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Dynamic Model of Costing Disaster Mitigation Policies

Nezh Altay
Sameer Prasad
Jasmine Tata

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A dynamic model for costing disaster mitigation policies

Nezih Altay Associate Professor, DePaul University, United States, **Sameer Prasad** Professor, University of Wisconsin-Whitewater, United States, and **Jasmine Tata** Associate Professor, Loyola University-Chicago, United States

The optimal level of investment in mitigation strategies is usually difficult to ascertain in the context of disaster planning. This research develops a model to provide such direction by relying on cost of quality literature. This paper begins by introducing a static approach inspired by Joseph M. Juran's cost of quality management model (Juran, 1951) to demonstrate the non-linear trade-offs in disaster management expenditure. Next it presents a dynamic model that includes the impact of dynamic interactions of the changing level of risk, the cost of living, and the learning/investments that may alter over time. It illustrates that there is an optimal point that minimises the total cost of disaster management, and that this optimal point moves as governments learn from experience or as states get richer. It is hoped that the propositions contained herein will help policymakers to plan, evaluate, and justify voluntary disaster mitigation expenditures.

Keywords: disaster, dynamic, investment, mitigation, optimal

Introduction

Disasters often evoke emotions that result in agencies and politicians being willing to allocate a liberal dose of resources to the afflicted communities (Lagadec, 1990). This type of reaction frequently is unrealistic and probably inefficient as it diverts resources away from disaster mitigation and preparedness (DMP) (Kelly, 1995). Pre-disaster measures, such as increasing DMP, are generally considered to be more cost-effective than post-disaster initiatives in the form of disaster relief and recovery (Christoplos, Mitchell, and Liljelund, 2001; Owens, Hoddinot, and Kinsey, 2003; Skoufias, 2003). For example, mitigation strategies such as microcredit and education programmes have the potential to prevent future economic losses that might materialise because of disasters (de Hoop and Ruben, 2010).

Ideally, federal, state, and local agencies need to expend resources on preparing for and mitigating disasters. The level of investment necessary for disaster planning and mitigation includes pre- and post-disaster costs. Specifically, Zeckhauser (1996) defines the cost of a catastrophe as the sum of losses from the event plus the cost of actions to reduce them. He goes on to include 'preventive measures to avoid disasters, expenditures after the disaster to ameliorate damage, plus any increase or decrease in future disasters due to the way the current one is handled' (Zeckhauser, 1996, pp. 121–122). His work implies that the optimal cost of a disaster lies at the point where marginal cost equals marginal benefit.

Prudent disaster management suggests the use of a cost management framework in making such investment decisions (Kelly, 1995). Mechler (2003) indicates that, despite having great potential in disaster management, cost-benefit analysis has not been applied sufficiently. However, it helps one to understand the impact of applied policies ex-post. In other words, the benefit versus investment data only becomes available after the fact. Although the exact cost of specific DMP policies could be estimated before implementation, there is no framework to aid policymakers in understanding the potential effect of such planned policies ex-ante. Such a framework would allow decision-makers to balance pre-disaster expenses with post-disaster allocations. Such expenditure data, though, needs to be collected within governmental units and shared with the public. To the best of our knowledge, Australia has the only publicly available dataset on government expenditure during all stages of disaster management (that is, mitigation, preparation, relief, and recovery).

Australia is prone to cyclones, drought, earthquakes, floods, heat waves, and wild fires, among other potential natural disasters. Between 1967 and 1999 the country experienced 265 natural disasters, costing more than AUD 10 million each. The average annual cost of these disasters was AUD 1.14 billion. Floods were the most costly of all disaster types, responsible for 29 per cent of total costs. Cyclones, floods, and storms together accounted for approximately 90 per cent of disasters and 80 per cent of costs between 1967 and 1999 (BTE, 2001).

