Economic Impacts of the Arkstorm Scenario

Ian Sue Wing[1]; Adam Z. Rose[2]; and Anne M. Wein[3]

Abstract

We estimate the business interruption (BI) impacts of ARkStorm, a severe winter storm scenario developed by the U.S. Geological Survey and partners. BI stems from loss of building function, lost productivity of agricultural land, and reduced lifeline services. We develop a dynamic computable general equilibrium model of the California economy to perform this economic consequence analysis. Economic resilience in the form of input and import substitution is inherent in the model's equilibrium solution, and we also adjust its parameterization to reflect other forms of resilience such as production recapture and lifeline importance. Varying assumptions about the timing and source of funds for reconstruction results in a range of recovery paths. Five years after the storm, flood-induced building damage is the overwhelming source of GDP losses, timely and partially externally-funded reconstruction mitigates impacts by approximately 50%, and the economy is not guaranteed to return to its baseline GDP trajectory. Our methodology serves as a template for assessing the macroeconomic consequences of disasters and the influence of resilience in reducing BI losses.

Subject Headings

California ARkstorm; winter storm hazard; flood and wind damages, economic impacts; business interruption; economic resilience; computable general equilibrium models; sensitivity analysis; reconstruction funding

Introduction

This paper estimates the business interruption impacts that arise from the ARkStorm (severe winter storm) Scenario developed by the U.S. Geological Survey (USGS). ARkStorm refers to

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[1] Associate Professor, Dept. of Earth & Environment, Boston Univ., 675 Commonwealth Ave., Boston MA 02215. Email: isw@bu.edu

[2] Research Professor, Coordinator for Economics, Center for Risk and Economic Analysis of Terrorism Events, Price School of Public Policy, Univ. of Southern California, Ralph and Goldy Lewis Hall 230, Los Angeles, CA 90089-0626. Email: Adam.Rose@usc.edu

[3] Operations Research Analyst, Western Geographic Science Center, U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94303. Email: awein@ugsg.gov

“Atmospheric River”, a meteorological phenomenon that brings large masses of moist air to California, resulting in intense winter rainstorms/snowstorms lasting several weeks. It is considered a once in every 500 to 1,000 year event. Such a series of storms took place during the winter of 1861-62, though with minimal economic damage due to the state’s relatively small population, infrastructure and economic activity at the time. A lengthy series of major winter storms also took place during the winter of 2010-11, though at less than catastrophic levels. ARkstorm hazards include flooding and wind damage in the short term and landslide damage in the long term. The major impacted regions of California from ARkStorm would likely include its principal urban areas—especially the Sacramento Delta, with its low-lying land and aging dam/levee protection system, and densely developed and flood-exposed Orange, Los Angeles, and Santa Clara counties—as well as California's Central Valley, the major agricultural region west of the Rockies (Porter et al. 2011).

Economic impacts stem from simultaneous damage to buildings, agricultural lands, and several types of infrastructure. Our business interruption (BI) estimates include not only direct impacts that manifest themselves at the precise location and time that damage occurs, but also indirect impacts stemming from consequent disruptions of the interdependent activities of businesses and households throughout the economy. The direct BI estimates are based on calculations of loss of building function, loss of productivity on agricultural land, and reduction of lifeline services from damaged infrastructure. They are translated into decreases in the capital stock or direct declines in the productivity of firms’ output, as appropriate, across 29 sectors of the economy.

Our indirect BI loss estimates are derived from a dynamic computable general equilibrium (CGE) model of the California economy. CGE models are state-of-the-art economic tools that calculate the commodity and factor prices and activity levels of firms and households that equalize supply and demand across all markets in the economy (Shoven and Whalley 1992). They are based on the behavioral responses of representative producers and consumers to market price signals within the limits of the economy’s aggregate endowment of productive factors (e.g., capital and labor), and capture both the technical interdependence between economic actors in terms of production inputs and sales of product, as well as market activity and interactions through prices and substitution responses. The model we develop is dynamic, solving for the equilibrium of the economy on a 6-month time-step.

Hazard Loss Estimation

Basic Considerations

Business interruption (BI) losses, refer to the reduction in the flow of goods and services produced by property (capital stock). This stock/flow distinction is fundamental in economics, with flow measures such as gross domestic product (GDP) having long held a dominant position in evaluating the performance of an economy and the well-being of its population. Direct and indirect versions of both categories of losses are prevalent. Direct property damage refers to the effects of flooding, winds, and landslides while collateral, or indirect, property damage is exemplified by toxic releases from HAZMAT facilities damaged by the hazards. Such indirect property damages have been identified under environmental and health issues in the ARkStorm USGS open-file report (Porter et al. 2010), but not with enough specificity to evaluate their economic impacts. Direct BI refers to the immediate reduction or cessation of economic production in a damaged production facility or in one cut off from a utility lifeline. Indirect BI stems from the interdependencies of the economy in the form of “multiplier” effects associated with the supply- or customer chain of the directly affected business or through the general equilibrium effects of market interactions. The reader is referred to Rose (2004a) for an exposition of these concepts and to European Union (2003), MMC (2005), National Research Council (2006) and Rose et al. (2007) for examples of their application.

An important consideration is that nearly all direct property and ancillary (or indirect) property damage takes place during the time span of the winter storm (with the exception of some deep-seated landslides. BI, being a flow variable, however, manifests itself over a longer time period than storm related damage. It begins when the damages from flooding, wind, and landslides occur and continues until the built environment is repaired and reconstructed to some desired or feasible level (not necessarily pre-disaster status) and a normal business environment is restored. As such, BI is complicated because it is highly influenced by the choices of private and public decision makers about the pattern of recovery, including repair and reconstruction. As in the ShakeOut (catastrophic Southern California Earthquake) scenario (Jones et al. 2008; Rose et al. 2010), the aggregate magnitude of BI can rival that of property damage. Also, embodied technological progress suggests that more rapid investment during reconstruction which replaces old, less efficient capital with new, more efficient capital can potentially generate a temporary increase in aggregate productivity that offsets some loses in the long-run. However, the magnitude of this effect is challenging to estimate, because of its substantial variation with the type of capital assets being replaced, and therefore with the identities of the sectors suffering physical capital damage.

