A Cost-Benefit Analysis of the New Orleans Flood Protection System

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Abstract

In the early stages of rebuilding New Orleans, a decision has to be made on the level of flood protection the city should implement. Such decisions are usually based on cost-benefit analyses. But in such an analysis, the results are contingent on a number of underlying assumptions and varying these assumptions can lead to different recommendations. Indeed, though a standard first-order analysis rules out category 5 hurricane protection, taking into account climate change and other human-related disruptions of environment, second-order impacts of large-scale disasters, possible changes in the discount rate, risk aversion and damage heterogeneity may make such a hurricane protection a rational investment, even if countervailing risks and moral hazard issues are included in the analysis. These results stress the high sensitivity of the CBA recommendation to several uncertain assumptions, highlight the importance of second-order costs and damage heterogeneity in welfare losses, and show how climate change creates an additional layer of uncertainty in infrastructure design that increases the probability of either under-adaptation (and increased risk) or over-adaptation (and sunk costs).

Introduction

Six months after the deadly landfall of the category 4 Hurricane Katrina on New Orleans, there is an active debate about the reconstruction of New Orleans and the design of its future flood protection system (*e.g.*, Schwartz, 2005; Bohannon and Enserink, 2005). Although the reconstruction of New Orleans has been questioned by House Speaker Dennis Hastert and is still a debated question (Hahn, 2005), this paper will assume that it will be eventually carried out and focus on an adjacent question, namely the necessity of making the city flood protection system able to cope with category 5 hurricanes.

The design of natural disaster protection systems is based on cost-benefit analyses (CBA; see for instance Arrow *et al.*, 1996), even though other decision-making frameworks have been proposed (*e.g.*, the precautionary principle). In a CBA framework, New Orleans would only benefit from a flood protection system able to cope with category 5 hurricanes, compared to a system able to cope with category 3 or 4 hurricanes, if the additional cost of the upgraded protection was lower than the expected benefits from reduced flood damages. This is not certain to be the case, as surprising as this might appear given Katrina's devastating impact, and this article will show how two evaluations can reach opposite conclusions.

To do so, we will first carry out a simple CBA using available data on the damages caused by Katrina in New Orleans. As we will see, this first CBA clearly rules out any category 5 protection system. Then, we will show how less optimistic assumptions on anthropogenic perturbations of environment and considering additional processes, namely second-order impacts, discount rate choice, countervailing risks and side-effects, risk aversion, and damage heterogeneity, can change the terms of the analysis and potentially justify the implementation of a category 5 system.

A first Cost-Benefit Assessment

To carry out a CBA of a category 5 flood protection system in New Orleans, one needs to assess the cost, C, of such a system, and its expected benefits, B. On the one hand, assessing the cost, C, of an upgrade of the protection system is not that complicated, even though it requires a precise definition of the system and an assessment of its construction and maintenance costs. In the very early stages of rebuilding, state officials evaluate the cost of category 5 protection at about $32 billion, compared with a $1 billion cost to restore the initial category 3 protection (Schwartz, 2005). Precise information on the cost of category 4 protection is unavailable but we will assume that it would be about $5 billion, making the additional cost of a category 5 protection $27 billion.

On the other hand, assessing expected benefits is much more problematic, as one needs to take into account benefits of various natures (avoidance of casualties, injuries, economic losses, psychological trauma, etc...) impacting different groups of people and possibly lying far in the future. This aggregation problem has been largely discussed; see, for instance, Adler (2005) or Schneider *et al.* (2000) for aggregation issues between different categories of impacts and Portney and Weyant (1999) for issues concerning inter-temporal aggregation.

Regardless of these important problems, benefits can be defined as the net present value of the expected amount of damages avoided by the protection system upgrade. These benefits can, therefore, be calculated as the discounted sum, for each year from now through the lifetime of the protection system, of the annual probability that a category 5 hurricane hits New Orleans multiplied by the difference between the damages of such a hurricane on a category 4 versus a category 5 protection system. This difference is discounted to take into account the fact that the same benefit is valuated at a higher value when it occurs in the near future rather than further in the future.

The values of three parameters are thus necessary: the discount rate (δ), the probability of occurrence (p), and the amount of avoidable damages in the year n (d_n). From them, expected benefits, B, are easy to calculate[2]:

$$B = \sum_0^{+\infty} p \cdot \left(\frac{1}{1+\delta}\right)^n \cdot d_n .$$ (1)

Assuming that damages are growing over time at the same rate as economic growth, g, which is a conservative hypothesis considering the current growth of economic losses due to natural disasters (Mills *et al.*, 2004; Munich Re, 2005), expected benefits read:

$$B = \sum_0^{+\infty} p \cdot \left(\frac{1}{1+\delta}\right)^n \cdot d_0 (1+g)^n \approx \frac{pd_0}{\delta - g} ,$$ (2)

where d_0 is the amount of damages a flooding of New Orleans would cause today. If the cost, C, of the flood protection system is lower than the expected benefits, B, then the system should be implemented. In spite of the difficulties already mentioned, a rough assessment of B can be made based on current information. From historical experience (i.e. by observing hurricane frequencies over the last century), one can evaluate the annual probability that a category 5 hurricane hits New Orleans at about $p = 1/500$ (H. Saffir, quoted in Schwartz, 2005).

