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The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience

Stephane Hallegatte

World Bank Group
Finance and Markets Global Practice Group
&
Global Facility for Disaster Reduction and Recovery
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Abstract

The welfare impact of a disaster does not depend only on the physical characteristics of the event or its direct impacts in terms of lost lives and assets. Depending on the ability of the economy to cope, recover, and reconstruct, the reconstruction will be more or less difficult, and the welfare effects smaller or larger. This ability, which can be referred to as the macroeconomic resilience of the economy to natural disasters, is an important parameter to estimate the overall vulnerability of a population. Here, resilience is decomposed into two components: instantaneous resilience, which is the ability to limit the magnitude of the immediate loss of income for a given amount of capital losses, and dynamic resilience, which is the ability to reconstruct and recover quickly. The paper proposes a rule of thumb to estimate macroeconomic resilience, based on the interest rate (a higher interest rate decreases resilience and increases welfare losses), the reconstruction duration (a longer reconstruction duration increases welfare losses), and a "ripple-effect" factor that increases or decreases immediate losses (negative if enough idle resources are available to cope; positive if cross-sector and supply-chain issues impair the production of non-affected capital). An optimal risk management strategy is very likely to include measures to reduce direct impacts (disaster risk reduction actions) and measures to reduce indirect impacts (resilience building actions).

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The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience[1][2]

Stephane Hallegatte

The World Bank
Climate Change Group – Office of the Chief Economist
shallegatte@worldbank.org

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1 Introduction

From an economic perspective, a natural disaster can be defined as a natural event that causes a perturbation to the functioning of the economic system, with a significant negative impact on assets, production factors, output, employment, or consumption. There are multiple formal definitions. The Center for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain defines a disaster as a natural situation or event which overwhelms local capacity and/or necessitates a request for external assistance.[3] When it happens, however, the perturbation affects the economic system in a way that goes beyond the loss of assets and the monetary expenditures to replace damaged property. Additional consequences include the loss of output and production, rationing in some sectors, loss of employment and tax revenues, etc.

Even though the most immediate consequences of natural disasters are obviously the fatalities and casualties they cause, the economic consequences need to be accounted for to assess the disaster impact on the population's well-being and welfare.

This paper discusses the economic consequences of natural disasters. It summarizes the most important mechanisms that determine the cost of disaster, and explains why the direct economic cost, i.e. the value of what has been damaged or destroyed by the disaster, is not a sufficient indicator of disaster seriousness and why estimating indirect losses is crucial. Then, it discusses the methodologies and the models that are able to measure indirect losses and proposes a simple rule of thumb to take them into account when time and resources do not allow for a full modeling exercise. Finally, the paper discusses the tools that are available to increase the resilience of the economic system, i.e. to make it better able to recover and reconstruct and to reduce the indirect consequences of disasters.

Throughout this paper, boxes will present an application of the methodologies on one case study conducted in an OECD project, on flood risk in Mumbai.[4] The study investigates the vulnerability to heavy precipitations of the city of Mumbai, a rapidly-growing coastal city in a developing country. The complete study is available in (Ranger et al., 2011), and a longer version with a survey of the slum dwellers affected during the 2005 floods in Mumbai is in (Hallegatte et al., 2010).

2 The economic cost of a disaster

2.1 Defining the economic cost of extreme events

Defining the economic cost of a disaster poses different theoretical and practical challenges. After each large-scale disaster, media, insurance companies and international institutions publish numerous assessments of the "cost of the disaster." These various assessments are based on different

[3] For a disaster to be listed in the EM-DAT database, at least one of the following criteria should be met: (i) 10 or more people are reported killed; (ii) 100 people are reported affected; (iii) a state of emergency is declared; (iv) a call for international assistance is issued.
[4] The study was carried out by a consortium including the OECD, Risk Management Solutions, CIRED, Météo-France, NATCOM PMC, and the Indian Institute for Technology Bombay at Mumbai, and published in Ranger et al. (2011).

methodologies and approaches, and they often reach quite different results. In the US, for instance, a systematic analysis by (Downton and Pielke, 2005) showed that loss estimates differ by a factor of 2 or more for half of the floods that cause less than $50 million in damages. These discrepancies are in part due to technical and practical problems, but also to the multi-dimensionality in disaster impacts and their large redistributive effects and the fact that the boundary of assessment dependent on the purpose of the assessment.[5] But the purpose of these assessments is rarely specified, even though different purposes correspond to different perimeters of analysis and different definitions of what a cost is.

This confusion translates into the multiplicity of words to characterize the cost of a disaster in published assessments: direct losses, asset losses, indirect losses, output losses, intangible losses, market and non-market losses, welfare losses, or some combination of those. It also makes it almost impossible to compare or aggregate published estimates that are based on many different assumptions and methods.

2.1.1 Direct and indirect costs

Many authors have discussed typologies of disaster impacts (e.g., Cochrane, 2004; Lindell and Prater, 2003; Pelling et al., 2002; Rose, 2004). These typologies usually distinguish between direct and indirect losses. Direct losses are the immediate consequences of the disaster physical phenomenon: the consequence of high winds, of water inundation, or of ground shaking. Typical examples include roofs that are destroyed by high winds, cars destroyed and roads washed away by floods, and injuries and fatalities from collapsed buildings. Direct losses are often classified into direct market losses (for goods that can be bought on a market, such as cars and buildings) and direct non-market losses (for what cannot be bought on a market, like human lives and ecosystems). Indirect losses (also labelled "higher-order losses" in Rose, 2004) include all losses that are not provoked by the disaster itself, but by its consequences; they span over a longer period of time than the event, and they affect a larger spatial scale or different economic sectors. They include some additional losses to assets (e.g., when an earthquake causes a fire or a toxic spill that damages assets) and effects on flows (e.g., through macroeconomic effects).

Here, instead of the direct/indirect typology, we use an alternative (and complementary) terminology. Like in (NRC, 2013, 2011; Rose et al., 2007b), we distinguish between *asset losses* (i.e., the *stock* of assets that is reduced), and *output losses* (i.e., a reduction in an income *flow*). Output losses include different categories that often overlap:

- *Business interruptions* (the interruption in production during the event);
- *Production losses directly due to asset losses* (because damaged or destroyed assets cannot produce, during a period that is much longer than the event itself);
- *Supply-chain disruptions* (when lack of input or reduced demand is responsible for a reduction in production from a production site that is not directly affected);

[5] For instance, an analysis can be carried out at national scale to estimate the impact on macroeconomic aggregates (e.g., GDP, tax revenues) and at local scale to estimate local welfare losses and the need for support. The latter will not include potential benefits outside the affected areas; the former will include them.

- *Macro-economic feedbacks* (e.g., the impact of reduced final demand because consumers and businesses suffer from a reduced income, and the effect of lost tax revenue on public demand);
- *Long-term adverse consequences on economic growth* (e.g., due to changes in risk perception (including over-reactions) that can drive investors and entrepreneurs out of the affected area);
- *Increased production from the "reconstruction boom"* that acts as a stimulus for the economy.

Note that these output losses include household production, not only production by the productive and commercial sectors. For instance, the reduction in housing service (a service produced by houses and dwellings) is considered as an output loss, as are all services from other household assets (e.g., appliances).

The impact on poverty or inequalities is also sometimes included in the indirect losses. The landfall of Katrina on New Orleans has renewed attention on the larger weather vulnerability of the poorest communities within a country, and on the inequality-widening effect of disasters (Atkins and Moy, 2005; Tierney, 2006). Rodriguez-Oreggia et al. (2009) show that municipalities affected by disasters in Mexico see an increase in poverty by 1.5 to 3.6 percentage points. Often, the poorest have little to lose in a disaster and the impact on their welfare is therefore invisible in aggregated economic statistics. If the aim of the assessment is to look at welfare impacts, focusing only on economic aggregates can be misleading.

Some of these impacts can be captured using classical economic indicators, such as Gross Domestic Product (GDP). There are however several issues when using GDP change as an indicator for output losses. A first question deals with the spatial scale: for large countries, the scale of the event and the scale of GDP measurement are very different, and a large shock for local populations can hardly be visible on national GDP. It does not mean, however, that welfare impacts are negligible. Second, GDP does not include non-market production and household production and therefore cannot capture a significant share of output losses. With a broader definition of output, it is possible to include at least some non-market and non-commercial impacts. Third, GDP is known to be a poor proxy for welfare because it does not capture wealth (e.g., stocks of assets) and does not account for inequality and distributional effects (Fleurbaey, 2009).

2.1.2 Assessing indirect losses: Defining a baseline

A first difficulty in disaster indirect cost assessment lies in the definition of the baseline scenario. The cost of the disaster has indeed to be calculated by comparing the actual trajectory (with disaster impacts) with a counterfactual baseline trajectory (i.e., a scenario of what would have occurred in the absence of disaster). This baseline is not easy to define, and several baselines are often possible. Moreover, in cases where recovery and reconstruction do not lead to a return to the baseline scenario, there are permanent (positive or negative) disaster effects that are difficult to compare with a non-disaster scenario.

For instance, a disaster can lead to a permanent extinction of vulnerable economic activities in a region, because these activities are already threatened and cannot recover, or because they can move to less risky locations. In that case, the disaster is not a temporary event, but a permanent negative shock for a region. Also, reconstruction can be used to develop new economic sectors, with larger productivity, and lead to a final situation that can be considered more desirable than the baseline scenario. This improvement can be seen as a benefit of the disaster. It is however difficult to attribute unambiguously this benefit to the disaster, because the same economic shift would have been possible in the absence of disaster, making it possible to get the benefits without suffering from the disaster-related human and welfare losses.

Box 1 – Direct flood losses in Mumbai

On Mumbai, the flood risk analysis begins with an analysis of past high precipitation events, to assess their probability of occurrence. It then assesses the impact of climate change on future heavy precipitation statistics using downscaling techniques (namely, the WXGEN weather generator). Next, it translates the statistics of heavy precipitation into river run-off and flood hazards, using the Storm Water Management Model (SWMM). The result is an assessment of the probability of various flood events. This exercise produces flood maps, in the current climate and in the climate projected by the PRECIS climate model with the IPCC/A2 emission scenario (see box figure).

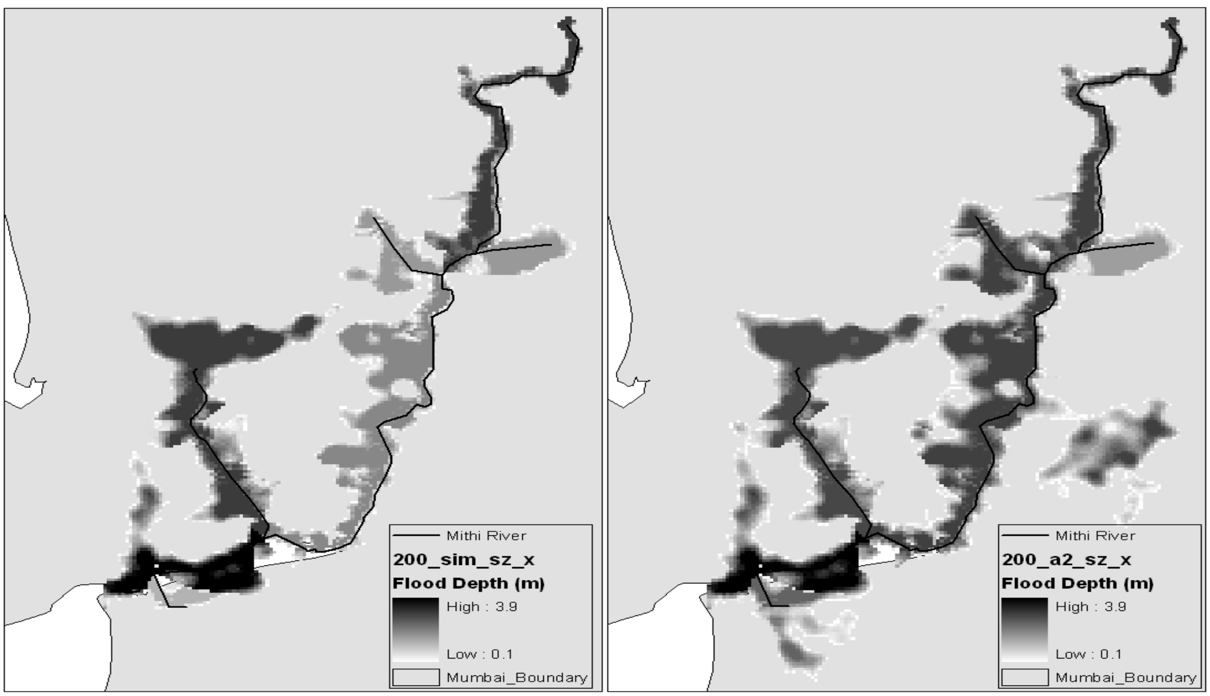

Figure. Flood map corresponding to the 200-year return period precipitation event, in the Mithi basin, in Mumbai, today (left panel) and in the 2080's in one climate scenario (right panel).

Then, the population and assets exposed to flood risks is assessed, using data on population and assets collected by Risk Management Solutions from an insurance database developed for the assessment of earthquake risks.