More recently, the loss estimation framework has been expanded in several ways, with the term economic consequence analysis used to highlight this broader scope (Rose 2009). The main extension is the incorporation of the loss reduction strategy of resilience, in both static and dynamic forms. We define static economic resilience as the ability of an entity or system to maintain function (e.g., continue producing) when shocked by the types of disruptions outlined above (see also Rose 2004b, 2009). It thus reflects the fundamental economic problem of efficient resource allocation, which is exacerbated in the context of disasters. This aspect is interpreted as static because the flexibility to engage in substitution on the demand side can make an economy resilient without repair and reconstruction activities, which affect not only the current level of economic activity but also its future time path. Another key feature of static economic resilience is that it is primarily a demand-side phenomenon involving users of inputs (customers) rather than producers (suppliers). This is in contrast to supply-side considerations, which definitely require the repair or reconstruction of critical inputs. By contrast, dynamic resilience is the speed at which an entity or system recovers from a severe shock to achieve a desired state. This also subsumes the concept of mathematical or system stability, as it implies the tendency of the system to “bounce back” to the equilibrium from which it was perturbed. This version of resilience is relatively more complex, because it encompasses long-term investment, which is intimately related to decisions about repair and reconstruction.

Throughout, we are careful to distinguish stock from flow effects and direct from indirect losses. We factor in BI associated with interdependent infrastructure failures. We include some major sources of resilience in the aftermath of disasters, including static resilience strategies of substitution responses to price signals and the ability to recapture lost production through overtime or extra shifts.

Conduits of Economic Shocks

Our focus is on the following conduits of shocks to the economic system arising from damages to the built environment:[6]

I. Direct damages to

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[6] There does not need to be actual damage for economic losses to occur—see, e.g., Dixon et al. (2010). Evacuation prior to disaster can cause even greater BI losses than a small version of the event itself. Also, some buildings can be closed for business because of their proximity to damaged structures. Some infrastructure services may be shut down as a precautionary measure as well.

    a. buildings and content from flood
    b. building damage from wind
II. crops, fruit and nut trees, and agricultural lands from flood
III. Direct lifeline service outages for:
    a. Electric power systems
    b. Water systems
    c. Wastewater treatment systems
    d. Telecommunication systems

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Our results are presented in terms of several economic impact indicators. We first present them in terms of property damage (loss of asset values). We also calculate the results in terms of state gross domestic product (GDP). The term “gross” here refers to the fact that depreciation (i.e., wear-and-tear or obsolescence of fixed capital assets) is included, although intermediate goods are not.

The Dynamic Computable General Equilibrium Model

A CGE model is a stylized computational representation of the circular flow of the economy. It solves for the set of commodity and factor prices and the set of activity levels of firms’ outputs and households’ incomes that equalize supply and demand across all markets in the economy (Sue Wing 2009, 2011). The model developed for this study divides California’s economy into 58 counties, each of which is modeled as an open economy with 29 industry sectors and households in nine different income categories. The industry aggregation is chosen to approximate the occupancy classes in HAZUS, the expert system used to calculate the building repair costs caused by ARkStorm’s floods and wind. Each sector is modeled as a representative firm characterized by a constant elasticity of substitution (CES) technology, which produces a single good or service. The households in each income class are modeled as a single representative agent with CES preferences and a constant marginal propensity to save and invest out of income. The government is represented in a simplified fashion. Its role in the circular flow of the economy is passive: collecting taxes from industries and passing some of the resulting revenue to the households as a lump-sum transfer, in addition to purchasing commodities to create a composite government good, which is also consumed by the households. Two factors of production are represented within the model: labor—whose endowments respond to changes in the wage rate, and capital,—which, over the time-step on which equilibrium is computed, is assumed to be sector-specific and immobile among industries and counties. Productive factors are owned by the representative agents, who “rent” them out to the firms in exchange for factor income.[9] Each county engages in trade with the rest of California, the rest of the U.S. and the rest of the world according to the Armington (1969) specification in which imports from other counties, and states and the rest of the world, are imperfect substitutes for goods produced locally.

The static component of the model computes the prices and quantities of goods and factors that bring supply and demand into line across all markets in the economy, subject to constraints on the external balance of payments. This equilibrium sub-model is embedded within a dynamic process, which, on a 6-month time-step, specifies exogenous improvements in firms’ productivity, increases households’ supply of labor according to the exogenous growth of the population, and updates household’s capital endowments based on investment-driven accumulation of the stocks of capital. The impacts of a severe storm are modeled as exogenous negative shocks to sectors’ capital stocks, generating concomitant reductions in the county-through-household endowments of sector-specific capital input.

The model is formulated as a mixed complementarity problem using the MPSGE subsystem for the General Algebraic Modeling System (GAMS) software (Rutherford 1999; Brooke et al. 1998) and is solved using the PATH solver (Ferris et al. 2000). The model’s algebraic structure is numerically calibrated using county-level IMPLAN social accounting matrices for the state of California for the year 2007 (Minnesota IMPLAN Group 2007). The key parameters of the model are summarized in an Appendix (available upon request), which also provides the sectoring scheme.

We model the consequences of storm’s damage impacts as an array of initial declines in sectoral capital stocks, which induce intra- and inter-sectoral substitution adjustments by producers and consumers, in addition to changes in the prices of commodities and factors. The result is a new equilibrium with reduced aggregate expenditure and investment, which generates contemporaneous losses of consumer welfare (relative to the model’s baseline solution), as well as slower growth of investment and stocks of capital. The latter ends up adversely affect the path of the economy’s endowment of capital input and its productive capacity in subsequent periods. This dynamic impact is a crucial source of hysteresis in the losses caused by physical storm damage, which only occurs in the first period of the simulation. Symmetrically, the principal channel through which repair and reconstruction

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[9] In the model capital is treated as sectorally and geographically immobile over the course of the 6-month period over which it solves for equilibrium. By contrast, to reflect the prevalence of commuting, labor is assumed to be sectorally and geographically mobile, employable by firms within as well as outside a particular agent’s county of residence.

investments dampen the persistence of losses is the output- and income-enhancing effect of restoring firms' productive capacity.

Methodological Details for Individual Loss Categories

In addition to the IMPLAN social accounting matrix, other data are critical for evaluating economic impacts and resilience associated with disasters. These include inventory data on both the built environment (commercial and industrial property, residences, and infrastructure) and the natural environment. Also needed is a set of damage functions that translate changes in the physical environment into property damage and loss of function. One such source is FEMA's Hazards United States-Multi-Hazard (HAZUS-MH) System (Federal Emergency Management Agency [FEMA] 2008). This is a large expert system that integrates detailed data on the built environment at the small-area level, a set of damage functions, and GIS capability to estimate direct dollar values of building repair costs and forgone sales revenue[10] .