The Office of Management and Budget (OMB), which carries out CBA of Federal regulations in the U.S., uses two different discount rates to analyze policy decisions (OMB, 2003; see Appendix D, OMB Circular A-4). These two discount rates are used to assess the robustness of findings to the choice of discount rate and to capture two approaches to CBA. First, the discount rate can be calculated as the opportunity cost of capital, especially when strong capital reallocation is involved, yielding a value of 7 percent in the U.S. Second, especially when the project affects consumption patterns (e.g., fiscal changes), the discount rate can be calculated as the "social rate of pure preference" used by the average American saver in his saving decisions, yielding a value of 3 percent. Because the New Orleans flood protection system deals with the optimal allocation of capital, the use of the first value of 7 percent can appear *a priori* more appropriate. Note also that, according to the *Ramsey growth discount rule* (Ramsey, 1928), the discount rate can be evaluated by the relationship $\delta = \rho + \alpha\, g$, where ρ describes value judgments about time preferences and is referred to as the *rate of pure preference for the present;* α is the elasticity of the marginal utility and describes value judgments about the distribution of wealth; and g is the growth rate in the considered economy. The 7 percent discount rate used by the U.S. agency is consistent with a rate of pure preference for the present of $\rho = 4$ percent and an elasticity of the marginal utility of $\alpha = 1$, with an expected economic growth of the U.S. economy of $g = 3$ percent. The 3 percent discount rate derived from the social rate of pure preference is consistent with a less optimistic prediction of economic growth, at 2 percent, and a pure preference for the present of $\rho = 1$. It is noteworthy that if damages are growing at the same rate as the economy, then a null pure preference for the present ($\rho = 0$) would imply that the flood protection would yield infinite benefit, provided that this flood protection system has a quasi-infinite lifetime.

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[2] It is assumed that protection systems have an infinite lifetime, after having checked that results were only weakly sensitive to the protection system lifetime, chosen in a reasonable range, for the selected values of the parameters. Indeed, as we will see, if $\delta \approx g$, where g is the economic growth rate (see below), the system lifetime becomes an important variable.

Insurance and reinsurance companies (e.g., Munich Re, Swiss Re, etc...) and disaster modeling companies (e.g., RMS, EQECAT, etc...) estimate the direct damages due to any hurricane or flood, and their results are widely used as proxies for the overall economic cost of disasters. These companies estimate the cost of the New Orleans flooding around $20 billion (RMS, 2005)[3]. Taking into account casualties (about 1,000 people died in the flooding) raises the difficult issue of attributing a cost to a loss of life. Because the expression "*value of the human life*" problematically suggests a market in which one could buy or sell human lives, it is preferable to use the expression "*amount the public is willing to devote to reducing risk in order to save an additional life*", which is a much more acceptable wording. Even though the value depends on the type of risk and the probability of occurrence of the considered event, most estimates lie between $1 million and $10 million in the U.S. We will use here the commonly-used estimation of the U.S. EPA (1997) of $5 million. Given this figure, the public would be willing to pay $5 billion to avoid the human toll of the New Orleans flood. An additional $5 billion will be added to take into account the numerous injuries and trauma. According to these rough estimates, $30 billion seems to be a good approximation of the New Orleans flood cost[4].

Assuming that a category 4 protection system does not reduce the damages yielded by category 5 hurricanes, which is likely since there is little difference between no levees and broken levees, the expected present benefit of a category 5 flood protection system in New Orleans can be calculated with Eq.(2) at $1.5 billion with a 7-percent discount rate and $6 billion with a 3-percent discount rate. Both are one order of magnitude lower than the building cost of such a system. This rough estimate clearly rules out an upgrade of the protection system to make it able to cope with category 5 storms. It might be difficult to believe that the risk of a repetition of the devastation caused by the category 4 hurricane Katrina is not enough to justify the implementation of the best possible protection system. However, our CBA suggests that it is more rational from an economic point-of-view to live the Katrina nightmare again in a more or less remote future[5].

This estimate is, however, not very solidly grounded, as it does not take into account important processes, whose impacts could be significant. In line with OMB requirements when uncertainty is large and economic implications are in excess of $1 billion (OMB, 2003), we will now review the parameters[6] of the CBA, and propose alternative estimates. We will not, however, attribute subjective probabilities to the various hypotheses that will be proposed and conduct a full probabilistic analysis, as can be found, for instance, in Mastrandrea and Schneider (2005) for the climate change issue. Indeed, current knowledge about natural disaster consequences seems still insufficient to assess these probabilities with any confidence, and the following sections will show how much research is still necessary.

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[3] Note that the losses due to the New Orleans flooding were only a fraction of the total cost of the Katrina landfall.

[4] In case of a repetition of the Katrina's scenario, a better evacuation would probably be able to avoid a large part of the human losses and reduce this amount of damages. It has to be mentioned, however, (i) that Katrina's track forecasts have been very good and allowed for anticipated decisions before landfall, which is not always possible, and (ii) that an evacuation is always subject to organisational problems and unexpected practical difficulties, making the human part of the damages highly variable and uncertain.

[5] An annual probability of 1/500 means that there is a 20 percent chance of having a category 5 hurricane hitting New Orleans in the next 100 years, and a 33 percent chance in the next 200 years.

[6] Among the necessary assumptions in the CBA, it is often useful to distinguish between the political choices that must arise from a political process (e.g., discounting scheme), and the scientific uncertainties that can be – at least theoretically – solved through additional research (e.g., future probability of occurrence).

Probability of occurrence

In the first CBA, historical evidence was used to assess the probability of occurrence of a category 5 hurricane landfall on New Orleans. This assessment cannot, however, be considered as robust in this CBA. Indeed, a flood protection system has a very long lifetime. Such a long lifetime arises, of course, from the long lifetime of infrastructures (dams, bridges, gates). But, above all, it comes from the fact that the flood protection system will shape the city development over an even longer time horizon. The decisions that will be taken in the next years will, therefore, constrain the flood protection of New Orleans for at least the next century.

