infrastructure resilience, respectively. The National Research Council (2012) and the Community and Regional Resilience Institute (2011a) provide recommendations to achieve a resilient nation. Finally, the role of resilience at the federal policy arena include interpretations of resilience by the White House (2013) and the Department of Homeland Security (2008).

2.5.2.1. Community Resilience as an Outcome

Bruneau et al.(2003) propose a broader definition of resilience applied to earthquakes that looks to minimize vulnerability to hazard events. Their conceptualization includes recovery and response actions as well as mitigation strategies (pre-disaster actions). These authors define community resilience as the ability of the social and physical units to mitigate hazards, contain the effects of disasters when these occur, and carry out activities that minimize social disruption (recovery) and mitigate the effects of future earthquakes (mitigation) (Bruneau et al., 2003). This definition describes a resilient system as one that lowers probabilities of failure, reduces consequences when failures occur and reduces the time required to recover (Bruneau et al., 2003).

Bruneau et al.(2003) also assert that to be resilient, a system (e.g. the physical and social units of a community) must be one with robustness (the ability to withstand a level of stress without suffering degradation), rapidity (the capacity to meet priorities and goals in a timely manner), redundancy (have access to substitutable elements), and resourcefulness (the capacity to mobilize resources to achieve a desired goal). While the first two features are desired characteristics for a resilient system the last two are the means to reaching these goals (Bruneau et al., 2003).

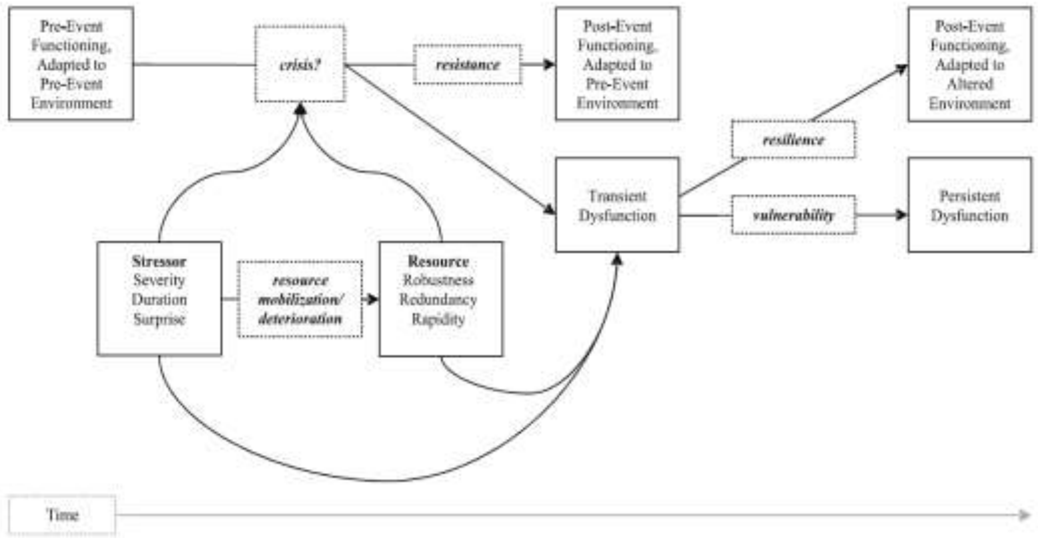
Bruneau et al. (2003) suggest that resilience of each of the physical and social units that constitute a community can be studied through four different lenses: economic, social, organizational and technical. These authors propose possible indicators to measure the community resilience dimensions for various physical and social units. However, their conceptualization does not provide a framework for measuring community resilience. The work of Chang & Shinozuka (2004) fill this gap and redefine the work of Bruneau et al. (2003) into a probabilistic framework. These authors define resilience as the probability that a system will meet both robustness and rapidity standards given an event *i*. These authors provide a measure of resilience that could be applied to each physical and social unit in each of the economic, organizational social and technical dimensions of resilience. This measure ($\sum_i \Pr(A|i) \Pr(i)$) is defined as the sum product of the probability that a system will meet both robustness (r*) and rapidity (t*) target standards given an event *i* ($\Pr(A|i) = \Pr(r < r^* and\ t < t^*)$) and the probability of occurrence of event *i* (Pr(i)). This framework was used to assess how mitigation strategies could improve the performance of community resilience when an earthquake affected lifelines (Chang & Shinozuka, 2004; Chang et al., 2008; Chang & Chamberlin, n.d.).

2.5.2.2. Community Resilience as a Process

Norris et al. (2008) define community resilience as a process that links a network of adaptive capacities to adaptation after a traumatic and unexpected event that is collectively experienced occurs. The adaptation process involves a trajectory towards a healthy, adapted, functioning "normal" state (Norris et al., 2008). This adapted, functioning system is manifested in population wellness and defined in terms of behavioral health and quality of life (Norris et al., 2008). Adaptive capacities are resources (economic development, social capital, information and communication and community competence) with dynamic attributes used by the community to face threats. Dynamic attributes provide resources with robust, redundant and rapid characteristics as defined by Bruneau et al. (2003).

A schematic of the stressor model structure they used to explain resilience is shown in figure 2.1. The stressor model shows resistance when the networked adaptive capacities have completely contended with the stressor. Otherwise the system faces a transient dysfunction. The process that produces adapted or resilience outcomes from a stable transient dysfunction is called resilience. If not, the system is classified as vulnerable (Norris et al., 2008).

Figure 2.1: Resilience, Resistance and Vulnerability Stressor Model



Source: Norris et al. (2008)

Norris et al. (2008) advocate enhancing resilience in a community by reducing risk, inequalities and social vulnerabilities, investing in infrastructure and resources, engaging local people in mitigation activities, creating and strengthening networks and relations, protecting social supports, and planning for not having a plan which means that communities should be able to be flexible, with decision making skills and trusted sources of information.

2.5.2.3. Community Resilience as a Process and an Outcome

Klein et al. (2003) describes resilience as having two possible sets of attributes. The first type of resilience has static attributes; specifically the amount of disturbance the system can absorb and remain functioning within the same state. These authors point out that this attribute is not necessarily desirable if the “within the same state” implies that they bounce back to a previous state that has proven to be vulnerable (Klein et al., 2003). The second type of attributes control the degree to which the system is capable of self-organization to preserve actual and potential functions under continually changing conditions. Self-organizational capacity does not provide the systems with capacities to reduce risks or to reduce immediate impacts. Klein et al. (2003) do not discount the relevance of recovery and mitigation strategies and the adaptation and learning characteristics that others authors have attributed to resilience. Their recommendation is to treat resilience as a single attribute and to include the recovery, mitigation, anticipation, resistance, adaptation and learning capabilities under the adaptive capacity umbrella (Klein et al., 2003). In their opinion, a single attribute interpretation would make the concept operational (Klein et al., 2003).

Cutter et al. (2008) define resilience as the ability of a community to respond and recover from threats. Unlike traditional approaches, the ability includes the inherent resilience responses, which are pre-conditions of the system that allow a community to recover and cope, and the post-disaster adaptive resilience processes, which permit the system to re-organize, change and learn.

Their Disaster Resilience of Place (DROP) model is a place based model that demonstrates how resilience emerges before and after disaster events. As shown in figure 2.2, a system is characterized by antecedent conditions. The antecedent conditions include the inherent resilience and the inherent vulnerability[11] that emerge from the interconnected social, natural and built environment systems.

Antecedent conditions, the characteristics of the event and the immediate pre-determined coping responses from the community (e.g. pre-determined evacuation plans, creation of shelters or information dissemination) determine the consequences of a disaster. If these pre-determined coping responses are able to absorb the impacts of the disaster, the system exhibits a high degree of recovery. Otherwise, the system might be able to employ adaptive resilience responses through unplanned and improvised actions and social learning to achieve a high degree of recovery. If these actions are insufficient to cope with the disaster, the system shows a low degree of recovery.

Unlike previous approaches, Cutter et al. (2008) do not explicitly advocate enhancing resilience by investing in capacities that increase the inherent resilience or reducing the inherent vulnerability of the system. However, these authors contend that these antecedent conditions are affected by the degree of recovery, the lessons learnt from the disruption, and preparedness and mitigation strategies.

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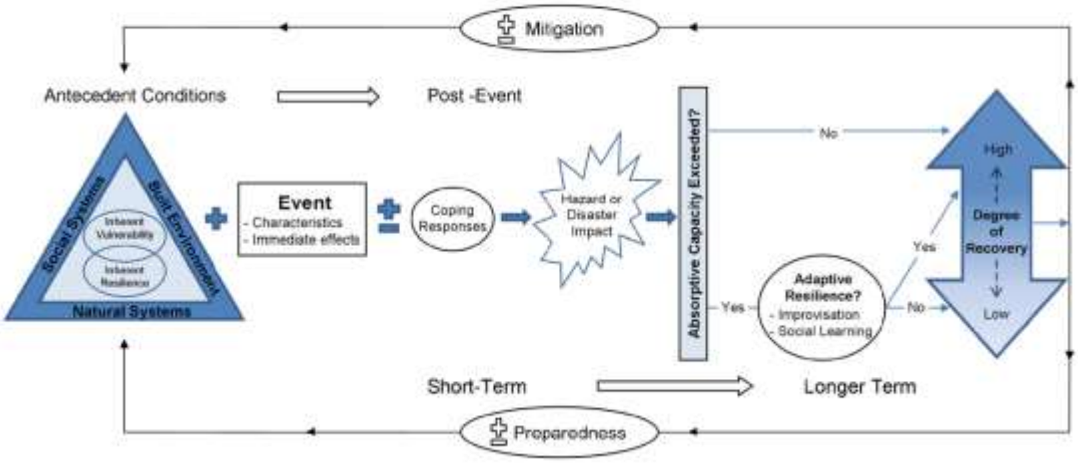
[11] Cutter et al. (2008) define inherent vulnerability as the qualities of a system that creates the potential to harm.

Figure 2.2: The DROP Model



Source: Cutter et al. (2008)

2.5.2.4. The Community Resilience System Tool to Build Resilient Communities

The Community and Regional System Initiative (CRSI) defines community resilience as “the capability of a community to anticipate risk, limit impacts and recovery rapidly through survival, adaptation, evolution and growth in the face of a turbulent change”(Community and Regional Resilience Institute [CARRI], 2011a, p.12). Unlike other contemporary approaches, this initiative considers turbulent changes such as natural and human-made disasters, economic downturns and pandemics outbreaks (Community and Regional Resilience Institute [CARRI], 2011a).

The CRSI approach builds resilience in communities by strengthen their community functions[12] through building system capacity in such a way that permits

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[12] The approach identified a community as a group of linked individuals located in a geographic space and that carry out community services. These community services are composed of 19 functions that range

communities to contend with the impacts of turbulent changes (Colten, 2010). Specifically, building resilience is an ongoing process that is accomplished through anticipation (preparedness), mitigation, response, recovery actions; and from the learning and experiences that improve these strategies (Colten, 2010).

This approach also assumes that resilience works to target chronic conditions that impede optimal community functions. These chronic conditions include unemployment, inadequate housing, inadequate transportation systems, degradation of the natural environment, and social inequities within the community (Community and Regional Resilience Institute [CARRI], 2011a).

The returns from building resilience are displayed in figure 2.3. Benefits from building resilient communities are observed when disaster occurs. Specifically, resilient communities are able to limit the loss of operational community functions (blue area) and avoid additional losses born by less resilient communities (pink area). Community resilience is also observed when a community takes advantage of the disaster and achieves a new normal and higher level of community function after recovery (line A). In addition, it happens when communities are able to target their chronic conditions and obtain additional economic and social benefits (green area) regardless of whether these communities face disturbances in the future (Community and Regional Resilience Institute [CARRI], 2011a). In this approach, potential disasters are seen as opportunities

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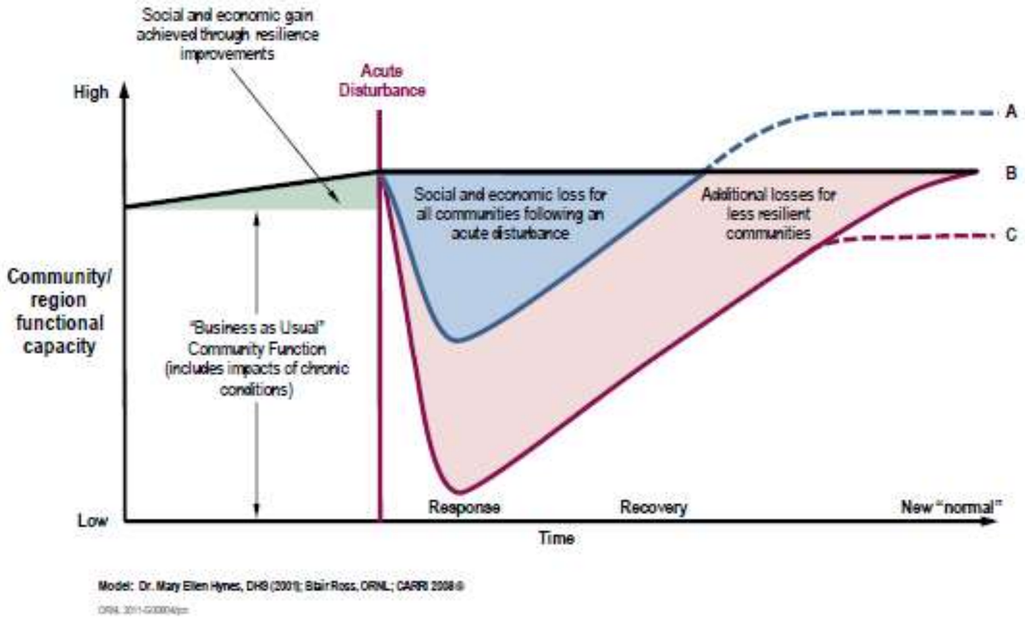
from the economic and the infrastructure, to the social and to cross cutting functions (strong leadership, governance and risk mitigation capacity).

to achieve more sustainable and robust regional economies (Community and Regional Resilience Institute [CARRI], 2011a; Dabson et al., 2012).

Figure 2.3: The Resilience Loss Recovery Curve[13]



Source: CARRI(2011a)

The CARRI built the Community Resilience System (CRS) web-based tool to help communities build resilience. This is a website portal that allows a community to understand what resilience means, see how far the community has to go to reach desirable resilience levels, and identify tangible benefits from their efforts. This evaluation is done by using a community approach (Community and Regional Resilience Institute [CARRI], 2011a). The CARRI (2013) has used this tool in eight communities to get further understanding on how communities assess resilience as well as to collect

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[13] The CARRI (2011a) Loss Recovery Curve contains an error. The A, B and C curves, should be lower at the disturbance point because they should not receive the social and economic benefits from resilience preparations prior to the disturbance (green area).

lessons learned in terms of practices that have helped communities to build community resilience.

2.5.2.5. Community Resilience Index Measures

Carlson et al. (2012) define resilience as the ability of an entity to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance. This definition is used to develop an index to measure the current community resilience of critical facilities/assets when faced with all type of hazards. This index, developed by Petit et al. (2013), is called the resilience measurement index (RMI). It was formulated to capture the six properties of resilience (anticipate, resist, absorb, respond, adapt and recover) to all hazards. The properties are incorporated into the four Level 1 components of the index (preparedness, mitigation, response, recovery). A total of six levels are measured. Each of the levels is composed of a series of indicators which are weighted to obtain a single index measure. Weights are defined by experts. The RMI values range from 0 to 100. The purpose of this metric is to allow owners and operators to compare the level of resilience of their infrastructure against those of others. The RMI is displayed in the Web-based “IST RMI Dashboard”, which provides measures of the different levels of the RMI and information that allows owners and operators to identify improvements in particular aspects of resilience (Petit et al., 2013).

Renschler et al. (2010a, b) develop the PEOPLES framework to measure community resilience at various dimensions (population and demographics, environmental ecosystem, organizational government services, physical infrastructure, lifestyle community competence, economic development and social cultural capital), at a global scale. The framework defines resilience as the capability to sustain a level of functionality. Under this approach, communities provide community services or functions. The PEOPLE approach evaluates these functions in the seven dimensions of community resilience using a series of indicators. The resilience measure for a particular dimension is obtained as the double integral of the evaluation of the functionalities in the dimension across space and time. A global community resilience index is obtained as the double integral of each evaluation of the function of each dimension across space and time. The measure accounts for the linkages between functions within each dimension and across dimensions. Results are displayed in a GIS layer for the region of interest (Renschler et al., 2010a, b).

2.5.2.6. Building a Resilient Nation

Recommendations to promote a resilient nation have as pre-requisites the bottom up support, and effective collaboration and cooperation between communities, and the top-down hierarchies (e.g. federal, state and local government agencies), to facilitate building local capacities.

The NRC (2012) and CARRI (2011) provide recommendations for building a resilient nation. The NRC (2012) looks to strengthen the role and commitment of the top-down hierarchies by requesting federal agencies to integrate national resilience as a guiding principle as well as to ensure the promotion and coordination of national resilience into their programs and policies, by promoting the collaboration and cooperation across public and private sectors to commit to, and invest in, risk management strategies and by requesting that all government agencies create and maintain community resilience coalitions at regional and local levels.

The CARRI (2011) recommendations focus on strengthening the bottom-up relationships. In particular, the initiative advises communities to modify their current programs, and to create new programs, that provide assistance and grants to build community capacity. They do so by encouraging communities adopt their evaluation criteria for enhancing community resilience capacity. This initiative also suggests that state and local community planning and research include community resilience as an objective. Finally, the initiative recommends that training, education and awareness activities carried out by regional organizations should integrate resilience into these programs in order to promote the knowledge and capacity of the communities.

2.5.2.7. Resilience and Federal Policy

The U.S. Department of Homeland Security (DHS) defines resilience as the ability to resist, absorb, recover from or successfully adapt to adversity or change (U.S. Homeland Security, 2008). In the context of critical infrastructure[14], resilience is interpreted as the ability to prepare for, and adapt to, changing conditions and to

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[14] Critical facilities refer assets, networks and systems which lack of function threats national security, the economy and the public health and safety (U.S. Homeland Security, 2013).

withstand, and recover rapidly from, deliberate attacks, accidents, or naturally occurring threats or incidents (The White House, 2013).

Resilience is emphasized in two of the core missions of the DHS: ensuring resilience to all disasters, and preventing terrorism and enhancing security (U.S. Homeland Security, 2013). Security and enhancing resilience of critical infrastructures was mandated by a Presidential Policy Directive-21 (PPD-21). In this directive, resilience is a desired outcome of the 16 critical infrastructures identified as essential for national security, public health and safety, economic vitality and general quality of life (The White House, 2013). The directive also requests a series of actions for which the DHS is responsible. These actions include enhancing resilience by promoting coordination and collaboration as well as information exchange across public and private partnerships (e.g. owners and operators of critical infrastructure, sector specific government agencies and various levels of government) and evaluating the capacity of these 16 critical infrastructures in order to plan and to operate decisions that aim to build resilience (The White House, 2013).

Subdivisions of DHS have also adopted the concept of resilience of critical infrastructure. Moteff (2012) cites three examples. The Office of Infrastructure Protection uses a resilience and protection index to compare levels of resilience and to analyze how improvements contribute to resilience. The Science and Technology Directorate supports resilience oriented research, and aims to develop better technologies to improve response and recovery and to strengthen physical structures.

Finally, the Federal Emergency Management Agency (FEMA) provides grants to state and local governments to improve the ability to respond to, and recovery from, disasters (Moteff, 2012).

2.5.2.8. Evidence of Resilience Strategies from Real Events

The evidence from actual events shows that businesses and households do employ resilience strategies. Among the resilience strategies identified are preparedness and mitigation responses before the disruption, coping responses during disruptions and recovery after the disruption ends.

2.5.2.8.1. Preparation Strategies

Tierney & Dahlhamer (1997) evaluate how businesses recovered from the Northridge earthquake disaster. Their evidence shows that businesses, in particular small firms, younger, less financially stable businesses, and businesses that did not belong to the manufacturing, finance, insurance and real estate sectors, had generally little interest in mitigation and preparedness (Tierney & Dahlhamer, 1997). Webb et al. (1999) also find that business preparedness strategies did not help reduce business interruption losses given that businesses had done little preparation, that those preparation strategies employed were directed towards safety, and that planning tended to concentrate on protecting business site and employees rather than on business continuity. (Webb et al., 1999). Webb et al. (1999) also affirm that businesses showed preferences for preparedness strategies that were less time consuming, complicated, expensive, or technically difficult to implement, and that provided protection against a range of different type of emergencies. After the disruption, the preparedness level did not increase except for those businesses that did experience significant losses (Tierney & Dahlhamer, 1997).

Case studies from Charleston, Gulfport and Memphis Urban Area (Colten, 2010) identify resilience preparations at the community level to all hazard events. These preparedness strategies include monitoring capabilities (e.g. warning systems and models for forecasting potential hazards), an all hazards evaluation of their communities and plans to respond and recover from future hazards. Colten points out that the communities' transportation and communication systems have been strengthened (or there were plans to strengthen them) by adding redundancy or identifying alternative routes. Other strategies have included sharing information through formal and informal networks, stocking emergency response material in strategic areas, plans for sheltering victims, and continuous education about hazards and preparations. Furthermore, these communities have identified socially vulnerable populations and have provided them with multilingual sources of information with respect to preparedness strategies (Colten, 2010).

2.5.2.8.2. Mitigation Strategies

The same case studies (Colten, 2010) show that communities have improved mitigation strategies based on previous disaster experiences (e.g. Katrina). Memphis and Charleston are building structures and infrastructure using earthquake proof construction. Following Katrina, many businesses in the Gulfport have moved to less exposed areas and the city’s new ordinance limits construction in exposed areas. Improvement in communication and cooperation is also an important component, especially after Katrina. Private and business interruption insurance has also been popular among many households and operators despite increased insurance rates. Finally, local relief funds in these communities have also been established (Colten, 2010).

2.5.2.8.3. Response Strategies

Communities respond by employing resilience strategies. However, responses have not always been satisfactory for many households (Colten, 2010). Not all the responses are completely successful and the lessons learned (e.g. the value of improved coordination and community channels) allows communities to improve their capacity to resist future disasters (Colten, 2010).