In the absence of vulnerability curves for the buildings that can be found in Mumbai, the analysis uses "average damage ratio". It is assumed that when a property is flooded, a constant share of its value is lost, regardless of the water level and the detailed characteristics of buildings. Using three different techniques (based on published loss estimates for the 2005 floods, insurance data for the 2005 floods, and simple vulnerability curves), these damage ratios are estimates at 5–15% for residential properties, 15–35% for commercial properties, and 10–30% for industrial properties. In the absence of data on infrastructure, a constant ratio of infrastructure to non-infrastructure losses is introduced. Based on previous events in various world cities, this ratio is taken at 40% (i.e., where there is $1 of non-infrastructure losses, there is $0.40 of infrastructure losses).

From this, the analysis can then provide an estimate of the direct economic losses that corresponds to various probability of occurrence, expressed in terms of return periods. For instance, the losses due to the 50-yr return period flood are estimated between $210 and $570 million.

To complete this analysis with information on how these losses are distributed in the population and especially on the poorest, a survey was conducted with informal dwellers affected by the 2005 floods. It was found that the aggregated losses they suffered from are about $250 million (for total losses due to the 2005 flood of about $2 billion), but the relative impact on their savings and consumption was extremely large, with average capital losses of the same order of magnitude than their average total savings (in other terms, their savings were totally wiped out by the event).

For instance, hurricanes in 1806 and 1807 participated in the shift that occurred at la Réunion – a French island in the Indian Ocean – from coffee to sugar cane production. Indeed, it takes about 5 years for a coffee plant to start producing usable fruits. When the hurricanes hit, the need to start producing again as soon as possible drove farmers to plant sugar cane, an annual crop that can be harvested in a year. Moreover, coffee production was then considered more vulnerable to wind damages than sugar cane. But sugar cane production also has a different economic vulnerability to other stresses such as changes in food markets, consumer tastes, and agricultural subsidies. Therefore, it is difficult to assess whether the shift from coffee to sugar cane should be considered as a cost of the hurricanes (if sugar cane eventually reveals less profitable than coffee) or as a benefit (if sugar cane is more profitable than coffee). The final outcome depends on many other factors that can hardly be predicted at the time of the disaster.

This baseline issue – very common in economics – is not easy to deal with, and different scholars have used different techniques. (Coffman and Noy, 2011) use two nearby islands to assess the impact of hurricane Iniki. Since the hurricane affected only one island, the other can be used as a “control”, i.e. as a proxy for the economic condition of the affected island if it had been spared. But such convenient control is not always available, making it necessary to construct the counterfactual, for instance using modelling tools (DuPont and Noy, 2012).

2.2 Output losses and their drivers

Damages to assets make them unable to produce: a damaged factory cannot build cars, a damaged road cannot be used, and a damaged house cannot be inhabited. The first step in an assessment of output losses is to estimate how much output is lost because of these direct asset losses.

2.2.1 From asset losses to output losses

Economic theory states that, at the economic equilibrium and under certain conditions, the value of an asset is the net present value[6] of its expected future production. In this case, the annual loss of output is equal to the value of the lost capital multiplied by the marginal productivity of capital (which is equal to the interest rate, increased by the depreciation rate). Assuming this equality is always verified, the output loss caused by capital loss is simply equal to the value of the lost asset, and summing the two is a double count.

Figure 1 illustrates this point in a scenario in which no reconstruction takes place: in that case, the production that is lost because of the disaster is equal to the value of the lost assets.[7] In estimates of disaster consequences, *what is referred to as "asset loss" is the replacement value of the capital*. To have the equality of asset loss and output loss, a double equality needs to be verified: replacement value has to be equal to market value; and market value has to be equal to the net present value of expected output.

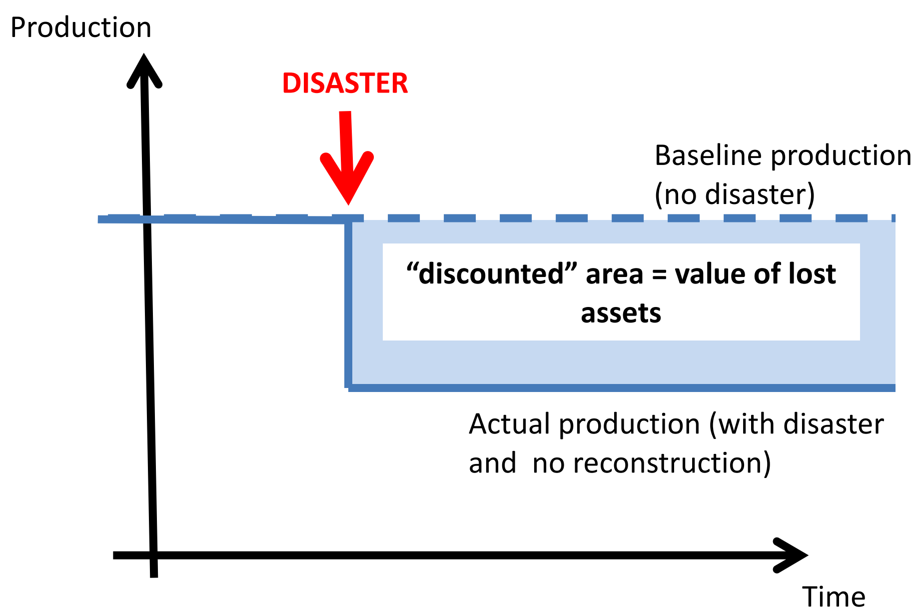

Figure 1. Production as a function of time, without disaster or in a scenario with disaster and no reconstruction. In the latter case, the discounted value of the lost production (from the disaster to the infinity) is equal to the value of lost assets. The production decrease is equal to the value of lost assets multiplied by the interest rate.

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[6] Note that the net present value is the sum of the production, discounted to account for the fact that production far in the future has less value than more immediate production.

[7] Note also the baseline issue: maintaining unchanged production requires investments to maintain the capital stock; the lower production level post-disaster is possible with a reduced investment level, thereby creating a benefit. This is taken into account by the fact that the marginal productivity of capital used to calculate asset value should include the depreciation rate.

In a theoretical and optimal economy at equilibrium – these two equalities are valid. First, if the market value of an asset is lower (resp. larger) than the net value of its output, then investors will buy more (resp. sell) more of this asset to capture the difference in value, making asset price increase (resp. decrease). Second, if market value were higher (resp. lower) than replacement value, then investors would increase (resp. decrease) the amount of physical capital to restore the equality between market and replacement value (assuming decreasing returns). In a realistic setting, however, these two assumptions are not always verified. The reasons why asset values and output losses can differ are discussed below.

The economy is not at its optimum. For the replacement value and the market value to be equal, the economy needs to be at its optimum, i.e. the amount of capital is such that its return is equal to the (unique) interest rate. This is not always the case especially in sectors affected by disasters. In some sectors, expectations can be heavily biased (e.g., in the housing market) and markets distorted, leading to large differences between capital returns and interest rate. This is also unlikely for infrastructure and public assets. Since these assets are not exchanged on markets, they have no market prices. Moreover, they are not financed by decisions of private investors using financial returns, but by government decisions through a political process taking into account multiple criteria (e.g., land-use planning objectives). Furthermore, output losses need to be estimated from a social point-of-view. The equality between market value (for the owner) and expected output (for the society) is valid only in absence of externalities. Some assets that are destroyed by disasters may exhibit positive externality. It means that their value to the society is larger than the value of the owner's expected output. Public goods have this characteristic, among which most infrastructures, health services, education services.

An example is provided by the San Francisco Oakland Bay Bridge, which is essential to economic activity in San Francisco and had to be closed for one month after the Loma Prieta earthquake in 1989. Its replacement value has no reason to be equal to the loss in activity caused by the bridge closure, because the bridge production is not sold on a market, the bridge has no market value, and the social return on capital of the bridge is unlikely to exhibit decreasing returns and is likely to be much higher than the interest rate. Another example is the health care system in New Orleans. Beyond the immediate economic value of the service it provided, a functioning health care is necessary for a region to attract workers (what economists call a "positive externality"). After Katrina's landfall on the city, the lack of health care services made it more difficult to reconstruct, and the cost for the region was much larger than the economic direct value of this service.

The shock is large ("non-marginal" in economic terms). The equality of asset value and output is valid only for marginal changes, i.e. for small shocks that do not affect the structure of the economy and the relative prices of different goods and services. The impact is different for large shocks. Most assets have "decreasing returns", i.e. their productivity decreases with the total amount of asset. For instance, if there are one million cars in a city, the loss of one car is a marginal shock, and the output of this car should be equal (at the optimum) to the production cost of a car. But in practice, some cars have a larger productivity than others: some cars are driven 1,000 km per year while others are driven 80,000 km per year; clearly the latter car is more productive than the former. In economic theory, the least productive car – i.e. the one that is driven the shortest distance per year – has an output equal to the production cost of cars. All the other ones have a higher productivity. As a result, the destruction of one car – assuming the least productive one is destroyed – leads to an output loss equal to the replacement cost of the car. But the destruction of many cars will affect cars with various productivity levels, and leads to an output loss that is larger than the replacement value of these cars. Moreover, the equality of asset value and output depends on the assumption that the destructions affect the least productive assets only. In the previous example, it is assumed that if one car is destroyed, then it is the least productive (i.e. the one that is driven the shortest distance per year). Or equivalently, it is assumed that the owner of the destroyed car will instantaneously buy the least used car to its owner (which makes sense because the former makes a more efficient use of the car than the latter).

To account for these effects, it is more realistic to assess the loss of output as the value of lost assets multiplied by the average productivity of capital, instead of the marginal productivity. Using classical production function and parameters, this approximation leads to output losses equal to approximately three times the value of lost assets; see details in (Hallegatte et al., 2007), and Appendix A.

Asset and output losses are often estimated assuming unchanged (pre-disaster) prices, which is valid only for marginal shocks. One can assume that if a house is destroyed, the family who owns the house will have to rent another house at the pre-disaster price. In other terms, the value of the housing service provided by the house can be estimated by the rental cost of a similar house before the disaster. But this assumption is unrealistic if the disaster causes more than a small shock. In post-disaster situations, indeed, a significant fraction of houses may be destroyed, leading to changes in the relative price structure. In this case, the price of alternative housing can be much higher than the pre-disaster price, as a consequence of the disaster-related scarcity in the housing market. For large shocks, estimating the value of lost housing service should take into account the price change. Compared with an assessment based on the pre-disaster prices, it can lead to a significant increase in the assessed disaster cost. The same reasoning is possible in all other sectors, including transportation, energy, water, health, etc.

In extreme cases, there may be rationing, i.e. the price cannot clear the market and supply is not equal to demand. This is because markets are not at equilibrium in disaster aftermath). The « If I can pay it, I can get it » assumption is not valid in post-disaster situations (e.g., there is no available house for rent at any price, there is no qualified worker to repair a roof). In these situations, therefore, the welfare impact of lost production cannot be estimated as the product of lost produced quantity and pre-disaster prices. Providing an unbiased estimate requires an assessment of the disaster impact on prices and taking into account rationing. Appendix B provides details.

Post-disaster price inflation (also referred to as "demand surge") is especially sensible in the construction sector, which sees final demand soar after a disaster. For instance, Figure 2 shows the large (and persistent) increase in wages for roofers in an area heavily affected by hurricane losses in Florida in 2004.

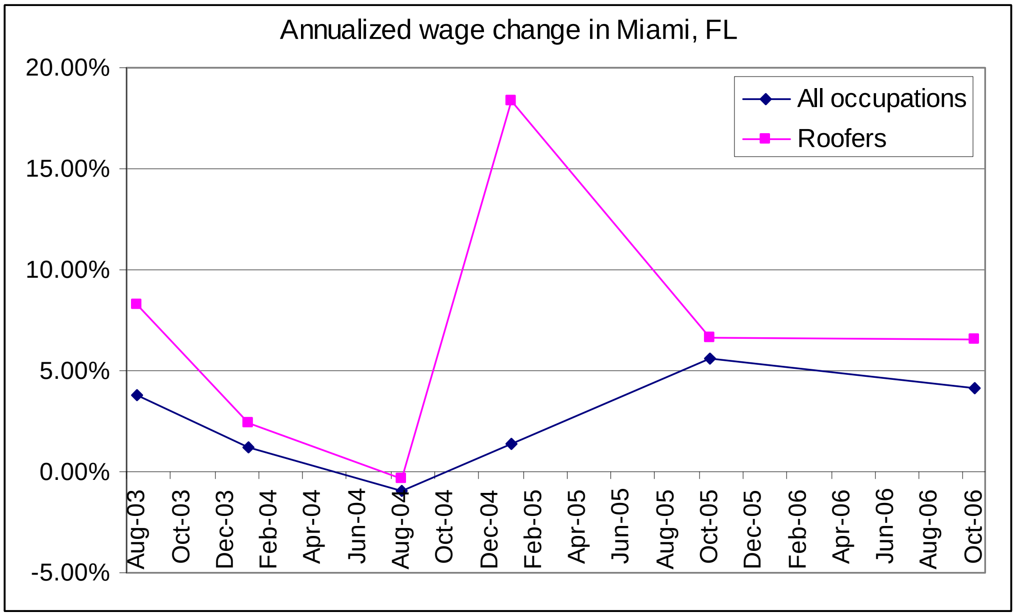

Figure 2: Roofer wages in an area where losses have been significant after the 2004 hurricane season in Florida. Data from the Bureau of Labor Statistics, Occupational Employment Surveys in May 03, Nov 03, May 04, Nov 04, May 05, May 06, May 07.