Estimation of the main conduits of business interruption are described in Porter et al. (2010) and applied as follows:

I. Flood damaged buildings. The flooded building damage estimates were calculated using HAZUS equations. . However, there is a substantial overlap between the forgone gross sales revenue estimates and the declines in production that would be determined by the CGE model in response to reductions in the capital stock and the supply of capital input. Consequently, we concluded that imposing additional, exogenously-determined output reductions (e.g., FEMA 2009, Chapter 7) onto the system of markets being simulated would result in widespread double counting—and thus overestimation—of losses. For this reason we captured the effects of flooding on the sectors in the economic simulation purely through damage to the capital stock, expressed as percentages of the benchmark value of building assets by HAZUS occupancy class and county. Within the CGE model, the initial-period sectoral capital stocks and endowments of capital input were decremented by the same proportions as the shocks thus calculated.

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[10] For details, see the HAZUS flood technical manual (FEMA, n.d.: Chapter 14). These figures include output losses for non-residential occupancy classes and nursing homes, imputed output losses for rental and owner-occupied structures in residential occupancy classes, and the opportunity cost of additional flooded building downtime (due to dry out and clean up, inspection, permitting and ordinance approval, contractor availability and HAZMAT delay).

II. Wind damaged buildings. Building wind damages are also calculated using HAZUS equations. We applied the same procedure using proportional capital stocks developed for flooding.

III. Damages to agricultural commodities. An adaptation of the methodology developed for the Delta Risk Management Strategy (United Research Services and Jack R. Benjamin & Associates 2008) was used to estimate agricultural damages. Field repair costs were calculated for annual and perennial crops and livestock. In addition, forgone income was calculated for flooded annual crops; perennial crops flooded for two weeks or more incurred crop replacement costs and forgone income for up to five years; and the replacement value of livestock (dairies, feedlots, poultry) at risk was estimated in areas flooded to a depth of at least six feet. As these calculations assumed no damage to agricultural capital stocks, we were satisfied that imposing the output losses directly in the CGE model would not result in double counting of damages. Accordingly, the dollar values of forgone output were expressed as percentages of the total value of the crops in each county, and the resulting trajectories of fractional reductions in output were imposed within the CGE model as adverse neutral shocks to the productivity of agricultural sectors. By neutral we mean that the shock equiproportionally reduces the productivity of all inputs to agriculture, so that the sectoral output is reduced by that same percentage.

IV. **One feature of the computations for most of the infrastructure categories considered in our analysis is the timing of disruptions. The percentage of customers affected by lifeline outages is not constant but decreases over time as services are restored. Like buildings, wind and flood damages to infrastructure were assessed, the dominant cause of damage identified for the different types of infrastructure in each county, and service reduction and restoration curves developed based on panel discussions and expert opinion.** Electric power. Tthe pattern of electric power restoration (percentage of electricity services recovered in individual restoration periods) differed by county and ranged from .2% to 69% of customers initially out of service, with most counties experiencing complete restoration of service within one month except for a handful of outliers that required six months to fully restore power to its customer base. The power outages were localized to counties because generation capacity sited "high and dry" was not considered to be a limiting factor. Each county restoration curve was transformed into semi-annual power shortages for each occupancy class by: (i) integrating under the inverse of each county restoration curve to estimate the percentage of county customers not served during each quarter, (ii) weighting this percentage by the proportion of occupancy class square footage in the county, and (iii) summing up weighted county power shortages for each occupancy class.

V. Water. BI losses stemming from disruption of the water system were estimated in a manner similar to the power system, except that flooding was the only cause of damage. Consequently, forty-two counties were not affected by water supply disruptions. Based on the proportion of water treatment plants inundated, the remaining counties have disrupted water services to 10-60% of their customers, with complete restoration of service within three months.

VI. Waste water. The estimation of BI losses stemming from wastewater disruption follows the procedure used for the water system. Forty-one counties were not affected by waste water treatment disruptions. The remaining counties presented disrupted waste water services to 17-100% of its customers with service completely restored within one month.

VII. Telecommunications. The estimation of BI losses stemming from disruption of the telecommunications system from flood and wind damage follows our procedures for the power system. All counties experience reduced telecommunication services affecting 2-25% of customers for up to 7 days.

As with other categories of damage, lifeline losses (IV-VII) are first expressed in percentage terms before being imposed within the CGE model as adverse neutral productivity shocks on the Armington supplies of utility services in each county.

Resilience

This study incorporates static resilience options, and we perform sensitivity analysis on the dynamic aspect of recovery. Only a limited number of static resilience options were incorporated, albeit those that have been found to have the greatest potential for reducing BI losses (see, e.g., Rose et al. 2007). The primary source of static resilience is “production rescheduling”, the ability of firms to work overtime or extra shifts after they have repaired or replaced the necessary plant and equipment and their employees and critical inputs become available once more..

Production rescheduling is incorporated in HAZUS' DELM module through the inclusion of production "recapture factors" (RFs), scaling parameters that represent the percentage of direct gross output losses that can be recovered at a later date. The original HAZUS RFs range from 0.30 to 0.99. Manufacturing enterprises that produce non-perishable commodities are at the high end, while sectors producing perishables (e.g., agricultural) or non-essential services (e.g., entertainment) are at the lower end of the scale. These RFs are subject to the caveat that they are applicable only for three months with no effect thereafter. This is meant to reflect the fact that customers will grow increasingly impatient as their orders go unfilled. Accordingly, we adjusted the HAZUS RFs downward by a linear decay rate of 25% for every three-month period during the first year, so that recapture becomes zero by the second year. In our view, this reflects a more realistic situation in which customers become increasingly impatient over time, canceling larger numbers of orders as delays mount (Rose 2009; Rose et al. 2011).

Our use of the percentage of capital stock destroyed as our measure of reduced productive capacity collapses the entire shock to the economy into the first period of our simulation, which prevents recapture from offsetting losses that persist beyond the initial period, biasing downward our estimates of the impact of resilience. Our remedy is to reinterpret HAZUS' time-varying RFs as applying not to sectors' output but to their productive capacity, which we define as the flow of services from those capital assets which survive the initial destructive event. The key effect of production rescheduling is therefore to temporarily increase the productivity of these capital services, with the result that counties' capital input measured in efficiency units no longer decline in lock-step with the storm-related losses in their underlying capital stocks.

A second type of resilience is infrastructure "importance." The term stems from ATC-25 (1991), which convened a panel of experts to advance hazard loss estimation. One of the contributions was to identify the percentage of a sector's business operations that does not depend on a specific category of infrastructure. Thus, even if there is a lifeline outage, a portion of the sector can keep operating. We did not include Importance in our analysis, however, because of the dominant impact of flood building damage, which renders separability of production activities moot during correlated water and wastewater service disruptions.