A 2002 report to the Council of Australian Governments (COAG) by a high-level officials' group titled *Natural Disasters in Australia: Reforming Mitigation, Relief and Recovery Arrangements* (COAG, 2002) recognises that investment in mitigation and preparedness presents savings opportunities in relation to post-disaster costs, and recommends finding the right balance among the four stages of disaster management activities. The report accepts that there is a rate of return from mitigation, estimating conservatively it to be 15 per cent. Furthermore, it states that the analysis shows that 'every dollar invested in flood mitigation saved more than \$2.10' (COAG, 2002, p. 24). Another related report titled *COAG Review of Natural Disasters Relief and Mitigation Arrangements: Government Expenditure Analysis* (COAG, n.d.) is the source of data on disaster-related government spending over 12 years (1990–2001) broken down into four categories: preparedness/response; relief/recovery; mitigation; and other related expenditure. One should note, though, that it points out that the data in the report significantly underestimates actual government expenditure on natural disasters.

The Australian data has some interesting characteristics that suggest a potential fit for Joseph M. Juran's quality management model concerning voluntary and involuntary costs in explaining the potential effect of mitigation policies over time (Juran, 1951). His model has been successfully adapted to other contexts, such as elucidating the impact of information management investment on supply-chain effectiveness (Prasad and Tata, 2000), and hence promises a viable pathway to a better understanding of the effect of DMP investment. As presented in Figure 1, the Australian data suggests a non-linear relationship between voluntary (that is, DMP) and involuntary (that is, relief and recovery) costs. Figure 1 points to an optimal level of spending

when it comes to DMP. The combined total cost expenditure (overall money spent on disaster management) in Figure 1 takes the form of a U-shaped curve.

This paper proposes an adaptation of Juran's quality management model in an attempt to enhance understanding of the potential impact of DMP policies. Furthermore, it recognises that the economic, political, and social state of regions may change over time, and this dynamic aspect of the problem is integrated into the model. The latter should be of value to agency officials as it will help them to comprehend the consequences of various disaster mitigation policies and enable them to offer greater protection to the public they serve.

The remainder of the paper is structured as follows: section two evaluates the salient literature. Juran's quality cost model is introduced and its adaptability to this research context is justified in section three. Section four contains an assessment of investment trade-offs before and after a disaster, as well as changes over time, and several propositions are developed that highlight the policy implications of the dynamic model with respect to planning for disasters. The final section contains some conclusions and ideas for the direction of future research.

A literature review

The body of knowledge of disaster mitigation and preparedness is extensive. This paper focuses on the salient literature relevant to policy, disaster costs and models, risk/protection, and non-linear and dynamic patterns.

Disaster mitigation and preparedness policies

In the United States, comprehensive disaster management is commonly described in terms of four programmatic phases: mitigation; preparedness; response; and recovery (Godschalk, 1991). Mitigation is the application of measures either to prevent a disaster or to reduce its impact. Such measures may include land-use controls and tax incentives to prevent occupation of hazard areas, barrier construction to deflect disaster forces, risk analysis to determine the probability of an event, and insurance to reduce its financial effect. Preparedness includes activities to prepare a community to respond to a disaster, such as stocking up on emergency supplies, budgeting for vehicles, equipment, and personnel, constructing emergency operations centres, training staff and concerned citizens, and educating the general public on potential threats (Altay and Green, 2006).

The effectiveness of DMP policies depends on the active participation and involvement of all levels of government as well as of the vulnerable communities. Winchester (2000) suggests that the best approach to reduce disaster vulnerability is to enhance the socioeconomic standing of the most vulnerable people by providing them with possibilities of assured income and credit-worthiness. A simulation study by de Hoop and Ruben (2010) to estimate the impact of microcredit and education programmes on consumption losses after an earthquake supports Winchester's point. It found that

microcredit or education programmes can prevent consumption losses. However, overconfidence or ethical issues such as corruption may result in a failure to balance benefits and costs at the margin for different types of disasters. The tendency for policy-makers to under-invest in protection and over-invest in response is another cause of failed disaster policies (Noll, 1996).