2.2.2 "Ripple effects"

Output losses are not only due to forgone production from the assets that have been destroyed or damaged by the event. Assets that have not been affected by the hazards can also be revealed to be unable to produce at the pre-event level because of indirect effects, sometimes referred to as "ripple effects". This is particularly the case for infrastructure and utility services (electricity, water and sanitation, gas, etc.). In past cases, it has been shown that the loss of utility services had larger consequences than direct asset losses, both on households (McCarty and Smith, 2005) and on businesses (Gordon et al., 1998; Tierney, 1997).

(McCarty and Smith, 2005) investigated the impact of the 2004 hurricane season on households in Florida, and find that among the 21% of the households who were forced to move after the disaster, 50% had to do so because of the loss of utilities (e.g., they had no running water). In only 37% of the cases, the main reason was structural damages to the house. (Tierney, 1997) and (Gordon et al., 1998) investigate the impact of the Northridge earthquake in 1994 in Los Angeles; they find also that loss of utility services and transport played a key role. Tierney surveys the reasons why small businesses had to close after the earthquake. The first reason, with 65% of the answers (several answers were possible), is the need for clean-up. After that, the five most important reasons are loss of electricity, employee unable to get to work, loss of telephones, damages to owner's or manager's home, and few or no customers, with percentages ranging from 59% to 40%. All these reasons are not related to structural damages to the business itself, but to offsite impacts. (Gordon et al., 1998) ask businesses to assess the earthquake loss due to transportation perturbations, and find that this loss amounts to 39% of total losses. (Kroll et al., 1991) find comparable results for the Loma Prieta earthquake at San Francisco in 1989: the major problems for small business were customer access, employee access, and shipping delays, not structural damages. Utilities (electricity, communication, etc.) caused problems, but only over the short term, since these services have been restored rapidly; only transportation issues have led to long lasting consequences. (Rose and Wei, 2013) investigate the impact of a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, and find that – even in the absence of other losses – regional gross output could decline by as much as $13 billion at the port region level (and that specific actions to cope with the shock can reduce these impacts by nearly 70%).

In theoretical terms, this effect arises from the fact that the capital is non-homogeneous and capital components are not perfectly substitutable. As a result, the consequences of disaster capital losses depend not only on the amount of capital that is lost, but also on which type of capital is lost. If the stock of capital consists of an ensemble of capital categories that have some complementarity, then the destruction of one component may reduce the productivity of other components and thus have an impact that is larger than what could be expected from the analysis of one component only (see Appendix A). One extreme example is the case of a road that is built out of a series of segments between point A and B: if one segment is destroyed, then the road is not usable and the other segments become useless. The output loss due to the destruction of one segment cannot be estimated based on the analysis of one segment, but requires an analysis of the entire system (the road). The same is true – at various degrees – of the entire economic system: the loss of one component can affect the other component and lead to losses that are higher (or lower) than the value of the asset loss suggests depending on the substitutability.

Output losses are also due to complex interactions between businesses. Business perturbations may indeed also arise from production bottlenecks through supply-chains of suppliers and producers.[8] These ripple-effects can be labelled “backward” or “forward”:

- Backward ripple-effects arise when the impact propagates from clients to suppliers, i.e. when a business cannot produce, and thus reduces its demand to its suppliers, reducing their own activity (even in absence of direct damages).
- Forward ripple-effects arise when the impact propagates from suppliers to clients, i.e. when a business cannot produce and thus cannot provide its clients with inputs needed for their own production.

The output losses due to a disaster depend on the characteristics of the firm-to-firm networks (Henriet et al., 2012), such as the average number of suppliers that firms have, or the shape and structure of the connection between firms. These results suggest that modern economies, with global supply chains, limited number of suppliers and small stocks, may be more vulnerable to natural disasters than traditional, close economies. But the model used in (Henriet et al., 2012) is too simple for providing realistic assessment of disaster costs, and detailed information on real-world economic networks is not available. The impact of disasters on supply chains are tragically illustrated by the recent Tohoku-Pacific earthquake in Japan, and its wide consequences on industrial production and exports, especially in the auto industry.

[8] These ripple effects can even take place within a factory, if one segment of the production process is impossible and therefore interrupts the entire production.

As an example, The Economic Times, an Indian newspaper, reports that "*Japan's Toyota Motor will cut production at its Indian subsidiary by up to 70% between April 25 and June 4 due to disruption of supplies.*"

When capital cannot produce because of a lack of input (e.g., electricity, water), several options are available: input substitution, production rescheduling, mobilization of existing idle resources, and longer work hours can compensate for a significant fraction of the losses (Rose et al., 2007a). Loss of output in the affected area and during the disaster aftermath could thus be compensated by increased production outside the affected area (e.g., when another region capture the market shares lost by the affected region) or later (e.g., when production is rescheduled after basic services are restored). Even within the affected area, output losses from destroyed capital can be compensated by increased production from factories and production units that did not suffer from losses and had idle capacity before the event (which depends on the pre-existing situation, see next section).

These mechanisms can damp output losses, and can especially reduce the crowding-out effects of reconstruction on normal consumption and investment. But their ability to do so is limited, especially when losses are large. In case of large disasters, output losses will be largely dependent on two characteristics of the economy: the adaptability and flexibility of its production processes; and its ability to channel economic production toward its most efficient uses.

2.2.3 Stimulus effect

Disasters lead to a reduction of production capacity, but also to an increase in the demand for the reconstruction sector and goods. Thus, the reconstruction acts in theory as a stimulus. However, as any stimulus, its consequences depend on the pre-existing economic situation, such as the phase of the business cycles and the existing of distortion that lead to under-utilization of production capacities.

If the economy is efficient and in a phase of high growth, in which all resources are fully used, the net effect of a stimulus on the economy will be negative, for instance through diverted resources, production capacity scarcity, and accelerated inflation. If the pre-disaster economy is depressed, on the other hand, the stimulus effect can yield benefits to the economy by mobilizing idle capacities.

Economies in recession are more resilient to the effects of natural disasters (see a model based analysis in Hallegatte and Ghil, 2008). This result appears consistent with empirical evidence. For instance, the 1999 earthquake in Turkey caused direct destructions amounting to 1.5 to 3% of Turkey's GDP, but consequences on growth remained limited, probably because the economy had significant unused resources at that time (the Turkish GDP contracted by 7% in the year preceding the earthquake). In this case, therefore, the earthquake may have acted as a stimulus, and have increased economic activities in spite of its human consequences. In 1992, when hurricane Andrew made landfall on south Florida, the economy was depressed and only 50% of the construction workers were employed (West and Lenze, 1994). The reconstruction needs had a stimulus effects on the construction sectors, which would have been impossible in a better economic situation (e.g., in 2004 when four hurricanes hit Florida during a housing construction boom).

The stimulus therefore exists only if there is idle capacity in the economy, i.e. some distortions in the economic system. In developing countries, where capital is scarce and (unskilled) labor abundant, it is unlikely that large idle capacity exist, except during recessions. However, many developing country economies are plagued with large distortions that sometimes lead to excess investments in capital. In that latter case, it is possible that idle capacity is available and that the reduction in capacity due to a disaster has no impact.

The stimulus benefits may be considered as a positive outcome of disasters, but they should not. Indeed, the same stimulus benefits could be captured in the absence of a disaster, through a standard stimulus policy, and without the negative welfare and human impacts that come with disasters. For instance, output may be stimulated by the reconstruction of many houses destroyed by a hurricane; but the same output generation is possible by building new and better housing or by retrofitting existing building to make them more energy efficient, without the need for any destruction. The possibility of a stimulus effect would only reflect the fact that pre-existing economic policy is inappropriate, and this could be corrected independently of a disaster. So, it would be improper to attribute this positive effect to the disaster itself.

2.2.4 Non-linearity in output losses

There are three main reasons why output losses are likely to increase non-linearly with the size of the disaster (and the amount of destruction):

- First, all economies have idle capacities (e.g., factories that do not produce as much as they technically can, and workers who could and sometime wish to work more hours). If lost production by affected capital is small enough to be fully compensated by increased production from non-affected idle capacity, then there is no output loss (Albala-Bertrand, 2013). As a result, output losses appear only if direct losses are larger than a given threshold that depends on the pre-existing economic situation.
- Second, the “ripple effects” from infrastructure to firms and households and across firms are also likely to increase with the number of affected firms (and the individual loss of output) (Henriet et al., 2012).
- Third, the reconstruction capacity is always limited by financial and technical constraints and it makes rebuilding after a large scale disaster much longer than after a small one (Benson and Clay, 2004). In other terms, the duration of the shock increases with its amplitude. As a result, the output losses – that depend on the magnitude of the shock and its duration – will increase more than proportionally with direct losses.

The amount of damages can be a misleading indicator of the reconstruction duration. The 10 billion euros of reconstruction expenditures after the 2002 floods in Germany correspond to 10 days of total German investments. But reconstruction has been spread out over more than 3 years, suggesting that only a small fraction of investments can be dedicated to reconstruction (even though the return on investment from reconstruction should theoretically be higher than other investments, as suggested in Appendix A), because of financial and technical constraints.

A model-based investigation of this issue using the Adaptive Regional Input-Output (ARIO) model (Hallegatte, 2008; Hallegatte, 2014) concludes that total losses due to a disaster affecting Louisiana increase nonlinearly with respect to direct losses when direct losses exceed $50 billion (see Figure 3). When direct losses are lower than $50bn, aggregated indirect losses are close to zero (even though the aggregation hides important disparities among sectors and among social categories). Beyond $50 billion of direct losses, indirect losses increase nonlinearly. When direct losses exceed $200 billion, for instance, total losses are twice as large as direct losses. For risk management, therefore, direct losses are insufficient measures of disaster consequences.

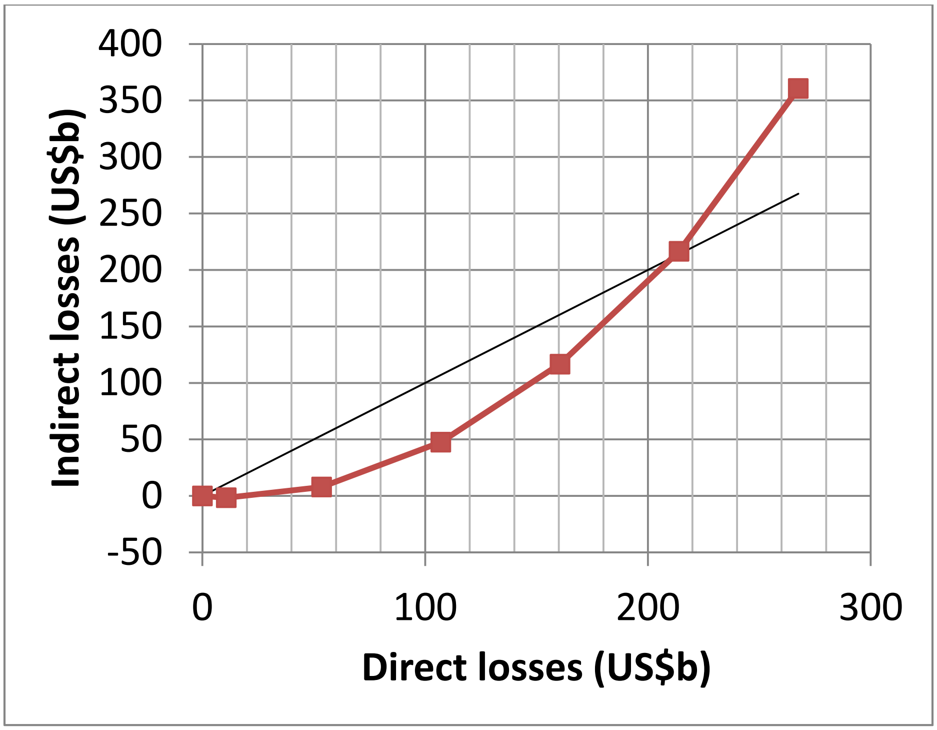

Figure 3: The direct losses – output losses as a function of direct (asset) losses, in Louisiana for Katrina-like disasters of increasing magnitude.

The output losses due to a hazard (and the resulting welfare impact) do not depend only on the physical intensity of the natural event, but also on the coping capacity of the affected human system. Physical measures of disaster intensity (e.g., in m/s for windstorm) or even measures of direct losses (e.g., the number and value of destroyed and damaged buildings) are very poor proxies of the real economic cost of a disaster. A corollary is that natural disasters can have significant macroeconomic impacts, when they are larger than the (context specific) economic coping capacity. Moreover, it means that reducing natural disaster impacts on welfare can be done through an increase of the coping capacity, to make reconstruction faster and more efficient and limit output losses.