During this century, climate is likely to change significantly in response to human emissions of greenhouse gases (GHG), with consequences for hurricane damages. We already detect a trend in hurricane destructiveness: Webster *et al.* (2005) observed that hurricanes in the strongest categories (4 and 5) have almost doubled in number and in proportion in 30 years; over the last 75 years, Emanuel (2005a) detected in the North Atlantic and western North Pacific basins a strong increase in the power-dissipation index (PDI), which is a proxy of the destructiveness of hurricanes. The debate on the significance and persistence of these trends, however, has yet to be solved (e.g., Landsea, 2005; Emanuel, 2005b)

Regardless, experts expect hurricane maximum intensities to increase as temperatures rise during the 21st century. Global climate-model experiments have suggested an increase in the relative risk of occurrence of category-5 hurricanes under high-GHG conditions (Knutson and Tuleya, 2004). A tropical-cyclone model run by Emanuel (2006) found that a 10 percent increase in potential intensity, corresponding approximately to a 2°C-warming, could lead to a 65 percent increase in PDI. Even though uncertainty remains in the amplitude of the change (Trenberth, 2005; Pielke *et al.*, 2005), it is noteworthy that any change in the mean characteristics of hurricanes might easily translate into large changes in the probability of the most powerful hurricanes. As an illustration, if the distribution shape of the hurricane PDI were unchanged, the 65-percent increase in the mean PDI found by Emanuel (2006) would multiply by 3.8 the frequency of the 1-percent most powerful hurricanes (see Appendix A).

Also, sea level rise and other human-induced disruptions to the Mississippi River delta (*e.g.*, sediment deposition reduction) will worsen the floods associated with any hurricane falling on this low-lying area (Burkett *et al.*, 2003). Thus, the probability of floods currently caused only by category 5 hurricanes might increase, as less powerful hurricanes could also produce such devastating floods.

To take into account these two phenomena in the CBA, they will be summarized through the assumption that the annual probability of floods currently caused by category 5 hurricanes will be multiplied by 3.8, to reach p=1/130 years. This higher probability alone would make expected benefits rise from $1.5 to $5.7 billion or from $6 to $22.8 billion, depending on the discount rate.

These results suggest that climate change may have an important impact on long-term hurricane risk, even though changes in population and capital at risk will obviously be the main driver of vulnerability during the next decades. Additionally, the large uncertainty of the future probability of occurrence highlights one mechanism that have been disregarded in the climate change impact literature so far, but through which climate change might be responsible for significant economic damages in the future: climate change increases the uncertainty on parameters that impact the

design of long-term infrastructure, making them more likely to be ill-suited in the future climate. In the present case, the risk is either to face a series of avoidable disasters in New Orleans, if the probability of occurrence turns out to be much larger than predicted when the protection system is designed, or to bear the sunk costs of an expensive protection system based on an overestimated probability of occurrence.

Avoidable damages

Another major difficulty remains in the assessment of the actual damages that could be avoided through an upgrade of the protection system. Assuming that New Orleans will be reconstructed and that all displaced households will return to their original city (we will address this issue later in the paper), the damages from the Katrina landfall can be used as a proxy for the damages a future flood may cause. As mentioned earlier, however, several authors suggest that the direct costs, evaluated by insurance companies, may be poor proxies of overall costs, especially concerning large-scale events (Tierney, 1995; Lindell and Prater, 2003; Hallegatte and Hourcade, 2006). Indeed, direct cost can be amplified (i) by spatial or sectoral propagation into the rest of the economic system over the short-term (*e.g.*, through disruptions of lifeline services[7]) and over the longer term (*e.g.*, sectoral inflation due to demand surge, energy costs, insurance company bankruptcy, larger public deficit, or housing prices that have second-order consequences on consumption); (ii) by responses to the shock (*e.g.*, loss of confidence, change in expectations, indirect consequences of inequality deepening); (iii) by financial constraints impairing reconstruction (*e.g.*, low-income families cannot finance rapidly the reconstruction of their home); and (iv) by technical constraints slowing down reconstruction (*e.g.*, availability of skilled workers, difficulties in equipment and material transportation, difficulties in accommodating workers). To measure the impact of these effects, Hallegatte and Hourcade (2006) introduced in their simple economic model a parameter measuring the ability of the economy to fund and carry out reconstruction, and derived the *Disaster Economic Amplification Ratio* (DEAR), which measures the ratio between the overall economic cost and the direct loss due to a disaster. While this ratio is less than one for small-scale disasters, DEAR is found, using a simple model, to increase dramatically for large-scale disasters like the New Orleans floods. This increase arises mainly from the addition to the capital replacement cost of the production losses during the reconstruction phase. For example, if a $1 million plant was destroyed and immediately rebuilt, the loss would be $1 million; if its reconstruction is delayed by one year, the total loss is the sum of the replacement cost and of the value of one year of production. For housing, the destruction of a house with a one-year delay in reconstruction has a total cost equal to the replacement cost of the house plus the value attributed to inhabiting the house during one year. The value of such production losses, in a broad sense, can be very high in some sectors, especially when basic needs are at stake (housing, health, employment, etc.).