Colten (2010) finds that common responses include the search and rescue of survivors and deceased by emergency personnel; and support from the military in rescue, emergency coordination, law enforcement, and fire and medical responses. Sheltering and providing for displaced households have also been strategies employed during disaster events but in prolonged events such as Katrina these have been insufficient. Backup supplies (alternative service suppliers) and the use of redundant capacities for provision of services have been another strategies used by lifeline utilities to continue their services during disasters. Participation by citizens and the decision to return to rebuild their cities after Katrina have been responses from residents and non-residents with deep attachments to places (Colten, 2010).

2.5.2.8.4. Businesses Recovery

Tierney (1997) investigates how businesses recovered from the Northridge earthquake. Her business survey responses demonstrate that only one quarter of the sample were reported to be better off while half were the same as before. Businesses that reported being better off attributed this change to the increased demand and the general upturn of the economy (Tierney, 1997). Tierney (1997) also found that small businesses, particular in the finance and real estate sector, were more likely to be worse off. Reasons were related to loss of customers and to the impact of the recession. In addition to business size, Dahlhamer & Tierney (1996) and Tierney & Dahlhamer (1997) report that businesses with more operational problems (e.g. lack of employees, impeded customer access and shipping delays), those that located in high intensity earthquake zones and those that received more financial aid support were more likely to be worse off. These authors attribute the negative impact of financial aid to the higher debts that many businesses incurred (Dahlhamer & Tierney, 1996; Tierney & Dahlhamer, 1997).

Evidence from Charleston, Gulfport and Memphis Urban Area recovery strategies (Colten, 2010) shows the importance of overall planning and management, adequate medical care for the injured and traumatized victims, and restoring basic institutions and the local economy. However, the study also indicates that less emphasis has been given to restoring basic social networks, rebuilding houses with appropriately high quality (e.g. to avoid roof leaks) or with more emphasis in particular income level families, and attention to mental health of households (Colten, 2010).

2.5.2.8.5. Resilient Responses to Water Contamination Events

Evidence from surveys of water contamination events has shown that households employ several resilience strategies. Resilience behavior occurs when individuals employ averting behavior. Averting behavior or defensive expenditures are viewed as behavior taken to mitigate environmental degradation (McConnell & Bockstael, 2005). In the context of water contamination events, averting behavior refers to substitution of alternative water sources for public water and it is considered a lower bound on willingness to pay for safe water when illnesses are not compromised (Abdalla et al., 1992; Collins & Steinback, 1993; Laughland et al., 1993). The averting behavior method not only considers the direct costs of these actions but also the related time and travel expenditures incurred. Moreover, when households make investments such as in filtration systems, only annual costs are considered (McConnell & Bockstael, 2005).

Hence, averting behavior could be classified as resilience substitution strategies for piped water.

Use of input substitution resilience strategies by households has been reported for water contamination events not involving illnesses. In general these studies find that individuals use substitutes for water to avoid using the contaminated water. Among the actions included by Abdalla et al. (1992), Laughland et al. (1993), and Collins & Steinback (1993) are purchase of bottled water, hauling water, boiling water and/or acquisition of new water filtration systems.

Input resilience strategies for water have also been found in studies that estimate the economic consequences of real water contamination events involving illnesses. In these studies, resilience behavior has included averting behavior, change of restaurant habits, acquisition of extra groceries, transportation of children and/or travel for medical treatment (Harrington et al., 1991; Livernois, 2001). The household economic consequences not only include the monetary cost of these strategies but also the time costs (including transportation time) involved in implementing these activities (Harrington et al., 1991; Livernois, 2001) and the productivity and leisure time losses due to illness (Harrington et al., 1991).

Business resilience strategies found in the literature have been mostly concentrated on input water substitution or averting strategies. However, the expenditures of these strategies together with the diversion of staff and related costs such as additional work caused by the contamination event, loss of profits due to the lost production and/or the losses from changes in demand have been important economic losses identified in these studies (Harrington et al., 1991; Livernois, 2001).

2.5.3. Summary and Discussion of Resilience Approaches

The review of definitions, measures and evidence of resilience strategies in real disaster events prove that resilience definitions are contextual. Resilience interpretations have taken traditional and contemporary approaches, have received single and multiple attributes, have been defined as a post-event, and as both pre-event and post-event response, and have been described as an outcome, process and outcome and processes. Attributes to resilience have included the four stages of emergency management responses (preparation, mitigation, recovery and response), adaptive capacities, and learning.

Resilience has been classified as desirable or undesirable. Desirable attributes involve the capacity to recover, to resist or to adapt and learn. Undesirable attributes lead to bouncing back to a previous state that has been proven to be vulnerable or that could promote the use of unsustainable practices.

Preferences for particular resilience definitions have also been a function of the purpose of study. Traditional definitions are preferred in disaster modeling and analysis since it lowers the impacts of economic losses from disasters. Contemporary approaches are popular in policy and public policy management settings since it involves whole community approaches to face all hazards, strengthening of community capacities and making preparations for potential threats in the future.

Despite the evolution of the concept, and attempts to make the concept appropriate to enhance and build resilience in communities and nations, some authors believe that the concept has become too broad, which makes it harder to operationalize and measure it (Klein et al., 2003; Rose, 2009b).

2.5.4. Resilience Approach Selected for Water Utility Disruption Events

The purpose of this dissertation is to advance our capacity for disaster modeling and analysis especially regarding the issue of economic consequences of water utility disruptions. In order to achieve this goal we need of a definition of resilience that is simple, measurable, and operational.

Following Rose (2009b), resilience will be defined here ***as the ability of the economy to maintain its function and recovery quickly***.

Resilience strategies produce savings in terms of reductions in output losses (for business and government enterprises) and income losses (for households and government institutions). However, resilience strategies also produce additional indirect changes in demand. The consequences of all these direct and indirect economic changes must be measured in order to achieve our goal.

Supply constraints potentially limit the effectiveness of resilience strategies since additional demands caused by resilient behavior might not be satisfied. Some industries face supply constraints not only from the water utility disruption but also from the constrained supply of inputs required for the production of their goods or services. There are also gainers and losers from water utility disruptions that are compounded and complicated by changes in behavior related to resilience strategies.

The model developed in this dissertation incorporates many of these aspects of resilience. Unlike previous disaster modeling and research studies, in this study, resilience is analyzed for businesses, households, and government institutions. Not all of the resilience strategies are available to all type of water customers. Indeed, resilience strategies are a function of the characteristics of the disruption (the type and duration of disruption) and the customer. For governments and businesses, characteristics include their specific industry and the preparedness strategies they have in place. The relevant household characteristic is the family size.

Table 2.4 shows resilience options available to the different types of customers during water utility disruptions. The activities correspond to those from the literature as well as evidence from recently water utility disruption events.

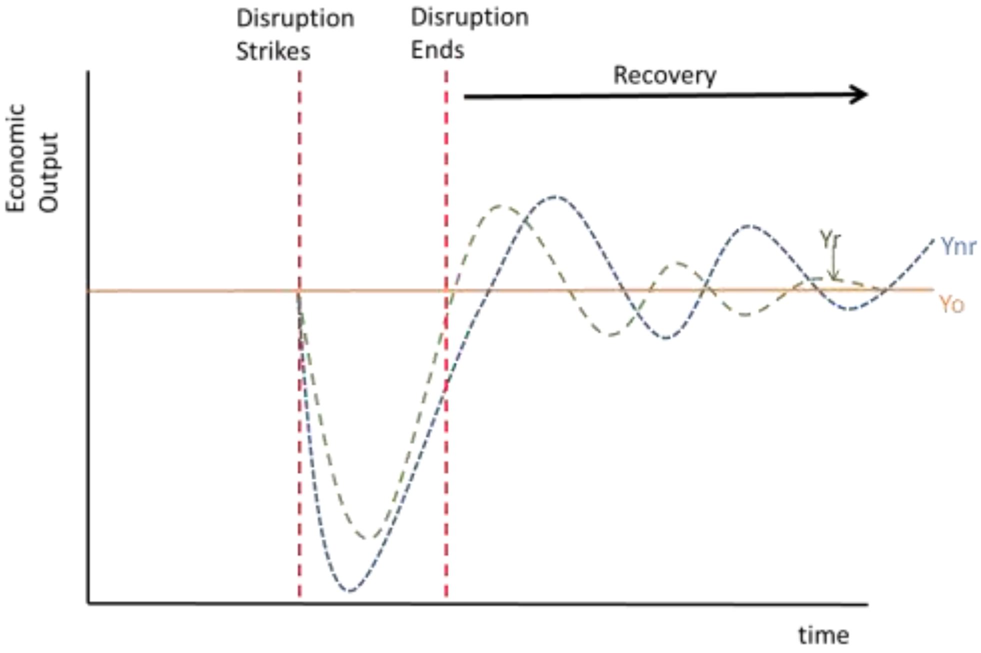
Table 2.4: Resilience Options Available by Type of Customer

Business and Government	Household
• Conservation of water • Substitution of inputs that use water (hand sanitizers, and plastic plates) • Substitution for piped water (bottled water, ice, trucked water) • Decontamination of Water (boiling) • Use of input and output inventories • Water importance (portion of operation not requiring water) • Production rescheduling	• Conservation of water (limiting water using activities) • Substitution of activities (eating more at restaurants using hand sanitizer instead of water) • Substitution of inputs (use of disposable dishes) • Substitution for piped water (bottled water, ice) • Decontamination of water (boiling)

• Use of more or less employees • Offering limited products and services	

Figure 2.4 illustrates different output patterns that emerge during water utility disruptions. The straight line *Yo* represents the baseline level. When water utility disruptions occur, the rate of production may display various patterns. The first, identified as *Ynr*, is the flow of output when resilience strategies are not in place. The second, labeled *Yr*, corresponds to the flow of output when resilience options are employed. Resilience gains (or losses) can be measured as the difference between the areas (*Yr* and *Yo*) and (*Ynr* and Y*o*).

Figure 2.4: Output Patterns during Water Utility Disruptions



Resilience (R) is defined as the discounted sum of the ratio of the output losses with resilience strategies, to the output losses without resilience strategies:

$$R = \sum_{t=0}^{n} \frac{(Yr(t) - Ynr(t))}{(Yo(t) - Ynr(t))} * e^{-rt}$$

where *n* is the evaluation period, *r* is the discount factor, *t* is time, *Yr* is the output with resilience measures, *Ynr* is the output without resilience measures and *Yo* is the baseline output level.

2.5.5. Limitation of the Resilience Approach Chosen

To argue in favor of a particular mitigation strategy that could potentially enhance resilience it would be valuable to know the impact of resilience on asset values and wealth. Capitals (assets) are inputs used for the production of market and non-markets goods and services and are also generators of future production. The adoption of a particular strategy produces benefits in terms of output loss avoidance, but it can also generate additional losses and profits that reduce financial capitals. The model developed in this study identifies current benefits and costs to businesses, governments and households. However it does not measure the impact of these costs and benefits on asset values (e.g. financial capital).

2.6. Conclusions

The literature review of disaster analyses shows that the type of disruption determines the types of losses that should be considered. Table 2.5 is a summary of the issues that should be considered when assessing the economic consequences of disaster events.

Table 2.5: Selected Issues of Total Losses from Disaster Events

Issues	Description
Direct and indirect damages	• Direct: property losses, loss of life. • Indirect (cascading): business interruption losses.
Measures of losses	• Flows: business interruption losses, impacts on wages and profits, transportation costs, remediation activities, opportunity costs (prices and taxes), utility revenue losses, household losses, loss of life and injuries. • Stocks: Property value losses, structural and non-structural property damage.
Factors considered	• Changed behavior: amplification of risk, sympathetic behavior, resilience behavior. • Modeling dimension: space, time, uncertainty • Restoration decisions.
Methods used to estimate business interruption losses	• Surveys, GIS map layer with location of businesses, hazard estimation tools, system flow programs and expert judgment.
Methods used to estimate the total economic output losses	• IO and CGE models. • Variants that include spatial, time and uncertainty dimensions.
Purpose of the analysis	• Economic impact assessment. • Improved performance: evaluation of mitigation strategies. • Risk assessment: consequence, threats and vulnerabilities.

The interpretations of resilience found in the literature shows that there is no universally accepted definition and that definitions are contextual. The resilience approach selected for this dissertation is one that identifies coping and adapting strategies during water utility disruption events that avoid further losses. This interpretation facilitates the identification and assessment of resilience strategies and also highlights the fact that resilience strategies have expenditure consequences with direct and indirect consequences.

CHAPTER III: THE MODEL

3.1. The Conceptual Model

The model constructed for this dissertation is a continuous dynamic social accounting matrix based model that considers both demand and supply constraints and that incorporates various resilience and other strategies used by both consumers and producers. The methodology proposed overcomes some of the limitations of static input-output models, in particular those corresponding to supply constraints, linearity and input substitution.

A system dynamics interpretation of a social accounting matrix as a continuous time dynamic disequilibrium model provides an ideal framework to study the consequences of restoration strategies on the economic consequences of water utility disruptions. The social accounting matrix approach is ideal for analyzing the interdependencies of industries in an economy and is one of the most commonly applied methods in economics (Miller & Blair, 2009). Columns in the transaction table show the industry and non-industry inputs (labor, depreciation of capital, indirect business taxes and imports) required for the industry production and the rows describe the distribution of a producer’s output throughout the economy (Miller & Blair, 2009). The economy includes not only industries but also final consumers such as households, government, investment and sales to buyers external to the region. When a water utility disruption event occurs there are not only disruptions in the final demand for goods and services but also in the input supplies. Since quantity demanded is not necessarily equal to quantity supplied anymore, disequilibrium in the system emerges. Restoration actions require time. Given the disequilibrium introduced by water utility disruptions, static demand driven input-output models are insufficient to model restoration strategies.

The system dynamics interpretation also facilitates the inclusion of supply constraints. Unlike previous attempts to introduce supply constraints in static input-output models, constraints can be introduced into the dynamic model without the use of iterative algorithms or the possibility of projecting negative outputs.

Resilience and other strategies adopted by both households and businesses can also be included in the model. In particular, the adoption of resilience strategies permits the firms, and thus the economy of the region, to keep producing and consuming goods and services. With these new strategies on place, new patterns of intersectoral relationships appear in the regional economy during the disruption. If it is assumed that the alternative technology is only available during this disruption period, new Leontief technical coefficients replace the standard coefficients during the disruption event. These new technical coefficients can be incorporated as changes in technology parameters.

3.1.1. Structure of the Model

Consider an economy with *s* sectors (industries and households) which purchase inputs from each other and combine these inputs to produce outputs for sale to other industries and to satisfy final demand[15]. In the standard static inter-industry framework, production technologies are given by a coefficients matrix, A. Outputs are reported as the vector X. Each sector's outputs are consumed as intermediate inputs ($\sum_j a_{ij} * X_j$) or as final demand (Y_i). Each sector's expenditures are composed of intermediate purchases ($\sum_i a_{ij} * X_j$) and primary inputs -labor, and owners of capital- (W_j).

$$X_i = \sum_j a_{ij} * X_j + Y_i$$

$$X_j = \sum_i a_{ij} * X_j + W_j$$

The dynamic model starts with the premise that industries produce into and sell out of output inventories. Output inventories include work in process and finished output inventories. In particular, *m* out of the *s* outputs has work in process and finished output inventories, and *s-m* has only work in process inventories[16]. Inventories work as

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[15] By closing the model with respect to households, the model is able to capture the induced effects that household income from labor and their related expenditures have on goods and services produced by various sectors. These effects are important when considering smaller regions (Miller & Blair, 2009).

[16] Example of the first and the second type of outputs include manufacturing and services outputs, respectively.

buffers that absorb differences between the instantaneous rates of production ($X_i^P(t)$) and sales ($X_i^{S,ID}(t) + X_i^{S,FD}(t)$)[17]:

$$\frac{dN_i(t)}{dt} = X_i^P(t) - X_i^{S,ID}(t) - X_i^{S,FD}(t)$$

(EQ1)

The rate of sales of output *i* is the sum of the rate of intermediate demand sales and rate of final demand sales. In cases of insufficient output inventories, a prioritization mechanism is implemented in favor of the intermediate demand. This prioritization mechanism follows the supply constraint assumptions in previous studies (e.g. Hallegatte, 2008; U.S. Federal Emergency Management Agency, 2010a).

The rate of sales to intermediate demand of the industry *i* is the sum of the desired rate of acquisition of inputs by all industries ($\sum_j^s X_{ij}^{S,ID^*}(t)$). However, if inventories are insufficient, the rate of intermediate demand sales is limited to what is produced ($X_i^P(t)$). The rate of final demand sales of output *i* ($X_i^{S,FD}(t)$) correspond to the exogenous final demand ($Y_i(t)$) if inventories are sufficient after the intermediate demand sales ($X_i^P(t) - X_i^{S,ID}(t)$)

$$X_i^{S,ID}(t) = \begin{cases} \sum_j^s X_{ij}^{S,ID^*}(t) & if\ N_i(t) > 0 \\ X_i^P(t) & if\ N_i(t) = 0 \end{cases}$$

(EQ2)

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[17] This idea of inventories as a buffer mechanism is also found in continuous econometric macroeconomic models (e.g. 1978; 1981; 1987; 1993; 1993; 1998).

$$X_i^{S,FD}(t) = \begin{cases} Y_i(t) & if\ N_i(t) > 0 \\ X_i^P(t) - X_i^{S,ID}(t) & if\ N_i(t) = 0 \end{cases}$$

(EQ3)

The desired rate of acquisition of inputs is equal to the sum over the output j of two components: the inputs needed to fulfill the desired rate of production $(a_{ij}(t) * X_j^{P^*}(t))$ and the adjustment needed to restore input inventories ($\frac{IN_{ij}^*(t)-IN_{ij}(t)}{AT_{1,ij}}$). The adjustment for input inventories reflects the need for more inputs when the desired level of input inventories $(IN_{ij}^*(t))$ is lower than the current level of inventories $(IN_{ij}(t))$, and is adjusted by the time it takes to correct this discrepancy $(AT_{1,ij})$.

$$X_{ij}^{S,ID^*}(t) = a_{ij}(t) * X_j^{P^*}(t) + \frac{IN_{ij}^*(t)-IN_{ij}(t)}{AT_{1,ij}}$$

(EQ4)

The desired level of input inventories is set equal to the proportion of desired levels of inputs required to fulfill the desired rate of production $(a_{ij}(t) * X_i^{P^*}(t))$. The proportion of desired level of inputs is chosen so the model is in equilibrium at the beginning of the simulation. For this model, the value will be equal to the adjustment time necessary to correct the discrepancy in input inventories $(AT_{1,ij})$. The variable $\alpha_{1,ij}$ distinguishes inputs *i* that can be stored in inventories from those of industry *j* which cannot be stored. There are *m* out of *s* types of outputs that can be stored as a final product. For these cases, $\alpha_{1,ij}$=0.

$$IN_{ij}^*(t) = \alpha_{1,ij} * AT_{1,ij} * a_{ij}(t) * X_i^{P^*}(t)$$

Industry *j* acquires inputs *i* to produce its output. Inputs that can be stored add to inventories of inputs. As in the case of outputs, input inventories held by industry *j* $(IN_{ij}(t))$ act as a buffer mechanism that absorbs the difference between the rate of inputs received $(X_{ij}^{S,I}(t))$ and used $(X_{ij}^{U,I}(t))$.

$$\frac{dIN_{ij}(t)}{dt} = X_{ij}^{S,I}(t) - X_{ij}^{U,I}(t)$$

(EQ5)

The rate of input used is the product of the technical coefficients $(a_{ij}(t))$ and the rate of production $(X_j^P(t))$:

$$X_{ij}^{U,I}(t) = a_{ij}(t) * X_j^P(t)$$

(EQ6)

The rate of inputs received *i* $(X_{ij}^{S,I}(t))$ by industry *j* is equal to the desired rate of acquisition of inputs $(X_{ij}^{S,ID^*}(t))$. In cases when there is insufficient production and inventories of output *i*, a proportional mechanism is implemented. This proportion is equal to the ratio of total intermediate demand sales for output *i* $(X_i^{S,ID}(t))$ and the total desired rate of acquisition of inputs *i* $(\sum_j^s X_{ij}^{S,ID^*}(t))$. Other researchers have used proportional mechanisms to obtain solutions to input-output models with supply constraints (e.g. Hallegatte, 2008).

$$X_{ij}^{S,I}(t) = \frac{X_i^{S,ID}(t)}{\sum_j^s X_{ij}^{S,ID^*}(t)} * X_{ij}^{S,ID^*}(t)$$

(EQ7)

The desired rate of production is defined as the sum of the rate of production to fulfill demand ($X_i^{ED}(t)$) and the addition to output inventories ($\frac{N_i^*(t)-N_i(t)}{AT_{2,i}}$). The adjustment of output inventories is equal to the difference between the desired and the current level of inventories, adjusted by the time it takes to correct for that difference ($AT_{2,i}$).

$$X_i^{P^*}(t) = X_i^{ED}(t) + \frac{N_i^*(t)-N_i(t)}{AT_{2,i}}$$

(EQ8)

The desired level of output inventories is set equal to the proportion ($\alpha_{2,i}$) of the rate of production required to fulfill demand($X_i^{ED}(t)$).

$$N_i^*(t) = \alpha_{2,i} * X_i^{ED}(t)$$

The adjustment of the rate of production to fulfill demand ($X_i^{ED}(t)$) is equal to the difference between the actual rate of production to fulfill demand ($X_i^{D}(t)$) and the current rate of production to fulfill demand, adjusted by the time it takes to correct the discrepancy ($AT_{3,i}$).

$$\frac{dX_i^{ED}(t)}{dt} = \frac{X_i^{D}(t)-X_i^{ED}(t)}{AT_{3,i}}$$

(EQ9)

The actual rate of production to fulfill demand is the sum of the rate of intermediate demand sales and the rate of final demand sales.

$$X_i^{D}(t) = X_i^{S,ID}(t) + X_i^{S,FD}(t)$$

The rate of production is equal to the desired rate of production if there are no constraints. Constraints arise if there are insufficient levels of inputs to produce at the desired rate of output. This condition defines rate of production ($X_j^P(t)$) as the lesser of the desired rate of production ($X_j^{P^*}$) and the feasible rate of production given inputs ($X_j^{P,IN}(t)$) . The household sector is not constrained by the feasible production given inputs.

$$X_j^P(t) = Min\{X_j^{P^*}(t), X_j^{P,IN}(t)\}$$

(EQ10)

The Leontief industry production technology is assumed for industries. The ability of the industry to produce its output depends on the inputs available to the industry for production. Therefore, the feasible rate of production given inputs is defined as the lesser of the contributions of each necessary intermediate input i available to the industry j ($\frac{\alpha_{3,ij}*X_{i,j}^{MAX}(t)}{a_{i,j}(t)}$) . Necessary intermediate inputs available to industry j are identified with the $\alpha_{3,ij}$ parameter.

$$X_j^{P,IN}(t) = Min\{\frac{\alpha_{3,i=1j} * X_{i=1,j}^{MAX}(t)}{a_{i=1,j}(t)}, \frac{\alpha_{3,i=2j} * X_{i=2,j}^{MAX}(t)}{a_{i=2,j}(t)} \ldots, \frac{\alpha_{3,i=sj} * X_{i=s,j}^{MAX}(t)}{a_{i=s,j}(t)}\}$$

In general, the rate of inputs available for production of output j ($X_{i,j}^{MAX}(t)$) is equal to the rate of inputs used ($X_{ij}^{U,I}(t)$). Only in cases when there are insufficient input inventories or no inventories (such as in the case of the *s- m* type of outputs), available inputs are equal to the rate of inputs received ($X_{ij}^{S,I}(t)$) :

$$X_{i,j}^{MAX}(t) = \begin{cases} X_{ij}^{U,I}(t) & if\ \ IN_{ij}(t) \geq 0 \\ X_{ij}^{S,I}(t) & if\ \ IN_{ij}(t) = 0 \end{cases}$$

3.1.2. Resilience and Other Strategies

When a temporary water utility disruption occurs, businesses and government enterprises must choose between two general strategies: temporarily ceasing operations or coping with the event to maintain production at some level. When businesses and government choose the first option, they stop producing but are usually unable to stop purchasing certain types of inputs. These inputs are “fixed” in the sense that these must be paid in the short term. Examples of these short-term fixed inputs are rent, insurance, contracted services or compensation for some workers. Other businesses and households[18] will respond by coping, e.g. temporarily substituting for, or limiting the use of, products that require public water in order to continue production. Both options involve reduced net operating surplus for industries (proprietor income). These strategies alter the technical input-output coefficients. As a consequence, new input-output coefficients will prevail during the disruption event:

$$a_{ij}(t) = \begin{cases} a_{ij}(t) & if\ t_1 \leq t \leq t_2 \\ a_{ij}(0) & if\ t > t_2\ or\ t < t_1 \end{cases}$$

(EQ11)

where $a_{ij}(t)$ are the technical input-output coefficients with resilience and other strategies in force and $a_{ij}(0)$ are the coefficients in the absence of the disruption event.