2.3 Assessing indirect losses

2.3.1 Measuring indirect losses using econometric analyses

Econometrics analyses have been used to measure output losses, understood as reduction in GDP following a disaster, but they reach contradictory conclusions (see great reviews in Dell et al., 2013; Kousky, 2014). Albala-Bertrand (1993) and Skidmore and Toya (2002) suggest that natural disasters have a positive influence on long-term economic growth, probably thanks to the stimulus effect of reconstruction (section 2.2.3) and possibly the replacement of damaged capital with more recent technologies (on this "productivity effect", see also critical discussions in Benson and Clay, 2004; Hallegatte and Dumas, 2009). Others, like (Hochrainer, 2009; Jaramillo, 2010; Noy and Nualsri, 2007; Noy, 2009; Raddatz, 2009) suggest that the overall impact of disasters on growth is negative. At local scale, (Strobl, 2010) investigates the impact of hurricane landfall on county-level economic growth in the US and shows that a county that is stuck by at least one hurricane over a year sees its economic growth reduced on average by 0.79 percentage point (and increased by only 0.22 percentage point the following year). On Vietnam, (Noy and Vu, 2010) investigate the impact of disasters on economic growth at the province level, and find that lethal disasters decrease economic production while costly disasters increase short-term growth.

The lack of consensus on the impact of disasters on GDP is likely to arise from different impacts from small and large disasters, the latter having a negative impact on growth while the former enhance growth, and from different impacts from different types of disasters. For instance, (Felbermayr and Gröschl, 2013) find that disasters in the top decile in terms of magnitude lead on average to a 3 percent reduction in GDP growth. The loss is only 1.5 percent for disasters in the top 15% percentile, and 0.8% for disasters in the top 20%. For smaller disasters, no impact can be detected. The type of disaster also matters: (Loayza et al., 2012) find that droughts reduce GDP growth by 1.7 percentage point, while floods increase GDP by 0.5% (possibly because floods enrich soils and increase agricultural productivity).

2.3.2 Modeling indirect losses

Many scholars have used economic models to estimate output losses. Many different models have been used, but the most common are Input-Output (IO) or Calculable General Equilibrium (CGE) models. In these models, the economy is described as an ensemble of economic sectors, which interact through intermediate consumptions. These models however describe differently how these different sectors interact with each other, and how they react to shocks.

Some models are based on the Input-Output (IO) linear assumption (Leontief, 1951), in which the production of one unit in one sector requires a fixed amount of inputs from other sectors, and in which prices do not play any role. These include (Bockarjova et al., 2004; Haimes and Jiang, 2001; Stéphane Hallegatte, 2014; Hallegatte, 2008; Okuyama, 2004; Okuyama et al., 2004; Santos and Haimes, 2004). Other models are based on the Calculable General Equilibrium (CGE) framework, which assumes that changes in relative prices balance supply and demand in each sector (Rose and Liao, 2005; Rose et al., 2007a).

Economic losses caused by a disaster are smaller in a CGE setting than in an IO setting. It is often considered that IO models represent the short-term economic dynamics, in which production technologies are fixed and prices cannot adjust. CGE models, on the other hand, represent the long-term dynamics, in which flexibility in production processes and markets allow for an adjustment of the economic system. In reality, it is likely that IO models are pessimistic in their assessment of disaster output losses, because there is flexibility even over the short term (for instance, maintenance can be postponed; workers can do more hours to cope with the shock; production can be rescheduled, see (Rose et al., 2007a)). It is also likely that CGE models are optimistic, even in the long run, because prices have stickiness and cannot adjust perfectly, and because substitution has technical limits that are not always adequately represented in production functions.

Considering the sensitivity of model results to many parameters, and the limitation of existing tools, it is fair to admit that models are useful tools to explore the indirect consequences of disasters but cannot estimate precisely the total economic cost of a disaster.

2.3.3 Rule of thumb

In the framework presented here (see details in Appendix A and B), one dollar of direct loss in productive capital translates into a decrease in instantaneous (annualized) output that equal to the average productivity of capital, that is about three times the interest rate (i.e. the marginal productivity of capital, r), possibly increased by a factor (1+α) that represents ripple-effects:

$$\Delta Y(t_0) = \frac{1+\alpha}{\mu} r \Delta K \tag{1}$$

The parameter α represent the "ripple-effects" through the supply chain and infrastructure interruption effects (see Section 2.2). It represents the lost production from capital that is not affected by the event, and depends on the ability of the economic system to (1) mobilize existing idle capacity (which depends on the existence of idle capacity); (2) adjust production network to compensate for damaged production units (e.g., producers find new suppliers and clients rapidly), (3) channel remaining production toward its most productive uses (including reconstruction needs), (4) increase imports to compensate for unavailable supplies. It is likely to be close to zero for relatively limited disasters, and to increase for large-scale events. It is lower (and possibly negative) if the pre-existing economic situation is depressed, with under-utilization of production capacity.

In the absence of convincing models or even theory, it can be recommended to take α=0, keeping in mind that we are disregarding some potentially important effects. In very specific cases, different values could be used, for instance a -20% value if the shock occurs during a recession with large idle resources (e.g., the landfall of hurricane Andrew in Florida in 1992), or a +20% if the transport sector is heavily affected, creating large-scale supply-chain issues (or in case of power generation issues such as in Japan after the 2011 earthquake and tsunami).

As shown in Appendix C, assuming that output losses are reduced to zero exponentially, and that 95% of the losses are repaired in N years, total *non-discounted* output losses $\overline{\Delta Y}$ are equal to:

$$\overline{\Delta Y} = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{3} \quad (2)$$

With discounting at a rate r, the net present value of output losses is[9]:

$$\widetilde{\Delta Y} = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{rN+3} \quad (3)$$

The parameter N is the reconstruction period and it can often be estimated by experts based on past experience. Note that the reconstruction time is not the time when the observed GDP or output returns to its pre-disaster value, but is much longer. Indeed, the GDP and output is affected by other mechanisms, including increase in labor productivity, other investments, and possibly the "stimulus effect" of the disaster. But the stimulus effect should not be accounted in disaster consequences (see Section 2.2.3), since it corresponds to benefits that could have been captured in the absence of the disaster, through a classical stimulus policy.

Taking on example of a disaster that make capital losses equal to \$500 million, in a country with a 10% interest rate, with a reconstruction period that is likely to span over 3 years would lead to (non-discounted) output losses equal to \$225 million (i.e. 45% of direct capital losses). In the context of figure 3 (hurricanes on Louisiana), this rule of thumb reproduces model results perfectly, assuming that losses lower than \$50 billion can be repaired in one year, and that losses amounting to \$100, \$150, \$200, and \$250 billion can be repaired in 5, 10, 12, and 15 years, respectively.

2.4 From output losses to welfare losses

Losses in economic output do not affect directly people welfare; for them, what matters most is consumption. It is thus important to investigate how output losses translate into consumption losses. And since capital and output losses partly interact, it is incorrect to simply sum them to estimate welfare losses.

Consider first a scenario in which all losses are repaired instantaneously by reducing consumption and directing all the goods and services that are not consumed toward reconstruction investments (this is a scenario where reconstruction capacity is infinite). In this theoretical scenario, there is no output loss since all asset damages are instantaneously repaired, and N=0 in Eq. (2-3). There are however consumption losses, since consumption has to be reduced to reconstruct, and this reduction is equal to the reconstruction value (i.e. the replacement cost of damages capital). In that case, consumption losses are thus simply equal to the value of lost assets (i.e., direct losses).

Consider now another scenario with no reconstruction, in which output losses are permanent (like in Figure 1) and all losses in output are absorbed by a reduction in consumption (but no share of income is used for reconstruction). In that case, consumption losses are equal to output losses (with no reconstruction), and N is equal to infinity in Eq. (2-3). The loss in consumption is thus equal to $(1+\alpha)\Delta K/\mu$. Consumption losses and welfare losses are thus larger than the value of lost assets in a no-reconstruction scenario.

[9] The variable noted with $\tilde{x}$ are the net present value of the future fluxes of $x(t)$.

In the instantaneous reconstruction scenario, consumption losses are equal to the share of consumption needed to repair and rebuild, i.e. to direct losses. In the no-reconstruction scenario, consumption losses are equal to output losses, i.e. larger than direct losses.[10] As a result, consumption (and welfare) losses are magnified when reconstruction is delayed or slowed down.[11] And in all realistic scenarios where reconstruction takes some time (from months for small events to years for large-scale disasters), welfare losses are larger than direct losses.

The actual welfare losses are thus the sum of the net present value of reconstruction cost (i.e. direct capital cost) and the net present value of indirect (output) losses. The reconstruction phase, and the economic recovery pace, will ultimately determine the final welfare cost of the natural disasters. If reconstruction is done over N years with investments equal to ΔK/N, the present value of consumption losses is equal to:

$$\widetilde{\Delta C} = \int_{t_0}^{+\infty} \left(\frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}} + \Delta K e^{-\frac{t-t_0}{N/3}} \frac{3}{N} \right) e^{-rt} dt = \Delta K \frac{\frac{1+\alpha}{\mu} r + 3/N}{r + 3/N} \qquad (4)$$

Note the two extreme cases:

- As N tends toward zero, $\widetilde{\Delta C}$ tends to ΔK.
- As N tends toward the infinity (no reconstruction), $\widetilde{\Delta C}$ tends to $(1+\alpha)\Delta K/\mu$.

And if we approximate this equation further, we get:

$$\widetilde{\Delta C} = \frac{1 + \frac{1+\alpha}{3\mu} rN}{1 + \frac{rN}{3}} \Delta K = \Gamma \cdot \Delta K \qquad (5)$$

So in that case, aggregate consumption losses are equal to capital losses, increased by a factor Γ that depends on a few parameters:

- the *interest rate*, as the welfare impacts of disasters will be higher in countries where capital is scarce and the interest rate (and the marginal productivity of capital) is high;
- the *decreasing return* μ in the production function, which is also equal to the share of profits in national income;
- an *instantaneous resilience*, i.e. the ability to limit the magnitude of the immediate loss of income for a given amount of capital losses, that is given by the parameter α.
- a *dynamic resilience*, i.e. the ability to reconstruct and recover quickly, that is given by the variable N.

[10] The reality is more complex that what has been described here because not all output losses are translated into consumption losses. In practice, the loss in output changes the terms of the inter-temporal investment-consumption trade-off and translates into ambiguous instantaneous changes in consumption and investment. But the main conclusions of the analysis are not affected by this complexity.

[11] The fact that rapid reconstruction is better for welfare than slow reconstruction – or equivalently, that reconstruction has a return that is much higher than that of “normal investments” and the interest rate – explains why reconstruction is usually a priority and crowds out consumption and other investments in the affected region.

Taking again the example of a disaster that makes capital losses equal to $500 million, in a country with a 10% interest rate, with a reconstruction period that is likely to span over 3 years, the discounted loss of consumption is $606 million, which is 21% larger than asset losses.

Box 2 – Indirect flood losses in Mumbai

The ARIO model is then used to assess the output impact that would be caused by different floods, accounting for the characteristics of the Mumbai region economy. In particular, the model accounts for the financial constraints that can make it very difficult for poor households to finance the reconstruction, and can thus slow down the recovery significantly. In the model, the 2005 floods – that caused direct losses amounting to about $2 billion – led to indirect losses amounting to $425 million, i.e. 18% of direct losses (see figure). In the model, reconstruction is carried out over a 12 months period.

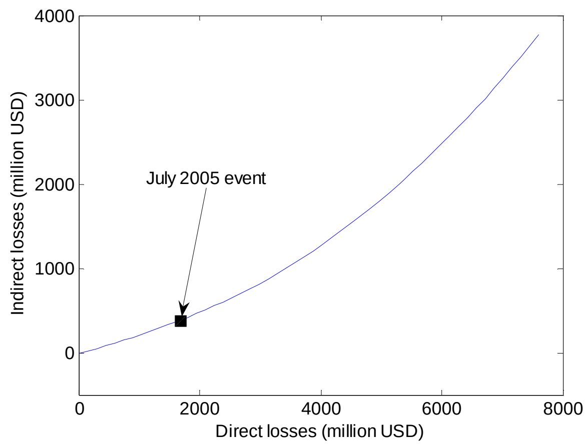

Figure. Relationship between direct losses due to an event and indirect losses (productive sectors plus housing sector), with the July 2005 event highlighted.

This number evaluated through a significant modeling exercise is broadly consistent with the rule of thumb proposed below and the fact that most of the reconstruction occurred in one year. With a marginal productivity of capital of 12.5% in Mumbai, the rule of thumb for the 2005 event would give:

$$\overline{\Delta Y} = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{3} = \Delta K r N = \$250 \text{ million USD.}$$

Of course, aggregated numbers hide the very large heterogeneity in indirect losses. As already mentioned, informal dwellers suffered from losses that were on average equal to their total savings, suggesting that their ability to invest has been strongly affected. Many of them also report forced reduced consumption, including of food. However, dwellers with stable jobs in the service sector reported only a few days of lost work.

3 Reducing disaster losses through higher resilience

The previous section demonstrates that welfare losses will depend on the amount of direct losses, but also on the ability of the economic system to recover and reconstruct (represented by the reconstruction period length, N). This ability can be referred to as the *macroeconomic resilience* of the affected economy. As discussed in Section 2.2, reconstruction investments – and thus the reconstruction speed – are constrained by a series of constraints. These constraints reduce the economic resilience and increase welfare costs. Relaxing them can therefore increase resilience and reduce total disaster losses. This section reviews a few policies to do so.