A couple of months after the Katrina landfall, initial analyses of the disaster aftermath unfortunately confirm this intuition; because the "*systemic functioning*" of the whole region is now impaired (both economically and technically), the reconstruction is dramatically slowed down and the total cost of the event will be much larger than its direct cost. In recent publications, the RMS research team (RMS, 2005) and the RAND Corporation (McCarthy *at al.*, 2006) highlight the existence of numerous "loss amplification" effects: demand surge (e.g., a 13-percent increase in cement prices between 2005 and 2008 is forecasted); longer delay in reconstruction due to technical

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[7] For instance, Tierney (1995) finds that data on the consequences of the 1993 Midwest floods and the 1994 Northridge earthquake suggest that "*business properties may escape direct damage and yet suffer extensive disruption as a result of lifeline service outages*". These short-term costs, however, are most of the time included in the assessments by the insurance industry through "business interruption" costs.

constraints; financial constraints in reconstruction due to insufficient flood-insurance policy coverage. These conclusions probably understate these effects, as they focus primarily on direct costs without considering most of the second-order costs, which are not insured but are supported by the overall community (*e.g.*, the impact of Katrina on tourism in New Orleans and its vicinity during future hurricane seasons, which is still unknown but might turn out to be significant; or the cost of taking in thousands of displaced people in other cities).

Social costs of large-scale disaster also involve other dimensions than direct economic losses and casualties, including psychological factors or political and social destabilization (see a review in Lindell and Prater, 2003). For instance, confidence in the ability of public services to carry out disaster relief in an efficient manner may have been undermined by this event, investors may be reluctant to invest large amounts of money into new businesses in the affected area, and tourists may change their favorite vacation destination if they feel endangered in New Orleans. Of course, a comparable event occurring in the next decades would strongly amplify all these reactions, possibly leading to a withdrawal from New Orleans, the cost of which is difficult to assess[8]. Also, natural disasters have been found in the past to cause strong political and social unrest when they amplified pre-existing tensions (*e.g.*, hurricane Bohla in 1970, which killed almost 300,000 persons in Pakistan without provoking an effective mobilization of the central government to provide relief, worsened social tensions that led to the creation of Bangladesh in 1971). Even though the social and political destabilization arising from a hurricane in the U.S. cannot but remain limited (Lindell and Prater, 2003), the consequences of a near repetition of a Katrina-like event on the social and economic climate of Louisiana are difficult to predict[9]. The cost of two Katrinas would be much larger than twice the cost of one Katrina.

Moreover, even if long-term consequences remain limited when considering a single event, the consequences of a distribution of events on regional economic growth can be significant (Hallegatte and Hourcade, 2006). Indeed, as already stated by Benson and Clay (2004), poor regions or countries affected by repeated natural disasters and suffering from a weak ability to conduct reconstruction may prove unable to maintain the infrastructures necessary for economic development, leading to the creation of "*poverty traps.*" As examples of this phenomenon, we cite Guatemala, whose impressive series of weather catastrophes between 1997 and 2001 prevented any development. Similarly, in Honduras, the single hurricane Michele in 2001 "*put the country's economic development back 20 years*" (Honduran Prime Minister, quoted in IFRCRCS, 2002). Again, it is possible that disasters have, at least in some regions, long-run consequences that are neglected in first-order estimates, through changes in potential economic growth.

For all these reasons, and given the large vulnerability of New Orleans and its vicinity (important economic activity in sensitive sectors like tourism, transportation or energy production; low reconstruction capacity due to a large proportion of low-income population, etc.), the extent of the damages (80% of the city under water), and the difficulties currently met in the reconstruction process, a conservative estimate of the actual overall cost of the New Orleans floods is at least 50%

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[8] In particular, a high value might be attributed to the historical and cultural content of New Orleans. In other terms, people can decide to pay an additional price to keep living in New Orleans instead of being relocated. The choice of this value, however, must involve a political process which is beyond the scope of this article.

[9] It may also be necessary to take into account the position of the ruling government. Indeed, the government is likely to be held directly responsible for a repetition of such an event in the same location, that would probably be considered more unacceptable than a comparable disaster in another place (e.g., Sacramento, CA, that runs the same kind of risks than New Orleans). This *private* interest may motivate an over-protection against events that have already occurred, justifying the use of economic analysis to assess risk management projects and avoid under-optimal risk management strategies.

larger than the insurers' approximation based on direct losses only, to reach $45 billion. It is difficult to assess the cost of a repetition of the Katrina scenario. Of course, the closer from the first hit the larger the additional cost. As a best guess hypothesis, we will assume the cost of a second hit to be, on average over the life-time of the protection system, 25% larger than the first hit, *i.e.* amounting to $56 billion. Using the new values of event probability (p=1/130) and potential damages (d_0=$56 billion), the expected benefit of an upgraded protection system would be $10.7 billion with a 7 percent discount rate and $42.4 billion with a 3 percent discount rate.

The resettlement issue

We assumed in the previous section that New Orleans will be rebuilt with the same structure it had before Katrina and that all previous inhabitants of New Orleans will return to the city, even if no improvement of the flood protection system is undertaken. This assumption is at odds with what is observed and what is predicted in the coming years. For instance, McCarthy *et al.* (2006) estimate that the New Orleans population will be down to 272,000 in 2008, from 485,000 in 2000. If this new population is maintained, the costs of a new flood would of course be largely reduced compared with the 2005 one, making our assessment of avoidable damages overestimated. But it must be remembered that the flood protection system, the design of which is currently being discussed, will protect New Orleans for at least one century. The pertinent variable is thus the population over the long term, not over the next decade. And the low repopulation rate predicted by McCarthy *et al.* (2006) is mainly explained by the slow reconstruction pace due to short term constraints. It provides, therefore, no estimate of the long-term repopulation of the city.