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[18] Unlike businesses, households cannot temporarily cease production.

It is assumed that the most efficient coefficients correspond to those in the initial period.

Government institutions also choose from a range of strategies in order to cope with the disruption. These alternatives will involve changes in expenditure patterns with incurred additional losses. The altered expenditure patterns induce changes in final demand. $Y_i(t)$ and $Y_i(0)$ correspond to final demand with and without the water utility disruption respectively.

$$Y_i(t) = \begin{cases} Y_i(t) & if\ t_1 \leq t \leq t_2 \\ Y_i(0) & if\ t > t_2\ or\ t < t_1 \end{cases}$$

(EQ12)

Production, sales, input use and received, and input and output inventories are always positive:

$$X_i^P(t), X_i^{S,ID}(t), X_{ij}^{U,I}(t), X_i^{S,FD}(t), N_i(t), IN_{ij}(t) \geq 0$$

(EQ13)

3.1.3. Static Equilibrium States

If equilibrium conditions are achieved, inputs acquired, inputs used and the inventories of inputs and output reach their static Leontief equilibrium state:

$$X_i^P(t) = X_i^{S,ID}(t) + X_i^{S,FD}(t)$$

(EQ14)

$$X_i^{S,ID}(t) = X_{ij}^{U,I}(t) = \sum_j^s a_{ij} * X_i^P(t)$$

(EQ15)

$X_i^{S,FD}(t) = Y_i(t)$

(EQ16)

$N_i(t) = \alpha_{2,i} * X_i^P(t)$

(EQ17)

$IN_{ij}(t) = \alpha_{1,ij} * AT_{1,ij} * a_{ij}(t) * X_i^P(t)$

(EQ18)

where the rate of sales, production and use and acquisition of inputs are flows (in monetary units per year). Inventories are the stocks of outputs and inputs (in monetary units). At equilibrium, the rates of production are equal to the rates of sales (EQ14). The rates of intermediate demand are equal to the use of inputs needed to produce (EQ15) and final demand sales are equal to the exogenous final demand (EQ16). Since these variables have reached their equilibrium values, changes in inventories are also equal to zero. These conditions make the level of output (EQ17) and input inventories (EQ18) equal to their equilibrium levels.

3.1.4. Commodity Supply Restrictions

A disruption event alters the desired rate of production of outputs by the industries affected which imposes constraints on the production of restricted industries ($X_j^C(t)$) during the disruption event ($t_1 \leq t \leq t_2$). As a consequence, equation (EQ8) is transformed into:

$$X_i^{P^*} = \begin{cases} Min\{X_i^{ED}(t) + \frac{N_i^*(t) - N_i(t)}{AT_{2,i}}, X_j^C(t)\} & \text{if} \quad \mathrm{t_1 \leq t \leq t_2} \\ X_i^{ED}(t) + \frac{N_i^*(t) - N_i(t)}{AT_{2,i}} & \text{if} \quad \mathrm{t > t_2 \text{ or } t < t_1} \end{cases}$$

(EQ8')

3.1.5. Assumptions

Several key assumptions are made in order to operationalize this model. First, given very short-term nature of disruptions, the implications of investment decisions on output are ignored. This assumption is acceptable when modeling short-term events. However, if a disruption event induces serious damages in productive capacity and if the simulation time frame is sufficiently long (at least a year), it would be more appropriate to incorporate the dynamics of investment decisions using an acceleration modeling approach. Second, production is constrained by exogenous events (such as disruption events) that limit the ability of industries to produce commodities. Third, the focus of this research is on the dynamics of sales and production of output and not on changes in production processes other than those related to resiliency. Finally, deviations between production and sales are adjusted through changes in quantities and not prices. In particular a proportional mechanism applied when demand of intermediate inputs are higher than supplies (production and inventories of outputs).

This last assumption deserves special attention. Prices work as a signaling mechanism for scarce resources. When prices change, resources are allocated to those who value them the most and with the ability to pay for them. This mechanism allows substitution of inputs (local and imported) and changes in quantity demanded/supplied and shifts in demand/supply. This process adjusts quantities demanded and supplied and would make a proportional adjustment mechanism unnecessary.

However, prices do not always increase in the very short-run. Several factors can lead to a lag in price adjustments. Transactions costs (such as costs of changing menus) make increases prices too costly during temporary disruptions. In addition, brand loyalty and damage to goodwill and reputation, which affect long-term profits, make short-run increases in price unlikely. There are also non-economic reasons for not increasing prices such as government rules (prohibition of price gouging). Several other authors including Harrington et al. (1991), Donaghy et al. (2007), Hallegatte (2008), Hallegatte & Henriet (2008) and U.S. Federal Emergency Management Agency (2010a), have made similar assumption.

3.2. The Simulation Model

As explained in section 3.1.2, the resilience and other strategies employed by businesses and households produce changes in expenditures that alter the technical input-output coefficients during the disruption event. For businesses, these expenditures will also imply changes in the operating surplus. For households, these expenditures will represent additional costs.

Government institutions also choose from a range of strategies in order to cope with disruptions. The strategies will alter the final demand and will produce subsequent additional costs.

There are m_T actions to be modeled during water utility disruptions with expenditure consequences; m_b of these actions are employed by k_b businesses and government institutions, and the rest (m_T-m_b=m_r), by households.

3.2.1. Business and Government Institutions Direct Expenditures Changes

For other than temporary closure, expenditure changes by category k_b for action m_b at day *j* ($\Delta BE_{k_b m_b j}$) is the product of the probability of implementing the action m_b by category k_b at day *j* ($\alpha_{k_b m_b j}$), a response duration indicator[19] for the action m_b employed by category k_b at day *j* ($\gamma_{k_b m_b j}$) and the average daily expenditures by category k_b for action m_b ($\beta_{k_b m_b}$)

$$\Delta B_{k_b m_b j} = \alpha_{k_b m_b j} * \gamma_{k_b m_b j} * \beta_{k_b m_b} \qquad for\ m_b <> closure$$

(EQ 19)

The expenditure consequences of temporary business closure include the savings in the use of variable inputs. There are *q* variable inputs. The changes in expenditures during temporary closure category k_b for input *v* at day *j* is the product of the probability of temporary closure for the category k_b at day *j* ($\alpha_{k_b m_b = closure j}$), a

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[19] The response duration indicator identifies whether the action was employed on each day *j* of the disruption.

response duration indicator for the closure action employed by category k_b at day j ($\gamma_{k_b m_b=closure\,j}$) and the average daily expenditure by category k_b for inputs v ($\beta_{k_b v}$).

$$\Delta BC_{k_b v j} = -\alpha_{k_b m_b j} * \gamma_{k_b m_b j} * \beta_{k_b v} \quad for\ m_b = closure$$

(EQ 20)

Changes in expenditures due to resilience and other strategies will alter the technical input-output coefficients during the disruption event.

3.2.2. Reduced Business and Government Institution Output

It is assumed that only temporary closure leads to reduced business and government output. Estimates of reduced output $\Delta BO_{k_b j}$ by category k_b at day j are equal to the product of the probability of temporary closure by category k_b at day j ($\alpha_{k_b m_b=closure\,j}$), a response duration indicator for closure by category k_b at day j ($\gamma_{k_b m_b=closure\,j}$) and the average daily output by category k (ϑ_{k_b}).

$$\Delta BO_{k_b j} = \begin{cases} -\alpha_{k_b m_b j} * \gamma_{k_b m_b j} * \vartheta_{k_b} & for\ m_b = closure \\ 0 & otherwise \end{cases}$$

(EQ 21)

3.2.3. Changes in Business Net Operating Surplus

Each of the actions adopted by businesses during water utility disruptions reduce net operating surplus. There are n_b total actions included in the model. The net operating surplus changes for category k_b per day j ($\Delta BP_{k_b j}$) is equal to the sum of the impacts of closure $\left(\Delta BO_{k_b j} - \sum_{v=1}^{q} \Delta BC_{k_b j v}\right)$ and the changes in expenditures

$(-\sum_{m=1}^{n} \Delta B_{kj})$. Change in operating surplus will alter the value added coefficients during water disruptions.

$$\Delta BP_{k_b j} = \left(\Delta BO_{k_b j} - \sum_{v=1}^{q} \Delta BC_{k_b jv}\right) + (-\sum\nolimits_{m=1}^{n_b} \Delta B_{k_b j})\ for\ k_b <> gov.institutions$$

(EQ 22)

3.2.4. Additional Government Institution Costs

The government institution's additional costs per day j $(\Delta GA_{k_b=gov.institution j})$ are equal to the sum of the changes of expenditures due to closure $\left(\Delta BO_{k_b j} - \sum_{v=1}^{q} \Delta BC_{k_b jv}\right)$ and the changes in expenditures due to other than closure $(-\sum_{m=1}^{n} \Delta B_{k_b j})$. This additional government institution costs will emerge during water disruptions.

$$\Delta GA_{k_b j} = \left(\Delta BO_{k_b j} - \sum_{v=1}^{q} \Delta BC_{k_b jv}\right) + (-\sum\nolimits_{m=1}^{n} \Delta B_{k_b j})\ for\ k_b = gov.institutions$$

(EQ 23)

3.2.5. Changes in Household Expenditures

When households employ particular resilience and other strategies to cope with the disruption event they incur additional expenditures and additional costs.

The additional household expenditures for action m_r at day j $(\Delta HE_{m_r j})$ is the product of the average household expenditures per person-day for action m_r at day j $(\rho_{m_r j})$, the population served by the water utility (τ), and the percentage of household customers affected by the disruption on day *j* (π_j). These additional expenditures will alter the technical input-output coefficients during water disruptions.

$$\Delta HE_{m_r j} = \rho_{m_r j} * \tau * \pi_j$$

(EQ 24)

3.2.6. Additional Household Costs

Each of the actions adopted by households during water utility disruptions involve additional costs. Total additional household costs per day *j* (ΔHA_j) equal the sum of additional expenditures for the n_r actions per day *j*. This additional household costs will emerge during water disruptions.

$$\Delta HA_j = -\sum_{m_r}^{n_r} \Delta HE_{m_r j}$$

(EQ 25)

CHAPTER IV: ANALYSIS OF RESILIENCE AND OTHER RESPONSES TO WATER UTILITY DISRUPTION EVENTS

This chapter reports on analysis of data collected with a survey of households and businesses affected by recent water disruption events. The purpose of the analysis was to identify the level of preparedness, capacity for resilience and responses to of, water utility disruption events. The survey also measured the immediate consequences of the disruption on the respondents. The survey involved 288 telephone interviews of businesses from 38 water contamination, water outage and precautionary boil water advisory events and 162 personal interviews of household members in 4 locations that experienced contamination events and water outages. The survey results are used to predict the level of resilience and the likely responses of, and consequences for, businesses and household customers during water utility disruptions events.

4.1. Survey Description

The goal of the business and household surveys in the current study was to collect information regarding preparedness, resilience and decisions of individuals and businesses during water service disruptions, as well as any short-term post-event consequences[20]. The target for the surveys was customers of public water utilities. The events analyzed were unexpected water service disruptions and do not include

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[20] The household and business surveys also describe the recovery patterns (e.g. whether businesses are better off after water utility disruption and whether households consume more or less tap water after the disruption). For more details see Alva-Lizarraga et al.(2013)

disruptions that occur in conjunction with other events such as earthquakes and floods (Miller et al., 2012).

Three types of disruption events were considered:

1. Water contamination events. Households and businesses are issued a boil advisory or a do-not-use advisory as a result of a positive test for a contaminant. Evidence of E. Coli in water samples followed by boil water advisories are the most common type of event under this classification. Chemicals and organic contaminants are less common but require a do-not-drink warning.
2. Water outage events. These are associated with structural failure (water main breaks) in the water system that leads to disruption in service to some or all customers. This disruption is usually accompanied of precautionary boil order after service is restored.
3. Precautionary boil orders. In these cases a boil water advisory is issued as a precaution until a formal test for contaminants can be completed. These events are most often associated with failures other than with the water system itself, such as power outages, computer system failure, failures in alarm systems, system maintenance, annual repair of water system units, or low pressure periods for unknown reasons. In these events, a boil advisory is usually in place until the water service was restored to normal.

The business survey employed a two stage stratified sampling process in which stratification variables were sector and water event. The survey excluded businesses that were not users of public water supplies (e.g. agricultural producers), and businesses directly involved in the water supply system (e.g. water utility companies and waste water treatment facilities) (Miller et al., 2012). Phone interviews were used to complete the surveys. The survey involved 798 phone calls to businesses involved in 49 events. A total of 288 responses from 38 events were usable for a response rate of 36%[21].

The business respondents are described in table 4.1:

Table 4.1: Classification of Sectors According to 2007 2-digit NAICS Code

Sector	Associated 2007 NAICS (2-digits)
Accommodation and Food services	72
Extractive, Utilities, Construction, Manufacturing	21-23, 31-33
Trade and Transportation	42,44-45,48-49
Services	51-56,71,81
Education and Day Care[1]	61
Health Care and Social Assistance	62
Government	92

Notes: [1] Child care, pre-school and day care and youth services were included in this sector even though these industries officially belong to NAICS 62.

The number of observations by sector and type of disruption event is described in table 4.2.

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[21] During data processing certain observations were reclassified based on additional information about their businesses.

Table 4.2: Business Sample by Type of Event

Sector	All Events	Type of Event		
		Contamination	Water Outage	Precautionary Boil Order
Accommodation and Food Services	46	9	30	7
Extractive, Utilities, Construction, Manufacturing	23	4	16	3
Trade and Transportation	41	2	30	9
Services	67	11	40	16
Education and Day Care	28	6	18	4
Health Care and Social Assistance	45	7	35	3
Government	35	1	28	6
Missing	3	1	2	0
Total	288	41	199	48

The household survey involved face-to-face interviews in four locations. A total of 162 responses were collected. All respondents were customers of one of the target public water supply systems and who were affected by a water utility disruption event. Table 4.3 shows that thirty-eight percent of the respondents experienced contamination events while the remaining respondents experienced water outages. There were no interviews of households who had experienced a precautionary boil water event.

Table 4.3: Household Sample by Type of Event

	All	Water Contamination	Water Outage
Total number of households interviewed	162	62	100
Total population represented[1]	465	191	274

Note: [1]The total population corresponds to the sum of adults and children in the household interviewed.

4.2. Business Survey Descriptive Statistics

Responses to questions about the most commonly employed strategies by businesses were used to determine the probability that businesses will employ a particular strategy during disruption events. A positive response to the question of whether the business employed a particular action during the disruption event was used as the dependent variable. Table 4.4 lists eight resilience and three other actions identified. Eleven logit regressions were estimated to obtain the probability of implementing these actions.

Table 4.4: Resilience and Other Actions Modeled

Actions	Resilience	Type of Resilience
Temporary closure of businesses	No	
Offering limited products and services	Yes	Limited
Rescheduling	Yes	Rescheduling
Purchase of bottled water	Yes	Substitute for potable water
Purchase of ice	Yes	Substitute for potable water
Purchase of hand sanitizer	Yes	Substitute for potable water
Do Something else: rent water truck, purchase of water filter, purchase of plastic plates/cups	Yes	Substitute for potable water
Incur higher transportation costs to acquire supplies (travel)	No	
Use of more or less employees	Yes/No	More: Input substitution/Less: No resilience strategy
Discard perishable inventories	No	
Boil water	Yes	Substitute for potable water

The descriptive statistics for this analysis are listed in table 4.5. Mean values for explanatory variables by sector are reported in table 4.6.

The average duration of the events was 6.3 days and the employee size was 19.8. The number of employees ranged from a maximum of almost 32 for the health care and social assistance sector to a minimum of 9 for the service sector.

Forty percent of the businesses interviewed belonged to the monthly income category of $10,000-$100,000. The majority of the businesses in the accommodation and food services, trade and transportation, and health care and social assistance sectors corresponded to this category. Most of the businesses in the government, and extractive, utilities, construction and manufacturing sectors correspond to the highest monthly income category (more than $100,000) while businesses in the services, and education and day care sectors belonged to the lowest monthly income category (less than $10,000).

Businesses showed preferences for certain preparedness strategies. Eighty percent of the respondents had at least hand sanitizer, 50 percent had bottled water on hand and 30 percent counted with inventories in order to prepare for unexpected events. Less frequent preparedness strategies included having an alternative outside water supplier (10 percent), insurance that covers water utilities disruptions (10 percent) and emergency plans for water loss or disruptions (20 percent). Businesses in the health care and social assistance sector were the most prepared. Twenty nine percent of businesses in this sector had alternative water supply and 18 percent had insurance that covers water utilities disruptions.

During water disruptions, businesses showed preference for the use of substitutes for water. Specifically, 40 percent of the business purchased additional bottled water during water utility disruptions; and 20 percent, boil water. Twenty percent of the businesses offered limited products, 20 percent used more or less employees and 10 percent rescheduled production during water utilities disruption events. The sample also showed that 20 percent of the businesses reported closing temporarily at some point during water utilities disruptions. Additional actions employed by businesses during water utility disruptions included traveling to acquire additional supplies and discarding of perishable inventories.

Table 4.5: Descriptive Statistics

Variable	Obs.	Mean	St. Dev.	Min	Max
Dependent Variables					
Temporary closure of business (1=Yes, 0=No) [Closure]	277	0.2	0.4	0	1
Offering limited products and services (1=Yes, 0=No) [Limited]	271	0.2	0.4	0	1
Rescheduling production (1=Yes, 0=No) [Rescheduling]	212	0.1	0.3	0	1
Purchase of bottled water (1=Yes, 0=No) [BottledWater]	275	0.4	0.5	0	1
Purchase of ice(1=Yes, 0=No) [PurchaseIce]	275	0.1	0.3	0	1
Purchase of hand sanitizer (1=Yes, 0=No) [PurchaseHSanitizer]	275	0.1	0.2	0	1
Do Something else: rent water truck, purchase of water filter, purchase plastic plates/cups (1=Yes, 0=No) [SomethingElse]	268	0.1	0.2	0	1
Incur higher transportation costs to acquire supplies (1=Yes, 0=No) [TravelforSupplies]	273	0.2	0.4	0	1
Use of more or less employees (1=Yes, 0=No) [EmployChange]	276	0.2	0.4	0	1
Discard perishable inventories (1=Yes, 0=No) [DiscardInventories]	105	0.1	0.4	0	1
Boil water (1=Yes, 0=No) [BoilingWater]	275	0.2	0.4	0	1
Independent Variables					
Type of event: Water Contamination (1=Yes, 0=No) [Contamination]	288	0.1	0.4	0	1
Type of event: Water Outage (1=Yes, 0=No) [Outage]	288	0.7	0.5	0	1
Type of event: Precautionary boil water order (1=Yes, 0=No) [PrecBoilOrder]	288	0.2	0.4	0	1
Duration of the event (in days) [Duration]	288	6.3	4.2	1	15
Sector: Accommodation and Food Services (1=Yes, 0=No) [AccFSS]	297	0.2	0.4	0	1
Sector: Extractive, Utilities, Construction, Manufacturing (1=Yes, 0=No) [ExtUtilConstManuf]	297	0.1	0.3	0	1
Sector: Trade and Transportation (1=Yes, 0=No) [TradeTrans]	297	0.1	0.3	0	1

Sector: Services (1=Yes, 0=No) [Services]	297	0.2	0.4	0	1
Sector: Education and Day Care (1=Yes, 0=No) [EduDayCare]	297	0.1	0.3	0	1
Sector: Health Care and Social Assistance (1=Yes, 0=No) [HealthCare]	297	0.2	0.4	0	1
Sector: Government (1=Yes, 0=No) [Government]	297	0.1	0.3	0	1
Number of employees [Employee]	296	19.8	51.1	1	500
Monthly revenue: $0-$10,000 (1=Yes, 0=No) [Rev1]	295	0.3	0.5	0	1
Monthly revenue: $10,000-$100,000 (1=Yes, 0=No) [Rev2]	295	0.4	0.5	0	1
Monthly revenue: more than $100,000 (1=Yes, 0=No) [Rev3]	295	0.2	0.4	0	1
Having bottled water before the disruption event (1=Yes, 0=No) [Beforebottled]	291	0.5	0.5	0	1
Having outside water supplier before the disruption event (1=Yes, 0=No) [BeforeOwnWaterSupplier]	292	0.1	0.3	0	1
Having an emergency plan for water loss or disruption before the disruption event (1=Yes, 0=No) [BeforeEmergencyPlan]	290	0.2	0.4	0	1
Having hand sanitizers before the disruption event (1=Yes, 0=No) [BeforeHSanitizer]	288	0.8	0.4	0	1
Having inventories before the disruption event (1=Yes, 0=No) [BeforeInventories]	268	0.3	0.5	0	1
Having insurance that covers water disruption before the disruption event (1=Yes, 0=No) [BeforeInsurance]	284	0.1	0.3	0	1
Doing something else in preparation before the disruption event (1=Yes, 0=No)[1] [BeforeSthElse]	290	0.1	0.3	0	1
Whether were affected by the water disruption (1=Yes, 0=No)[2] [Affected]	278	0.6	0.5	0	1

Notes: [1]The business survey did not ask for details about the "do something else" activities. [2]This variable was calculated by identifying if business answered yes to the question of whether the business was affected by water outage, water contamination or precautionary boil water order.