Disaster cost categories

Venton and Venton (2004) argue that cost-benefit analysis can be a critical tool for measuring the effect of disasters and for making educated choices regarding future initiatives. The literature provides a variety of approaches to judge the costs and the benefits of DMP initiatives. Some of these are described in terms of opportunity costs and present value. Stephenson and DuFrane (2005) refer to five different losses due to disasters: (i) direct monetary losses (such as damage to infrastructure and buildings); (ii) indirect monetary losses (such as a loss of production and clean-up costs); (iii) direct non-monetary losses (such as deaths, injuries, and a loss of cultural items); (iv) indirect non-monetary losses (such as a disruption of public services and education, stress, and health issues); and (v) a loss of non-renewable natural resources (such as agricultural land and forests). Parker, Green, and Thompson (1987) define disaster damage costs based on welfare economics. They distinguish between the direct costs that relate to loss of land, capital, and machinery (that is, loss of inventory), primary indirect costs that relate to business interruption (that is, loss of product and cash flow), and secondary indirect effects that relate to upstream and downstream consequences for the economy. Costs, therefore, especially indirect and non-monetary costs, can be difficult to quantify. Furthermore, there may be some disagreement on the classification and definition of these costs. For instance, some researchers consider clean-up costs to be a direct cost owing to a disaster (Stephenson and DuFrane, 2005).

This research puts disaster-related costs into two broad categories: voluntary costs and involuntary costs. Voluntary costs are expenditures on various mitigation and preparedness strategies, whereas involuntary costs pertain to the number of fatalities/injuries, damage/property losses, and disruptions to services provided by the public and the private sectors.

Some types of direct involuntary costs can be quantified as they include damage to buildings and roads, production failures, and property losses (Tirasirichai and Enke, 2007). These losses can be estimated using repair or replacement costs. However, some measures are inherently more difficult to assess, such as the value of human life, different levels of private and social costs, and losses associated with different specifications of building codes (Kunreuther, 1974). Indirect costs are much more difficult to quantify. These losses extend beyond the location of the direct physical impact of a disaster (Tirasirichai and Enke, 2007). For example, in supply chains, any disturbance can be felt by buyers and suppliers that are quite distant from the actual location of the disaster (Boisvert, 1992; Cochrane, 1997). Some indirect costs are difficult to define, let alone measure. Increased individual stress, long-term health problems, and a loss of memorabilia can all be indirect costs of disasters (van der Veen, 2004) and may need to be quantified.

The costs of various mitigation strategies and the expected level of losses/damage given the different levels of intervention need to be estimated (Kelly, 1995) for different disaster scenarios. Voluntary cost expenditures can be expected to incur throughout the entire disaster management lifecycle, including planning, mitigation, detection, response, and recovery (Hale and Moberg, 2005). Voluntary expenses can be related both to structural and non-structural items (Khan, 2000). Examples of voluntary structural investments include the construction of embankments and drainage systems and the establishment of afforestation programmes, whereas non-structural investments include housing code enforcement, the creation of a forecasting system, and even education (Khan, 2000). Generally, voluntary costs are easier to quantify as they involve direct expenditures by the various authorities. However, if the expenditure is passed on to the community or individuals through an assortment of regulations, these costs become more difficult to quantify.

Costs estimation models

Numerous attempts have been made in the literature to develop cost estimation models for disasters. Freeman et al. (2004) came up with a methodology that integrates future probabilistic losses to capital stock (direct losses) into The World Bank's revised minimum standard model, the macroeconomic projection model used at the organisation. This approach estimates the potential losses to capital stock but does not attempt to calculate the necessary investment that should be made to cut them. Alternatively, Vora, Lee, and Pong (2008) provide probabilistic cost estimates to building inventory due to an earthquake using the HAZUS-MH software. Their methodology could also serve as a cost-benefit analysis of mitigation (for instance: if one spends a given amount of money on strengthening buildings what would be the expected reduction in building losses?) Other researchers, such as Mechler (2003) and Venton and Venton (2004), explain the use of cost-benefit analysis in natural disaster mitigation. For example, Venton and Venton (2004) applied it to two DMP interventions in India and concluded that it demonstrates an economic argument for DMP. However, such a method has its limitations as it requires assigning a monetary value to loss (including loss of life), while some of the impacts of DMP may not be easy to quantify. Chang (2003) reached a similar conclusion with her application of a lifecycle cost analysis, a method often used in infrastructure management to evaluate disaster mitigation measures.