To assess the long-term repopulation, we assume that, before Katrina, the risk of hurricane was perfectly known and that the New Orleans inhabitants had a rational behavior. We neglect here the potentially important role of social networks (see McCarthy *et al.*, 2006). Within this framework, the large population of New Orleans before the storm can only be explained by comparative advantages of the city's location in some sectors (e.g., tourism, shipping) and by the households' willingness-to-pay (WTP) to live there, because of environmental amenities. Both should have more than compensated the well-known hurricane and flood risk, even in absence of improved flood protection system. If these comparative advantages and this WTP have not been changed by Katrina, and if basic services, infrastructures and social networks can be restored, these assumptions mean that the New Orleans population will eventually return to its pre-Katrina level, even in absence of improved flood protection. They also suggest that the currently observed population reduction is more related to financial and technical constraints than to voluntary choices.

These assumptions, even though questionable, can explain the pre-storm New Orleans and allow us to separate the design of the flood protection system from the reconstruction issue and to justify the use of the 2005 flood data to estimate the cost of a future flood.

Countervailing risks, side-effects and reduced

Unfortunately, it is also necessary to take into account the possible side-effects implied by the implementation of a large-scale protection system. These side-effects can yield ancillary benefits like infrastructure improvement, as mentioned by Allenby and Fink (2005), or create or increase other risks, referred to as *countervailing risks*[10] by Wiener (1998), who calls for a broader accounting of them in risk management.

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[10] Examples of such countervailing risks in flood management are provided by Glenn *et al.* (1996) or Christensen (1997).

One cannot assess a flood protection system without taking into account moral hazard and equity issues. A flood protection system funded through nationwide taxes, like a uniform insurance premium, can constitute an incentive for people to settle in at-risk areas, as they do not pay for the risk their location choice creates. Indeed, even if they prefer to live in New Orleans rather than anywhere else, it is likely that less people will resettle in New Orleans if they think the Katrina catastrophe can happen again than if a flood protection system makes the probability of such an event negligible. This mechanism is potentially significant, since the large increases in population and investments in hurricane-prone regions are responsible for most of the explosive trend in hurricane damages observed over the last decades (Mills *et al.*, 2004; Munich Re, 2005; Pielke *et al.*, 2005). It should be noticed, however, that the urbanization of vulnerable areas around New Orleans in the past few decades does not seem to have been driven mainly by an over-protection against hurricane floods, but rather by the trade-off carried out by low-income households, who have high rates of preference for the present and poor access to information, between long-term flooding risks and immediate lower housing prices.

These side-effects, however, create a paradox. We would expect an increase in the system benefits from the fact that the protection system would allow a larger number of households to resettle in New Orleans, where they prefer to live. It is not the case. Instead, it reduces the benefits, by lowering the number of persons at-risk if the protection system is not built. This paradox arises from the fact that, again, we do not take into account the comparative advantages of New Orleans and the welfare gain or loss (or WTP) of households who would like to live in this city if they were protected from floods. This paradox suggests that a CBA analysis of the flood protection system taking into account countervailing risks cannot be carried out in a rigorous manner independently of a modeling of individual location choices. Such a modeling, however, is made very difficult by the uncertainty of household WTP, and we will have to rely on other approximations to take into account countervailing risks in our analysis.

The importance of these side-effects will be heavily dependent on the design and practical implementation of the protection system. In particular, huge negative consequences would certainly result from the implementation of an ambitious flood protection system that would not be followed by a careful long-term maintenance. In this worst case scenario, the existence of the protection system would raise investment and population in the so-called protected area, which would not be protected any more after a few decades of negligence, making vulnerability even larger than if no protection was implemented in the first place. As a consequence, the implementation of a protection system must be considered as a long-term commitment.

Also, avoiding negative outcomes from the future flood protection system requires careful design and implementation, in order to protect already urbanized areas without steering additional urbanization toward non-protected flood-prone locations. In this respect, the future flood protection system in New Orleans is certainly not only a system of dams, bridges, and gates. It should also include an important set of new regulations for future urban developments. A wisely designed flood protection system should protect selected areas, with dams and levees, and ensure, through land-use regulations, that investments are not attracted to non-protected areas. Hopefully, increased experience with flood management and the high visibility of the project will foster a flood protection plan that limits the negative effects and promotes positive ones, making the overall consequences of these side-effects positive or, if it reveals impossible, negligible compared with direct costs and benefits.

To be conservative, however, we will take into account the fact that a flood protection system could increase the population and capital at risk compared with an optimal situation. To do so, we will

assume that, if no protection system is implemented, the potential damages growth rate will be lower than nationwide economic growth, by an amount Δg=0.5 percent, because of the influence of hurricane risks on housing and investment location choices[11]. We will neglect the fact that, if the protection system is not implemented, there is a loss of welfare for households who would move to New Orleans if the city was protected from flood but who do not move because of the absence of such a protection.

It means that Eq.(2) is changed into:

$$B = \sum_0^{+\infty} p \cdot \left(\frac{1}{1+\delta} \right)^n \cdot d_0 (1 + g - \Delta g)^n \approx \frac{p d_0}{\delta - g + \Delta g} \qquad (3)$$

With this new equation, the expected benefit of an upgraded protection system would be $9.5 billion with a 7-percent discount rate and $28.4 with a 3-percent discount rate. With a project cost of $27 billion, the decision would, therefore, be dependent on the discount rate, making it necessary to discuss its value in more detail.