The market system itself is a major source of resilience. Price increases signal that resources have become scarcer, and thereby have a higher value, and that we should reallocate inputs accordingly. Accordingly, it bears noting that not all price increases represent gouging, and our CGE simulations indicate what increases are warranted on the basis of economic efficiency. The CGE model also incorporates substitution possibilities as part of the production function of individual businesses.

Finally, it bears emphasizing that in the absence of detailed information we have often employ scalar or linear relationships to characterize resilience. Notwithstanding this, we acknowledge that there is likely to be a threshold at which even resilience is eroded, beyond which the economic system will be overwhelmed and rendered much less able to return to its pre-disaster equilibrium. This has been the case for Hurricane Katrina, and is likely to be the case for some areas hit by ARkStorm.

Benchmark Macroeconomic Impacts

In this section, we summarize the macroeconomic impacts of the ARkStorm Scenario as estimated in the CGE model results. First, we present GDP losses for both the pure damage effects and for the case where we factor in reconstruction spending. Results for the “no reconstruction, no recapture” case are used in this summary because they represent the gross damage from the storm. Below, we simulate additional “with recapture” and “with reconstruction” cases, which incorporate production rescheduling as an additional margin of adjustment and include the offsetting stimulus of financing of repair investments from outside of the affected region. We then present the results of sensitivity analyses related to direct loss estimates, reconstruction timing, and the extent to which reconstruction spending offsets ordinary investment. BI losses are presented in two ways. The first are calculated relative to California’s projected business as usual (BAU) trajectory of GDP, which in the absence of any catastrophic storm or other major shock increases at an annual average rate of 1.7%, or 8.7% over the 5-year simulation horizon. The second set of BI loss estimates is calculated relative to the pre-storm GDP of $945 billion for the initial 6-month period of the simulation (this reflects California’s 2007 annual GDP of $1.89 trillion). There is no consensus on which of the two approaches best reflects losses, so we have opted to present both, which can be thought of as long- and short-run estimates, respectively.

Figs. 1 and 2 illustrate the temporal patterns of ARkStorm’s impacts, in terms of the contributions of individual components of damage to the path of California’s GDP in the aftermath of the storm, as well as the business interruption losses incurred during the recovery to the pre-storm level of income (the “loss triangle”). The impacts of wind damage to buildings and damage to crops and utility lifelines are all generally small and are broadly similar in terms of the magnitude of their long-run effects on GDP. By contrast, building flood damage has a large and persistent impact, representing a one-time downward shift in the growth path of the economy. This trajectory is closely tracked by our base case simulation, in which damages in all four of these categories are imposed simultaneously. Interestingly, the path of GDP implied by the sum of the individual damage components falls short of our base case.

The implication is that ex-post summation of the various categories of damages overstates the true simultaneous impact, principally because producers and consumers are able to adjust to temporary lifeline outages and reduced supplies of agricultural goods by engaging in substitution within and across counties, in response to the storm's differential impacts on the relative prices of input commodities and factors. In the present setting, the difference in the resulting estimate is substantial, ranging from 6% in the initial period to 33% at the end of the 5-year simulation horizon. Nevertheless, in every case ARkStorm's long-run impact is to move the economy to a lower growth path that parallels the slight exponential GDP increase in the BAU trajectory.[17] The key implication of the CGE model's supply-driven framework is that without reconstruction of destroyed capital or some other exogenous infusion of resources there is no mechanism by which the economy can recoup BI-related forgone output and investment on its own. The result that business-as-usual levels of output and income are never re-attained within our evaluation time-frame.

Fig. 2 provides a clearer picture of the differences among the lifeline, building wind damage and agricultural impacts. Here, near-term losses are the value of forgone output over the period of recovery to the pre-event level of GDP, given by the area of the triangle bounded by the axes and the trajectories in the figure. Losses from agriculture damage vastly exceed those from the first two damage components, because of the small magnitude of wind damage and the fact that lifeline losses attenuate quickly. The corollary is that the hysteresis introduced by the very large loss of capital—and productive capacity—due to flooding is the principal driver of overall losses, whether estimated as the short-run loss triangle in Fig. 2 or as the area between BAU and post-event trajectories of GDP in Fig. 1. One final noteworthy feature of Fig. 2 is the difference between the simultaneous and sum-of-damage loss measures indicated by the solid and dashed heavy lines. After the first 6 months, losses in the latter measure increase slightly before declining, reflecting the additional drag on the economy's output from persistent lifeline and agriculture damages. The simultaneous damages measure highlights the fact that in cases such as this where the persistent effects are small, they can be counteracted by variable input substitution.

The main results of our analysis are summarized in Table 1. . The first numerical column lists property damage estimates developed by other research team members (see Porter et al. 2011). The total is $353.6 billion (2007 dollars). The second column tabulates the loss estimates which form the

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[17] In a recursive-dynamic model with constant marginal propensity to save of the kind used here, a one-time loss of a portion of the capital stock shifts the economy onto a lower trajectory of output and capital accumulation. Holding constant other economic forces, output growth will resume at the rate that prevailed prior to the shock, but with smaller values of all economic quantities.

inputs to the CGE model, computed by normalizing the quantities in column 1 by their respective totals and multiplying the result by the corresponding economic quantities in the CGE model. The difference from column 1 highlights the fact that HAZUS' "bottom-up" calculations based on estimates of the book value of asset stocks produce results are largely incommensurate with the "top-down" macroeconomic input-output accounts used to calibrate CGE models. While this divide is precisely what our data translation procedures in Section IV attempts to bridge, we in no way expect the methodology developed here to be the last word on this issue. Rather, our results are an invitation to economists and engineers to jointly advance the methodological underpinnings of economic loss calculations.

Total BI losses relative to the BAU trajectory of the California economy are presented in column 3. When computed on a sum-of-damage-components basis, losses amount to $386.6 billion, similar in magnitude to the losses tabulated in column 2 and some 9% larger than total property damage in column 1. By far the largest component (nearly 65% of the total) is attributable to flooding. Losses from Wind, Agriculture (damage to crops and arable land), and lifeline disruption are roughly equivalent.. Some BI losses, such as those associated with Levee Repair and Relocation were not computed, but are not likely to exceed their property damage counterparts, and thus do not represent any major omission in the estimates. Total BI losses relative to the Pre-Storm GDP are presented in column 4. They amount to $115.7 billion, 35% of the size of the estimates in column 1. Here, flood losses are an even higher percentage of the total (90%). To put these results in perspective, the estimates in columns 1-4 would render ARkStorm the largest disaster ever to hit the US. Property damages in column 1 are more than three times those of Hurricane Katrina, as are the BI losses, which are more than three times those of the September 11, 2001 World Trade Center attacks (Rose et al. 2009; Rose and Blomberg 2010). The property losses from ARkStorm exceed the property damage estimates of the ShakeOut scenario (approximately $100 billon). ShakeOut BI estimates were about $67 billion but were computed relative to the pre-event GDP only. Moreover they were computed for a much smaller region (8 counties in southern California).