Disaster risk

According to Christoplos, Mitchell, and Liljelund (2001), risk management refers to both mitigation and preparedness. In developing a cost model, it is essential to understand the underlying level of risk reflecting the intensity and frequency of a disaster (Kunreuther, 1974). This information is now available at the aggregate (country) level. For example, The World Bank¹ provides a rough aggregate measure of vulnerability by country to different types of disasters and EM-DAT² (The International Disaster

Database) supplies frequency and intensity data. However, both of these datasets may suffer from systematic measurement errors and therefore produce some bias.

Various mathematical models have been reported in the literature to assuage risk. Keller and Al-Madhari (1996), for instance, compute the estimated number of fatalities by applying an exponential probability density function and recoverable insurance losses through a two-parameter Weibull probability density function. This allows one to develop a risk profile that may be employed in disaster planning and mitigation. Alternatively, Tamura et al. (2000) apply a value function under the risk to evaluate mitigation efforts. The risk probability density functions coupled with costs associated with the expected involuntary and voluntary costs of the disaster at each risk level can be used to create aggregate involuntary and voluntary cost curves for different levels of protections. However, the risk profile in a country could change over time.

Non-linear and dynamic patterns

Researchers also have alluded to the importance of understanding the dynamic aspects of disaster planning, including inter-temporal trade-offs and extreme non-linearity (Rose, 2004). Inter-temporal trade-offs include the instances when investments in disaster mitigation are expected to pay dividends in the future. Dynamic patterns are also observed in DMP. Over time, as countries develop, their cost curves shift and the level of risk changes as well. For example, dynamics can be seen in the interactions between the level of development and the level of vulnerability in a locality (Maon, Lindgreen, and Vanhamme, 2009). Chang (2003) demonstrates the importance of considering changes over time, signalling that disaster mitigation is a dynamic problem. Perry and Lindell (2003) point out that no effective disaster planning process can be static. Non-linear patterns are prevalent in disasters, and Kelly (1998) notes the limitations of linear conceptualisations in disaster relief. Thus, any discussion of a cost curve should assume non-linearity.

As Christoplos, Mitchell, and Liljelund (200, p. 192) state: 'DMP today is no longer a matter of just buying radios, digging dykes, building warehouses and training relief teams. These elements may be all part of DMP, but prioritization and adaptation must be based on a continuous scanning of the environment to ensure that activities are appropriate and respond to changing patterns of vulnerability'. Hence, a cost model needs to encapsulate both dynamic and non-linear patterns of DMP.

Juran's Quality Management Model

The quality cost model of Juran (1951), which has been readily accepted by practitioners, provides a simple and clear method to examine the non-linear trade-off between voluntary and involuntary costs. There is considerable support in the literature for Juran's model (Emsley, 2008). In addition, this model can be found in accounting textbooks (Langfield-Smith, Thorne, and Hilton, 2003) and management practitioner journals and textbooks (Wilkinson et al., 1998).

Given its simplicity and ability to capture non-linear patterns, we believe that an adaptation of Juran's model could also be widely accepted by the disaster planning community. In the quality management context, voluntary costs include prevention and appraisal expenditures. In our context (DMP), prevention costs entail time and effort spent on designing disaster mitigation plans, training personnel, setting up infrastructure, organisational development, and acquisition and use of communication technologies. In quality management, the cost of appraisal includes running tests and collecting data on the rate of success. Involuntary costs in the DMP context tend to be more difficult to define as they relate to loss of life, long-term physical and psychological disabilities, business failures, and rebuilding infrastructure.

This trade-off in costs is both non-linear in nature and dynamic (changing in time) relative to the level of risk protection provided. Hence, this research makes the following critical assumptions in its adaptation of Juran's model: (i) the trade-offs between voluntary and involuntary costs are non-linear; and (ii) the voluntary and involuntary cost curves shift over time.

A dynamic cost model

This research attempts to demonstrate a new model through which policymakers can determine the optimum level of voluntary expenses to minimise total cost. Before developing the dynamic model, a static model to elucidate the non-linear interplay between voluntary and involuntary costs is presented.

Figure 1. Disaster expenditures of the Government of Australia

Non-linear trade-offs

The quality cost model of Juran (1951) captures and offers a simple way to understand the interplay of the non-linear patterns of voluntary and involuntary costs, as seen in the Australian data (see Figure 1). In this model, total cost is minimised when the marginal voluntary costs equal marginal involuntary costs given a number of restrictive assumptions. In addition, this model provides a relatively easy way to assess the trade-offs between voluntary and involuntary costs.