Choice of the discount rate

As already mentioned, the CBA of a flood protection system has to deal with very long time horizons, making the value of the discount rate controversial. Indeed, there are intense debates (Portney and Weyant, 1999) about the discount rate that should be used for environmental or long-term issues that involve intergenerational issues. When intergenerational equity is strongly involved, OMB suggests that discount rates between 1 and 3 percent are appropriate, since welfare of next generations should not be discounted and only the fact that they are likely to enjoy higher consumption levels should be taken into account. Other governments (e.g., U.K.) favor a decreasing discount rate over time, justified by the uncertainty over future economic situations (The Green Book, U.K. Treasury, 2003; Oxera, 2002).

Another approach is to calculate the discount rate that would make equal costs and benefits and assess its relevance. Using our parameters (probability of occurrence p=1/130 years and potential damages of $56 billion, rising at a growth rate 0.5 percent lower than economic growth), the benefits of the protection system are found equal to its cost if the pure preference for the present is lower than $\rho_0 = 1.1$ percent. With an expected growth rate of 2 or 3 percent, it would correspond to a discount rate of 3.1 or 4.1 percent, respectively. Since these discount rates are both greater than the largest bound of the OMB's discount rate range for projects involving intergenerational equity issues (3 percent), the last set of hypotheses justifies the implementation of the $27-billion flood protection system.

Risk aversion and damage heterogeneity

A society that would use the previous method to assess a protection system is called *risk-neutral*. A risk-neutral agent is indifferent to risk, *i.e.* it does not see any difference between losing $1 with certainty and having a 10% chance of losing $10, because the expected loss is the same in both cases. Theoretically, such an agent would never pay for insurance. Regarding protection against large-scale floods, however, there are good reasons to justify *risk-averse* behavior: people might

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[11] In other terms, the existence of the protection system is assumed to increase economic growth in the protected area by 0.5 percent per year, making it equal to the nationwide economic growth.

indeed prefer to pay an additional amount of money (a *risk premium*) to avoid the risk of costly and deadly floods.

To incorporate risk aversion, we change our assessment framework to use a *utility function* that measures the welfare gain or loss that is associated with any financial gain or loss. An utility function with risk aversion assumes that the increase in utility due to a $1 gain is smaller – in absolute value – than the decrease in utility due to a $1 loss. As a consequence, the risk of gaining or losing $1 with equal probability lowers the expected utility and is, therefore, equivalent to a certain financial loss, which is referred to as the *risk premium* or the *equivalent-certain* outcome.

However, if we assume that the damages due to a hurricane landfall are perfectly shared among the whole population of the U.S., the damage per capita is small (a few hundred U.S.$ per capita). In such a situation, the Arrow-Lind (1970) theorem demonstrates formally why risk-aversion can be neglected, supporting the choice of the states that consider self-insurance as a basic principle (e.g., France). Indeed, using an utility function with a constant relative risk aversion of one, as suggested in Arrow (1971) for households in developed countries, the risk-premium amounts only to 0.2% of the damages, *i.e.* $120 million (see appendix B).

The picture is different, however, if a substantial part of the damages impacts only by a small fraction of the population. Indeed, when the utility function is not linear, the utility derived from the consumption of $1 becomes lower as consumption increases. This effect represents the fact that rich people do not gain as much from the consumption of $1 as poor people do. But, it also means that it is not equivalent for a group of 10 people to lose $1 each or to know that one of them will lose $10.

The consequences of these factors on the CBA analysis of a hurricane landfall can be very significant. To assess them, we consider a hurricane landfall on New Orleans, which generates $56 billion of damages, 50 percent of which being equally supported by the whole U.S. population (through government spending in reconstruction[12], increase in insurance premium and other propagation effects into the national economy) and 50 percent being shared only by the *affected population*, which represents 0.4% of the total population, *i.e.* one million people. In this case, individual losses become significant (as large as 90% of annual consumption for the affected population) and risk aversion appears far from negligible. The loss of utility due to such an event is found to be equivalent to the loss of utility of a hurricane that would generate $69 billion of damages shared by the whole U.S. population, without risk-aversion (see appendix C). This value corresponds to a risk premium of $13 billion, *i.e.* 23 percent of the damages. This figure can even be considered as underestimated, because (i) low-income population being more likely to belong to the affected population (Lindell and Prater, 2003), accounting for pre-existing income inequalities would increase utility losses; and (ii) the actual repartition of damages is even more unequal than we assumed, as a few people usually suffer from most of the losses (house, belongings, life environment, but also friends and relatives). Regardless, neglecting the damage heterogeneity in the CBA would lead to a large underestimation of the benefits from an improved protection system.

To carry out a CBA in utility terms, we must compare the utility loss due to the risk of hurricane if no upgraded protection system is implemented with the utility loss due to the reduction of consumption, which is needed to fund the protection system. To do so, we use the *present equivalent-certain cost of the risk of hurricane* (B_c), which is the equivalent of the expected benefit,

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[12] Federal spending formally related to the Katrina reconstruction might even exceed the amount of damages, because reconstruction can be used to improve regional infrastructures.

B, when utility losses are used instead of monetary costs. B_c is such that paying, immediately, the amount B_c to build a protection system would reduce utility by the same amount than supporting the risk of hurricane flooding. As a consequence, the protection system should be built if its cost C is lower than the present equivalent-certain cost of the risk of hurricane (B_c). In this case, the calculation with a pure preference for the present of 1 percent (see Appendix C) leads to a value B_c = \$35.3 billion, which makes a category 5 hurricane flood protection system economically efficient.

Conclusion

Building a flood protection system able to cope with a category 5 hurricane in New Orleans is a huge investment, and it is wise to precisely assess its benefits before any implementation decision, as other, less-costly projects might be more efficient to improve the population's well-being[13]. One must, however, be very careful of the underlying assumptions used in the benefit assessment. Indeed, using probabilities derived from historical experience and direct cost estimates produced by insurance companies lead to low assessments of benefits and rule out any additional flood protection system. Nonetheless, making less optimistic assumptions about possible anthropogenic increases in flood probabilities and taking into account estimates of second-order disaster costs, public risk-aversion, and damage heterogeneity can reverse the conclusion of the CBA, even if countervailing risks and moral hazard issues are accounted for.