In percentage terms, the summed BI losses represent 4.4% of GDP for the BAU Trajectory and 2.1% of pre-event GDP, comparable to the 4% loss in gross regional product incurred by ShakeOut. Note that although total BI in column 3 is nearly four times as great as that in column 4, the percentage relative to the baseline is less than twice as large, a result which reflects the consistent upward trend of GDP in the various scenarios in Figs. 1 and 2. Even in the absence of dedicated reconstruction investment, economic growth does resume after the shock to the economy, leading to more rapid decay of losses relative to the Pre-Event GDP level, which causes the economic base for the calculation of losses in column 4 to be much smaller than that used to compute losses for column 3.

Relative to pre-event GDP (column 4) and BAU trajectory (column 3) simultaneous losses are 41% and 29% lower than the corresponding sum-of-damage-components estimates, respectively. Interestingly, the disparity between the simultaneous impacts underscores the difference in the dynamic effects of storm damage. The absence of substitution reflected in the sum-of-damage-components estimate suggests a sub-optimal response by economic actors that implicitly leaves fewer resources available for contemporaneous investment, leading to a diminished pace of capital accumulation that places the economy on a growth path that is not just lower, but also *slower*. Thus, as reinforced by Fig. 2, both the distance and the area between the trajectories of losses (indicated respectively by the heavy solid and dashed lines) grows as time goes on. Consequently, the areas of two near-term loss triangles are closer to one another in size than the corresponding trapezoids of GDP losses relative to the BAU scenario over the entire simulation horizon.

Columns 5 and 6 summarize the results of these scenarios assuming producers' ability to recoup losses through recapture. While production rescheduling has a slight effect on the costs of agricultural and lifeline damage, it has a more substantial mitigating impact on the present value of wind and particularly flood losses, to the tune of $1.8 billion and $29.5 billion, respectively. Recapture lowers both the sum-of-damage-components and simultaneous-damage loss estimates by 8%, to $358.8 billion and $249.3 billion. The impact on losses computed relative to pre-event GDP is more pronounced because recapture is confined to the initial 12-month period after the storm, with a larger effect on the near-term loss triangle than on costs incurred over the longer simulation horizon. Present value losses are 23% lower when computed on a sum-of-damage-components basis, and 34% lower when all damages are imposed simultaneously. The difference in these figures primarily reflects the larger loss triangle in the former case, consistent with Fig. 2.

Sensitivity Analyses

We also performed several sensitivity tests on the base case simultaneous results. First, the direct property damage/lifeline outage estimates were increased and decreased by 25% relative to their base levels. This broad range is admittedly impressionistic. but our intent is to shed light on the potential impact of uncertainty in the magnitude of the meteorological forcing (i.e., a larger or smaller storm).

As well, we simulated the effects of reconstruction investment on the economy following ARkStorm. Our base case with reconstruction assumes full repair of wind and flood damage to the capital stock by 24 months after the storm, with reconstruction spending making up lump sum quantities of investment in the amount of 50% of initial capital losses 6-12 months after the storm, and 25% of capital losses in each of the subsequent semi-annual periods. Crucially, our default assumption is that 50% of the funds for repair and reconstruction come from within California (via household savings and retained earnings of businesses), and 50% flow in from outside (principally insurance payments and federal government assistance). The use of domestic or "internal" funds displaces ordinary investment in plant and equipment and residential structures, while "external" financing from outside California results in a pure additive boost to the state's productive capacity, with no opportunity cost. In particular, we assume that every dollar of internal capital formation is purchased at the cost of more than a dollar's worth of principal and interest payments over the remainder of the simulation horizon, which dampens the overall stimulus effect of repair and reconstruction in the long run.[18] We quantify the importance of this effect by performing sensitivity analyses around our equal division of financing between California and rest-of-world sources, simulating cases with 75%-25% and 25%-75% internal-external financing splits, as well as our 50%-50% base case with a 6-month delay in the availability of reconstruction funds.

Fig. 3 shows the strong influence of production recapture (which takes place at a declining rate during the first 12 months after the disaster). It also shows that the results are more sensitive to initial property damage (from storms of different magnitudes) than to the influence of reconstruction. Fig. 4 presents sensitivity analyses for the geographic origin of financing of reconstruction and for the effect of delays in reconstruction. The former is far less influential on GDP losses than the latter.

The impact of scaling the various damage components is straightforward, shifting the base case GDP trajectory upward or downward to the tune of $7 billion in each period (Fig. 3). More interesting is the effect of reconstruction investment, the sign of which depends critically on the fraction of reconstruction spending sourced internally (Fig. 4). Relative to the no reconstruction, no recapture base case, our 50%-50% financing scenario generates savings of $3 billion 6-12 months after the storm, a beneficial effect that decays linearly as time proceeds. The largest savings are an upward shift of GDP by $8.5 billion to$15 billion, which arise when 75% of the cost of capital stock reconstruction comes from outside California. Conversely, imposing a mandate that these economic actors raise these funds internally *exacerbates* the long-run reduction in GDP, shifting it *downward* by $2 billion to $12 billion.

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[18] We assumed that each tranche of reconstruction spending was first distributed among counties in proportion to their aggregate capital stock damage, and then among the sectors within each county in proportion to their pre-event shares of capital. The resulting increment to investment stimulated additional growth in counties' sectoral capital stocks. In simulating internal financing we made the simplest possible assumptions that the costs are distributed across households according to their ownership shares of California's pre-event aggregate capital endowment, and are incurred at the opportunity cost of investment goods.

This additional loss stems from the resources dissipated in financing investment at a higher rate than in the base case. For this reason, the need to rely heavily on domestic financing sources would seem to militate against such a program of reconstruction, as economic actors would find it more cost-effective to simply pursue a slower pace of investment, capital accumulation and economic growth, trading off savings from avoided capital adjustment costs against forgone output at the margin.

The sensitivity results are summarized in Table 2. For the BAU Trajectory case, the 25% higher (lower) direct damage case yielded an increase (decrease) in total BI losses of 22.9% (22.6%), indicating that aggregate losses increase approximately linearly with the magnitude of the shock. Measured in terms of pre-event GDP, the corresponding losses increase by 42.8% and decline by 36.7%, an asymmetry reflecting the predominance of persistent capital stock and investment related damages (with larger loss triangles) relative to shorter term lifeline and agriculture related damages. It is straightforward to show that if the average rate of growth of aggregate GDP is invariant to the magnitude of the overall shock, the area of the loss triangle varies approximately with the square of the initial damage. Consequently, the same percentage increase and decrease in initial damage generate a different percentage increase and decrease in the size of the loss triangle.