Proposition 1: there is an optimum level of voluntary expenditure on disaster management to minimise total cost.

In Figure 2, one can see that, as the level of voluntary costs increases, the marginal cost to protect an additional citizen rises in a non-linear fashion. Correspondingly, the involuntary costs decrease in a non-linear manner towards zero. The curves can be described in terms of equations. Let us define x as the proportion of the population covered prior to a disaster. We assume that the voluntary cost curve is non-linear and that, as we try to protect a higher percentage of the population, the cost to protect an additional citizen gets increasingly more expensive. As x approaches one (or 100 per cent coverage), the marginal cost becomes extremely high and there would be little or no involuntary costs. However, if we choose not to protect any citizens ($x = 0$), the involuntary costs will be extremely high but the voluntary costs would be nil. The total costs associated with either of the extremes is very high and could be reduced by balancing the marginal voluntary and involuntary costs. This pattern could be represented via a number of polynomial functions, but for simplicity a squared function would suffice. For example, we could define voluntary cost as αMx^2 , where α is a parameter and M is the maximum level of voluntary expenses, and the involuntary cost as $\beta N(x-1)^2$, where β is a parameter and N is the maximum level of involuntary expenses. The two costs can be combined into a total cost (y) where $y = \alpha Mx^2 + \beta N(x-1)^2$. The minimum level of expenditure can be determined by taking the first derivative of the total cost function with respect to x and setting it equal to zero, as follows:

$$y = \alpha Mx^2 + \beta Nx^2 - 2\beta Nx + 1\beta N$$

$$\frac{dy}{dx} = 2\alpha Mx + 2\beta Nx - 2\beta N = 0$$

$$\alpha Mx + \beta Nx = \beta N$$

$$x^* = \frac{\beta N}{\alpha M + \beta N}$$

The total cost is minimised when the marginal voluntary cost is equal to the marginal involuntary cost. Once this point has been reached (x^*), further investments are neither required nor economically rational. The parameters and exact form of the equation would vary by the probability risk density function by country and the respective voluntary and involuntary costs associated with the different risk levels.

Some difficulties with the policy implications of the static model lie in how indirect involuntary costs are measured. Feigenbaum (1983) broadened the definition of involuntary costs by describing indirect and intangible failure costs as far more ambiguous and much harder to quantify, but potentially far greater in magnitude than out-of-pocket failure costs. Indirect failure costs may be concealed in other categories and include long-term health-care costs, a shrinking tax base, and a loss of competitiveness. Indirect involuntary costs could far exceed out-of-pocket involuntary expenditures (Brown and Kane, 1984). Given this underestimation, it is likely that marginal mitigation expenses are relatively small in comparison to the involuntary costs. As a demonstration, we initially set α at 0.5 and β at 0.5 (see Figure 2), but these variables may take on any value ranging between 0.0 and 1.0—later, we demonstrate the dynamic aspects of the model by varying α and β from the midpoint (0.5). In addition, for our demonstration we assume that M and N are equal to one (although disaster planning officials would use sums reflecting their local conditions). Under the current scenario ($\alpha = 0.5$ and $\beta = 0.5$)—point A—the total cost (voluntary plus involuntary costs) is relatively high and the percentage of the population protected is relatively low. Policymakers can take advantage of the non-linearity of the cost curves and actually reduce the total cost when protecting a larger percentage of its citizens by investing in additional resources for mitigation purposes—point B.

As mentioned earlier in this paper, the COAG *Natural Disasters in Australia* report notes that every dollar invested in flood mitigation saves more than AUD 2.10 (COAG, 2002). However, as the static model (see Figure 2) indicates, if every dollar invested in mitigation results in a savings of AUD 2.10, the level of investment in DMP is insufficient—point A. Total cost savings can occur by increasing the level of voluntary expenditure—point B—to the point where the marginal costs are equal to the marginal savings (that is, every dollar invested should result in the saving of a dollar). This would also result in greater protection of citizens.