Table 4.6: Business Characteristics by Sector (Mean Values)

Variable Name	Accommodation and Food Services	Extractive, Utilities, Construction, Manufacturing	Trade and Transportation	Services	Education and Day Care	Health Care and Social Assistance	Government
Employee per Establishment	15.29	28.91	10.76	8.76	18.73	31.82	16.00
Monthly revenue: $0-$10,000 (1=Yes, 0=No)	0.37	0.09	0.34	0.46	0.54	0.20	0.23
Monthly revenue: $10,000-$100,000 (1=Yes,	0.48	0.26	0.41	0.37	0.36	0.60	0.37

0=No)							
Monthly revenue: more than $100,000 (1=Yes, 0=No)	0.15	0.65	0.24	0.16	0.11	0.20	0.40
Having bottled water before the disruption event (1=Yes, 0=No)	0.37	0.52	0.49	0.55	0.29	0.51	0.40
Having outside water supplier before the disruption event (1=Yes, 0=No)	0.02	-	0.05	0.04	0.04	0.29	0.03
Having an emergency plan for water loss or disruption before the disruption event (1=Yes, 0=No)	0.17	0.17	0.02	0.09	0.32	0.38	0.43
Having hand sanitizers before the disruption event (1=Yes, 0=No)	0.80	0.61	0.71	0.67	0.86	0.89	0.71
Having inventories before the disruption event (1=Yes, 0=No)	0.37	0.13	0.37	0.16	0.29	0.44	0.26
Having insurance that covers water disruption before the disruption event (1=Yes, 0=No)	0.09	0.09	0.10	0.04	0.14	0.16	0.23
Doing something else in preparation before the disruption event (1=Yes, 0=No)	0.07	-	0.02	0.03	0.18	0.11	0.17

Table 4.7 lists the average time businesses reported temporarily closing or offering a limited range of products. These values are reported as proportion of the duration of the disruption, by type of event and business sector[22]. Accommodation and food services frequently closed during water contamination events. During water outages, businesses in different sectors employed a diversity of strategies. During the

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[22] Questions 14 and 16 of the business survey asked for how long these two activities were implemented.

majority of the precautionary boil orders, it was the health care and the accommodation and food services that temporarily closed most frequently.

Table 4.7: Response Duration by Sector and Type of Event (as Percentage of the Total Duration of the Event)

Sector	Contamination	Outage	Precautionary Boil Order
	Temporary closure		
Accommodation and Food Services	81.0%	22.1%	50.0%
Extractive, Utilities, Construction, Manufacturing	0.0%	33.1%	0.0%
Trade and Transportation	0.0%	33.3%	0.0%
Services	0.0%	23.4%	0.0%
Education and Day Care	0.0%	24.6%	0.0%
Health Care and Social Assistance	0.0%	33.4%	62.5%
Government	0.0%	15.1%	0.0%
	Offering limited products and services		
Accommodation and Food Services	3.8%	1.6%	2.6%
Extractive, Utilities, Construction, Manufacturing	2.1%	0.8%	0.0%
Trade and Transportation	100.0%	4.3%	0.7%
Services	11.6%	1.7%	0.0%
Education and Day Care	0.0%	26.9%	0.0%
Health Care and Social Assistance	0.0%	15.1%	3.0%
Government	0.0%	24.2%	8.3%
	Other activities[1]		
Accommodation and Food Services	19.0%	77.9%	50.0%
Extractive, Utilities, Construction, Manufacturing	100.0%	66.9%	100.0%
Trade and Transportation	100.0%	66.7%	100.0%
Services	100.0%	76.6%	100.0%
Education and Day Care	100.0%	75.4%	100.0%
Health Care and Social Assistance	100.0%	66.6%	37.5%
Government	100.0%	84.9%	100.0%

Note: [1] The survey did not ask the time spent in other strategies. Hence, the time spent in other activities was estimated as the difference between the duration of the event and the time the businesses reported being temporarily closed.

The expenditures or income losses in dollars per employee-hour of duration of the event that businesses reported employing a particularly activity are shown in table 4.8.

Table 4.8: Change in Expenditures and Income by Activity by Sector and Type of Event (in Dollars/Employee-Hour)[1]

Sector	Contamination	Outage	Precautionary Boil Order
Offering limited products and services (Income losses)			
Accommodation and Food Services	-0.521	-1.722	-1.225
Extractive, Utilities, Construction, Manufacturing	-0.035	-1.263	0.000
Trade and Transportation	-0.339	-4.278	-1.029
Services	-0.339	-1.263	0.000
Education and Day Care	0.000	-2.431	0.000
Health Care and Social Assistance	0.000	-0.041	-1.029
Government	0.000	-0.079	-0.365
Acquisition of bottled water (Additional expenditures)			
Accommodation and Food Services	0.090	0.024	0.120
Extractive, Utilities, Construction, Manufacturing	0.005	0.011	0.010
Trade and Transportation	0.000	0.040	0.000
Services	0.034	0.021	0.036
Education and Day Care	0.079	0.098	0.070
Health Care and Social Assistance	0.044	0.145	0.021
Government	0.000	0.022	0.078
Acquisition of ice (Additional expenditures)			
Accommodation and Food Services	0.136	0.050	0.218
Extractive, Utilities, Construction, Manufacturing	0.000	0.012	0.000
Trade and Transportation	0.000	0.001	0.000
Services	0.000	0.000	0.000
Education and Day Care	0.069	0.067	0.000
Health Care and Social Assistance	0.135	0.214	0.014
Government	0.000	0.008	0.000
Acquisition of hand sanitizer (Additional expenditures)			
Accommodation and Food Services	0.000	0.007	0.044
Extractive, Utilities, Construction, Manufacturing	0.017	0.009	0.000
Trade and Transportation	0.000	0.003	0.000
Services	0.021	0.005	0.000
Education and Day Care	0.000	0.018	0.017
Health Care and Social Assistance	0.017	0.003	0.000
Government	0.000	0.000	0.000
Boiling staff time costs			

	(Additional expenditures)		
Accommodation and Food Services	0.038	0.084	0.166
Extractive, Utilities, Construction, Manufacturing	0.000	0.074	0.000
Trade and Transportation	0.000	0.154	0.166
Services	0.000	0.074	0.000
Education and Day Care	0.008	0.016	0.166
Health Care and Social Assistance	0.000	0.024	0.166
Government	0.000	0.118	0.000
	Employment salary change[2] (Additional expenditures)		
Accommodation and Food Services	-0.544	-0.035	0.384
Extractive, Utilities, Construction, Manufacturing	0.000	0.005	0.000
Trade and Transportation	0.000	0.129	0.000
Services	-0.104	-1.179	0.000
Education and Day Care	0.000	0.015	0.000
Health Care and Social Assistance	0.000	0.005	0.482
Government	-0.398	0.567	0.769
	Transportation costs (Additional expenditures)		
Accommodation and Food Services	0.062	0.008	0.182
Extractive, Utilities, Construction, Manufacturing	0.017	0.014	0.000
Trade and Transportation	0.000	0.021	0.000
Services	0.150	0.011	0.088
Education and Day Care	0.000	0.021	0.030
Health Care and Social Assistance	0.082	0.015	0.088
Government	0.000	0.017	0.088
	Rescheduling activities losses (Income losses)		
Accommodation and Food Services	0.000	-0.500	0.000
Extractive, Utilities, Construction, Manufacturing	0.000	0.000	0.000
Trade and Transportation	0.000	0.000	0.000
Services	0.000	-0.500	0.000
Education and Day Care	0.000	-0.641	0.000
Health Care and Social Assistance	0.000	-0.487	-0.500
Government	0.000	-0.500	-0.500
	Discard perishable inventories losses (Income losses)		
Accommodation and Food Services	-1.161	-0.039	-0.172
Extractive, Utilities, Construction, Manufacturing	-0.052	0.000	0.000
Trade and Transportation	0.000	0.000	0.000
Services	0.000	-0.174	0.000

Education and Day Care	0.000	0.000	0.000
Health Care and Social Assistance	0.000	-0.038	0.000
Government	0.000	0.000	0.000
		Acquisition of plastic plates/cups (Additional expenditures)	
Accommodation and Food Services	0.000	0.009	0.061
Extractive, Utilities, Construction, Manufacturing	0.000	0.006	0.000
Trade and Transportation	0.000	0.130	0.000
Services	0.015	0.000	0.000
Education and Day Care	0.000	0.000	0.000
Health Care and Social Assistance	0.000	0.062	0.000
Government	0.000	0.006	0.058
		Acquisition of water filter (Additional expenditures)	
Accommodation and Food Services	0.000	0.002	0.002
Extractive, Utilities, Construction, Manufacturing	0.000	0.002	0.000
Trade and Transportation	0.000	0.167	0.000
Services	0.278	0.000	0.000
Education and Day Care	0.000	0.000	0.000
Health Care and Social Assistance	0.000	0.002	0.000
Government	0.000	0.002	0.002
		Rental of water trucks (Additional expenditures)	
Accommodation and Food Services	0.000	0.195	0.545
Extractive, Utilities, Construction, Manufacturing	0.000	0.341	0.000
Trade and Transportation	0.000	0.195	0.000
Services	0.255	0.000	0.000
Education and Day Care	0.000	0.000	0.000
Health Care and Social Assistance	0.000	0.195	0.000
Government	0.000	0.195	1.157

Note: [1] Missing values reflect average values by type of business and type of event. [2]Businesses reported that they used more or fewer workers during water utility disruptions. The values reported correspond to the net changes in wages and salaries from this action.

4.3. Probability of Adopting Each Business Strategy

The business responses comprise binary variables. Maximum likelihood (MLE) was used to estimate the probability that a business will adopt a particular strategy. The log-likelihood method is required to estimate models with binary responses. Wooldridge (2010) defines the log-likelihood for a sample N as:

$$\mathcal{L}(\beta) = \sum_{i=1}^{N} \ell_i(\beta),\, \ell_i(\beta) = y_i \log[G(x_i\beta)] + (1 - y_i)\log[1 - G(x_i\beta)]$$

where G is the cumulative distribution function between 0 and 1 and $\hat{\beta}$ is the logit estimator that maximizes the MLE of the log-likelihood.

Table 4.9 shows the hypothesis about the factors that affect the probability of adopting resilience and other actions. Variables include the type of event (water contamination, water outage and precautionary boil order), the event characteristics (duration and whether the disruption affects the business) and the business characteristics (business size, sector that the business belongs to, and preparedness strategies that they have in place before the water disruption).

4.3.1. Event Characteristics

Rose (2009a) suggests that resilience strategies are a function of the type and the duration of the disruption event. It is hypothesized that resilience and other strategies employed during water utility disruption events are also a function of the type and the duration of the event and on whether the business is affected by the particular disruption.

Water contamination is the result of a positive contaminant test in water samples. Unlike water outages and precautionary boil water orders, water is available in water contamination events but usually must either be treated before consumption or its use must be limited to certain activities (e.g. for toilet use but not for drinking). Hence, it is expected that in comparison to water contamination, water outages and precautionary boil orders increase the probability of activities that do not involve substitutes for water (e.g. acquire more bottled water and travel to acquire more supplies). These activities include temporary closure of businesses, offering limited products, rescheduling production and use of more or less employees.

Discarding perishable inventories and boiling water are also expected to be adopted more frequently in water contamination events given limitations on the potential use of contaminated water during the production of goods and services.

Acquiring substitutes for water and traveling to acquire additional supplies are not necessarily associated with a particular type of event. Hence the hypothesized relationship between type of event and these strategies is uncertain.

Adoption of a particular strategy is also a function of the duration of the disruption event and if the business reported being directly affected by the event. Both variables are expected to increase the likelihood of employing a particular strategy during water utility disruptions.

4.3.2. Business Characteristics

Studies that have explained the factors that influence business preparedness and recovery have usually included business size, business age, ownership, financial assets, and business sector (Dahlhamer & Tierney, 1996; Tierney & Dahlhamer, 1997; Webb et al., 1999). Business characteristics have also been a relevant factor in temporary closure during disaster events (Tierney, 1997).

It is hypothesized that business size, business sector and business preparedness strategies are relevant factors in explaining the adoption of resilience and other strategies.

Business size is a proxy of business preparedness. In particular, larger businesses have been shown to be more prepared (Dahlhamer & Tierney, 1996; Tierney & Dahlhamer, 1997; Webb et al., 1999). In this analysis, business size is indicated by the number of employees and the monthly revenue. It is expected that larger values of these indicators will reduce the probability of temporary closure, offering limited products, acquiring substitutes for water, boiling water and traveling to acquire additional supplies. Other activities employed such as rescheduling production, changing the use of employees and discarding perishable inventories could positively or negatively influence in the probability of these actions.

Business sector is another key explanatory variable. Tierney (1997) found that businesses in the finance, insurance, and real estate sector are more likely to temporarily cease operations during earthquakes. Summaries conducted by Webb et al. (1999) concluded that businesses in these sectors are better prepared than business in other sectors. Furthermore, these sectors can rearrange their appointments after closure and cease their operations during disasters. For the adoption of resilience and other strategies during water utility disruptions, it is expected that businesses in the accommodation and food services sector have a high probability of temporary closure, offering limited products, acquiring substitutes of water, traveling to acquire additional supplies, discarding perishable inventories, using more or less employees and boiling water. Rescheduling production is expected to be more commonly adopted by businesses other than those in the accommodation and food services sector.

Preparedness strategies refer to inputs the customer has in place before disruptions. The literature on earthquake and flood disasters has shown that in general the average business places little emphasis on specific disaster preparedness actions (Dahlhamer & Tierney, 1996; Tierney & Dahlhamer, 1997; Webb et al., 1999). Not all the preparedness strategies are well suited to all type of disaster events.

Responses from the business survey found that the most common preparedness strategies include the storage of bottled water, procurement of alternative water supplies, development of emergency contingency plan that covers water utility disruptions, storage of hand sanitizers, increased inventories, and purchase of insurance that covers water disruptions. Each of these preparedness strategies could positively or negatively influence the level of resilience and adoption of other strategies during water disruptions.

It is expected that having bottled water before water utility disruptions decreases the likelihood of temporary closure of businesses, offering limited products, acquiring more substitutes of water, traveling to acquire additional supplies, doing something else such as renting water trucks and boiling water during water utility disruptions.

Not all the businesses are able to have an outside alternative water supplier contract to use when facing water utility disruptions. However, those that do will have a lower likelihood of adopting any other strategy during water utility disruptions.

Emergency contingency plans allow businesses to be more organized and flexible to react during water utility disruptions. Businesses that report having a plan should have a higher likelihood of offering more limited products, rescheduling production, acquiring substitutes of water, boiling water, and using more or less employees. This strategy decreases the probability of temporary closure. Whether we should expect that having a plan will increase or decrease the probability of discarding perishable inventories or travel to acquire additional supplies are unclear.

Having hand sanitizers in place before a water disruptions may decrease the probability of acquiring substitutes of water such as bottled water, ice, hand sanitizer, boiling water, and traveling to acquire additional supplies. The impact of this strategy is unclear for temporary closure of businesses, offering limited products, rescheduling production, doing something else such as renting water trucks, using more or less employees and discarding perishable inventories.

Having larger inventories before water utility disruptions will increase the ability of the businesses to offer limited products, to use more or less employees or to reschedule production because businesses with larger inventories can be more flexible when responding to water disruptions. Whether this preparedness strategy would have a positive or negative impact on the probability of boiling water, acquiring substitutes for water, using more or less employees, discarding perishable inventories or temporary closure is not predictable.

Insurance that covers water utility disruptions will increase the probability of temporary closure of business and decrease the probability of adopting any other strategy.

Doing something else in preparation for water disruptions could have positive or negative effects on the likelihood of implementing other strategies during water disruptions.

Table 4.9: Expected Signs of the Logit Regressions

Variables	Closure	Limited	Rescheduling	Bottled Water	Purchase Ice	Purchase HSanitizer
Type of event (base: Water Contamination category)						
Water outage	+	+	+	+/-	+/-	+/-
Precautionary boil order	+	+	+	+/-	+/-	+/-
Duration of the event	+	+	+	+	+	+
Sector (base: Accommodation and Food Services category)						
Extract., Util., Const., Manuf.	-	-	+	-	-	-
Trade and Transportation	-	-	+	-	-	-
Services	-	-	+	-	-	-
Education and Day Care	-	-	+	-	-	-
Health Care and Social Assistance	-	-	+	-	-	-
Government	-	-	+	-	-	-
Number of employees	-	-	+/-	-	-	-
Monthly revenue (base: $0-$10,000 category)	-	-	+/-	-	-	-
$10,000-$100,000	-	-	+/-	-	-	-
more than $100,000	-	-	+/-	-	-	-
Having bottled water before the disruption event (1=Yes, 0=No)	-	-	+/-	-	-	-
Having outside water supplier before the disruption event (1=Yes, 0=No)	-	-	-	-	-	-
Having an emergency plan for water loss or disruption before the disruption event (1=Yes, 0=No)	-	+	+	+	+	+
Having hand sanitizers before the disruption event (1=Yes, 0=No)	+/-	+/-	+/-	-	-	-
Having inventories before the disruption event (1=Yes, 0=No)	+/-	+	+	+/-	+/-	+/-
Having insurance that covers water disruption before the disruption event (1=Yes, 0=No)	+	-	-	-	-	-
Doing something else in preparation before the disruption event (1=Yes, 0=No)[1]	+/-	+/-	+/-	+/-	+/-	+/-

Whether were affected by the water disruption (1=Yes, 0=No)[2]	+	+	+	+	+	+

Notes: [1]The business survey did not ask for details about the “do something else” response. [2]This variable was calculated by identifying whether the respondent business answered yes to whether the business was affected by water outage, water contamination or precautionary boil water order.

Variables	SomethingElse	Travelfor Supplies	Employ Change[1]	Discard Inventories	Boiling Water
Type of event (base: Water Contamination category)					
Water outage	+/-	+/-	+	-	-
Precautionary boil order	+/-	+/-	+	-	-
Duration of the event	+	+	+	+	+
Sector (base: Accommodation and Food Services category)					
Extract., Util., Const., Manuf.	-	-	-	-	-
Trade and Transportation	-	-	-	-	-
Services	-	-	-	-	-
Education and Day Care	-	-	-	-	-
Health Care and Social Assistance	-	-	-	-	-
Government	-	-	-	-	-
Number of employees	-	-	+/-	+/-	-
Monthly revenue (base: $0-$10,000 category)	-	-			
$10,000-$100,000	-	-	+/-	+/-	-
more than $100,000	-	-	+/-	+/-	-
Having bottled water before the disruption event (1=Yes, 0=No)	-	-	+/-	+/-	-
Having outside water supplier before the disruption event (1=Yes, 0=No)	-	-	-	+/-	-
Having an emergency plan for water loss or disruption before the disruption event (1=Yes, 0=No)	+	+/-	+	+/-	+
Having hand sanitizers before the disruption event (1=Yes, 0=No)	+/-	-	+/-	+/-	-
Having inventories before the disruption event (1=Yes, 0=No)	+/-	+/-	+/-	+/-	+/-

Having insurance that covers water disruption before the disruption event (1=Yes, 0=No)	-	-	-	-	-
Doing something else in preparation before the disruption event (1=Yes, 0=No)[2]	+/-	+/-	+/-	+/-	+/-
Whether were affected by the water disruption (1=Yes, 0=No)[3]	+	+	+	+	+

Notes: [1] The number of observations was in sufficient to separate respondents into those reporting increased employment and those reporting decreased employment. Thus these two responses were aggregated. [2]The business survey did not ask for details about the "do something else" response. [3]This variable was calculated by identifying whether the respondent business answered yes to whether the business was affected by water outage, water contamination or precautionary boil water order.

4.3.3. Regression Results

The logit regression results are shown in table 4.10. Following Sribney (1998), robust variance estimators were used to more accurately estimate the parameters in the absence of additional explanatory variables. Factors that are found to be significant at the 10 percent level of less have an asterisk (*).

The type of event is a relevant factor that determines the likelihood that businesses temporary close, use of more or less employees, acquisition of ice and disposal of perishable inventories during water utility disruptions. As expected, water outages rather than water contamination events increase the likelihood that businesses temporarily close and use more or less employees. During water outages, businesses might choose to close or use more or less employees until water pressure and quality are back to adequate levels.

Water contamination rather than precautionary boil order events increases the probability of discarding perishable inventories. Products that may have previosuly involved the use of water in their preparation are discarded given the concerns of producers that contaminated water was unknowingly used in their products. Another possible explanation is that producers might feel that a contamination event may take longer to resolve than an outage. Water contamination also increases the probability of acquiring additional ice.

The duration of the event increases the likelihood of acquiring additional bottled water and ice, and boiling water. Contrary to what was expected, longer water utility disruption events decrease the probability of temporary closure of businesses and using more or less employees. A possible explanation is that the longer disruption event makes these strategies less attractive since they are more costly strategies.