Under our default financing assumptions, reconstruction lowers the present value of BI losses by 6% over the 5-year horizon, to $257.4 billion and by 14% when measured relative to pre-event GDP, to $57.9 billion. This more elastic near-term response is symptomatic of the drag on the economy created by the additional expenditure necessary to finance the domestic component of reconstruction. While the supplemental investment provided by the principal stimulates a rapid increase in the economy's productive capacity and output in early periods, the associated financing charges reduce the resources available for investment over the entire horizon, slowing the growth of output in later periods.

Rows E, F and G illustrate the sensitivity to our assumption of a 50%-50% internal-external financing split. As expected a larger share of external financing reduces the quantity of investment principal and the stream of internal financing payments, and long-term drag on economic growth. The sensitivity of losses to financing assumptions are larger when calculated over the entire simulation horizon than over the short-run loss triangle. Losses for 75%-25% internal-external case were estimated to be $343 billion, one-third higher than in the 50%-50% case. Symmetrically, losses in the 25%-75% internal-external case are one third lower. Recasting these figures in terms of recovery to pre-event GDP, financing 75% of reconstruction through domestic sources is accompanied by 48% higher BI losses than in row E ($85.9 billion), while having to finance only 25% internally reduces BI losses by one quarter ($43.3 billion).

Row H assumes a 6-month delay in reconstruction spending, which generates a 7% increase in BI losses over row E, to $275.2 billion, while losses relative to pre-event GDP increase by 10%, to $63.8 billion.. Delayed reconstruction lengthens the lag between the initial capital stock losses and the compensating output-expanding stimulus, increasing the size of the near-term loss triangle. In addition to forcing the economy to forgo six months of higher output, our assumption of a fixed-end date for reconstruction financing translates into a shorter sequence of larger payments, which further attenuates long-term economic growth. The former lump-sum loss outweighs the latter amortized loss, resulting in a front-loaded BI cost that is larger in present value terms. Lastly, rows D and I summarize the results of simulations with recapture as a point of comparison. In row D, the mitigating effects of recapture alone offset BI by a somewhat larger amount than our reconstruction case with 50% internal financing..

Overall, the sensitivity results exhibit a modest range of variation, which gives us confidence in the robustness of our base case loss estimates. The key insight from the difference in the savings due to recapture versus reconstruction investment is that time is of the essence in disaster recovery. The biggest benefit of resilience derives from components whose mitigating effects kick in quickly after the event. Recapture's larger effect in both the short- and the long run arises from its ability to offset damage to productive capacity in the first post-storm period that is not only large but carries the heaviest weight in our present value calculation. This mitigates the large drop in initial output that would otherwise occur, and indirectly cushions the shock to investment, which makes available a larger supply of capital—facilitating the generation of more output—in every subsequent period. Finally, our analysis indicates that even a very high level of external financing is not sufficient to completely shift the economy back to its BAU trajectory of growth, as has been the case in a small percentage of disaster aftermaths (e.g., the Northridge Earthquake).

Conclusion

We have estimated the economic impacts of ARkStorm to potentially much more than one hundred billion dollars over a five-year period. There are uncertainties in the cost estimates (noted as ranges for lifelines and agricultural damages). However, the relative order of magnitude of the results is likely representative of the domination of flooded building damages and economic impacts followed by lifeline services, water service in particular. Although agricultural impacts are estimated as relatively light, they are of a much greater scale than experienced during previous California storms.

The novel aspect of this study is its use of a computable general equilibrium approach to systematically characterize and quantify the economic consequences of the full spectrum of individual but overlapping impacts of a large-scale natural disaster. The input-output approaches utilized by ShakeOut and similar studies (for reviews see Okuyama and Chang 2004; Okuyama 2007) have difficulty capturing the feedback effects of property damage, temporary interruptions in labor supplies, and hysteretic adverse productivity shocks on prices, producers' and consumers' substitution responses, and concomitant intersectoral supply-demand adjustments across the economy. Distinctly, prior CGE analyses of the effects of disasters either limit consideration of impacts to a fairly narrow range of damage categories (e.g., Rose et al. 1997; Rose and Liao 2005; Rose et al. 2007), or express the shock to the economy in a highly aggregate fashion with little differentiation among different types of damage (e.g., Selcuk and Yeldan 2001; Narayan 2003), potentially leading to under- or double-counting of impacts (respectively) and their associated macroeconomic costs. within a CGE framework , remaining issues depend on empirical characterization of technological progress from innovations embodied in new capital, changes in household savings rates in the post-disaster economic environment, geographic relocation of firms, and optimal use of reconstruction investment.. Bearing these issues in mind, our key contribution is the development of algorithms for translating the outputs of geospatial engineering models of disaster damage (HAZUS) into sequences of shocks to capital stocks and productivity in various industry sectors that can be employed as inputs to economic impact assessment simulations. By addressing several of the methodological concerns outlined in Rose (2004) and Okuyama (2007), the current advance provides a roadmap for refining future estimates of both the macroeconomic costs of disasters and the influence of resilience in reducing economic losses.

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Table 1. Summary of ARkStorm Property Damage and Business Interruption for California, Without Reconstruction (billion 2007 $)

	Property Damage		Business Interruption[a]			
			Without Recapture		With Recapture	
	(1) HAZUS/ DWR models	(2) CGE model[b]	(3) Relative to projected GDP	(4) Relative to pre-event GDP	(5) Relative to projected GDP	(6) Relative to pre-event GDP
Building Flood Damage	195.0[c]	376.6	270.5 [3.1%]	62.5 [1.8%]	246.0 [2.8%]	42.6 [1.2%]
related content damage	103.0					
Building Wind Damage	5.6	4.7	40.8 [0.5%]	1.7 [0.2%]	39.0 [0.4%]	0.3 [0.03%]
Agricultural Damage[d]	3.6[e]	1.3[a]	38.5 [0.4%]	1.5 [0.07%]	37.3 [0.4%]	0.6 [0.07%]
Lifeline Damage	6.9[f,g,h]	0.5[a]	36.8 [0.4%]	0.04 [0.005%]	36.5 [0.4%]	0.02 [0.002%]
Levee Repair/Island Dewatering	0.5[i]	n.a.[j]	n.a.	n.a.	n.a.	n.a.
Relocation	39.0[k]	n.a.[l]	n.a.	n.a.	n.a.	n.a.
Sum of Damage Categories	353.6	383.0	386.6 [4.4%]	115.7 [2.1%]	358.8 [4.1%]	89.3 [1.3%]
Simultaneous Impact of Damages			274.6 [3.1%]	67.6 [1.9%]	249.3 [2.8%]	44.4 [1.2%]

[a] Present value calculation using a 5% discount rate. Absolute and percentages losses calculated relative to the present value of real GDP in the BAU scenario.