Figure 2. Static model of mitigation expenditure with $\alpha = 0.5$ and $\beta = 0.5$

Table 1. Relative optimum points and total costs as a function of α and β parameter values given $M = 1$ and $N = 1$

α	β	Optimum point (x^*) (percentage of citizens covered prior to disaster)	Total cost (y)	Figure number
0.5	0.5	50.0	0.2500	2
0.1	0.5	83.5	0.0833	3
0.5	0.9	64.0	0.3214	4
0.4	0.9	69.0	0.2769	5
0.2	0.6	75.0	0.1500	6

The cost curves cannot be assumed to stay stationary as they shift over time. The dynamic model described next accounts for such changes. Specifically, the parameters α and β fluctuate over time and correspondingly affect the shape of the voluntary and involuntary cost curves. Table 1 presents a summary of the different values assigned to α and β , the optimum percentage of citizens covered (x), as well as the total cost. Correspondingly, the interplay among the cost curves can be seen in Figures 2–6 and is discussed below.

Dynamic interplay

Agencies planning for mitigation strategies need to ensure their model and their data are current. As costs and risks change over time, it is necessary to develop a model that incorporates such changes. Over time, voluntary costs can be reduced by the learning process and prior investments in disaster mitigation. For example, large countries such as India suffer disasters every year and the National Disaster Management Authority (Ministry of Home Affairs) is able to rely on past experiences to improve the level of protection. Evidence of the effects of learning on costs has been well documented (Cooke and Rohleder, 2006; Moe et al., 2007).

Involuntary costs, in the form of tangible and intangible failure expenses, are a function of the underlying risk and the level of development of a region. The level of risk that a region faces in relation to various natural and man-made disasters changes based on assessment methods and environmental degradation. As the level of risk alters, the level of investment in disaster mitigation strategies needs to be updated correspondingly. Furthermore, as regions develop, and the standard of living goes up, the value of the losses increases and DMP needs to reflect these changes in society.

Prior investments in disaster mitigation and learning could potentially lower the total cost and increase the percentage of the population protected. As suggested by Fine (1986) and Dawes (1989), the learning curve effect has a major influence on voluntary cost expenditures. Some developing countries experience disasters annually. If properly documented, the knowledge accrued through their experiences can be extremely useful in lowering costs and protecting a larger percentage of the population.

Figure 3. Dynamic model: influence of learning and prior investment with $\alpha = 0.1$ and $\beta = 0.5$

Proposition 2: as governments learn from past disasters, the new optimal point results in a greater proportion of the population being protected while the total cost decreases.

In addition, prior investments in disaster mitigation in terms of planning and development of soft (technical expertise) and hard (construction of distribution centres) infrastructure could pay off over the years. The dynamic impact of learning can be seen in Figure 3, as the voluntary cost curve (αMx^2) shifts lower from period t ($\alpha = 0.5$) to period $t + 1$ ($\alpha = 0.1$). The learning process enables a country to achieve higher levels of protection at lower costs—point C.

Figure 4. Dynamic model: influence of learning and prior investment with $\alpha = 0.5$ and $\beta = 0.9$

Proposition 3: an increased level of risk increases the total cost at the new optimal point while a larger percentage of the population is protected.

The environment is not constant and the level of risk associated with various types of disasters changes. For instance, deforestation is expected to raise not only the likelihood of drought and flooding but also their intensity. The dynamic model captures such developments. An increase in risk and severity will shift the involuntary cost curve $\beta N(x-100)^2$ upwards. The impact of such developments would be seen in the Figure 4 time period $t + 1$ ($\beta = 0.9$) as the new equilibrium moves from point B to point D. The shift in the involuntary cost not only requires an increase in necessary expenditure levels, but also it leads to the protection of a large percentage of the population.

Proposition 4: as countries become wealthier the total cost at the new optimal point increases while a larger percentage of the population is protected.

A similar result occurs as societies develop and become more prosperous. As countries become richer, infrastructure, technology, and personal property become more expensive, and the financial effects of a disaster tend to be larger. Thus, as countries develop, the involuntary cost curve shifts upwards. Correspondingly, states need to invest additional resources in disaster mitigation while protecting a larger percentage of their population.