One source of friction is that consumers, firms and public organizations need time to direct high amounts of money to reconstruction activities. This constraint is crucial in developing economies (Benson and Clay, 2004). Insurance can of course play an important role in helping finance reconstruction (see next section), but access to credit is also extremely important. The second source of friction is linked the capacity of the economic system to produce enough to satisfy reconstruction needs. Finally, one constraint to reconstruction is linked to the limited ability of the government to finance reconstruction, directly when public assets are affected and indirectly through the support the government provides to private actor to help them rebuild.

3.1 Insurance benefits

Insurance is useful for several reasons. First, it spreads the risk among customers, over space, and over time. By doing so, it replaces rare and large losses by regular and small payments. If economic agents are risk averse, they prefer smooth and regular losses to an unknown and potentially large loss, and insurance increases welfare.

Second, most economic agents are not aware of the risk they are facing (World Bank, 2013, Chapter 2). If insurance premiums are risk-based (which is not the case in most of the world), they provide an accessible measure of the level of risk. This signaling effect can help households and businesses make smarter choices (e.g., settling in lower-risk areas), and be an incentive to risk-mitigation actions (e.g., by reducing insurance premium if homeowners invest in flood-mitigation). The signaling effect of risk-based insurance premium should not be overstated, however. In many places, it would be too small to trigger significant behavioral changes.

But most importantly, insurance claims support the affected population after a disaster, reducing immediate welfare losses and consumption reductions, and allowing a faster and more efficient reconstruction (by relaxing financial constraints, see (Benson and Clay, 2004)). Faster reconstruction means that overall output losses are reduced.[12] Also, reconstruction needs and lost output and income have a strong impact on households, firm, and public agency budgets, especially in developing countries,

[12] In Mumbai, our survey shows that loans was almost absent in the 2005 recovery and reconstruction. An improved access to credit (especially for the underprivileged) could help during the post-disaster period; e.g. the government guaranteeing reconstruction loans.

forcing them to reduce consumption (or non-reconstruction-related investments). The reduction in consumption can then have second-order consequences on other businesses that will see reduced demand and may respond by cutting on production and employment, magnifying the negative impact of the shock further (and affecting firms and households that have not been directly affected).

A last benefit of insurance is linked to the predictability of post-disaster support. Government support is often necessary to some extent (for instance, after Katrina, the U.S. Federal government partly replaced insurance for households that had no flood insurance). But when it is ad hoc, government support creates inefficient uncertainty for economic actors (e.g., because, after an event, they cannot known the exact scope of the government support they will receive) and can lead to moral hazard (e.g. if households know that they will be compensated by government, they will have little incentive to reduce their own risks or to pay for insurance). International support (grants or goods provided to affected people) can help reconstruction, but (in addition to the moral hazard issue) is very volatile and unpredictable.

Box 3 – The current and potential effect of insurance in Mumbai

We can use the ARIO model to investigate the benefits of insurance by exploring the sensitivity of indirect losses to the insurance penetration rate (γ) assumed in the model. In ARIO, the insurance penetration affects the response to the shock through two mechanisms: first, if the insurance penetration of households is low, they have to pay for their reconstruction (either directly, or by getting into debt and then paying off later), and reduce their consumption to so. Second, if the insurance penetration of firms is low, firms have to pay for reconstruction, reducing their profits. As a portion of these profits normally goes to local households, this affects the household budget, also reducing their consumption.

The box figure illustrates the effect of insurance penetration[13] on the household's budget, for a July 2005 like flood estimated using the ARIO model. Three scenarios are included: (i) $\gamma=0$, equivalent to the absence of insurance system, but with an access to credit; (ii) the current value of flood insurance penetration estimated by RMS ($\gamma=0.08$ for households, $\gamma=0.15$ for firms); and (iii) $\gamma=1$, representing the situation where all the reconstruction is paid for by insurance. Where the budget is positive in the figure, it can be interpreted as the additional savings of households, and where negative it represents debt. When insurance penetration is large, households make savings after the disaster. This occurs because in this case, households are rationed and consume less than what they would like to and as a result, they involuntarily save money. Variations in household budget affect the local demand, as households in debt reduce their consumption. This decrease in demand affects local production. Total output losses is reduced from \$455 million in the absence of insurance to \$425 million with the current insurance penetration to \$265 million if all losses are covered by insurance.

[13] It is important to note that our "insurance penetration rate" does not represent the fraction of the total amount of houses that is insured (as is often done), but the fraction of the total value of goods that is insured (never equal to one in the real world, because of ceilings or deductibles).

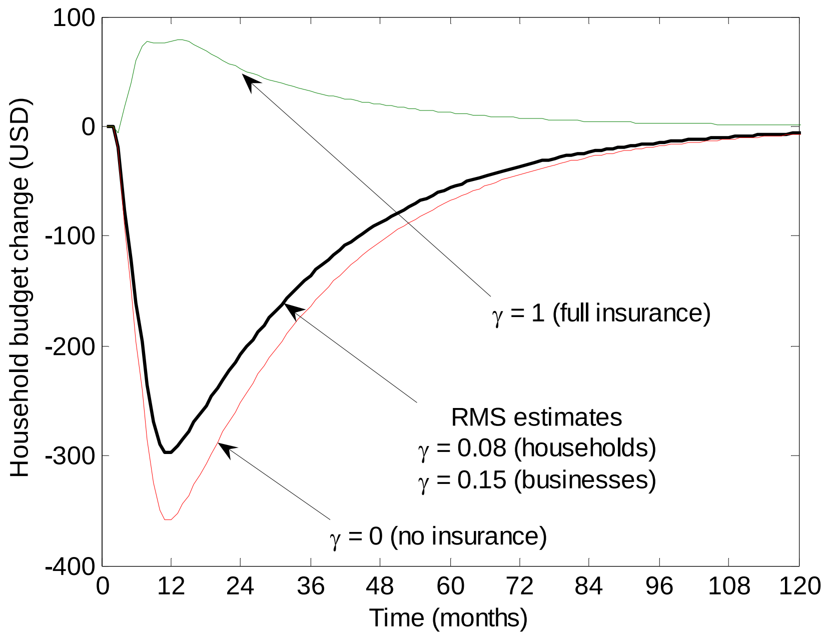

Figure. Household Budget as a function of time, for 3 different penetration rates. Note : γ=0 (no insurance), current value estimated by RMS (γ=0.08 for households and γ=0.15 for businesses) and γ=1 (reconstruction is entirely paid by the insurance system).

In sum, insurance yields macroeconomic (at the aggregated output level) and microeconomic benefits (at the household level). Microeconomic benefits include in particular the avoidance of increased poverty and inequality, the avoidance of the reduction in food intake (observed for about 40% of households in Mumbai after the 2005 floods), and facilitation and acceleration of reconstruction. Even though they are difficult to estimate in monetary terms, all these benefits should be taken into account, e.g. in the cost-benefit analysis of the implementation of a micro-insurance scheme.

3.2 Increase in reconstruction capacity

Another source of friction is that the sectors involved in reconstruction activities have skills, equipment, access to material, and organizational capacities adapted to the normal state of affairs and cannot face huge increases in demand. After the French storms in 1999 or after the explosion in a chemical plant in Toulouse in 2001, reconstruction took several years largely because roofers and glaziers were not numerous enough.

Indeed, over short timescales, local production capacity is highly constrained by existing capacities, equipment and infrastructure. Only imports from outside the affected region and postponement of some non-urgent tasks (e.g., maintenance) can create a limited flexibility over the short-term. Over the longer term and the entire reconstruction period, which can stretch over years for large-scale events, the flexibility is much higher: relative prices change, incentivizing production in scarce sectors; equipment and qualified workers move into the affected region, accelerating reconstruction and replacing lost capacities;

and different technologies and production strategies can be implemented to cope with long-lasting scarcities.

Large economic losses can be avoided with increased flexibility in the construction sector production capacity. The flexibility depends heavily on the pre-event conditions; for example, if idle capacities are present (e.g. unused equipment) they can be mobilized to cope with the disaster (Hallegatte and Ghil, 2008; West and Lenze, 1994), whereas if capacities are fully used then no additional capacity can be mobilized. The flexibility of the construction section could be enhanced through:

- Enabling qualified workers to settle down temporarily in the affected region (e.g. by providing working permit or helping workers to find accommodation).
- Organizing and sharing reconstruction resources among regions, states or cities and setting super-national policies to ensure reconstruction capacity is adequate to cope with possible disasters.
- Empowering governments to mobilize their workers (e.g., soldiers) and equipment to speed up reconstruction.

Past disasters illustrate the barriers to efficient reconstruction and suggest good practices. For instance, in the Katrina aftermath, many qualified workers from the entire U.S. moved to New Orleans to help reconstruct the city and capture higher construction-sector wages. Most of these workers, however, had to leave the area rapidly because they could not find proper accommodation or because of insufficient public services. Providing housing to temporary workers, therefore, seems to be extremely important to speed up reconstruction. Also, these workers left the region because the reconstruction of many buildings was delayed by legal problems, either due to delays in insurance claim payments or to the slow approval of building permits. For reconstruction to be as effective as possible, therefore, it seems that all administrative and legal issues must be solved rapidly, to benefit for the mobilization of internal and external resources.

3.3 Increase in public expenditures

Government with fiscal space or insurance or other risk sharing mechanisms will be able to increase public expenditure to deal with the disaster. The benefits from doing so will depend on how these resources are spent and used.

The first element is of course the management of the emergency situation. Resources are necessary to (i) maintain the functioning of the national and local authorities (civil servant salaries need to be paid, for instance); (ii) provide emergency services to the population, for instance through in-kind support (food, temporary shelters, drugs and medical services, etc.).

Over the long-term and the whole reconstruction phase, a few elements have to be taken into account. The reconstruction is a period of supply-side constraints in the sectors involved in reconstruction (especially the construction sector), so increasing public reconstruction expenditure may crowd out private reconstruction efforts (by firms and households) and increase prices for all. This may or may not happen, depending on (1) which reconstruction tasks are concerned (there is less crowding out between highway and housing reconstruction than between public buildings and housing reconstruction), (2) the situation of the construction sector and the available worker skills.

Box 4 – Enhancing reconstruction capacity in Mumbai

The ARIO model also allows us to assess the benefits of sets of policies that aim to accelerate reconstruction. We find that, for the July 2005 event, the indirect effect of the disaster on the local economy can vary by a factor of 4 (see box figure), depending on the amplitude and quickness of response of the construction sector. Of course, the ability to reconstruct impacts mostly the reconstruction duration and through it the rule of thumb proposed in Section 2.3.3.

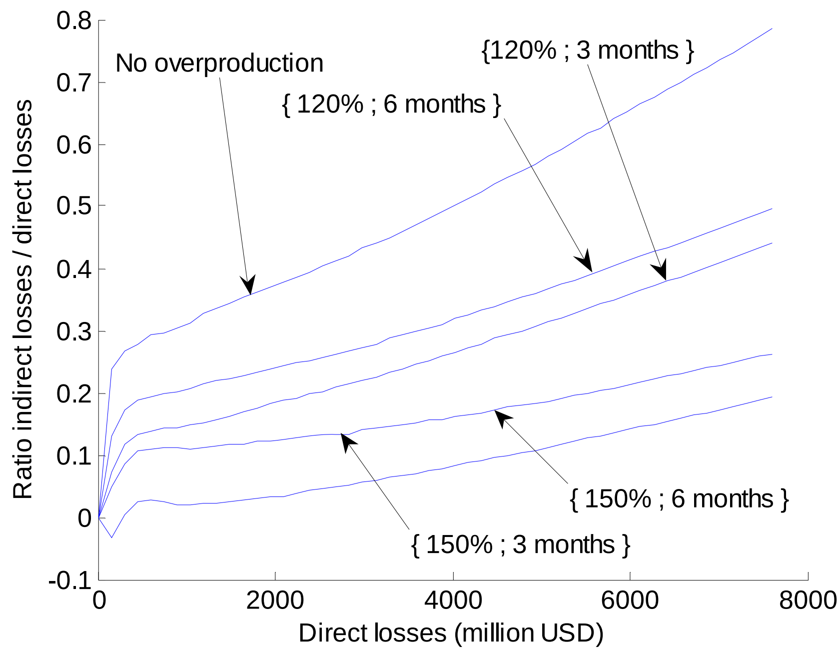

Figure. Indirect losses to direct losses ratio, as a function of the amount of direct losses, for four sets of adaptation parameters (the first parameter describes the amount of additional production that is possible, and the second parameter the time it takes to increase production to this level)

Public resources can be used to increase supply-side capacity in the reconstruction sector – for instance by supporting the migration of workers in the affected areas with temporary housing and the rapid provision of basic services. It can also focus on restoring transport infrastructure to facilitate the import of reconstruction materials, equipment, and skilled workers, and more generally of rationed goods and services.

Public resources can also be used to help private actors reconstruct and rebuild, especially where insurance penetration is low. The goal is to accelerate reconstruction (but using private actors to determine priorities) and mitigate the needed reduction in consumption (see previous section). More generally, they can support the population through classical safety nets, in particular to help it cope with lost income. Moreover, they can help the affected population import (possibly at a higher costs) goods and services that are not produced locally (e.g., through a reduction in import tariffs).

These different aspects can be combined, for instance using cash-for-work programs in which the affected population gets paid for reconstruction work. This approach combines demand- and supply-side benefits and is very likely to maximize the welfare benefits.