[b] These numbers represent HAZUS and DWR losses normalized by their respective benchmark values to generate percentage shocks, which are then multiplied by the relevant economic quantities in the CGE model see Section IV for details).

[c] Weather and flood warning (of at least 48) hours could reduce building and content damages by $30 billion, while demand surge could increase property repair cost by $70 billion (Porter, 2011).

[d] Agricultural costs pertain to field damage, crop and livestock replacement and forgone income from crop losses.

[e] Agricultural losses increase to $6.8 billion for high-end range of flood duration estimate

[f] Power system repair cost estimates range from $0.3-$3 billion.

[g] Water system repair cost estimate ranges from $1-10 billion.

[h] Highway repair cost estimate ranges from $2-3 billion.

[i] Levee repair and dewatering costs pertain to the levees and islands in the San Joaquin Delta only.

[j] Potentially, levee repair and Island dewatering time could increase BI losses by increasing agricultural damages.

[k] $39 billion relocation costs calculated using HAZUS formulas, $25 billion for relocation of residences, $11 billion for relocation of commercial establishments, and the remainder for industry, education, religion and agricultural occupancy classes.

[l] Indirect effects of relocation have not been evaluated; building service interruption multipliers have not been developed for the flood module of HAZUS-MH.

Table 2. Present Value of Absolute and Percentage GDP Losses (5% discount rate)

		Relative to BAU GDP Trajectory		Relative to Pre-Event GDP Level	
		(billion 2007$)	(%)	(billion 2007$)	(%)
A.	Base case damages (no recapture, no reconstruction)	274.6	3.1	67.6	1.9
B.	125% x all base case damages	337.4	3.8	96.5	2.1
C.	75% x all base case damages	212.5	2.4	42.8	1.5
D.	Base case damages with recapture (no reconstruction)	249.3	2.8	44.4	1.2
E.	Base case damages with reconstruction (50%-50% internal-external financing)	257.4	2.9	57.9	1.6
F.	Base case damages with reconstruction (75%-25% internal-external financing)	343.0	3.9	85.9	1.9
G.	Base case damages with reconstruction (25%-75% internal-external financing)	170.0	1.9	43.3	1.6
H.	Base case damages with reconstruction (delayed 6 months)	275.2	3.1	63.8	1.7
I.	Base case damages with recapture and reconstruction (50%-50% internal-external financing)	236.4	2.7	38.5	1.1