Results also show the importance of whether businesses were directly affected by the water utility disruption. As expected, this factor increases the likelihood of temporary closure, offering limited products, rescheduling production and using more or less employees. However, it is not significant for other activities including the acquisition of substitutes for water, the disposal of perishable inventories, boiling water, additional travel to acquire supplies and in doing something else such as renting water trucks.

Higher employee size is found to increase instead of decrease the probability of acquiring additional ice and of incurring additional trips to acquire supplies. Larger businesses could be in fact more prepared than smaller businesses. However, larger businesses require additional ice and incur additional trips to acquire supplies since they have more employees.

The sector that business belongs to impacts the probability of employing particular actions during water utility disruptions. Temporary closure, offering limited products, acquiring additional bottled water and ice, using more or less employees, and incurring higher transportation costs to acquire supplies are more common strategies employed by businesses in the accommodation and food services sector. Rescheduling production is more commonly adopted by businesses in the health care sector.

Not all preparedness strategies influence the likelihood of actions employed by businesses during water utility disruptions. Having bottled water before the disruption decreases the likelihood of acquiring additional bottled water and hand sanitizer, and the use of more or less employees.

Storage of inventories is another effective preparedness strategy. It increases the probability of rescheduling production, offering limited products, acquiring additional ice, incurring additional trips to acquire travel supplies, using more or less employees and boiling water. However, it is also found to increase the likelihood of temporary closure of businesses.

Having insurance that covers water utility disruptions increases the likelihood of limited products sold but reduces the likelihood of using more or less employees.

Emergency plans for water utility disruptions and having an alternative water supply are preparedness strategies with significant impact in the likelihood of rescheduling production with the expected signs.

Having hand sanitizers in place before water utility disruptions is a positive and significant predictor of the probability of doing something else such as renting water trucks. This preparedness strategy is also a significant negative factor in the probability of discarding perishable inventories.

Doing something else increases the likelihood of acquiring additional bottled water, hand sanitizer and to travel to acquire additional supplies.

Table 4.10: Robust Logit Regressions Results

	Closure	Limited	Rescheduling	BottedWater	PurchaseIce	PurchaseHSanitizer
Contamination						
	--	--	--	--	--	--
Outage	2.99*	(0.31)	(0.44)	0.09	-2.55*	(0.32)
	(0.82)	(0.67)	(0.97)	(0.48)	(0.75)	(0.92)
PrecBoilOrder	0.10	0.35	(omitted)	0.05	-1.83*	0.77
	(1.26)	(0.90)	(omitted)	(0.60)	(1.11)	(1.18)
Duration	-0.21*	0.01	(0.04)	0.08*	0.24*	0.02
	(0.07)	(0.05)	(0.08)	(0.04)	(0.08)	(0.07)
AccFSS	--	--	--	--	--	--
	--	--	--	--	--	--
ExtUtilConstManuf	(1.15)	(1.30)	(empty)	0.06	-1.72*	1.00
	(0.90)	(0.88)	(empty)	(0.66)	(1.26)	(1.56)
TradeTrans	(3.24)	-1.75*	(empty)	-1.31*	-3.73*	(0.09)
	(0.95)	(0.78)	(empty)	(0.61)	(0.99)	(1.09)
Services	-1.63*	-2.20*	(0.54)	-1.37*	(empty)	(0.08)
	(0.65)	(0.70)	(1.11)	(0.51)	(empty)	(0.92)
EduDayCare	-1.04*	-3.36*	0.43	(0.02)	-2.82*	0.90
	(0.71)	(1.52)	(1.21)	(0.65)	(0.83)	(0.82)
HealthCare	(1.34)	(0.30)	1.90*	-1.09*	-2.51*	(0.41)
	(0.88)	(0.69)	(0.93)	(0.52)	(0.86)	(0.98)
Government	-1.40*	(0.81)	(omitted)	-1.96*	-3.06*	(empty)
	(0.82)	(0.67)	(omitted)	(0.60)	(1.09)	(empty)
Employee	0.00	(0.00)	(0.01)	0.00	0.01*	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Rev1	--	--	--	--	--	--
	--	--	--	--	--	--
Rev2	0.20	0.63	(1.21)	(0.00)	-1.17*	(0.65)

	(0.55)	(0.57)	(1.15)	(0.38)	(0.69)	(0.55)
Rev3	(0.60)	(0.18)	(1.06)	0.20	(0.55)	0.42
	(0.79)	(0.72)	(1.00)	(0.50)	(1.11)	(1.14)
Beforebottled	(0.66)	(0.55)	0.20	-1.04*	(0.49)	-1.11*
	(0.49)	(0.44)	(0.98)	(0.31)	(0.57)	(0.61)
BeforeOwnWaterSupplier	(1.09)	(1.09)	-2.48*	0.12	(0.90)	0.43
	(1.18)	(1.02)	(1.40)	(0.63)	(1.21)	(1.00)
BeforeEmergencyPlan	0.15	(0.21)	1.35*	0.36	0.84	(0.39)
	(0.68)	(0.58)	(0.76)	(0.36)	(0.71)	(0.62)
BeforeHSanitizer	0.20	(0.04)	1.56	0.16	1.08	1.17
	(0.59)	(0.59)	(1.10)	(0.41)	(0.88)	(0.77)
BeforeInventories	0.90*	1.04*	1.93*	0.42	1.21*	0.63
	(0.49)	(0.48)	(0.85)	(0.37)	(0.66)	(0.63)
BeforeInsurance	(0.70)	1.37*	(0.15)	(0.35)	(1.19)	(0.85)
	(0.82)	(0.63)	(1.20)	(0.48)	(1.16)	(1.05)
BeforeSthElse	(0.79)	(0.21)	(0.07)	1.15*	0.73	2.14*
	(0.87)	(0.69)	(0.91)	(0.62)	(1.04)	(0.76)
Affected	2.53*	1.79*	1.53*	0.20	(0.98)	(0.26)
	(0.68)	(0.56)	(0.75)	(0.39)	(0.80)	(0.75)
Constant	-3.19*	-2.26*	(4.70)	(0.19)	0.09	-3.27*
	(1.06)	(0.98)	(1.23)	(0.70)	(1.17)	(1.57)
Observations	241.00	238.00	124.00	241.00	183.00	209.00
Wald chisquare prob	0.01	0.00	0.06	0.00	0.00	0.01
Pseudo R2	0.29	0.24	0.32	0.19	0.40	0.17
Log pseudolikelihood	(79.24)	(78.51)	(31.17)	(133.52)	(49.81)	(49.10)

Notes: *Significant at 10%. “Omitted” means that the variable was excluded from the analysis to avoid perfect multicollinearity between independent variables. “Empty” means that that no observations were reported for that particular variable.

	SomethingElse	TravelforSupplies	EmployChange	DiscardInventories	BoilingWater
Contamination					
	--	--	--	--	--
Outage	1.01	0.01	1.66*	(1.66)	0.52
	(1.93)	(0.54)	(0.65)	(1.11)	(0.67)
PrecBoilOrder	2.70	0.57	1.05	-3.10*	0.90
	(2.18)	(0.71)	(0.79)	(1.83)	(0.81)
Duration	(0.07)	0.03	-0.13*	0.08	0.12*
	(0.12)	(0.05)	(0.06)	(0.10)	(0.05)
AccFSS	--	--	--	--	--
	--	--	--	--	--
ExtUtilConstManuf	0.18	1.16	-2.75*	(1.11)	-2.83*
	(1.35)	(0.74)	(1.24)	(1.17)	(1.08)
TradeTrans	(0.36)	-1.51*	-3.34*	(empty)	-1.86*
	(0.91)	(0.70)	(1.01)	(empty)	(0.69)
Services	(1.56)	-0.92*	-1.52*	2.09	-1.90*
	(1.18)	(0.56)	(0.62)	(1.63)	(0.55)
EduDayCare	(empty)	(0.91)	(1.66)	(empty)	0.41
	(empty)	(0.65)	(0.72)	(empty)	(0.61)
HealthCare	0.72	-1.03*	-2.13*	-2.36*	-1.27*
	(0.94)	(0.58)	(0.81)	(1.20)	(0.61)
Government	0.78	(1.60)	(0.36)	(empty)	-2.10*
	(0.96)	(0.79)	(0.75)	(empty)	(0.72)
Employee	0.04	0.01*	0.01	0.02	(0.01)
	(0.02)	(0.00)	(0.00)	(0.01)	(0.00)
Rev1	--	--	--	--	--
	--	--	--	--	--
Rev2	(0.61)	(0.54)	0.29	(0.47)	(0.57)
	(0.73)	(0.41)	(0.43)	(1.09)	(0.47)

Rev3	(0.92)	-1.18*	(0.65)	(2.55)	0.02
	(1.25)	(0.67)	(0.83)	(1.89)	(0.56)
Beforebottled	0.44	(0.38)	-0.78*	(0.31)	0.08
	(0.65)	(0.38)	(0.44)	(0.64)	(0.37)
BeforeOwnWaterSupplier	(omitted)	(0.69)	(0.79)	(omitted)	0.56
	(omitted)	(0.69)	(0.79)	(omitted)	(0.75)
BeforeEmergencyPlan	(0.61)	0.17	0.81	0.23	0.70
	(0.99)	(0.45)	(0.50)	(0.93)	(0.46)
BeforeHSanitizer	1.86*	0.65	0.32	-1.55*	0.27
	(0.86)	(0.50)	(0.58)	(0.88)	(0.56)
BeforeInventories	1.24	0.96*	1.70*	(0.25)	0.91*
	(0.83)	(0.41)	(0.47)	(0.88)	(0.43)
BeforeInsurance	0.66	(0.58)	-1.35*	(0.32)	(0.38)
	(0.93)	(0.60)	(0.81)	(1.21)	(0.65)
BeforeSthElse	(0.58)	2.01*	0.69	0.40	(0.18)
	(0.97)	(0.67)	(0.72)	(1.64)	(0.69)
Affected	0.53	0.35	2.03*	(0.86)	(0.61)
	(0.69)	(0.47)	(0.58)	(0.90)	(0.48)
Constant	-6.21*	-1.43*	-2.72*	2.17	-1.49*
	(2.38)	(0.80)	(0.97)	(1.63)	(0.86)
Observations	198.00	240.00	241.00	71.00	241.00
Wald chisquare prob	0.00	0.00	0.01	0.35	0.00
Pseudo R2	0.28	0.20	0.31	0.26	0.20
Log pseudolikelihood	(36.47)	(106.09)	(87.11)	(23.90)	(101.82)

Notes: *Significant at 10%. “Omitted” means that the variable was excluded from the analysis to avoid perfect multicollinearity between independent variables. “Empty” means that that no observations were reported for that particular variable.

4.4. Household Survey Responses

Table 4.11 lists six resilience and five other actions most commonly adopted by households during water utility disruption events.

Table 4.11: Household Resilience and Other Actions Modeled

Actions Modeled	Resilience	Type of Resilience
Purchase of bottled water	Yes	Substitute for potable water
Transportation to acquire bottled water	No	
Boil Water: energy, water, and time	Yes	Substitute for potable water
Overnight in another location (Hotels)	Yes	Substitution
Transportation cost for staying in another location	No	
Purchase of paper and plastic cups/plates	Yes	Substitution
Eat more or less at restaurants	Yes	Substitution
Illness impacts (medication and out of pocket expenditures)	No	
Extra babysitting costs	Yes	Substitution
Conservation of water	Yes	Conservation

The weighted average responses from the household survey are used to estimate probabilities households will adopt particular actions[23]. The weighted averages consider the average household size (number of children and adults in the household), the duration of the disruption and the type of event.

Table 4.12 lists the mean values for each of the daily activities that respondents reported having difficulties with. Households faced more difficulties in performing daily activities during water outages than during water contamination events. Using the toilet

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[23] Logit regressions were estimated to identify the probability of household responses. However, no significant results were obtained.

was the most affected activity during water outages. Cooking was the most affected activity during water contamination events.

More acquisition of bottled water gallons (in gallons/person-day), more trips to acquire bottled water (in miles/person-day), more purchase of paper or plastic dishes (in dollars/person-day) and more respondents who boiled water were the most frequently report activities during water outages. However, the most common responses reported during water contamination events were changes in expenditures on eating at restaurants (in dollars/person-day), more expenditures on overnight stays away from home (in dollars/person-day), more trips to another location to spend the night (in miles/person-day), more expenditures on medications or visits to the hospital (in dollars/person-day), more trips to acquire medications (in miles/person-day) and more expenditures on babysitting (in dollars/person-day).

Table 4.12: Household Resilience and Other Activities during Disruption Events (Mean Values)

Resilience and Other Activities	Units	Contamination	Outage
Respondents experiencing difficulties in brushing teeth	person/person-day	0.52	0.59
Respondents experiencing difficulties in bathing or showering	person/person-day	0.40	0.74
Respondents experiencing difficulties in using the toilet	person/person-day	0.09	0.80
Respondents experiencing difficulties in doing laundry	person/person-day	0.24	0.50
Respondents experiencing difficulties in cooking	person/person-day	0.60	0.64
Respondents experiencing difficulties in cleaning dishes	person/person-day	0.37	0.71
Gallons of bottled water consumed	person/person-day	0.63	0.80
Miles driven to acquire bottled water	miles/person-day	2.69	3.69

Respondents boiling water	person/person-day	0.45	0.49
Staying overnight in another location expenditures	dollars/person-day	1.59	0.11
Miles driven to stay in another location	miles/person-day	2.86	1.04
Purchase of paper and plastic cups/plates	dollars/person-day	0.37	0.40
Eat more or less at restaurants expenditures	dollars/person-day	3.50	3.29
Illness impacts (medication and out of pocket expenditures)	dollars/person-day	1.40	0.01
Miles driven to acquire medications	miles/person-day	0.34	0.30
Extra babysitting or daycare costs	dollars/person-day	0.37	0.20

4.5. Conclusions

The business and household surveys provide approximate estimates of the behavior of households and businesses during water utility disruptions given their small size sample and the limited geographic coverage of the samples. Despite these limitations the data reported here provide data on the resilience and other behavior of households and businesses as well as the economic consequences of water utility disruption events. Data of this type are quite rare.

The survey responses show that businesses do have some preparedness strategies in place. The majority of businesses prefer to store bottled water and have hand sanitizers for emergencies. Businesses in the Health Care and Social Assistance sectors have the most elaborate preparedness strategies in place.

Some specific preparedness strategies allow businesses to employ additional coping strategies during water utility disruptions. Adequate inventories support the adoption of additional resilience strategies such as offering limited range of products, rescheduling or changing the number workers, acquiring additional ice, and boiling water. Having insurance that covers water utility disruptions increases the ability of the firms to offer a limited range of products and decreases the need to change the number of employees. Emergency contingency plans and having another water supplier increase the probability that firms can adjust their production schedule.

Other preparedness strategies reduce the rate of adoption of resilience strategies. Having bottled water in place reduces the probability of acquiring additional bottled water and ice during disruptions and decreases the likelihood of changing the number of employees.

The type of business also affects the rate of adoption resilience strategies. Tap water is an important input for businesses in the accommodation and food services. In particular, businesses in this sector have the likelihood of employing more resilience and other strategies during water utility disruptions. However, rescheduling production is a more common strategy of businesses in the health care sector. With the exception of acquiring more ice and of incurring additional trips to acquire supplies, business size is not found to be a significant factor in the adoption of resilience and other activities during water utility disruption events.

The type of the event is an important factor to consider when understanding the adoption of resilience and other strategies. Employing more or less employees and temporarily closing of the business are more common strategies employed by businesses during water outages than during other types of events. Discarding perishable inventories and acquiring additional ice are employed more often in water contamination events than in outages or precautionary boil orders.

The duration of the event is another important factor. Longer duration events increase the likelihood of using substitutes for piped water, in particular of acquiring additional bottled water, ice and of boiling water. Longer duration events were also associated with a reduced likelihood of temporary closure and the use of more or less employees. These last two strategies are costly. Therefore, longer events could make these strategies less appealing for businesses. Businesses that are directly affected by the disruption event have a higher likelihood of offering limited products, rescheduling, using more or less employees as well as temporary closure.

The majority of households in the sample faced more difficulties in performing daily activities during water outage events. More acquisition of bottled water, more trips to acquire bottled water, more purchase of paper or plastic dishes and more boiling of water are more frequent activities during water outages than during water contamination events. Other activities are more commonly reported during water contamination events.

The ultimate reason for collecting this information was to establish a basis for estimating the direct consequences faced by households, businesses and government institutions and their behavior when facing water utility disruptions. By combining this data with characteristics of the region and the event, it is possible to predict the direct and indirect consequences from strategies employed by utility customers during water utility disruption events. In the next chapter the data and simulation model is used to explore the role of resilience on the local economy.

CHAPTER V: SIMULATION AND ANALYSIS

5.1. Data Requirements and Sources

The simulation model is applied to a hypothetical water disruption event in Barren County, Kentucky. The data requirements include the social accounting matrix, the characteristics of the region, the characteristics of the water utility and the adjustment rates and other relevant parameters.

5.1.1. Social Accounting Matrix

Data on technical coefficients and output levels are obtained from the Social Accounting Matrix (SAM) provided by IMPLAN system V3 as developed by MIG (2012a). IMPLAN data is organized in 440 industries and commodities. This data was transformed into an industry by industry format using the market share technology assumption. The data was also aggregated to 13 industries labeled as Agriculture (80001), Mining (80002), Utilities (80003), Construction (80004), Manufacturing (80005), Wholesale trade (80006), Retail Trade (80007), Transportation and Warehousing (80008), Educational Services (80009), Health Care and Social Assistance (80010), Accommodation and Food Services (80011), Professional, Recreational and Other Services (excluding Public Administration) (80012) and Government and Non NAICs (80013)[24][25].

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[24] North American Industry Classification System (NAICS).

[25] Government enterprises (as industry) are distinguished from government institutions (as final demand). Government enterprises produce goods and services that are sold as inputs or final use much like private

Dynamic models such as the one used in this dissertation requires the SAM coefficients to reflect actual production and not sales. Since production differs from sales by changes in inventories this implies that the inventory changes account (140002) in the row and the column must be eliminated (set to zero). The values in the inventory changes row were subtracted from the inventory change column to reflect net inventory changes. These net inventory changes were then removed by redistributing them among the industries' input expenditures. The difference between the rows and the columns in the SAM after these operations was adjusted through changes in the export final demand category (250001).

For small regions such as Barren County, Kentucky, the household expenditures patterns are important since in small regions, the expenditure of household income comprises a large part of the local interrelationships[26]. To fully account for household income, income received by households in terms of compensation (5001), proprietor income (6001) and other property type income (7001) was summed in the household row (10001).

After these modifications, the SAM used in the simulation is shown in table 5.1:

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firms. Government institutions undertake administrative activities not necessarily associated with the production of consumable goods and services (Minnesota IMPLAN Group, 2012b).

[26] Unlike industries, households do not produce goods or services directly but receive income for their work and spend their income on goods and services in the region. By closing the model with respect to households, the model is able to capture the induced effects between consumers and producers.

Table 5.1: Social Accounting Matrix for Barren County, Kentucky (in 2010 US Millions of Dollars)

	11 Agriculture 80001	21 Mining 80002	22 Utilities 80003	23 Construction 80004	31-33 Manufacturing 80005	42 Wholesale Trade 80006	44-45 Retail Trade 80007	48-49 Trans and Warehousing 80008	61 Educational Services 80009	62 Health Care and Social Assistance 80010
80001	13.226	0.018	0.000	0.281	22.254	0.003	0.013	0.002	0.000	0.013
80002	0.167	1.116	1.445	1.445	0.428	0.003	0.011	0.012	0.000	0.011
80003	0.947	0.130	0.006	0.377	9.355	0.121	1.094	0.172	0.007	0.984
80004	0.410	0.532	0.351	0.209	4.887	0.094	0.863	0.240	0.049	0.645
80005	10.744	0.188	0.045	3.684	51.923	0.322	1.428	0.482	0.053	2.144
80006	1.043	0.054	0.014	1.480	17.373	0.477	0.638	0.170	0.008	1.036
80007	0.055	0.020	0.001	4.816	4.158	0.039	0.437	0.158	0.001	0.396
80008	1.453	0.208	0.095	1.631	15.293	1.609	5.027	4.783	0.060	1.224
80009	0.029	0.000	0.001	0.001	0.012	0.004	0.058	0.000	0.004	0.005
80010	-	-	-	-	-	-	0.000	-	-	3.049
80011	0.046	0.027	0.142	0.347	2.995	0.169	0.784	0.142	0.014	1.863
80012	6.476	0.983	0.557	15.244	40.414	4.287	20.924	3.442	0.770	20.450
80013	1.095	0.150	0.024	0.659	10.915	0.512	2.362	1.169	0.035	2.024

5001	1.326	0.175	0.530	3.767	23.549	2.752	9.446	2.277	0.202	14.568
6001	0.725	0.132	0.036	0.494	0.003	0.145	0.193	0.256	0.005	0.238
7001	1.490	5.377	13.208	9.730	50.824	10.772	5.873	6.480	(0.095)	5.398
8001	2.222	1.847	6.194	0.967	9.015	12.299	29.618	1.386	0.068	4.068
10001	24.477	5.468	8.081	38.428	173.028	24.637	69.314	22.598	1.441	104.581
11001	0.446	0.009	0.008	0.141	0.890	0.055	0.439	0.036	0.024	0.714
13001	-	-	-	-	-	-	-	-	-	-
14001	0.001	0.000	0.001	0.001	0.049	0.027	0.081	0.075	0.002	0.077
25001	36.031	5.170	5.745	70.013	660.302	9.287	30.758	13.745	1.228	62.470
TOTAL	102.409	21.605	36.483	153.714	1,097.668	67.613	179.361	57.626	3.875	225.959

	72 Accommodation and Food SS. 80011	51-56,71, 81 Prof., Rec and Other SS (No Public Ad) 80012	92 Government & non NAICs 80013	Employee Compensation 5001	Proprietor Income 6001	Other Property Type Income 7001	Indirect Business Tax 8001	Households 10001	Government 11001
80001	0.038	0.104	0.006					0.745	0.147
80002	0.013	0.066	1.450					0.010	0.002
80003	0.676	1.558	0.978					9.294	2.043
80004	0.314	4.888	5.394					-	49.159
80005	1.057	6.715	0.957					17.757	3.805
80006	0.616	0.807	0.306					12.195	2.241
80007	0.206	0.599	0.003					75.741	0.026
80008	0.459	3.205	0.731					6.014	2.469
80009	-	0.066	0.004					3.166	0.305
80010	-	0.028	-					154.827	0.886
80011	0.568	5.206	0.217					41.761	3.912
80012	5.959	103.657	9.216					213.087	32.370
80013	1.261	4.280	1.647					16.883	99.488
5001	2.752	11.903	14.884					-	-
6001	0.038	1.719	-					-	-
7001	6.920	131.506	19.421					-	-
8001	5.133	28.182	(5.029)					-	-
10001	21.345	153.631	105.711					15.015	35.475

11001	0.059	1.189	0.107	88.129	3.986	11.721	95.971	147.975	226.255
13001	-	-	-	-	-	121.892	-	-	6.367
14001	0.053	0.131	0.057	-	-	142.778	-	22.838	94.089
25001	24.107	110.779	27.102	-	-	(9.489)	-	402.720	101.641
TOTAL	71.572	570.218	183.162	88.129	3.986	266.903	95.971	1,140.031	660.678

	Enterprises (Corporations) 13001	Capital 14001	Trade 25001	TOTAL
80001	-	0.003	65.556	102.409
80002	-	3.103	12.323	21.605
80003	-	-	8.743	36.483
80004	-	84.873	0.807	153.714
80005	-	0.735	995.630	1,097.668
80006	-	2.434	26.722	67.613
80007	-	6.484	86.218	179.361
80008	-	1.264	12.102	57.626
80009	-	-	0.220	3.875
80010	-	-	67.168	225.959
80011	-	-	13.380	71.572
80012	-	5.070	87.312	570.218
80013	-	0.135	40.521	183.162
5001	-	-	-	88.129
6001	-	-	(0.000)	3.986
7001	-	-	-	266.903
8001	-	-	-	95.971
10001	59.861	267.150	9.791	1,140.031
11001	29.775	22.069	30.681	660.678
13001	-	-	8.112	136.371
14001	46.734	-	129.288	436.281
25001	-	42.964	155.144	1,749.717
TOTAL	136.371	436.281	1,749.717	

Source: IMPLAN (2010)

5.1.2. Characteristics of the Region

Table 5.2 lists the average water rate per hour, the price per kilowatt hour of electricity and the transportation costs in dollars per miles used in the analysis. These values are based on national statistics and adjusted to 2010 dollars using IMPLAN deflator values.