4 Macroeconomic resilience and risk management policies

This analysis shows that the welfare cost of a disaster does not depend only on either the physical characteristics of the event or its direct impacts. Depending on the ability of the economy to cope, recover and reconstruct, the reconstruction will be more or less difficult, and its welfare effects smaller or larger. This ability, which can be referred to as the *macroeconomic resilience* of the economy to natural disasters, is an important parameter to estimate the overall vulnerability of a population. Here, resilience is recomposed into two components: *instantaneous resilience*, i.e. the ability to limit the magnitude of the immediate loss of income for a given amount of capital losses; and *dynamic resilience*, i.e. the ability to reconstruct and recover quickly.

This paper proposes to assess the total discounted consumption loss of a disaster through the following relationship:

$$\widetilde{\Delta C} = \frac{1+\frac{1+\alpha}{3\mu}rN}{1+\frac{rN}{3}}\Delta K = \Gamma \cdot \Delta K$$

Where *r* is the interest rate (a higher interest rate decreases resilience and increases consumption losses), μ is the share of profit in the production function (and a measure of decreasing returns), *N* is the reconstruction duration (a longer reconstruction duration increases losses), and α is the factor that increase or decrease immediate output losses and is negative if enough idle resources are available and positive if ripple-effects impair production of non-affected capital.

After a disaster, it is easy to estimate N, and r and μ are also known. The parameter α is more difficult to estimate, and can be taken at zero as a first-order estimate, except in very specific situations.

To reduce the negative impact of natural disasters on population welfare, a first approach is to reduce the direct impacts on the economic systems, using for instance better coastal protections and stricter building norms. But another approach consists of reducing indirect losses through an increase in the resilience of the socio-economic system, using for instance insurance schemes or government support to the affected population.

An optimal risk management strategy is very likely to include measures targeting direct impacts (disaster risk reduction actions) and measures targeting indirect impacts (resilience building actions); see an example in Figure 4. For instance:

- Frequent low-impact events (like the floods that occur several times a year in Mumbai) can be avoided co-effectively thanks to improved drainage;
- For rarer events that cannot be avoided through improved drainage or at an excessive cost (i.e., heavy precipitations), population information, zoning and land-use plans could reduce the exposure (i.e. the population and assets at risk) by preventing inhabitant to settle in flood-prone zones and favoring safe settlement locations.
- For exceptional floods that cannot be avoided with drainage or zoning (because it would prevent construction is very large areas, at an unacceptable cost in a rapidly growing city), early warning and evacuation can reduce human consequences, and reduced building vulnerability, support for reconstruction, and insurance can mitigate economic losses through improved resilience.

There is no "optimal" risk management policy mix, and different approaches are possible. To minimize the cost of risk management, and maximize its benefits, the different policies of the mix should be designed together. With very strong physical protections – like in the Netherlands – there are limited needs in terms of evacuation system, insurance regulations and building norms. Where financial constraints make such protection unaffordable – like in Bangladesh – it is all the more critical to implement an efficient early warning and evacuation scheme (Hallegatte, 2012).

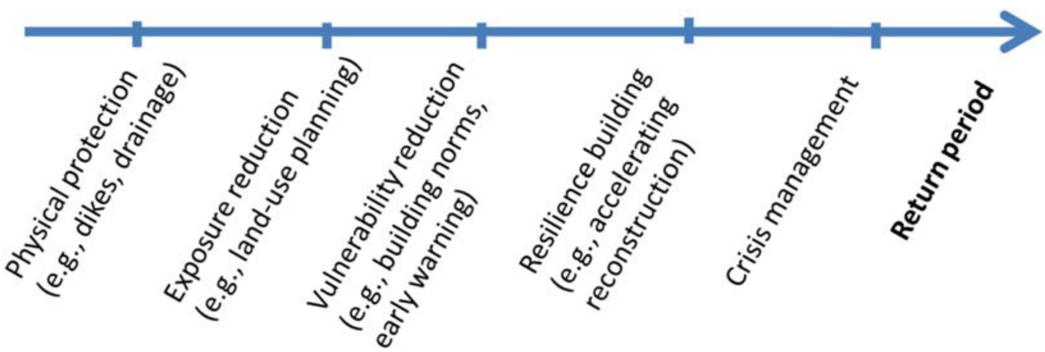

Figure 4: An example of risk-management policy mix, in which: (1) physical protections avoid frequent events, (2) land-use planning limit losses in these protections are overtopped, (3) vulnerability-reduction measures such as early warning and building norms minimize the direct losses from unavoidable disasters; (4) resilience-building measures minimize indirect losses from unavoidable disasters. Regardless of other measures, crisis management is always potentially needed to cope with the largest events that exceed the planned capacities.

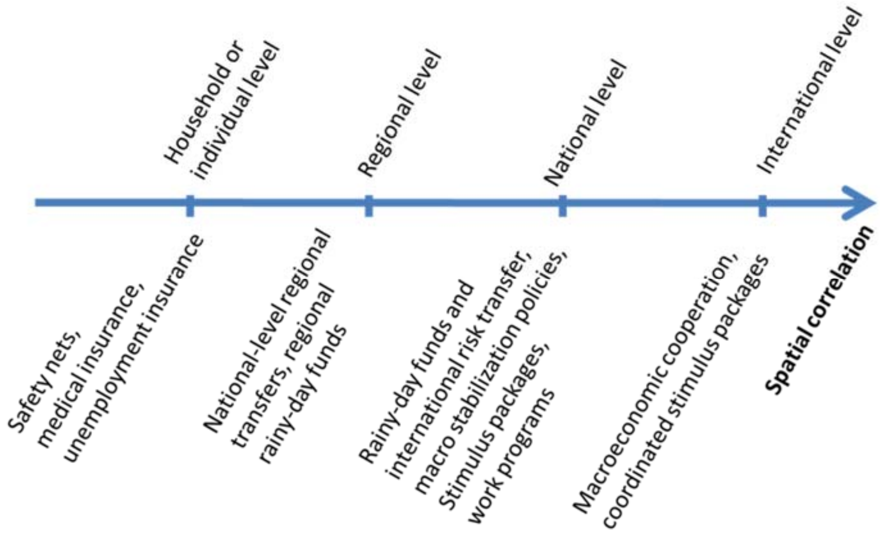

Figure 5. Policies to cope with correlated risks, depending on the spatial correlation

Finally, risk management needs also to be designed as a series of scales (see Figure 5). For idiosyncratic shocks – car accidents or illness – risk sharing across a small population may be sufficient. But when correlation increases – say for instance for floods or epidemics – then a large share of the local population may be affected at the same time, stretching the coping capacity of local systems. This is when risks need to be transferred to a higher scale, at the regional or national level. And when risks cannot be shared horizontally – across a larger population in one given year – they need to be shared across time, through increased savings (with non-correlated returns) and reinsurance schemes.[14]

In practice, institutional fragmentation and coordination issues makes it difficult to design a risk management strategy that takes a holistic and integrated view and coordinates across policy options (figure 4) and across scale (figure 5) (see World Bank, 2013). It makes it even more important to create the right institutions – able to coordinate across the government, across national and subnational entities, and between the public and private sectors – and to make risk management enough of a priority to mobilize the right actors and make the right decisions.

The macro-level resilience that is discussed in this paper is an important factor to determine the welfare impact of disasters, but it does not include all the factors that have an influence. In particular, this macro-resilience does not account for micro-resilience, i.e. the ability of households, firms, and individuals to manage the shock (and its indirect consequences). For instance, the reduction in consumption due to lost income and reconstruction needs can have direct consequences on individuals and households, for instance when reduction in food uptake leads to reduced productivity or to children stunting. These effects are essential to assess the full impact of a disaster on well-being, but are often invisible in macro-estimates, especially when the poorest are concerned, since their income and assets are negligible at the

[14] Reinsurance firms receive insurance premiums every year and save (and invest) them to be able to pay claims when a disaster hits. As such, reinsurance premiums are a form of savings.

aggregate level. The benefits from insurance, for instance, arise probably more from such micro-benefits than from the macro-effects discussed earlier (even though the latter is not negligible and should not be overlooked). The macro-level concept of economic resilience presented here should thus be completed with other aspects regarding the ability of firms to cope (see a framework to define firm resilience in Rose and Krausmann, 2013) and the ability of household to cope (see for instance Adger et al., 2002; Morris et al., 2002). Hallegatte (2014) builds on this work to propose a more comprehensive economic resilience indicator, taking into account the macro-level as described here and additional micro-level effects (including the role of inequalities and social protection).

5 References

Adger, W.N., Kelly, P.M., Winkels, A., Huy, L.Q., Locke, C., 2002. Migration, Remittances, Livelihood Trajectories, and Social Resilience. AMBIO J. Hum. Environ. 31, 358–366. doi:10.1579/0044-7447-31.4.358

Albala-Bertrand, J.M., 1993. Political economy of large natural disasters: with special reference to developing countries. Clarendon Press ; Oxford University Press, Oxford, [England] : New York.

Albala-Bertrand, J.M., 2013. Disasters and the Networked Economy. Routledge.

Atkins, D., Moy, E.M., 2005. Left behind: the legacy of hurricane Katrina. BMJ 331, 916–918.

Benson, C., Clay, E.J., 2004. Understanding the economic and financial impacts of natural disasters. World Bank Publications.

Bockarjova, M., Steenge, A.E., Veen, A. van der, 2004. On direct estimation of initial damage in the case of a major catastrophe: derivation of the “basic equation”. Disaster Prev. Manag. 13, 330–336. doi:10.1108/09653560410556555

Cochrane, H., 2004. Economic loss: myth and measurement. Disaster Prev. Manag. 13, 290–296. doi:10.1108/09653560410556500

Coffman, M., Noy, I., 2011. Hurricane Iniki: measuring the long-term economic impact of a natural disaster using synthetic control. Environ. Dev. Econ. 17, 187–205. doi:10.1017/S1355770X11000350

Dell, M., Jones, B.F., Olken, B.A., 2013. What Do We Learn from the Weather? The New Climate-Economy Literature (Working Paper No. 19578). National Bureau of Economic Research.

Downton, M.W., Pielke, R.A., 2005. How Accurate are Disaster Loss Data? The Case of U.S. Flood Damage. Nat. Hazards 35, 211–228. doi:10.1007/s11069-004-4808-4

DuPont, W., Noy, I., 2012. What Happened to Kobe? A Reassessment of the Impact of the 1995 Earthquake in Japan, Working Paper No. 12-4. University of Hawaii at Mānoa Department of Economics.

Felbermayr, G., Gröschl, J., 2013. Economic Effects of Natural Disasters: New Insights from New Data.

Fleurbaey, M., 2009. Beyond GDP: The quest for a measure of social welfare. J. Econ. Lit. 1029–1075.

Gordon, P., Richardson, H.W., Davis, B., 1998. Transport-related impacts of the Northridge earthquake. National Emergency Training Center.

Haimes, Y.Y., Jiang, P., 2001. Leontief-based model of risk in complex interconnected infrastructures. J. Infrastruct. Syst. 7, 1–12.

Hallegatte, S., 2008. An Adaptive Regional Input ‐ Output Model and its Application to the Assessment of the Economic Cost of Katrina. Risk Anal. 28, 779–799.

Hallegatte, S., 2012. A Cost Effective Solution to Reduce Disaster Losses in Developing Countries: Hydro-Meteorological Services, Early Warning, and Evacuation. World Bank Policy Res. Work. Pap. No 6058.