Fig. 1. ARkStorm impacts on the trajectory of semi-annual real GDP

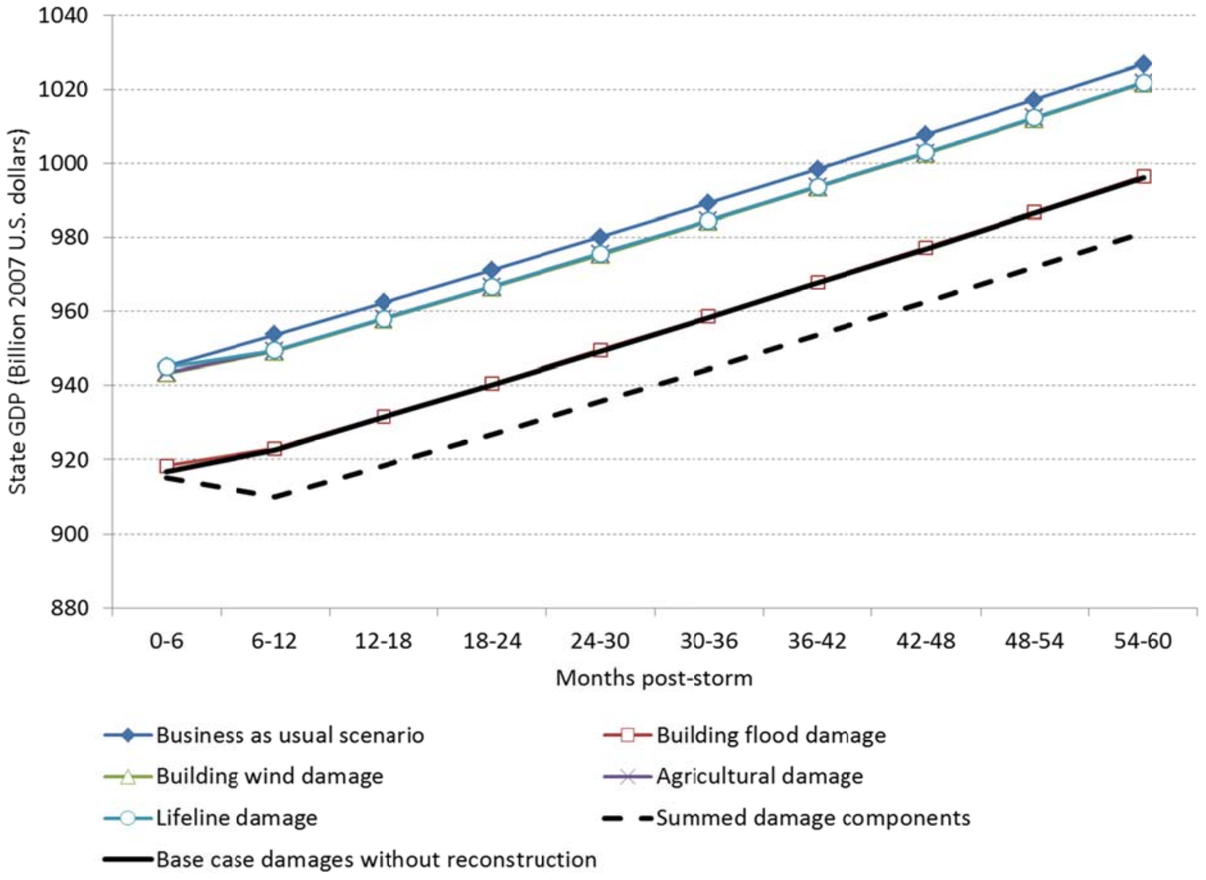

Fig. 2. ARkStorm semi-annual losses and recovery relative to pre-event GDP

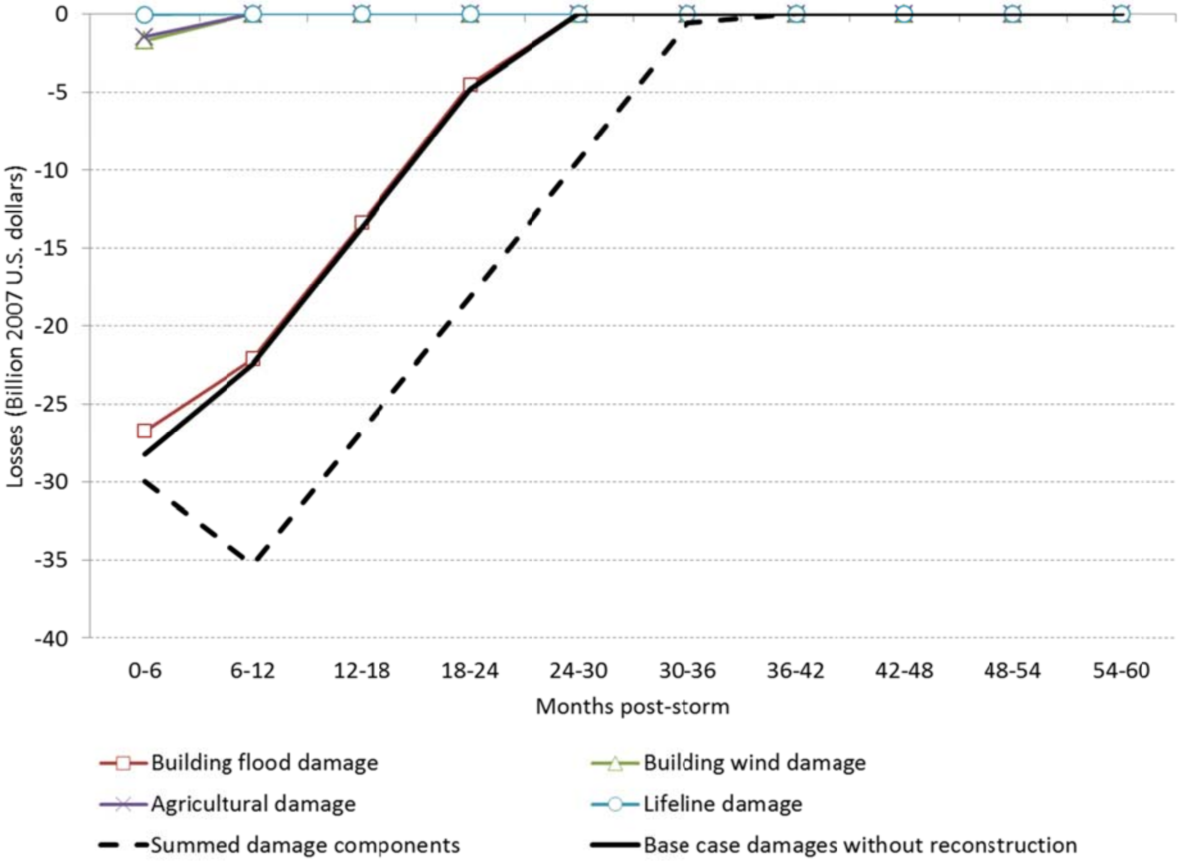

Fig. 3. Real semi-annual GDP: Sensitivity to storm magnitude and recapture

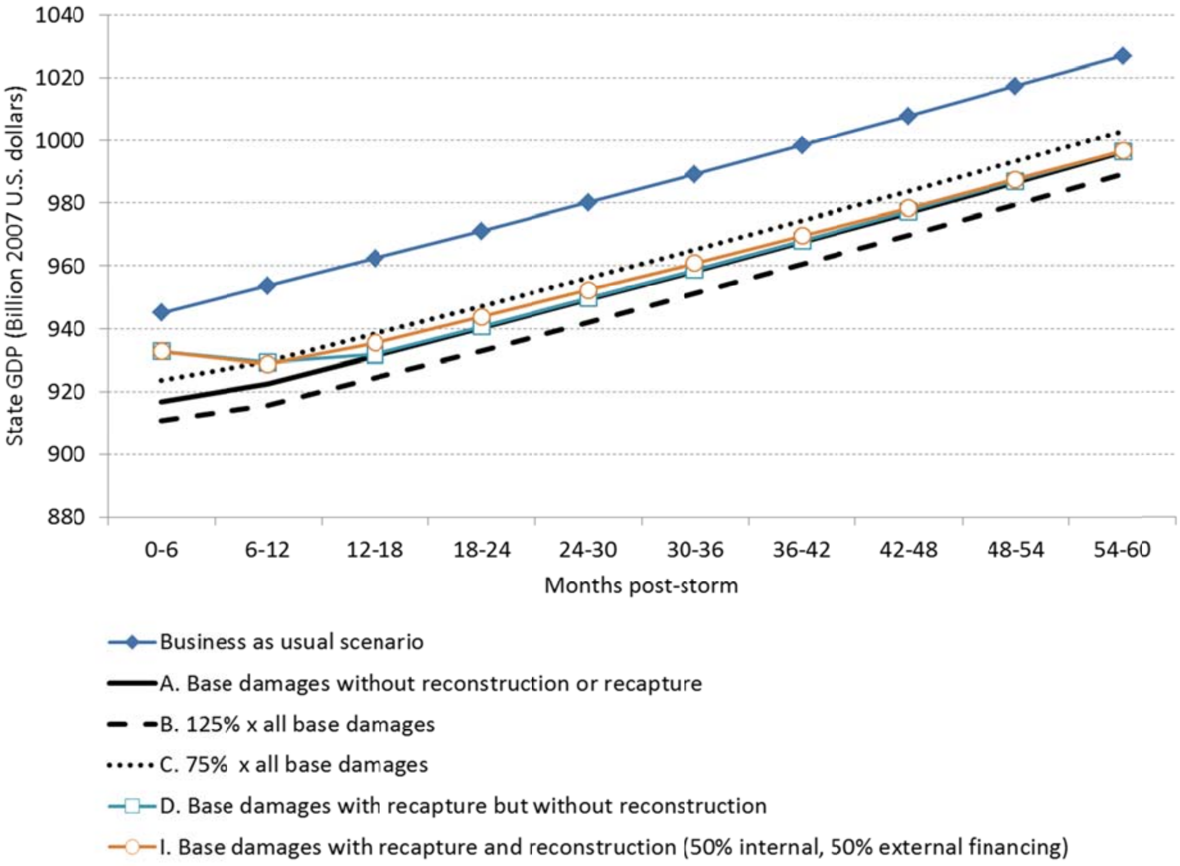

Fig. 4. Semi-annual real GDP: Sensitivity to reconstruction and its financing