The opportunity cost of time and the electricity costs of boiling water are important expenditures that affect households who boil water, or expend time on other atypical activities during water utility disruptions. The national average wage rate in dollars per hour from the US Census Bureau (2011) and the national average price per kilowatt hour of electricity for customers from the USEIA (2011) are proxies used for these variables.

An estimate of gasoline cost in dollars per mile is required to transform miles driven into transportation costs in dollars. This value is obtained as the ratio of the national average retail gasoline prices of all grades and all formulations (dollars per gallon) from USBTS (2012) to the national average fuel efficiency for light duty vehicles (miles per gallon) from USEIA (2012)[27].

The cost of acquiring additional bottled water for customers is another relevant parameter used to transform bottled gallons consumed into dollars. The average wholesale price per gallon of bottled water reported by the IBWA (2011) is used and

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[27] There are other relevant transportation costs such as depreciation and maintenance of vehicles. A proxy for transportation cost that includes these components is the Federal Standard Mileage Rate reported by the Internal Revenue Service (2012). In the short run only the gasoline costs have a local economic consequence.

adjusted to include retail and transportation margins from IMPLAN V3 database to reflect final customer prices.

Table 5.2: Characteristics of the Water Utility and the Region

Information Required	Units	Source	Values
Population of the region	people	IMPLAN V3 (2012)	41,727
Proportion of population served by utility	percent	USGS (2005)	88%
Average daily domestic demand	gallons/day	USGS(2005)	2,490,000
Average price of water	dollars/gallon	USEPA (2009)	0.002
Average wage rate	dollars/hour	USCENSUS (2011)	22.770
Average bottled water price	dollars/gallon	IBWA (2011)	1.260
Price of electricity	dollars/kilowatt hour	USEIA (2011)	0.120
Gasoline Costs	dollars/miles	USEIA (2012), USBTS (2012)	0.139

Note: All dollar values in this data set were converted to 2010 dollars using the IMPLAN price deflator.

5.1.3. Water Utility Service District Characteristics

The characteristics of the water utility service district include the proportion of the population served by the water utility, the average daily domestic (household) demand and the average daily domestic consumption per capita. Table 5.2 reports the parameters used based on latest data available from USGS (2005) for Barren County, Kentucky. The national average price of water per gallon was obtained from USEPA (2009) of $2.00 per 1,000 gallons is used. This value is converted to 2010 dollars using the IMPLAN deflator values.

Water needs by type of activity are parameters required to estimate the economic consequences of employing conservation and substitution strategies used by households during water utility disruptions. Table 5.3 reports water needs based on national estimates by the USEPA (2009). Lawn watering and pools, flushing toilet and bathing are activities with the highest gallons per capita per day consumption.

Table 5.3: National Estimates of Water Needs by Activity

Activity	Gallons per Capita Day	Percentage
Bathing	20	23%
Flushing toilet	24	28%
Laundry	8.5	10%
Lawn watering and pools	25	29%
Car washing	2.5	3%
Drinking and cooking	2	2%
Garbage disposal	1	1%
Dishwashing	4	5%
Total	87	100%

Source: USEPA (2009)

5.1.4. Adjustment Rates and Other Relevant Parameters

The adjustment rates for inputs ($AT_{1,ij}$) and output inventories ($AT_{2,i}$) are estimated from national statistics. The annualized modified version of the inventory days indicator is used as a proxy for these estimates. This indicator evaluates how long it takes for inventories to turn into sales.

Investopedia US (2013) defines the inventory days formula as:

$$Inventory\ days = 365 * \frac{Average\ Inventory}{Cost\ of\ Sales}$$

The annualized adapted version of the inventory days used for the adjustment rate is:

$$AT_{1,ij} = \frac{Average\ Materials\ Inventories_{ij}}{Intermediate\ Demand_{,ij}}$$

for input inventories and,

$$AT_{2,i} = \frac{Average\ Work\ in\ Process\ and\ Finished\ Inventories_{i}}{Total\ Output\ Net\ of\ Changes\ in\ Inventories_{i}}$$

for output inventories.

Mining and manufacturing commodities can be stored as materials and supplies, work in process and finished products[28]. Adjustment rates of input and output inventories of these commodities are estimated using USBEA national economic accounts. These accounts reports private stocks of inventories at the national level but do not distinguish which industries hold these inventories.

For input inventories, it is assumed that industries equally adjust their manufacturing and mining input commodities for the production of their outputs. Other input commodities cannot be stored and are set equal to zero. These assumptions make the adjustment rate of input inventories to be:

$$AT_{1,ij} = \begin{cases} AT_{1,i} \ for\ i = manufacturing\ and\ mining \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad otherwise \end{cases}$$

Manufacturing and mining output inventories can be stored as work in process and finished products. Other output commodities can only be stored as work in process.

Table 5.4lists the adjustment rates for manufacturing and mining input and output inventories estimates. Manufacturing commodities adjust faster than mining commodities.

Table 5.4: Adjustment Rates of Input and Output Inventories

Indicator	Scale	2010 Estimates
Manufacturing		
Average finished and work in process inventories[2]	2010 Dollars	1,454,144.08
Average materials and supplies inventories[3]	2010 Dollars	722,238.64
Total intermediate demand[4]	2010 Dollars	3,580,662.57
Total output commodity net of inventory changes[1]	2010 Dollars	5,453,918.08
Adjustment rate of input inventories[5]		0.202
Adjustment rate of output inventories[6]		0.267

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[28] Agriculture commodities can also be stored. However, these were excluded from the analysis since this industry is not explicitly analyzed.

Mining		
Average finished and work in process inventories[2]	2010 Dollars	79,756.07
Average materials and supplies inventories[3]	2010 Dollars	45,617.02
Total intermediate demand[4]	2010 Dollars	91,908.03
Total output commodity net of inventory changes[1]	2010 Dollars	252,598.55
Adjustment rate of input inventories[5]		0.496
Adjustment rate of output inventories[6]		0.316

Notes:

[1] Total output commodity net of inventory changes is the sum of final demand, intermediate demand and minus change in inventories. Source: USBEA (2012)

[2] Average finished and work in process inventories is the national average of the quarterly stock of private finished and work in process inventories for the year 2005. Source: USBEA (2013b, c).
It is adjusted to 2010 dollars using IMPLAN V3 (2012a) deflators.

[3] Average materials and supplies inventories is the national average of the quarterly stock of materials and supplies inventories for the year 2005. Source: USBEA (2013a). It is adjusted to 2010 dollars using IMPLAN V3 (2012a) deflators.

[4] Total intermediate demand is obtained from USBEA (2012).

[5] This indicator is obtained as the ratio of average materials and supplies inventories to total intermediate demand.

[6] This indicator is obtained as the ratio of average finished and work in process inventories to total output commodity net of inventory changes.

The adjustment rate of output inventories for other than mining and manufacturing products ($AT_{2,i<>mining,manufacturing}$), the adjustment rate to adjust production to fulfill demand ($AT_{3,i}$), the rate of desired output inventories ($\alpha_{2,i}$) and the necessary intermediate inputs available to production ($\alpha_{3,ij}$) are parameters based on a variety of previous research and simulation results. Table 5.5 reports these assumptions.

Commodities other than mining and manufacturing hold only work in process inventories. No data is available to estimate the adjustment rates of these inventories. Hence, the adjustment rate for these output inventories is set equal to one hour. As a result, estimates of the adjustment rate for output inventories are:

$$AT_{2,i} = \begin{cases} 0.267 & for\ i = manufacturing \\ 0.316 & for\ i = mining \\ 0.0001142 & otherwise \end{cases}$$

The proportion of the rate of production required to fulfill demand ($\alpha_{2,i}$), is assumed to be equal to 1 year of desired level of production required to fulfill for those outputs that could be held as work in process and finished inventories and to 1 hour for those outputs that could be stored only as work in process:

$$\alpha_{2,i} = \begin{cases} 1 \quad for\ i = manufacturing, mining \\ 0.0001142 \qquad\qquad\qquad otherwise \end{cases}$$

The adjustment rate of production to fulfill demand ($AT_{3,i}$) is assumed to be the same for all industries $AT_{3,i} = AT_3$. This rate is defined as one week or 1/52 of a year.

Table 5.5: Additional Assumptions

Indicator	Value
Adjustment rate to adjust production to fulfill demand	0.0192
Proportion of the rate of production to fulfill demand for Manufacturing and Mining commodities	1
Adjustment rate of output inventories for other than Manufacturing and Mining commodities	0.0001142
Proportion of the rate of production to fulfill demand for other than Manufacturing and Mining commodities	0.0001142

The necessary intermediate inputs available to the industry *j* are identified with the $\alpha_{3,ij}$ parameter. It is assumed that all inputs are necessary for the production of goods and services. Household is the only sector for which production of goods and services is not constrained by the availability of inputs.

5.1.5. Classification of the Business Sectors

Estimates of direct economic consequences from resilience and other strategies employed during water utility disruptions are implemented for each of the 18 category levels. As shown in column 2 of table 5.6, these categories include industries, government enterprises and institutions, and households[29].

Table 5.6: Categories Used for the Analysis

Level of Analysis		Aggregation Level (based on IMPLAN)		Sector Type (based on Business Survey)	
Code	Industry Analysis	Code	Industries	Code	Sector
1	21 Mining	80002	21 Mining	2	Extractive, Utilities, Construction, Manufacturing
2	22 Utilities	80003	22 Utilities	2	Extractive, Utilities, Construction, Manufacturing
3	23 Construction	80004	23 Construction	2	Extractive, Utilities, Construction, Manufacturing
4	31-33 Manufacturing	80005	31-33 Manufacturing	2	Extractive, Utilities, Construction, Manufacturing
5	42 Wholesale Trade	80006	42 Wholesale Trade	3	Trade and Transportation
6	44-45 Retail Trade	80007	44-45 Retail Trade	3	Trade and Transportation
7	48-49 Transportation and Warehousing	80008	48-49 Transportation and Warehousing	3	Trade and Transportation
8	51-56,71,81 Professional, Recreational and Other Services (excluding Public Administration)	80012	51-56,71,81 Professional, Recreational and Other Services (excluding Public Administration)	4	Services
9	61 Educational Services	80009	61 Educational Services	5	Education and Day Care
10	62 Health Care and Social Assistance	80010	62 Health Care and Social Assistance	6	Health Care and Social Assistance
11	72 Accommodation and Food Services	80011	72 Accommodation and Food SS	1	Accommodation and Food Services
12	Child Care (I: 399)	80010	62 Health Care and Social Assistance	5	Education and Day Care
13	US Postal Service (I: 427), 429 Federal Gov. Enterprises (I:429),	80013	92 Government and Non NAICs	3	Trade and Transportation

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[29] The model does not directly estimate the total economic consequences for the agriculture sector because of its seasonal nature and because farm operations rarely depend on water utilities for their water. However, farmers are households and the total economic consequences include impacts that they experience.

	State/Local Transit (I: 430)				
14	Federal Electric Utilities (I: 428), State/Local Electric Utilities (I:431), State/Local Enterprises (I: 432)	80013	92 Government and Non NAICs	2	Extractive, Utilities, Construction, Manufacturing
15	State/Local Gov. Education (I: 437) [1] /Government Institution (I:12001)	80013/ 11001	State/Local Gov. Education (I: 437) /Government Institution (I:12001)	7	Government
16	State/Local Gov. Non Education (I: 438) [1]/Government Institution(I: 12002)	80013/ 11001	State/Local Gov. Non Education (I: 438) /Government Institution(I: 12002)	5	Education and Day Care
17	Federal Gov. Non-Military (I: 439) [1]/Government Institution (I: 11001)	80013/ 11001	Federal Gov. Non-Military (I: 439) /Government Institution (I: 11001)	4	Services
18	Households	10001	Households	-	-

Notes:

"I" Corresponds to the IMPLAN category.

[1] IMPLAN gives special treatment to the government institution accounts 12001, 12002 and 11001 accounts. Their expenditure patterns are included in the IMPLAN government institution category as final demand but the valued added is included in the government enterprise category 437, 438 and 439, respectively. Therefore, expenditure from coping strategies such as changes in wages and salaries are included in these government enterprise categories while expenditures such as additional bottled water are included in the government institution accounts.

5.1.6. Direct Economic Consequences Data Requirements

The direct economic consequences to be modeled are derived from the resilience and other strategies employed during water utility disruptions. Actions to be modeled are shown in tables 4.4 and 4.11. Each of these actions have consequences in terms of changes in expenditures, reduced rates of output, additional costs and/or changes in operating surplus.

To estimate the consequences for business and government institutions from these actions, four variables are required: the probability of adopting a particular action, the expenditure per day, the response duration indicator and the daily output. The economic consequences for households require estimates for the average household expenditures per person-day, the percentage of customers affected by the disruption each day and the population served by the water utility.

5.1.6.1. Response Probability Estimates for Businesses and Government Institutions

There are 17 business and government categories and 11 actions to be modeled. To estimate the probabilities that each of these types of customer will adopt a particular action ($\alpha_{k_b m_b j}$), two sources of data are required: the type of event and the characteristics of these customer categories. The characteristics of the business and government institutions include the average employment per establishment, the average monthly revenue and the preparedness strategies on place.

The average employment per establishment is obtained from US Census data. In the absence of detailed information for Barren County, national rates are used. Table 5.7 shows these estimates for 2010. For the government category (92 Government & non NAICs), the data is derived from the Census of Government (U.S. Census Bureau [USCensus], 2012b). For the other categories, the data corresponds to the County Business Patterns (U.S. Census Bureau [USCensus], 2012a).

Table 5.7: National Estimates of Employees per Establishment (year 2010)

Industry	Employment Per Establishment
21 Mining	21.47
22 Utilities	36.25
23 Construction	7.89
31-33 Manufacturing	36.21
42 Wholesale Trade	13.50
44-45 Retail Trade	13.57
48-49 Trans and Warehousing	19.24
61 Educational Services	36.33
62 Health Care and Social Assistance	21.88
72 Accommodation and Food SS.	17.57
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	12.25
92 Government & non NAICs	253.32

Source: US Census (2012b, a)

The average monthly revenues and preparedness strategies in place by businesses and government institutions categories correspond to the average values from the business survey reported in table 4.6. The business survey aggregated responses into 7 categories, while the analysis is implemented with 17 categories. In order to use the information from the survey, the 17 categories are classified according to the 7 categories from the business surveys. This categorization appears in column 6 of table 5.6.

The characteristics of the event vary by type of simulation. Three water outages scenarios are modeled and the percentage of business and government institutions affected by these disruptions are described in tables 5.10, 5.11 and 5.12.

The characteristics of the businesses and the event, together with the coefficients obtained from the robust logit regressions shown in table 4.10 are used to estimate the probabilities for these 17 categories.

5.1.6.2. Response Duration for Businesses and Government Institutions

For each day *j*, the calculation of the response duration for action m_b by category k_b is made as follows:

$$\gamma_{k_b m_b j} = \begin{cases} 1 \; if \; round\left(\tau_{k_b m_b} * n\right) > j \\ 0 \qquad\qquad otherwise \end{cases}$$

where n represents the duration of the event, and τ_{km} is the time the action m_b is employed by category k_b ($\tau_{k_b m_b}$). The parameter $\tau_{k_b m_b}$ corresponds to the average business response duration reported in table 4.7.

5.1.6.3. Average Daily Business and Government Institution Expenditures

Estimates of the average daily expenditures for responses other than closure m_b employed by category k_b ($\beta_{k_b m_b}$) are obtained as the product of the average business responses expenditure in employee-days, shown in table 4.8, and the number of employees per category k_b. The number of employees per category is obtained from the IMPLAN database.

For the closure action, the average daily savings for each category k_b corresponds to the q variable inputs that are not spent during water utility disruptions given that business has stopped producing. The variable inputs refer to other than fixed inputs that can be avoided. Fixed inputs such as rent, insurance, contracted services or compensation of workers cannot be avoided and have to be paid. The expenditures in variable and fixed inputs are obtained from the SAM database which is divided by 365 to obtain daily expenditures.

5.1.6.4. Daily Output

The daily output is used to estimate the output losses and this is obtained from the SAM.

Table 5.8 summarizes the sources of data used to estimate the direct economic consequences of resilience and other strategies employed by businesses and government institutions. Changes in expenditures for action m_b by category k_b per day j are also margined[30] and the components allocated to the appropriate accounts using IMPLAN margins.

Table 5.8: Direct Business and Government Institutions Economic Consequences Data Requirements

Variables	Source of Information
Probability of businesses and government institutions to employ actions per day	
Characteristics of the event • Type of disruption • Daily rationing of water	• Water outage • Tables 5.10, 5.11, 5.12
Characteristics of the businesses • Employees per establishment • Size of business • Preparedness strategies in place	• Table 5.7 • Table 4.6 • Table 4.6
Time indicator	
• Type of event • Duration of the event • Response duration	• Water outage • 6 days • Table 4.7
Average daily expenditures	
• Average daily expenditures • Employees per category • Variable daily inputs savings	• Table 4.8 • IMPLAN database • Table 5.1
Average daily output	
• Average daily output	• Table 5.1

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[30] Margining changes expenditures at purchaser prices to expenditures at producer prices plus trade, transportation and tax margins.

5.1.6.5. Average Daily Household Expenditures

The average household responses from table 4.12 are complemented with additional information from the characteristics of the region from table 5.2 to estimate the daily expenditures of a particular action per person-day ($\rho_{m_r j}$). For example, miles driven per person-day are transformed into dollars per person-day using the transportation costs from table 5.2.

Two resilience strategies deserve special mention. Boil water incurs additional time costs and energy expenditures. The household survey only provides estimates of the proportion of the population who boil water. The formula in Harrington et al. (1991) is used to estimate costs per person-day

$$\rho_{m=boil\ costs} = \begin{cases} \mathrm{p}_e(0.055 + 0.5 * \omega) & \text{for energy expenditures and } \omega > 0 \\ p_w(0.021 + 0.19 * \omega) & \text{for time costs and } \omega > 0 \end{cases}$$

where ω represents the water fulfilled by boiling water in gallons per capita per day, $(0.055 + 0.5 * \omega)$ are the kilowatt hours required to boil ω gallons, p_e is the energy price in kilowatt hours, $(0.021 + 0.19 * \omega)$ is the hours required to boil ω gallons and p_w is the hourly wage rate. It was assumed that 100% of the water needs for drinking water and cooking and washing dishes was done with boiled water. The quantity of water used for these activities are shown in table 5.3. Energy price and the hourly wage rate used are listed in table 5.2.

Conservation for water is a response to the difficulty in implementing daily activities that involves use of piped water. These actions include difficulty in using the toilet, in cooking, in washing dishes, in bathing and in doing laundry. Water needs used for these activities are shown in table 5.3. These are multiplied by the price of water per gallon to obtain the total expenditures savings in water conservation. The price of water per gallon used corresponds to the one from table 5.2.

5.1.6.6. Population Served by the Utility and Affected by the Disruption

The population served by the water utility (τ) is, shown in table 5.2. The percentage of household customers affected by the disruption on day *j* (π_j) are described in tables 5.10, 5.11 and 5.12.

Table 5.9 summarizes the sources of data used to estimate the direct economic consequences of resilience and other strategies employed by households. Changes in expenditures for action m_r per day *j* are also margined and the components allocated to the appropriate accounts using IMPLAN margins.

Table 5.9: Direct Household Economic Consequences Data Requirements

Variable	Source of Information
• Average daily responses in person-day	• Table 4.12
• Price of water per gallon, energy price, hourly wage rate, transportation costs	• Table 5.2
• Population served by the water utility	• Table 5.2
• Daily rationing of water	• Tables 5.10, 5.11, 5.12

5.2. Simulation Results

The simulation model is applied to a hypothetical 6 day water utility disruption event caused by a water main break in Barren County, Kentucky. In this scenario, the water outage imposes various constraints for industries and households. The event is assumed to occur at day 1 (t1= 0.0014) and continue until day 7 (t2= 0.0178) at which time the utility restores production back to 100%. During this period, resilience and other activities determine the expenditure patterns available to businesses and households. Once the disruption is over, businesses and households return to their previous expenditure patterns[31]. No further changes are imposed. Simulations results are reported for a period of one year[32].