Hallegatte, S., 2014. Economic Resilience: definition and measurement.
Hallegatte, S., 2014. Modeling the role of inventories and heterogeneity in the assessment of the economic costs of natural disasters. Risk Anal. 34, 152–167.
Hallegatte, S., Dumas, P., 2009. Can natural disasters have positive consequences? Investigating the role of embodied technical change. Ecol. Econ. 68, 777–786.
Hallegatte, S., Ghil, M., 2008. Natural disasters impacting a macroeconomic model with endogenous dynamics. Ecol. Econ. 68, 582–592.
Hallegatte, S., Henriet, F., Patwardhan, A., Narayanan, K., Ghosh, S., Karmakar, S., Patnaik, U., Abhayankar, A., Pohit, S., Corfee-Morlot, J., 2010. Flood risks, climate change impacts and adaptation benefits in Mumbai: an initial assessment of socio-economic consequences of present and climate change induced flood risks and of possible adaptation options. OECD Publishing.
Hallegatte, S., Hourcade, J.C., Dumas, P., 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecol. Econ. 62, 330–340.
Henriet, F., Hallegatte, S., Tabourier, L., 2012. Firm-network characteristics and economic robustness to natural disasters. J. Econ. Dyn. Control 36, 150–167. doi:10.1016/j.jedc.2011.10.001
Hochrainer, S., 2009. Assessing the Macroeconomic Impacts of Natural Disasters: Are there any? World Bank Policy Res. Work. Pap. Ser. Vol.
Jaramillo, C., 2010. Do natural disasters have long-term effects on growth?
Kousky, C., 2014. Informing climate adaptation: A review of the economic costs of natural disasters. Energy Econ. doi:10.1016/j.eneco.2013.09.029
Kroll, C.A., Landis, J.D., Shen, Q., Stryker, S., 1991. Economic impacts of the Loma Prieta earthquake: A focus on small businesses.
Leontief, W.W., 1951. The structure of American economy, 1919-1939: an empirical application of equilibrium analysis. Oxford University Press New York.
Lindell, M.K., Prater, C.S., 2003. Assessing community impacts of natural disasters. Nat. Hazards Rev. 4, 176–185.
Loayza, N.V., Olaberria, E., Rigolini, J., Christiaensen, L., 2012. Natural Disasters and Growth: Going Beyond the Averages. World Dev.
McCarty, C., Smith, S., 2005. Florida's 2004 hurricane season: Local effects. Fla. Focus BEBR Univ. Fla. 1.
Mechler, R., 2004. Natural disaster risk management and financing disaster losses in developing countries. Verlag Versicherungswirtsch.
Morris, S.S., Neidecker-Gonzales, O., Carletto, C., Munguía, M., Medina, J.M., Wodon, Q., 2002. Hurricane Mitch and the Livelihoods of the Rural Poor in Honduras. World Dev. 30, 49–60. doi:10.1016/S0305-750X(01)00091-2
Noy, I., 2009. The macroeconomic consequences of disasters. J. Dev. Econ. 88, 221–231.
Noy, I., Nualsri, A., 2007. What do exogenous shocks tell us about growth theories? Working Papers, Santa Cruz Center for International Economics.
Noy, I., Vu, T.B., 2010. The economics of natural disasters in a developing country: The case of Vietnam. J. Asian Econ. 21, 345–354. doi:10.1016/j.asieco.2010.03.002
NRC, 2011. National Earthquake Resilience: Research, Implementation, and Outreach.
NRC, 2013. Disaster Resilience: A National Imperative.
Okuyama, Y., 2004. Modeling spatial economic impacts of an earthquake: Input-output approaches. Disaster Prev. Manag. 13, 297–306.
Okuyama, Y., Hewings, G.J., Sonis, M., 2004. Measuring economic impacts of disasters: interregional input-output analysis using sequential interindustry model. Model. Spat. Econ. Impacts Disasters 77–101.

Pelling, M., Özerdem, A., Barakat, S., 2002. The macro-economic impact of disasters. Prog. Dev. Stud. 2, 283–305.
Raddatz, C., 2009. The wrath of God: macroeconomic costs of natural disasters.
Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., others, 2011. An assessment of the potential impact of climate change on flood risk in Mumbai. Clim. Change 104, 139–167.
Rodriguez-Oreggia, E., de la Fuente, A., de la Torre, R., Moreno, H., 2009. The impact of natural disasters on human development and poverty at the municipal level in Mexico.
Rose, A., 2004. Economic principles, issues, and research priorities in hazard loss estimation. Model. Spat. Econ. Impacts Disasters 13–36.
Rose, A., 2009. Economic Resilience to Disasters (CARRI Research Report 8). Community and Regional Resilience Institute.
Rose, A., 2013. Defining and measuring societal resilience from an economic, environmental and personal security perspective (Background paper for the 2014 Human Development Report). UNDP.
Rose, A., Krausmann, E., 2013. An economic framework for the development of a resilience index for business recovery. Int. J. Disaster Risk Reduct. 5, 73–83. doi:10.1016/j.ijdrr.2013.08.003
Rose, A., Liao, S.-Y., 2005. Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions*. J. Reg. Sci. 45, 75–112.
Rose, A., Oladosu, G., Liao, S.-Y., 2007a. Business interruption impacts of a terrorist attack on the electric power system of Los Angeles: customer resilience to a total blackout. Risk Anal. 27, 513–531.
Rose, A., Porter, K., Dash, N., Bouabid, J., Huyck, C., Whitehead, J., Shaw, D., Eguchi, R., Taylor, C., McLane, T., 2007b. Benefit-cost analysis of FEMA hazard mitigation grants. Nat. Hazards Rev. 8, 97–111.
Rose, A., Wei, D., 2013. Estimating the economic consequences of a port shutdown: the special role of resilience. Econ. Syst. Res. 25, 212–232.
Santos, J.R., Haimes, Y.Y., 2004. Modeling the Demand Reduction Input ‐ Output (I ‐ O) Inoperability Due to Terrorism of Interconnected Infrastructures*. Risk Anal. 24, 1437–1451.
Skidmore, M., Toya, H., 2002. Do natural disasters promote long ‐ run growth? Econ. Inq. 40, 664–687.
Strobl, E., 2010. The Economic Growth Impact of Hurricanes: Evidence from U.S. Coastal Counties. Rev. Econ. Stat. 93, 575–589. doi:10.1162/REST_a_00082
Tierney, K., 2006. Social inequality, hazards, and disasters. Risk Disaster Lessons Hurric. Katrina 109–128.
Tierney, K.J., 1997. Business Impacts of the Northridge Earthquake. J. Contingencies Crisis Manag. 5, 87–97. doi:10.1111/1468-5973.00040
West, C.T., Lenze, D.G., 1994. Modeling the regional impact of natural disaster and recovery: a general framework and an application to Hurricane Andrew. Int. Reg. Sci. Rev. 17, 121–150.
World Bank, 2013. Risk and Opportunity: Managing Risk for Development (World Development Report).

6 Appendix A: The use of classical production function leads to underestimating output losses

There are several possible biases resulting from disaster modelling using classical production function (Hallegatte et al., 2007). Production functions are classically used in economics to relate the inputs and the outputs of a production process. Often, the production function takes as inputs the amount of labor used in the production process (referred to as L) and the amount of capital (i.e., the value of all equipment used in the process, referred to as K), and gives the value of the production (expressed as Y):

$$Y = f(L,K) \,. \tag{A1}$$

Disasters mainly destroy the stock of productive capital and a natural modelling option to represent their consequences is to consider that they reduce instantaneously the total productive capital ($K_0 \rightarrow K_0 - \Delta K$). Figure A1 illustrates several ways of assessing the impact on production. The figure represents the production Y as a function of capital K. The production function is the blue line linking the origin of the graph to the point A. It is assumed that the pre-disaster situation is the point A, with capital K_0 and production Y_0.

The impact on production can be estimated using the marginal productivity of capital, i.e. the interest rate at the optimum. This case is shown in Figure A1 as the point B. Point B is estimated using the orange line, which is the tangent to the production function at point A; its slope is the marginal productivity of capital (i.e., how much more production do I get if I increase capital by one unit). The production Y_1 is given by the orange line at the X-coordinate $K_0 - \Delta K$, and is the estimated residual production if the output loss is estimated by multiplying the value of the lost capital ΔK by the interest rate. It is also what is done when the net present value of all output losses is assumed to be equal to the value of lost assets.

The impact on production can also be estimated using the full production function, and decreasing the amount of capital from K_0 to $K_0 - \Delta K$. This is what is shown by the point C in the figure. The point C gives the value of production Y_2 given by the production function, i.e. $f(L, K_0 - \Delta K)$. This option, however, amounts to assuming that only the least-productive capital has been affected. Obviously, this is not the case: when a disaster hits, it destroys the capital indiscriminately, not only the least efficient capital.

Because of decreasing returns in the production function, using a classical production function amounts to assuming that capital destructions affect only the less efficient capital. In a Cobb–Douglas setting ($Y=AL^{\lambda}K^{\mu}$), indeed, the after-disaster production would be $Y_2=AL^{\lambda}(K_0-\Delta K)^{\mu}$. Since μ is classically estimated around 0.3, an x% loss of equipment would reduce the production by a factor (μ x), i.e. approximately (0.3 x) % (see figure below).

To account for the fact that disasters affect the capital independently of its productivity, Hallegatte et al. (2007) propose to modify the Cobb–Douglas production function by introducing a term ξ_K, which is the proportion of non-destroyed capital. This new variable ξ_K is such that the effective capital is $K=\xi_K \cdot K_0$, where K_0 is the potential productive capital, in absence of disaster. The new production function is

$$Y_3 = \xi_K f(L,K_0) = A \xi_K L^{\lambda} K_0^{\mu} \quad \text{(A2)}$$

In Figure A1, the new production function is the red line and the new production Y_3 is given by the point C'.

With these assumptions, the decrease in output from a disaster is not equal to the value of lost assets multiplied by the marginal productivity of capital anymore. Instead, output losses are equal to the value of lost assets multiplied by the average productivity of capital, which is $1/\mu$ times larger than the marginal capital productivity. With classical values for μ, it means that output reduction at the time of shock (t_0) is about 3 times larger than what is suggested by the market value of damaged assets. As result, production losses are then given by:

$$\Delta Y(t_0) = \frac{1}{\mu} r \Delta K$$

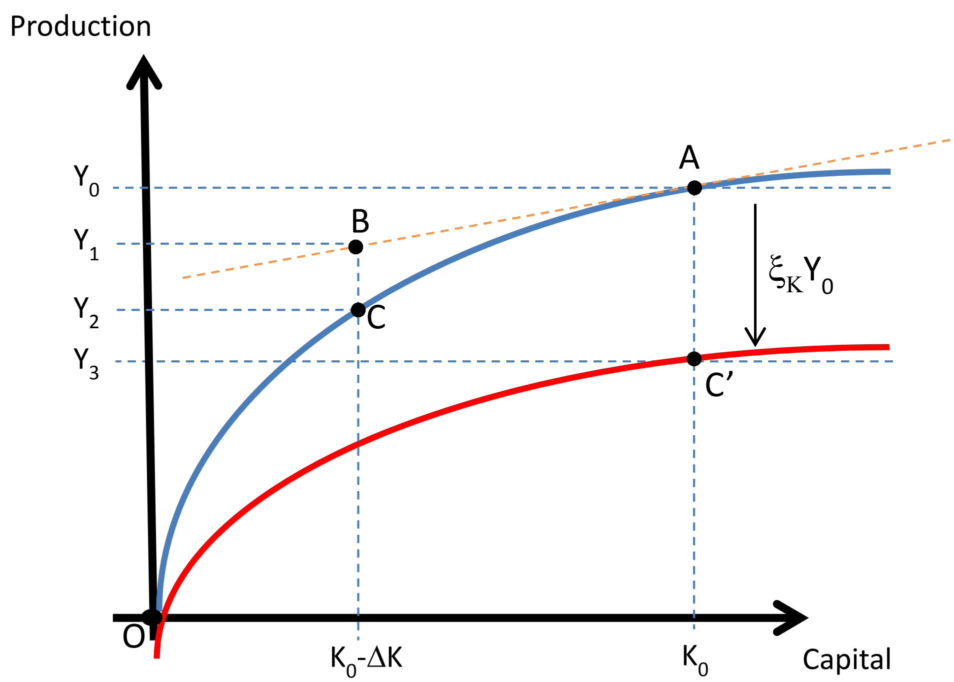

Figure A1. Production with respect to productive capital for different modelling assumptions.

Another bias arises from the aggregation of many different types of capital within only one variable – capital K – in economic models. If the function f(L,K) is replaced by a function with two types of capital $f(L,K_1,K_2)$, the impact of disasters can change dramatically. In particular, because of decreasing returns in K_1 and K_2, the impact of a given loss $\Delta K=\Delta K_1+\Delta K_2$ depends on how losses are distributed across the two capitals. The loss in output is larger if all losses affect one type of capital, compared with a scenario where the two capitals are more homogeneously affected. As a result, disaster loss estimates can be dependent on the aggregation level of the economic models used to assess them: the more disaggregated the model is, the more likely it is that one type of capital is heavily affected, leading to large output losses. The use of production functions may create another problem: production functions assume that the output of the production process is continuous in K and L. In reality, there are discontinuities in the production function: the loss of a segment of a road can make the entire road impracticable and useless; damages to one small piece of equipment in a factory can make it unable to produce the final product, etc. So a small ΔK can lead to a large loss in output, if the complementary of different capital items is taken into account. This is especially true when large network infrastructure is concerned.

One way of investigating these two issues is to assume that there are two categories of capital, K_1 and K_2, that are not substitutable (i.e. the production function is a Leontieff function with decreasing returns):

$$Y = [\mathrm{Min}(\alpha_1 K_1, \alpha_2 K_2)]^{\gamma} \quad \text{(A3)}$$

K_1 and K_2 could be interpreted as two segments of a road, for instance: if one segment is completely destroyed, the second segment productivity falls to zero, and the total capacity of the road is given by its segment with the lowest capacity.

Total capital is $K = K_1 + K_2$. At the optimum, we have $\alpha_1 K_1 = \alpha_2 K_2$, and:

$$K_i = \left(\frac{\alpha_j}{\alpha_1+\alpha_2}\right) K \quad \text{(A4)}$$

(with j equal to 2 when i is equal to 1, and vice-et-versa). Assuming that capital K is distributed optimally across K_1 and K_2, the production function becomes:

$$Y = \left[\frac{\alpha_1 \alpha_2}{\alpha_1+\alpha_2} K\right]^{\gamma} \quad \text{(A5)}$$

This production function is equivalent to a classical Cobb-Douglas function (assuming that the labor input is fixed and included in the parameters). In fact, one assumption in a production function is that capital can be aggregated into a unique variable K, assuming that capital is then optimally distributed across categories of capital (i.e. across sectors, technologies, localization, etc.).