These results suggest that a CBA is useful but should encompass the whole set of possible assumptions to check its robustness. In the New Orleans case, the recommendation is highly sensitive to these assumptions, even if the protection system is found worth building only for pessimistic assumptions on climate change.

This analysis also shows that second-order damages and impact heterogeneity are responsible for a large increase in welfare losses. Climate change, even though negligible during the next decades compared to other drivers, might also be an important factor of hurricane risk over the long-term. More generally, climate change creates an additional layer of uncertainty in infrastructure design that increases the probability of either under-adaptation (and increased disaster risk) or over-adaptation (and sunk costs in protection).

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[13] This is especially true if improved track forecasts, warning systems and evacuation plans can avoid human losses at low costs.

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Appendix A: The link between mean PDI change and the most powerful hurricane probability

Figure 1 shows in blue the current cumulative distribution function of the hurricane power dissipation index (PDI), as calculated from the NHC/NOAA HURDAT database (www.nhc.noaa.gov) between 1900 and 2004. The horizontal blue line distinguishes the 1-percent most powerful hurricanes, *i.e.*, in the current distribution, the hurricanes with PDI larger than $164 \cdot 10^9$ $m^3 s^{-2}$ (vertical black line).

It has been predicted that the mean value of North Atlantic PDI could rise, between now and the end of the century, by 50 percent, according to the predicted rise in sea surface temperature (SST) and the observed correlation between SST and PDI (Emanuel, 2005b), or by 65 percent, according to a hurricane intensity model (Emanuel, 2006).

If climate change increased the mean hurricane PDI by 65 percent through a shift of the distribution to the right, the shape being unchanged, the new cumulative distribution function would be the red line in Fig. 1. With this new distribution, 3.8 percent of the hurricanes would have a PDI larger than $164 \cdot 10^9$ $m^3 s^{-2}$. It means that the frequency of the 1-percent most powerful hurricanes in the present climate would be multiplied by 3.8.
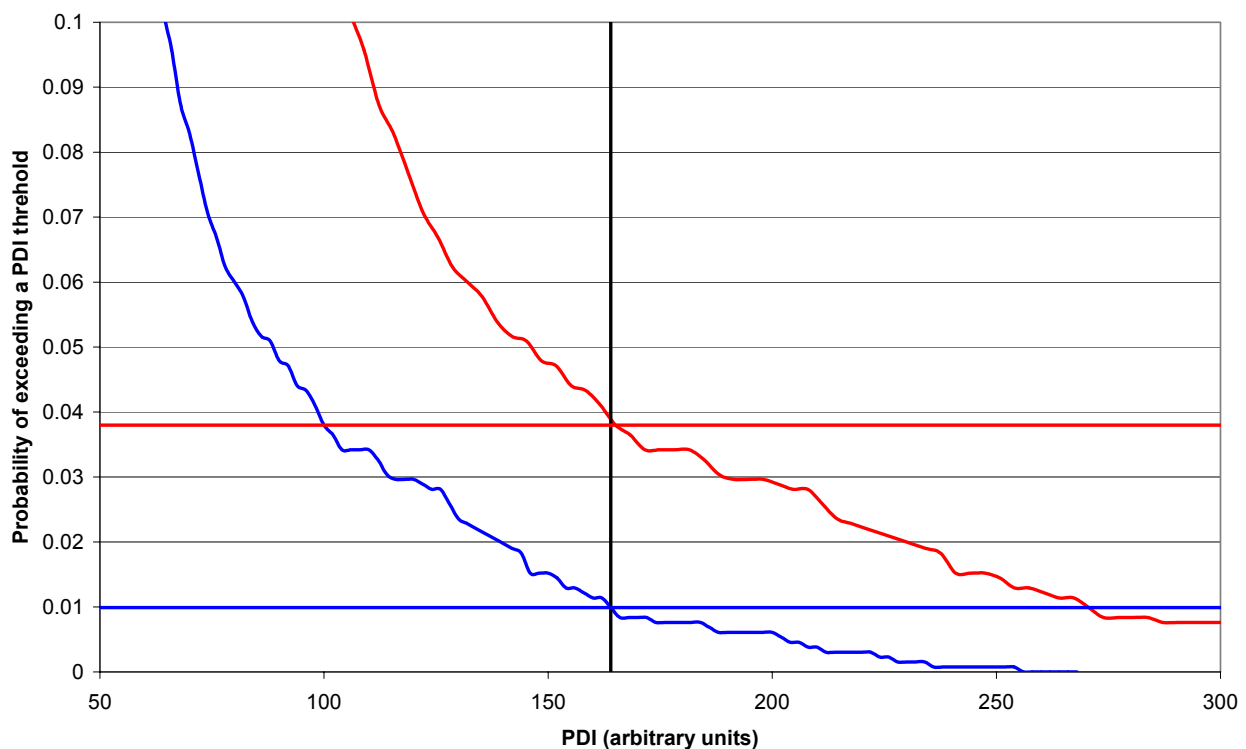

Figure 1: cumulative distribution function of hurricane PDI in the 1900-2004 climate (in blue) and in a modified climate in which mean PDI would be increased by 65 percent, the shape being unchanged (in red).