To demonstrate the economic impact of different restoration strategies, three scenarios are modeled[33, 34]. The first scenario assigns an equal proportion rationing scheme to all customers. The second prioritizes health and safety and assigns faster recovery rates to the health and public administration industries[35]. The third restores the manufacturing, wholesale and retail sectors. Tables 5.10, 5.11 and 5.12 list the daily rationing of water by type of customer for each of the scenarios described. The numbers should be interpreted as the proportion of customers within the sector affected by the disruption.

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[31] Other combinations are also possible. For example, industries and households that have not been affected by the disruption event operate under the default expenditure patterns while those affected operate with the expenditure patterns related to resilience and other strategies.

[32] The DT (increment in the numerical integration algorithm) was 1/1000th of a year.

[33] No information on water consumption per industry was available. Furthermore, expenditures on water are included under the IMPLAN account 432 (other state and local government enterprises). The scenarios were constructed in such a way that the amount of direct output losses during the water utility disruption is the same in the three scenarios. For businesses, the direct output losses was obtained as the weighted average of the percentage of businesses affected in the industry per day and the daily output over all the days of disruption. For households, the direct output losses corresponded to the weighted average of the percentage of households per day and the daily income over all the days of disruption.

[34] In these scenarios the volume of water used by customers is not known, thus the alternative restoration schemes do not imply a restoration of a particular volume of water but rather a percent of normal service. This approach is appropriate in cases of water outages from structural failures in the pipelines but not necessarily in scenarios where the volume of water is restricted such as droughts. In cases of volume limits the level of restoration should be based on volumes delivered.

[35] Public administration corresponds to the 92 2 digit 2007-NAICS code and includes the fire department, ambulance and fire combined, fire prevention, police, health departments and others businesses related.

The alternative restoration schemes in each scenario produce different reactions of industries and household customers. These reactions correspond to the resilience and other strategies employed by the customers during water utility disruptions and are reflected not only in terms of output for industries or income for households but also in change in the use of inputs and in expenditures.

The model simulates the direct and indirect economic consequences of these reactions. Then, it reports the annual rate of sales, production, value added for the region and each industry[36], the annual rate of household income, expenditures and additional costs; the annual rate of government institution additional costs[37], and the work in process and finished inventories for the region and at the industry level. It also reports estimates of the time costs incurred by households for the additional time needed for boiling water during water utility disruptions.

The scenarios will be compared in terms of the rate and cumulative losses in the rate of production and value added at the industry and region level, household income, and additional costs to households and government institutions. The cumulative losses reflect the integral of the difference between the rates during the simulation and its baseline level at every point of the analysis and it is discounted to reflect the time value of money.

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[36] Industries include government enterprises. Unlike government institutions, government enterprises produce goods and services that are sold as inputs or final use much like private firms. Government institutions undertake administrative activities not necessarily associated with the production of consumable goods and services (Minnesota IMPLAN Group, 2012b).

[37] Households and government institutions do not reduce their profit or value added but do experience additional costs when the adoption of resilience and other strategies induce changes in expenditures.

Table 5.10: Scenario 1. Proportional Rationing (S1)

Industries/Households	Days					
	1	2	3	4	5	6
21 Mining	60%	40%	30%	20%	10%	2%
22 Utilities	60%	40%	30%	20%	10%	2%
23 Construction	60%	40%	30%	20%	10%	2%
31-33 Manufacturing	60%	40%	30%	20%	10%	2%
42 Wholesale Trade	60%	40%	30%	20%	10%	2%
44-45 Retail trade	60%	40%	30%	20%	10%	2%
48-49 Trans & Warehousing	60%	40%	30%	20%	10%	2%
61 Educational Services	60%	40%	30%	20%	10%	2%
62 Health Care and Social Assistance	60%	40%	30%	20%	10%	2%
72 Accommodation and Food SS	60%	40%	30%	20%	10%	2%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	60%	40%	30%	20%	10%	2%
92 Government & non NAICs	60%	40%	30%	20%	10%	2%
Households	60%	40%	30%	20%	10%	2%

Table 5.11: Scenario 2. Differential Rationing with Focus on the Health and Public Administration (S2)

Industries/Households	Days					
	1	2	3	4	5	6
21 Mining	80%	80%	60%	50%	40%	30%
22 Utilities	60%	40%	30%	20%	10%	2%
23 Construction	80%	80%	60%	50%	40%	30%
31-33 Manufacturing	60%	40%	30%	20%	10%	2%
42 Wholesale Trade	60%	40%	30%	20%	10%	2%
44-45 Retail trade	60%	40%	30%	20%	10%	2%
48-49 Trans & Warehousing	80%	80%	60%	50%	40%	30%
61 Educational Services	80%	80%	60%	50%	40%	30%
62 Health Care and Social Assistance	10%	5%	2%	1%	0%	0%
72 Accommodation and Food SS	80%	80%	60%	50%	40%	30%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	60%	40%	30%	20%	10%	2%
92 Government & non NAICs	10%	5%	5%	1%	1%	1%
Households	60%	40%	30%	20%	10%	5%

Table 5.12: Scenario 3.Differential Rationing with focus on the Manufacturing, Wholesale Trade and Retail Trade (S3)

Industries/Households	Days					
	1	2	3	4	5	6
21 Mining	80%	70%	60%	50%	30%	2%
22 Utilities	60%	40%	30%	20%	10%	2%
23 Construction	80%	70%	60%	50%	30%	2%
31-33 Manufacturing	40%	20%	5%	5%	5%	2%
42 Wholesale Trade	40%	20%	5%	5%	5%	2%
44-45 Retail trade	40%	20%	5%	5%	5%	2%
48-49 Trans & Warehousing	80%	70%	60%	50%	30%	2%
61 Educational Services	80%	70%	60%	50%	30%	2%
62 Health Care and Social Assistance	60%	40%	30%	20%	10%	2%
72 Accommodation and Food SS	80%	70%	60%	50%	30%	2%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	80%	70%	60%	50%	30%	2%
92 Government & non NAICs	60%	40%	30%	20%	10%	2%
Households	60%	40%	30%	20%	10%	2%

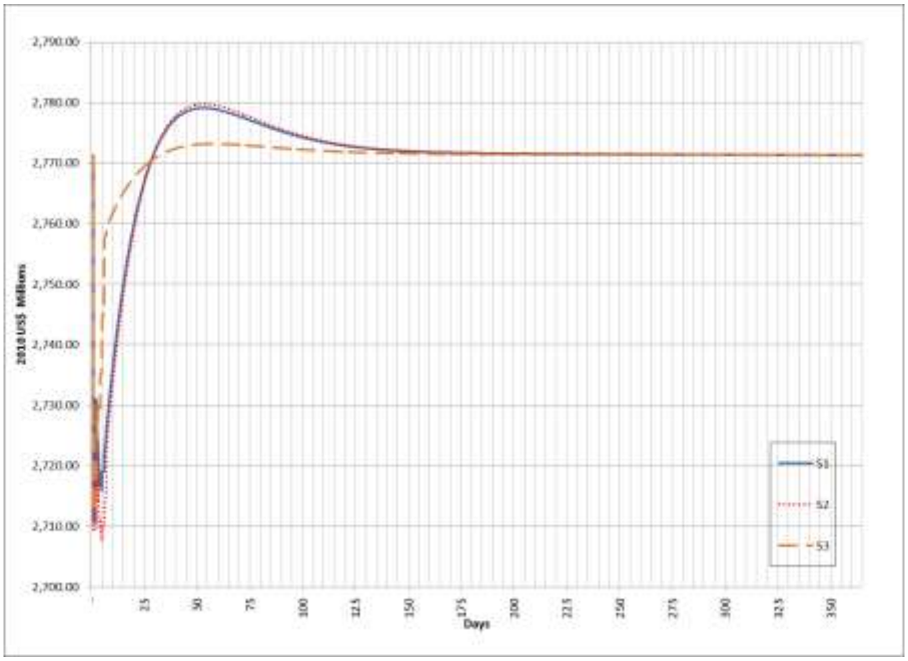
Figure 5.1 displays the annual rate of production for the region for the entire year. Table 5.13 provides information on the annual rate of production for the region for selected days.

The S3 scenario produces the highest annual rate of production for the region during the disruption event. The disrupted rate of production starts at 97.88% of baseline and reaches 99.55% of the baseline level by the end of the disruption event. Unlike S3, S2 scenario produces the lowest rate of production during the disruption starting at 97.77% and reaching 98.10% of the baseline level.

The annual rate of production does not return to its baseline level after the end of the disruption. It takes 21 more days for scenarios S1 and S2 and 25 more days for the scenario S3.

After the rates of production have returned to their baseline levels, they often achieve values above their baseline levels. This reflects the fact that industries are replenishing their input and output inventories, thus increasing their demand for input and their rate of production. As a result, the rate of production for the region reaches its peak on the 55th day with values of 100.28% and 100.35% of the baseline output levels for scenarios S1 and S2. The S3 rate of production reaches a peak at 100.07% of the annual baseline output levels on the 58th day. By the 150th day, all the scenarios have essentially reached their baseline levels.

Figure 5.1: Annual Rate of Production for the Region



Note: Vertical scale is not set at “0”

Table 5.13: Annual Rate of Production for the Region for Selected Days (Percentage from the Baseline

Scenario		S1	S2	S3
Baseline (in 2010 US$ Millions)		$ 2,771.26	$ 2,771.26	$ 2,771.26
Days	1	97.82%	97.77%	97.88%
	3	98.30%	98.09%	98.54%
	6	98.14%	97.80%	99.11%
	7	98.35%	98.10%	99.55%
	15	99.22%	99.16%	99.78%
	30	100.02%	100.02%	99.98%
	45	100.26%	100.28%	100.06%
	75	100.21%	100.23%	100.06%
	90	100.14%	100.16%	100.04%
	120	100.06%	100.06%	100.02%
	150	100.03%	100.03%	100.01%

The cumulative losses in production for the region are shown in figure 5.2 and table 5.14. Losses under the S3 scenario are lower than under the S2 scenarios. Indeed, the S2 scenario produces the highest cumulative losses.

Figure 5.2: Cumulative Losses in Production for the Region

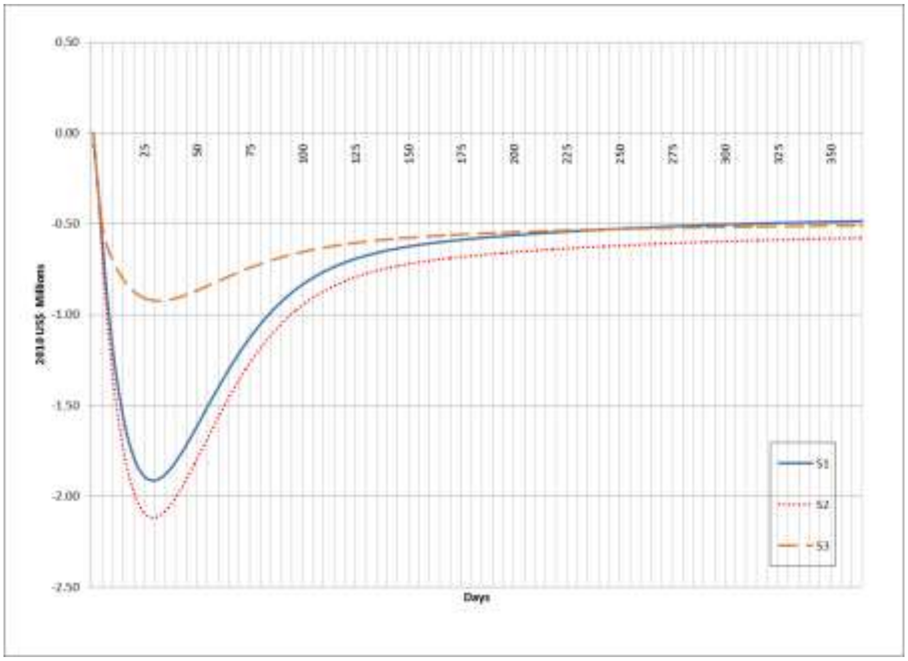


Table 5.14: Cumulative Changes in Production (in 2010 US$ Millions)

Day	Scenario			Gains	
	S1	S2	S3	S2 versus S1	S3 versus S1
1	$ (0.001)	$ (0.001)	$ (0.001)	-2.5%	2.8%
3	$ (0.286)	$ (0.311)	$ (0.285)	-8.8%	0.4%
6	$ (0.714)	$ (0.804)	$ (0.570)	-12.6%	20.1%
7	$ (0.848)	$ (0.965)	$ (0.609)	-13.7%	28.2%
15	$ (1.562)	$ (1.736)	$ (0.805)	-11.1%	48.5%
30	$ (1.913)	$ (2.118)	$ (0.923)	-10.7%	51.7%
45	$ (1.717)	$ (1.907)	$ (0.891)	-11.0%	48.1%
75	$ (1.128)	$ (1.267)	$ (0.743)	-12.3%	34.1%
90	$ (0.929)	$ (1.050)	$ (0.685)	-13.1%	26.2%
120	$ (0.713)	$ (0.816)	$ (0.613)	-14.4%	14.0%
150	$ (0.626)	$ (0.722)	$ (0.577)	-15.3%	7.8%

Industries are affected in quite different ways. The type of rationing scheme and the linkages between industries determine whether industries are better off or worse off. Rationing schemes that prioritize one or more industries would make these industries better off in terms of cumulative losses in production. In addition, the linkages of these industries with the local economy could make other industries better off as well. Table 5.15.6 shows the cumulative losses in terms of production by sector and for selected days.

The manufacturing, wholesale and retail sectors prefer the rationing schedule in S3 over that in S1 since their cumulative losses in production are lower because their water service was restored faster. These three industries receive the same rationing treatment under scenarios S2 and S1. However, it is the retail sector that is worse off under S2 than under S1 in terms of cumulative losses. Although the professional, recreational and other services sectors receive the same rationing scheme in S2 and S1 scenarios, this sector also is worse off under the S2 scenario relative to S1.

The health care and the public administration sectors prefer the rationing scheme in S2 over that in S1 since their water service is restored faster. These industries would also choose S3 over S1 since their cumulative losses in their rate of production are lower.

Industries with the same rationing scheme under the three scenarios such as the utility sector show preferences for the S3 as well. The utility sector is an important input for the production of goods and services from industries that are in better position under the S3 scenario. Hence, this scenario is preferable for this industry as well.

Sectors that show more cumulative losses under the S3 scenarios include the construction, transportation, educational services, accommodation and food services and the professional and recreational services industries. The disadvantaged restoration scheme under S3 relative to S1 explains part of this result.

Household do not produce tradable goods and services. However, they receive income as the owners of the primary inputs (labor, capital). Table 5.15 shows that lowest cumulative losses in income for households occur in the S3 scenario for the selected days.

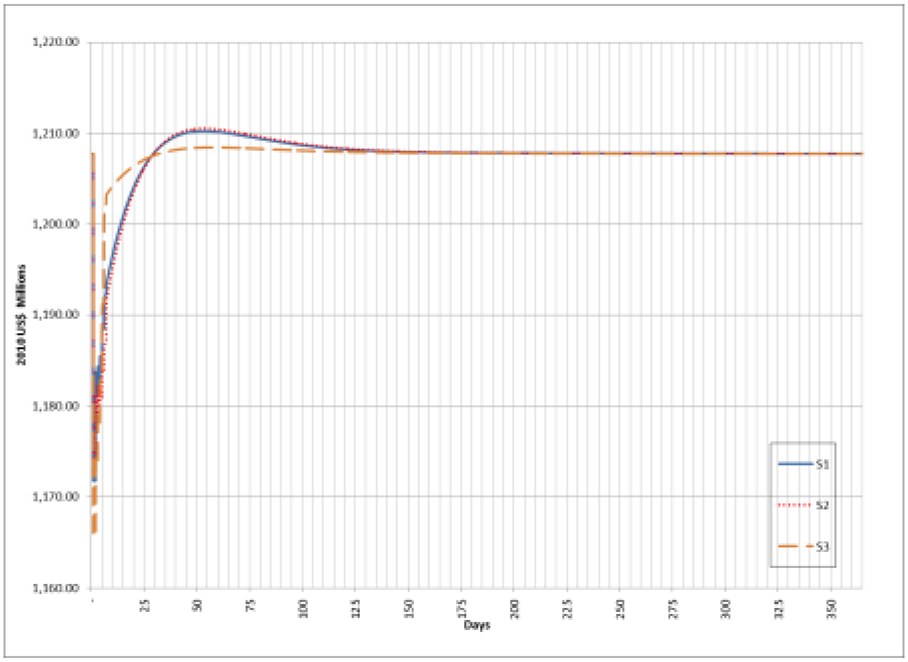
Table 5.15: Cumulative Changes in Production for Selected Days under Different Scenarios (relative to the Baseline)

	Baseline	Day 7			Day 30		
Sectors	Annual Output (in 2010 US$ Millions)	S1 (% Baseline)	Gain S2 vs. S1	Gain S3 vs. S1	S1 (% Baseline)	Gain S2 vs. S1	Gain S3 vs. S1
21 Mining	$ 21.60	-0.06%	-180.3%	-141.0%	-0.19%	-170.6%	-101.1%
22 Utilities	$ 36.48	-0.03%	-1.8%	23.1%	-0.06%	-4.4%	45.5%
23 Construction	$ 153.71	-0.02%	-263.1%	-181.5%	-0.03%	-226.8%	-145.2%
31-33 Manufacturing	$ 1,097.67	-0.05%	-1.6%	74.0%	-0.12%	-2.1%	75.1%
42 Wholesale Trade	$ 67.61	-0.01%	-2.7%	73.6%	-0.04%	-3.9%	73.8%
44-45 Retail Trade	$ 179.36	-0.01%	-3.0%	70.4%	-0.02%	-6.6%	69.9%
48-49 Trans & Warehousing	$ 57.63	-0.01%	-99.8%	-15.9%	-0.04%	-39.3%	41.3%
61 Educational Services	$ 3.87	-0.03%	-152.1%	-103.2%	-0.04%	-98.5%	-37.9%
62 Health Care and Social Assistance	$ 225.96	-0.03%	76.8%	12.4%	-0.04%	48.1%	30.8%
72 Accommodation and Food SS	$ 71.57	-0.05%	-136.1%	-95.0%	-0.06%	-103.5%	-52.3%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	$ 570.22	-0.02%	-2.7%	-81.3%	-0.03%	-6.3%	-5.2%
92 Government & non NAICs	$ 183.16	-0.01%	72.4%	15.8%	-0.02%	42.5%	36.4%
11 Agriculture	$ 102.41	0.00%	0.0%	0.0%	0.00%	0.0%	0.0%
Total Production	$ 2,771.26	-0.03%	-13.7%	28.2%	-0.07%	-10.7%	51.7%
Household Income	$ 1,140.03	-0.01%	-6.9%	68.8%	-0.03%	-9.6%	68.6%

	Baseline	Day 90			Day 150		
Sectors	Annual Output (in 2010 US$ Millions)	S1 (% Baseline)	S2 vs. S1	S3 vs. S1	S1 (% Baseline)	S2 vs. S1	S3 vs. S1
21 Mining	$ 21.60	-0.07%	-269.8%	-199.0%	-0.02%	-480.1%	-395.9%
22 Utilities	$ 36.48	-0.03%	-1.8%	22.4%	-0.03%	-0.2%	9.6%
23 Construction	$ 153.71	-0.02%	-260.9%	-179.4%	-0.02%	-273.5%	-191.5%
31-33 Manufacturing	$ 1,097.67	-0.06%	0.6%	68.4%	-0.03%	1.6%	66.0%
42 Wholesale Trade	$ 67.61	-0.02%	-1.2%	66.7%	-0.01%	0.9%	64.6%
44-45 Retail Trade	$ 179.36	-0.01%	-3.8%	64.9%	-0.01%	-0.9%	65.9%
48-49 Trans & Warehousing	$ 57.63	-0.02%	-87.1%	-12.3%	-0.01%	-155.6%	-79.0%
61 Educational Services	$ 3.87	-0.03%	-146.2%	-98.2%	-0.02%	-172.8%	-129.7%
62 Health Care and Social Assistance	$ 225.96	-0.03%	73.3%	12.1%	-0.02%	86.3%	4.5%
72 Accommodation and Food SS	$ 71.57	-0.05%	-133.0%	-92.2%	-0.04%	-146.1%	-108.6%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	$ 570.22	-0.02%	-3.5%	-74.8%	-0.01%	-1.0%	-124.8%
92 Government & non NAICs	$ 183.16	-0.01%	68.9%	15.6%	-0.01%	83.5%	6.2%
11 Agriculture	$ 102.41	0.00%	0.0%	0.0%	0.00%	0.0%	0.0%
Total Production	$ 2,771.26	-0.03%	-13.1%	26.2%	-0.02%	-15.3%	7.8%
Household Income	$ 1,140.03	-0.01%	-8.7%	57.6%	0.00%	-4.4%	50.9%

Figure 5.3 and table 5.16 illustrate the annual rate of value added for the region. At the first day of the disruption event, the S3 scenario produces the lowest annual rate of value added relative to the baseline level, a value of 96.52%. However, by the end of the disruption event, this scenario produces the highest rate, a value of 99.6% of the baseline levels, in comparison with 98.79% and 98.52% for scenarios S1 and S2, respectively.