The return on capital is equal to the interest rate plus the depreciation rate:

$$\frac{\partial Y}{\partial K} = i + \delta \quad \text{(A6)}$$

This relationship gives the optimal amount of capital:

$$\overline{K} = \left(\frac{\gamma A}{i+\delta}\right)^{\frac{1}{1-\gamma}} \quad \text{(A7)}$$

Where $A = \left[\frac{\alpha_1 \alpha_2}{\alpha_1+\alpha_2}\right]^{\gamma}$.

If only K_i is affected by a disaster, then $K_i < K_j$, and the production is driven by K_i only and becomes:

$$Y = [\alpha_i K_i]^\gamma \tag{A8}$$

And the loss in output from a marginal loss of K_i is:

$$\frac{\partial Y}{\partial K_i} = \gamma \alpha_i^\gamma K_i^{\gamma-1} \tag{A9}$$

Replacing K_i, we get:

$$\frac{\partial Y}{\partial K_i} = \left(\frac{\alpha_1+\alpha_2}{\alpha_2}\right)(i+\delta) \tag{A10}$$

This can be generalized for case with N categories of capital into:

$$\frac{\partial Y}{\partial K_i} = \left(\frac{\sum \alpha_j}{\sum \alpha_j - \alpha_i}\right)(i+\delta) \tag{A11}$$

If α_i is really small, the marginal productivity of capital K_i can be extremely high, much higher than the marginal capital productivity given by Eq. (A6). This case is somewhat extreme because the different categories of capital are assumed non-substitutable, but the qualitative result remain valid with higher substitutability: *considering disaggregated capital categories with imperfect substitutability[15], a disaster would break the assumption that the total amount of capital is optimally distributed across these categories, increasing the marginal productivity of destroyed capital (and as a result, the marginal productivity of reconstruction).*

Because of these effects of imperfect subsitution, the loss of output estimated is magnified (or reduced) by a factor ($1+\alpha$). The reduction in output just after the shock is thus given by the equation:

$$\Delta Y(t_0) = \frac{1+\alpha}{\mu} r \Delta K$$

The parameter α represents the reduced (or increased) production of the capital that is not directly affected by the event, and depends on the ability of the economic system to (1) mobilize existing idle capacity (which depends on the existence of idle capacity); (2) adjust production networks to compensate for damaged production units (e.g., producers find new suppliers and clients rapidly), (3) channel remaining production toward its most productive uses (including reconstruction needs), and (4) increase imports to compensate for unavailable supplies. It is likely to be negative for relatively small disasters, and to become positive and then increase for larger-scale events. It is lower (and possibly negative) if there is a larger under-utilization of production capacity and idle capacity that can be mobilized.

[15] The only case where this result does not hold is when the production function is in the form: $Y=f(K_1+K_2+\ldots+K_n)$.

This parameter also depends on other – more micro – considerations regarding the ability of firms to cope with shocks (see a framework to define firm resilience in Rose and Krausmann, 2013).[16] As such, the parameter α is linked to the concept of *"static resilience*" proposed by (Rose, 2013, 2009). He defines it as follows: *"Static resilience refers to the ability of an entity or system to maintain function when shocked. This is related in turn to a fundamental economic problem—how to efficiently allocate the resources remaining after the disaster. It is static because it can be attained by various means, such as conservation, input substitution, relocation, etc., that increase capacity to produce in subsequent time periods.*"

7 Appendix B. Quantity and prices in disaster aftermaths

Figure B1 is a classical quantity-price plot, showing the long-term demand and supply curves for a goods or service aggregated at the macroeconomic level. The green line is the demand curve: it shows how the quantity demanded by consumers decreases when the price increases. The blue curve is the pre-disaster (long-term) supply curve: it shows how the quantity produced increases with the price (or, equivalently, the price asked by producers to produce a given quantity). The point A is the intersection of demand and supply and shows the price and quantity that clear the market (at that point, supply equals demand). The economic "surplus" is the area ADE. The consumer surplus is the upper area (AFE) and the producer surplus the bottom area (AFD).

The red line is the short-term supply curve after the disaster: because of damages, production cannot exceed Q_1, and the supply curve becomes vertical at this level (whatever the price consumers are ready to pay, producers cannot produce more than Q_1). If the market clears, the new equilibrium is reached at point B, where the quantity is reduced to Q_1 and the price increases to p_1.

In classical economic reasoning, the move from A to B is reducing the pre-disaster surplus ADE to the area BCDE. In other terms, the surplus loss is ABC. But this would be correct only if firms were deciding to reduce production from Q_0 to Q_1 *and to reduce the expenditure needed to produce Q_0*. If firms decided to reduce investment and production capacity from Q_0 to Q1, they would reduce their sales from p_0Q_0 to p_1Q_1, and reduce their production expenses from the area $ODAQ_0$ to the area $ODCQ_1$.

[16] Note that these ripple-effects can be particularly large when critical infrastructure (e.g., electricity networks) is affected. An extreme case is when terrorist attacks target critical infrastructure, see (Rose et al., 2007a); in this case, α can be extremely high, much higher than for natural disasters.

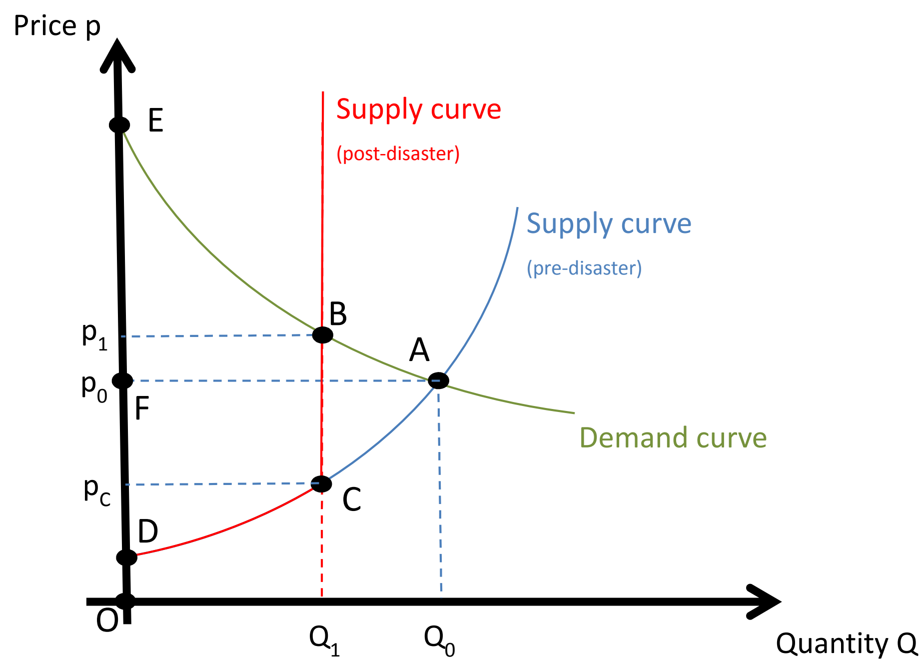

Figure B1. Supply and demand curves in the pre- and post-disaster situations.

When a disaster hits, however, the sales are reduced from p_0Q_0 to p_1Q_1, but the expenses are not reduced from the area $ODAQ_0$ to the area $ODCQ_1$. This is because firm expenses have three components: intermediate consumptions, capital expenses, and labor. The reduction in intermediate consumptions translates into a loss of output for another firm, so at the macroeconomic level, a reduction in intermediate is not a gain. Reduction in labor expenditures is also a loss for workers, so it should not be counted at the macroeconomic level (unless, workers can find instantaneously another job, which is mostly not the case in disaster contexts). Finally, when a disaster reduces the production capacity from Q_0 to Q_1, it does not do so by reducing capital expenses, but by damaging existing capital. If a firm at a loan to pay for its capital (factory, equipment, etc.), the capital is destroyed but the loan is still there. In other terms, the capital expenditures are not reduced by the disaster.

So to assess the disaster impact on welfare over the short-term, it makes sense to consider the area Q_0ABQ_1 (and not the area ABC as in classical long-term welfare analysis). If the price is unchanged, then the impact can be estimated as $p_0\Delta Q$ (i.e. the loss of output). If the price change is significant, then it is necessary to take it into account, but it is challenging because the shape of the form Q_0ABQ_1 is complex. A linear assumption would simply be: $(p_0 + p_1)\ \Delta Q/2$.

8 Appendix C: Total output losses and reconstruction pathway

Assuming that output losses are reduced to zero exponentially, and that 95% of the losses are repaired in N years, then the output losses are also decreasing exponentially, with a characteristic time N/3; Output losses after t_0 are thus given by: [17]

$$\Delta Y(t) = \frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}}$$

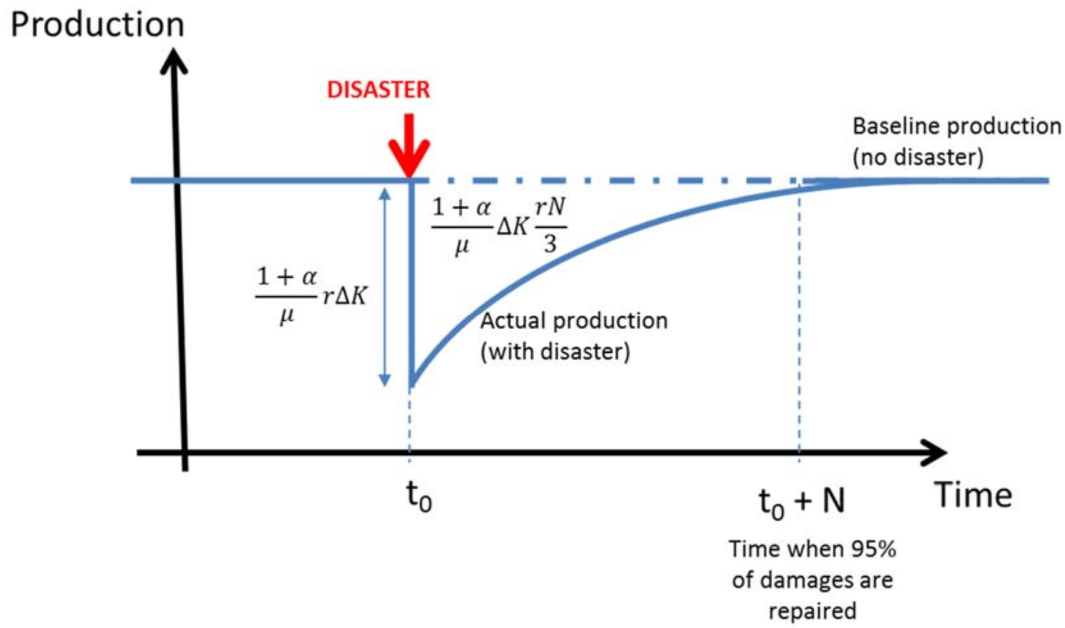

Figure C1: (Very) simplified representation of the return to "initial state" after a disaster. The area between the horizontal line and the actual production is the total loss of production.

With this reconstruction pathway, total *non-discounted* output losses $\overline{\Delta Y}$ are equal to (see Figure C1):

$$\overline{\Delta Y} = \int_{t_0}^{+\infty} \frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}} dt = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{3}$$

The parameter N is the reconstruction period and it can often be estimated by experts based on past experience.[18] Note that the reconstruction time is not the time when the observed GDP or output returns to its pre-disaster value, but may be much longer. Indeed, GDP and output are affected by other mechanisms, including changes in labour productivity, trade effects, other investments, and possibly the "stimulus effect" of the disaster. In this framework, as mentioned in Section 2.2.3, the stimulus effect is

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[17] In that case, a fraction *3/N* of remaining damages is repaired every year and remaining losses are given by an exponential. The characteristic time (also referred to as the e-folding time) is equal to *3/N* because $\exp(-3) \approx 0.05$ so that $\Delta Y(N) = 0.05\, \Delta Y(t_0)$.

[18] Production losses also depend on the reconstruction pathway. Here we assume an exponential reconstruction; if the reconstruction is linear in N years, then Eq.(11) becomes $\overline{\Delta Y} = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{2}$.

not accounted for in disaster consequences since it corresponds to benefits that could have been captured in the absence of the disaster, through a classical stimulus policy.

The length of the reconstruction period will depend on many characteristics of the affected economy, including (1) the capacity of the sectors involved in the reconstruction process (especially the construction sector); (2) the flexibility of the economy and its ability to mobilize resources for reconstruction (e.g., the ability of workers to move to the construction sector, see Hallegatte, 2008); (3) the openness of the economy and its ability to access resources (e.g., skilled workers and materials for reconstruction); (4) the financial strength of private actors, households and firms, and their ability to access financial resources for reconstruction, through savings, insurance claims, or credit; and (5) the financial strength of the public sector and its ability to access financial resources to reconstruct (see the very thorough analysis of financing options in developing countries in Mechler, 2004).[19]

With discounting at a rate r, the net present value of output losses is[20]:

$$\widetilde{\Delta Y} = \int_{t_0}^{+\infty} \frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}} e^{-r(t-t_0)} dt = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{rN+3}$$

[19] Specific instruments such as contingent credit lines help with reconstruction financing. See for instance on the World Bank's Cat-DDO, http://treasury.worldbank.org/bdm/pdf/Handouts_Finance/CatDDO_Product_Note.pdf.
[20] The variable noted with $\tilde{x}$ are the net present value of the future fluxes of $x(t)$.