Appendix B: Calculation of the risk-premium

The calculation of the risk-premium is done using the following utility function, with a constant relative risk aversion of one (see Arrow, 1971):

$$u(c) \; = \; N \ln(c) \, ,$$

(B-1)

where N is the size of the population and c is the consumption per-capita (about \$31,200 in 2005). Note that we assume here that all citizens have the same consumption and that this utility function aggregates all citizens by summing their individual utility function with the same weight. This method is usually referred to as "*one-man, one-vote*". When income inequalities are taken into account, other aggregation rules are possible, reflecting different moral position with regard to income distribution within a given generation (Lecocq and Hourcade, 2003) (*e.g.*, the "one-dollar, one-vote" aggregation rule, in which weightings are chosen so that the currently observed income distribution is considered socially optimal).

We define the *risk-neutral damages d_0'* by the fact that supporting with certainty an amount of 2005-equivalent damages $p d_0$' every year would lower utility by the same amount than the risk of having a hurricane that causes an amount d_0 of 2005-equivalent damages with a probability p. Note that all damages are expressed in 2005-equivalent; actual damages are supposed to rise according to economic growth minus Δg=0.5 percent: $d_n = d_0 (1+g-\Delta g)^n$.

The risk-neutral damages d'_0 can be calculated by the equality[14]:

$$\sum_0^{+\infty} \left(\frac{1}{1+\rho}\right)^n \left[(1-p)u(c_0(1+g)^n) + pu\left(c_0(1+g)^n - \frac{d_0}{N}(1+g-\Delta g)^n\right)\right]$$
$$= \sum_0^{+\infty} \left(\frac{1}{1+\rho}\right)^n u\left(c_0(1+g)^n - \frac{pd'_0}{N}(1+g-\Delta g)^n\right)$$

(B-2)

This equation states that the expected utility from consumption, every year possibly reduced by hurricane damages $d_0(1+g-\Delta g)^n$, with $d_0 = \$56$ billion, is equal to the utility from the expected consumption reduced every year by the probability of occurrence p multiplied by the risk-neutral damages d_0', also rising according to economic growth minus Δg. Note that the rate of pure preference for the present ρ is used to discount utility, while the discount rate δ is used to discount monetary values.

For a disaster causing \$56 billion of damages, and using the hypotheses consistent with a discount rate of 3 percent, *i.e.* a growth rate of 2 percent and a pure preference for the present $\rho = 1$ percent, the resolution of Eq.(B-2) gives the value of the risk-neutral damages $d'_0 = \$56,12$ billion, corresponding to a risk-premium of \$120 million.

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[14] Note that population is supposed to be constant.

We now define the *present equivalent-certain cost of the risk of hurricane (B_c)* by the equality of (i) the utility loss due to the risk of hurricane if no upgraded protection system is implemented and (ii) the utility loss due to the immediate payment of an amount B_c. It reads:

$$\sum_{0}^{+\infty} \left(\frac{1}{1+\rho}\right)^n \left[(1-p)u(c_0(1+g)^n) + pu\left(c_0(1+g)^n - \frac{d_0}{N}(1+g-\Delta g)^n\right)\right]$$
$$= u(c_0 - B_c) + \sum_{1}^{+\infty} \left(\frac{1}{1+\rho}\right)^n u\left(c_0(1+g)^n\right) \qquad \text{(B-3)}$$

The protection system should now be implemented if its building costs are lower than the present equivalent-certain cost of the risk of hurricane. Solving (B-3) leads to a value of B_c of $28.4 billion.

Appendix C: Calculation of the combined consequences of damage heterogeneity and risk-aversion

The calculation of the impact of the damage heterogeneity is done using the same utility function [Eq.(B-1)]. If a hurricane makes landfall, and if 50% of the damages d_0 are perfectly shared, while 50% of the damages are shared by one million persons, *i.e.* 0.4% of the population, the whole population utility is given by:

$$u_n^* = qNu\left(c_0(1+g)^n - \left(\frac{d_0/2}{N} - \frac{d_0/2}{qN}\right)(1+g-\Delta g)^n\right)$$
$$+ (1-q)Nu\left(c_0(1+g)^n - \frac{d_0/2}{N}(1+g-\Delta g)^n\right) \qquad \text{(C-1)}$$

where q is the proportion of affected population (here q=0.4%).

The *homogenous and risk-neutral equivalent damages d_0''* are defined by the fact that supporting, every year, with certainty and with perfect sharing among the population, an amount of damages pd_0'', would lower the utility by the same amount than the risk of having, with a probability p, a hurricane that would cause an amount d of damages that would be imperfectly shared among the population.

The *homogenous and risk-neutral equivalent damages d''_0* is calculated using the relationship:

$$\sum_{0}^{+\infty} \left(\frac{1}{1+\rho}\right)^n \left[(1-p)u(c_0(1+g)^n) + pu_n^*\right]$$
$$= \sum_{0}^{+\infty} \left(\frac{1}{1+\rho}\right)^n u\left(c_0(1+g)^n - \frac{pd_0''}{N}(1+g-\Delta g)^n\right) \qquad \text{(C-2)}$$

where the left-hand-side member gives the expected utility under the risk of an amount of 2005-equivalent damages d_0 that would be imperfectly shared; and the right-hand-side member gives the utility of the consumption when an amount of 2005-equivalent damages pd_0'' is perfectly shared

every year among the whole population. For a disaster causing $56 billion of damages, the resolution of Eq.(C-2) gives a value of the homogenous-risk-neutral damages $d''_0 =$ $69 billion, corresponding to a risk-premium of $13 billion. In this case, the present equivalent-certain cost of the risk of hurricane B_c is $35.3 billion.