Figure 5.3: Annual Rate of Value Added for the Region



Note: Vertical scale is not set at “0”

Table 5.16: Annual Rate of Value Added for the Region for Selected Days (Percentage from the Baseline)

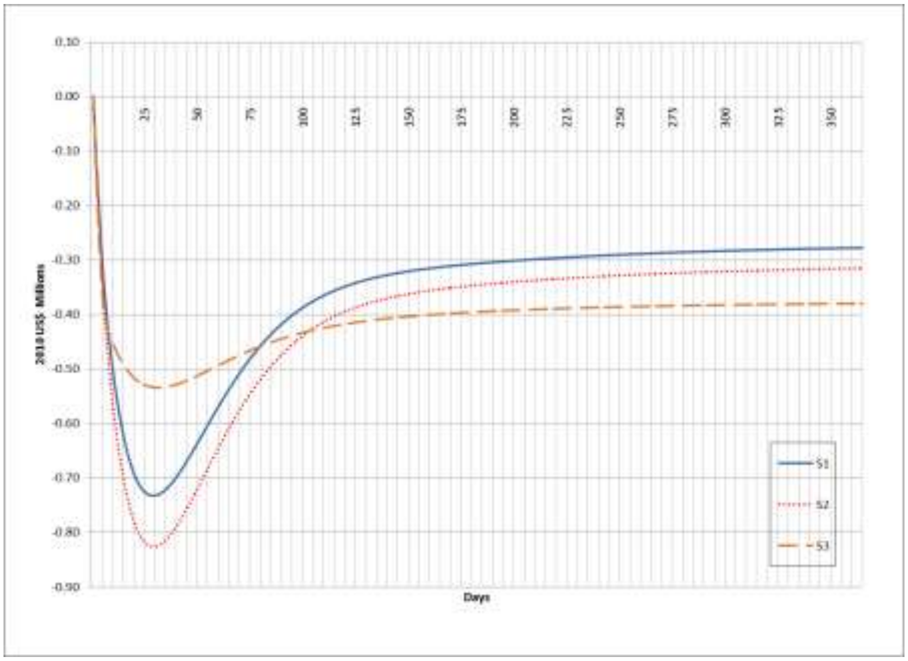
Scenario		S1	S2	S3
Baseline (in 2010 US$ Millions)		$ 1,207.73	$ 1,207.73	$ 1,207.73
Days	1	97.02%	97.13%	96.52%
	3	98.05%	97.89%	97.64%
	6	98.56%	98.15%	99.05%
	7	98.79%	98.52%	99.60%

	15	99.43%	99.36%	99.81%
	30	100.02%	100.02%	99.99%
	45	100.19%	100.21%	100.05%
	75	100.16%	100.18%	100.05%
	90	100.11%	100.12%	100.04%
	120	100.04%	100.05%	100.02%
	150	100.02%	100.02%	100.01%

The value added measure the net contribution of industries to the total regional output. It excludes the role of intermediate inputs. Divergences in conclusions can occur from using the rate of value added versus the rate of production. This will occur in scenarios where industries which contribute heavily to value added relative to their total output and receive a low priority in terms of restoration of the water service.

Figure 5.4 and table 5.17 shows that the S1 scenario leads to the lowest cumulative losses in value added by the end of the disruption event. The initial impact in the annual rate of value added at the beginning of the disruption event in S3 does not compensate for the additional reduction in the rate and makes the S1 scenario the preferred option. Between the 8th and the 80th days the cumulative losses in value added in S3 are lower than in S1. After the 80th day the lowest cumulative losses in value added are generated by the S1 scenario.

Figure 5.4: Cumulative Losses in Value Added for the Region



Note: Vertical scale is not set at "0"

Table 5.17: Cumulative Changes in Value Added for Selected Days (in 2010 US$ Millions)

Day	Scenario			Gains	
	S1	S2	S3	S2 versus S1	S3 versus S1
1	$ (0.001)	$ (0.001)	$ (0.001)	3.5%	-17.0%
3	$ (0.167)	$ (0.172)	$ (0.208)	-2.7%	-24.1%
6	$ (0.349)	$ (0.383)	$ (0.401)	-9.7%	-15.0%
7	$ (0.393)	$ (0.441)	$ (0.418)	-12.3%	-6.3%
15	$ (0.620)	$ (0.698)	$ (0.491)	-12.6%	20.8%
30	$ (0.732)	$ (0.826)	$ (0.534)	-12.8%	27.1%
45	$ (0.670)	$ (0.758)	$ (0.521)	-13.0%	22.2%
75	$ (0.482)	$ (0.546)	$ (0.466)	-13.4%	3.2%
90	$ (0.418)	$ (0.474)	$ (0.445)	-13.4%	-6.4%
120	$ (0.349)	$ (0.395)	$ (0.418)	-13.2%	-19.8%
150	$ (0.321)	$ (0.362)	$ (0.404)	-13.0%	-25.9%

Table 5.18 lists the cumulative losses in value added at the industry level and the additional costs born of households and government institutions. The S3 scenario is not

preferred for industries that contribute 50% of more of their value added to their total output if the restoration sequence affects them more than on an equal rationing scheme. That is the case of the mining, transportation and warehousing, accommodation and food services and recreational, professional and other services.

Industries such as utilities, health care and social assistance and public administration contribute 50% of their value added to their total output and receive the same treatment under S3 and S1 scenarios show lower cumulative losses in value added over the S3 scenario relative to S1 given that their water services are disrupted less. The positive impacts from these industries is insufficient to overcome the effects from industries whose contribution to value added is important but which have been affected more under the S3 scenario.

The S3 scenario also reflects higher cumulative additional losses for households relative to the S1 scenario. Higher savings might be used in the S3 scenario to fulfill the additional expenditures incurred from the actions employed by these customers during water utility disruptions. The direct and indirect effects from these additional savings are an important factor to consider and a topic for future research and model development.

Table 5.18: Cumulative Changes in Value Added for Selected Days under Different Scenarios (relative to the Baseline)

	Baseline (in 2010 US$ Millions)			Day 7			Day 30		
Sectors	Output	Value Added	%	S1 (% Baseline)	S2 vs. S1	S3 vs. S1	S1 (% Baseline)	S2 vs. S1	S3 vs. S1
21 Mining	$ 21.60	$ 13.00	60%	-0.06%	-182.5%	-142.1%	-0.20%	-171.4%	-102.0%
22 Utilities	$ 36.48	$ 28.05	77%	-0.03%	-1.7%	22.6%	-0.06%	-4.3%	44.9%
23 Construction	$ 153.71	$ 53.39	35%	-0.03%	-261.0%	-181.3%	-0.03%	-233.2%	-153.3%
31-33 Manufacturing	$ 1,097.67	$ 256.42	23%	-0.06%	-1.4%	73.1%	-0.13%	-1.9%	74.7%
42 Wholesale Trade	$ 67.61	$ 50.60	75%	-0.01%	-2.5%	72.7%	-0.04%	-3.8%	73.5%
44-45 Retail Trade	$ 179.36	$ 114.44	64%	-0.01%	-2.2%	68.1%	-0.02%	-5.7%	68.8%
48-49 Trans & Warehousing	$ 57.63	$ 33.00	57%	-0.02%	-117.9%	-36.9%	-0.05%	-49.7%	29.9%
61 Educational Services	$ 3.87	$ 1.62	42%	-0.06%	-158.4%	-114.4%	-0.08%	-128.0%	-76.6%
62 Health Care and Social Assistance	$ 225.96	$ 128.85	57%	-0.04%	81.5%	8.4%	-0.05%	58.5%	23.5%
72 Accommodation and Food SS	$ 71.57	$ 36.19	51%	-0.06%	-136.7%	-97.3%	-0.08%	-110.8%	-63.2%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	$ 570.22	$ 326.94	57%	-0.03%	-1.5%	-90.8%	-0.05%	-4.6%	-32.0%
92 Government & non NAICs	$ 183.16	$ 134.99	74%	-0.01%	67.3%	17.9%	-0.02%	37.1%	39.2%
11 Agriculture	$ 102.41	$ 30.24	30%	0.00%	0.0%	0.0%	0.00%	0.0%	0.0%
Total	$ 2,771.26	$ 1,207.73	44%	-0.03%	-12.3%	-6.3%	-0.06%	-12.8%	27.1%
Additional Losses Households	$ -				-3.3%	-0.1%		-3.3%	-0.1%
Additional Losses Government	$ -				93.6%	0.0%		93.6%	0.0%

	Baseline (in 2010 US$ Millions)			Day 90			Day 150		
Sectors	Output	Value Added	%	S1 (% Baseline)	S2 vs. S1	S3 vs. S1	S1 (% Baseline)	S2 vs. S1	S3 vs. S1
21 Mining	$ 21.60	$ 13.00	60%	-0.07%	-268.2%	-197.7%	-0.02%	-451.3%	-369.4%
22 Utilities	$ 36.48	$ 28.05	77%	-0.03%	-1.8%	21.9%	-0.03%	-0.2%	9.3%
23 Construction	$ 153.71	$ 53.39	35%	-0.03%	-259.3%	-179.7%	-0.03%	-268.5%	-188.6%
31-33 Manufacturing	$ 1,097.67	$ 256.42	23%	-0.06%	0.5%	68.3%	-0.04%	1.3%	66.3%
42 Wholesale Trade	$ 67.61	$ 50.60	75%	-0.02%	-1.1%	66.4%	-0.01%	0.7%	64.4%
44-45 Retail Trade	$ 179.36	$ 114.44	64%	-0.01%	-2.9%	64.1%	-0.01%	-0.6%	64.5%
48-49 Trans & Warehousing	$ 57.63	$ 33.00	57%	-0.02%	-104.9%	-31.5%	-0.01%	-170.3%	-96.5%
61 Educational Services	$ 3.87	$ 1.62	42%	-0.06%	-155.7%	-112.1%	-0.06%	-166.9%	-125.5%
62 Health Care and Social Assistance	$ 225.96	$ 128.85	57%	-0.04%	79.1%	8.3%	-0.04%	88.2%	2.9%
72 Accommodation and Food SS	$ 71.57	$ 36.19	51%	-0.06%	-134.4%	-95.3%	-0.06%	-143.9%	-107.3%
51-56,71, 81 Prof., Rec and Other SS (No Public Ad)	$ 570.22	$ 326.94	57%	-0.03%	-2.1%	-86.6%	-0.03%	-0.5%	-114.3%
92 Government & non NAICs	$ 183.16	$ 134.99	74%	-0.01%	63.6%	17.5%	-0.01%	79.3%	7.1%
11 Agriculture	$ 102.41	$ 30.24	30%	0.00%	0.0%	0.0%	0.00%	0.0%	0.0%
Total	$ 2,771.26	$ 1,207.73	44%	-0.03%	-13.4%	-6.4%	-0.03%	-13.0%	-25.9%
Additional Losses Households	$ -				-3.3%	-0.1%		-3.3%	-0.1%
Additional Losses Government	$ -				93.6%	0.0%		93.6%	0.0%

Additional time spent responding to water utility disruption is another relevant aspect to evaluate when assessing the economic consequences of water utility disruptions. This estimate is usually not considered in regional impact models. The model here only estimates household's time costs for boiling water. Table 5.19 shows that time costs represents a significant component of the total losses from water utility disruptions.

Ultimately, the selection of a particular scenario will depend on two factors: the period of evaluation and the costs included as total losses in the estimates. Table 5.19 shows the total losses based on the results from the three scenarios and for selected days. Total losses are estimated using either the cumulative losses in the rate of production or in value added.

Many researchers only evaluate the economic losses until the end of the disruption event. For example, if only accounting for cumulative losses in value added, the S1 is the preferred scenario by the 7th day. The conclusions change when including other relevant costs. For example, by adding the household time costs of boiling water, the additional losses of households and government institutions to the cumulative losses in value added, the S2 is the elected scenario.

Previous research has considered the relevance of the recovery period after the disruption has ended. By the end of the 30th day, total losses by using either value added or total production reflect preferences for the S3 scenario. By the 90th day, the conclusions in terms of total losses using value added recognize the S2 scenario as the preferred option while S3 is the option for the total losses using total production.

Table 5.19: Total Losses under Different Scenarios (in 2010 US$ Millions)

	S1	S2	S3	Selected
Day 7				
Time costs[1] (1)	$ (0.62)	$ (0.63)	$ (0.62)	S1 and S3
Cumulative losses in value added (2)	$ (0.39)	$ (0.44)	$ (0.42)	S1
Cumulative losses in production (3)	$ (0.85)	$ (0.96)	$ (0.61)	S3
Cumulative additional losses of government institutions (4)	$ (0.09)	$ (0.01)	$ (0.09)	S2
Cumulative additional losses of households (5)	$ (0.09)	$ (0.10)	$ (0.09)	S1
Total losses based on (1) + (3) + (4) + (5)	$ (1.65)	$ (1.70)	$ (1.41)	S3
Total losses based on (1) + (2) + (4) + (5)	$ (1.20)	$ (1.17)	$ (1.22)	S2
Day 30				
Time costs[1] (1)	$ (0.62)	$ (0.63)	$ (0.62)	S1 and S3
Cumulative losses in value added (2)	$ (0.73)	$ (0.83)	$ (0.53)	S3
Cumulative losses in production (3)	$ (1.91)	$ (2.12)	$ (0.92)	S3
Cumulative additional losses of government institutions (4)	$ (0.09)	$ (0.01)	$ (0.09)	S2
Cumulative additional losses of households (5)	$ (0.09)	$ (0.10)	$ (0.09)	S1
Total losses based on (1) + (3) + (4) + (5)	$ (2.72)	$ (2.85)	$ (1.73)	S3
Total losses based on (1) + (2) + (4) + (5)	$ (1.54)	$ (1.56)	$ (1.34)	S3
Day 90				
Time costs[1] (1)	$ (0.62)	$ (0.63)	$ (0.62)	S1 and S3
Cumulative losses in value added (2)	$ (0.42)	$ (0.47)	$ (0.44)	S1
Cumulative losses in production (3)	$ (0.93)	$ (1.05)	$ (0.68)	S3
Cumulative additional losses of government institutions (4)	$ (0.09)	$ (0.01)	$ (0.09)	S2
Cumulative additional losses of households (5)	$ (0.09)	$ (0.10)	$ (0.09)	S1
Total losses based on (1) + (3) + (4) + (5)	$ (1.73)	$ (1.78)	$ (1.49)	S3
Total losses based on (1) + (2) + (4) + (5)	$ (1.22)	$ (1.21)	$ (1.25)	S2
Day 150				
Time costs[1] (1)	$ (0.62)	$ (0.63)	$ (0.62)	S1 and S3
Cumulative losses in value added (2)	$ (0.32)	$ (0.36)	$ (0.40)	S1
Cumulative losses in production (3)	$ (0.63)	$ (0.72)	$ (0.58)	S3
Cumulative additional losses of government institutions (4)	$ (0.09)	$ (0.01)	$ (0.09)	S2
Cumulative additional losses of households (5)	$ (0.09)	$ (0.10)	$ (0.09)	S1
Total losses based on (1) + (3) + (4) + (5)	$ (1.43)	$ (1.45)	$ (1.38)	S3
Total losses based on (1) + (2) + (4) + (5)	$ (1.12)	$ (1.10)	$ (1.21)	S2
Days when:				
Production reaches the 100% baseline level	29	29	32	

Production reaches the highest level	53	53	57	
Production reaches the lowest level	1	5	1	
Value added reaches the 100% baseline level	29	29	32	
Value added reaches the highest level	53	53	57	
Value added reaches the lowest level	1	1	1	

Note: [1] Time costs only consider the household's direct time costs of boiling water during the disruption event and ignore the other inconveniences such as extra time spent driving, shopping, doing laundry, etc. For this reason, time costs should be considered a lower boundary.

Researchers have questioned the use of total output rather than value added to evaluate results. Value added avoids double counting of intermediate sectors and the value of outputs produced outside the region. Hence, it is preferable to output as an indicator of change in economic production.

Based on the estimated cost of a water disruption using the cumulative losses in value added, time costs and additional costs born by government and households, the S2 is the selected scenario by the end of the 150th day. It also favors the health and public administration sectors. The linkages of these industries with the local economy produce positive impacts to other industries as well.

CHAPTER VI: SUMMARY AND CONCLUSIONS

Some researchers consider time as a relevant dimension to include in the evaluation of economic consequences. Other researchers suggest that the new equilibrium would not be achieved immediately after a disruption has ended. Few researchers acknowledge the importance of delays and the counteracting feedback loops (Wheat, 2007). This is especially true in models that assess the economic consequences of unexpected events such as water utility disruptions. This study developed a continuous dynamic social accounting matrix based model that considers both demand and supply constraints model to evaluate restoration strategies.

The model takes an industry approach and distinguished between inputs used and acquired, production and sales of output, input and output inventories and the adjustment process of these inventories. The simplicity of the model relies in the role of adjusting supply and demand through quantities. Excluded from the analysis is the direct implications from relative prices, in particular when desired demand is different from production and available inventories. The literature review has shown that prices are unlikely to immediately change for short run disruptions such as those modeled in this study. A next step in this area of research could be to include a price adjustment mechanism especially when modeling longer term events. However, additional information including consumption per type of good and service, estimates of elasticities might be required.

Our model is sensitive to the adjustment rates assumed. In this study, the parameters were not estimated. Instead, these were selected based on national data and simulations. Surveys that collect information on the time it takes to adjust planned production and inventories of inputs and outputs could potentially allow us to estimate these parameters using econometric methods. This is a potential future topic of research.

Previous research has shown that restoration strategies are a relevant component when assessing the economic consequences of lifeline disruptions. Two factors are relevant when analyzing the implications of restoration strategies in economic impact analysis of water utility disruptions events: the type of losses included and the period of evaluation. Some researchers have assumed that a period of analysis to the point where the service has been restored is acceptable. However, evidence from surveys and this study suggest that consumers (businesses and households) do not immediately return back to their previous behavioral patterns[38]. Adjustment lags emerge between and within consumers and producers which delay the return to previous behavior patterns. Conclusions also change when additional losses of households and government institutions and household 'time costs of boiling water[39]

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[38] The household and business surveys show that not all consumption patterns are restored completely after a water utility disruption event. Households sometimes decide to drink less water, or even no tap water, after a water contamination event. Confidence in the water safety seems to be shaken during these events. Water utility disruptions events have also affected businesses after the official end of the event. Without longer term data, it was not possible to conclude for how long these impacts occur (Alva-Lizarraga et al., 2013).

[39] Boiling water is just one of the ways in which households must spend additional time to complete typical tasks. Hence, household's time cost of boiling should be considered an estimate of the lower boundary of household' time costs.

are included as part of the total losses. Hence, it is important to consider a period of analysis that expands beyond the end of the disruption period and to include the impacts from households and government institutions as they assess the economic consequences of water utility disruptions. The results also show the importance of the linkages between sectors and between producers and consumers.

In terms of priorities for restoring water service, researchers have claimed that some of these restoration strategies are based on other than economic considerations and focused on health and safety. To demonstrate the economic consequences from different restoration schemes, three scenarios were evaluated. The first produces an equal rationing scheme by which all water service customers are restored in the same manner. The second gives preference to the health and public administration sectors. The third scenario focuses on priorities to the manufacturing, wholesale and trade sectors. Based on the simulation results, S2 is the preferred scenario since it generates the least total losses when including household 'time costs of boiling water, additional expenditures from households and government institutions and cumulative losses in value added. Value added is a preferable outcome indicator compared to total output since it avoids double counting of intermediate sectors and the value of outputs produced outside the region.

The modeled scenarios did not account for potential injuries or even casualties. This analysis only calculates the economic cost of priorities to the different sectors under different rationing schemes but including the economic value of potential injuries or even casualties may change the conclusions. The household surveys analyzed did not report injuries or casualties from the recent water utility disruption events. However, water contamination events could potentially lead to a significant number of illnesses or deaths. One mechanism to account for this type of loss is to include potential injuries and fatalities from scenarios that involve water contamination using TEVA-SPOT[40]. The monetary losses of these injuries and casualties could be included using "official" guidelines of value of statistical life (VSL) estimates from federal agencies such as the Environmental Protection Agency (U.S. Environmental Protection Agency, 2000, 2010a) and the Department of Transportation (2008, 2011).

A complementary methodology to identify the most adequate restoration strategy is a dynamic optimization model that minimizes the total cumulative losses subject to the linkages between and within producers and consumers and subject to the availability of constrained water. Transforming the model developed in this study into a dynamic optimization model framework could be another extension of this research.

Although the ultimate objective of the research is to build an economic impact model to evaluate alternative water service restoration schemes, the model is also able to measure static direct resilience[41]of industries as well as households and government institutions. Table 6.1 displays the resilience measures based exclusively on the direct static consequences resulting from the resilience and other strategies employed during the disruption event. These strategies exclude the use of inventories and their indirect

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[40] TEVA-SPOT identifies the optimal placement of sensors in order to maximize a utility company's ability to respond to water contamination events. This tool could model the incidence of a water contamination in terms of number of people susceptible, exposed, with symptoms, recovering and dead from the ingestion of contaminated water (EPA National Homeland Security Research Center, 2010).

[41] Static direct resilience refers to the fact that the indirect and induce effects of the direct economic consequences of resilience and other strategies are not considered.

effects. From these results one can conclude that resilience is a function of the characteristics of the disruption. In addition, household resilience is important and accounts for a significant absorption in potential income losses. Finally, and less evaluated, government resilience is another important aspect to consider when assessing resilience. Future research should measure the role of inventories and the indirect effects of these strategies to assess a more precise measure of total resilience.

Table 6.1: Static Direct Resilience Measures Until the End of the Disruption Event (in 2010 US$ Millions)

Scenario 1	
Variable	Value
Direct output industry losses with resilience and other strategies	$ 2.00
Maximum direct output industry losses	$ 11.85
Additional direct losses of households	$ 0.34
Maximum direct income losses of households	$ 5.06
Additional direct losses from government institutions	$ 0.34
Maximum direct income losses of government institutions	$ 2.93
Direct industry resilience	83%
Direct household resilience	93%
Direct government resilience	89%
Scenario 2	
Direct output industry losses with resilience and other strategies	$ 1.74
Maximum direct output industry losses	$ 11.76
Additional direct losses of households	$ 0.35
Maximum direct income losses of households	$ 5.14
Additional direct losses from government institutions	$ 0.15
Maximum direct income losses of government institutions	$ 0.42
Direct industry resilience	85%
Direct household resilience	93%
Direct government resilience	64%
Scenario 3	
Direct output industry losses with resilience and other strategies	$ 1.91
Maximum direct output industry losses	$ 11.85
Additional direct losses of households	$ 0.34
Maximum direct income losses of households	$ 5.06
Additional direct losses from government institutions	$ 0.34
Maximum direct income losses of government institutions	$ 2.93

Direct industry resilience	84%
Direct household resilience	93%
Direct government resilience	89%

Short duration water utility disruptions are seldom evaluated. It is hoped that this study will shed new light on the consequences of water utility disruptions on regions when restoration policies by utility companies are applied. Ultimately, the model could help policy makers assess post-alternative recovery and restoration strategies when this type of event occurs. It can also be used to identify the industries in which precautionary measures and mitigation strategies can lead to the lowest possible economic losses.

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