Two scenarios are employed in this research to highlight the interaction between learning/prior investments and changes in the level of risk and development. Scenario 1 relates to a relatively small country that does not have a well-developed knowledge base system for disaster management but is growing rapidly. Scenario 2 relates to a rapidly growing country that has the capability to learn from prior disasters.

Figure 5. Scenario 1: case of a growing country with limited learning capacity given $\alpha = 0.4$ and $\beta = 0.9$

Figure 6. Scenario 2: case of a growing country with a learning capacity given $\alpha = 0.2$ and $\beta = 0.6$

The optimal level of investment and total cost is influenced by the learning curve effect as well as by involuntary costs. The effects of Scenario 1 can be seen in Figure 5, which shows that, owing to a rise in the standard of living, the involuntary cost curve moves upward from period t ($\alpha = 0.5$ and $\beta = 0.5$) to period $t + 1$ ($\alpha = 0.4$ and $\beta = 0.9$.) Simultaneously, the voluntary curve shifts downward from period t to period $t + 1$ due to a limited learning curve effect. The new optimum point (E) yields a greater degree of protection for citizens at a higher cost. The savings enjoyed due to the learning curve do not compensate for the increased opportunity costs arising from the rise in the standard of living.

Figure 6 illustrates Scenario 2, with similar directional shifts in both cost curves from period t ($\alpha = 0.5$ and $\beta = 0.5$) to period $t + 1$ ($\alpha = 0.2$ and $\beta = 0.6$). Here, the new optimal point (F) yields greater protection at a lower overall total cost. As it happens, the cost savings due to learning are more than the opportunity cost incurred owing to improvements in the standard of living. In either case, the dynamic model shows that the rise in the standard of living and changes in the risk level can have an important effect on the optimum level of voluntary cost expenditure. In addition, the dynamic model underscores the necessity of learning from past experience and taking advantage of prior investments in disaster mitigation.

For example, Australia has the capacity, resources, and exposure to learn from disasters. The federal government, states, and research institutions have been working on the potential impacts of global warming on disaster mitigation and preparedness since the late 1980s (Smith, 1999; Jones et al., 2007). A 2002 study by the Commonwealth Scientific and Industrial Research Organization (CSIRO, 2002) suggests that, in the future, the warmer climate may increase the risk of coastal flooding. A country

such as Australia (see Figure 6) would be able to learn from disasters to such a degree that it would be able to lower the total cost while protecting a larger proportion of its citizens in spite of the additional costs incurred due to a rising standard of living.

Conclusion

This research developed a dynamic model to help agency officials to determine the necessary level of disaster mitigation investment to minimise total cost. It provides a mechanism to establish the optimal allocation by balancing marginal voluntary expenditure with marginal involuntary expenses. Countries that are not investing sufficient resources in DMP will be able to take advantage of the non-linear trade-off between voluntary and involuntary costs. By following the static model, countries can reduce the total cost and protect a larger percentage of the population simply by adjusting the level of voluntary expenditure to the optimal level.

The dynamic model helps officials to visualise how cost curves shift over time, affecting the optimal level of investment in voluntary expenditure and the percentage of the population protected prior to a disaster event. In addition, while recognising the limitations of the model given the assumptions, it is possible to make a number of general statements. One can assume that the standard of living and the level of development will continue to rise in most countries. Assuming the same level of risk, the expected losses will also rise and shift the involuntary curves upwards over time. Correspondingly, countries will have to increase continually their level of voluntary expenditure to ensure that the total cost is minimised. Another expected long-term pattern is deforestation, which is expected to augment the likelihood and severity of disasters. Hence, the involuntary cost curve is also expected to shift upwards continuously. To ensure that total costs are minimised, therefore, disaster relief officials need to increase continually their investments in disaster mitigation strategies, including afforestation efforts.

The model developed in this research, and the scenarios examined, indicate that the influence of learning and prior investments can be critical in lowering overall costs. Learning occurs when experiences and best practices are documented, incorporated into training programmes, and coded in regulations. Large countries have an edge in this respect as they can rely on more experiences and distribute the findings to a much larger populace. Smaller countries might need to collaborate through international organisations so that experiences and best practices are distributed widely. With access to the internet and the support of international agencies such as The World Bank, this type of learning could flourish. Finally, in all of the scenarios, a greater percentage of the population protected is associated with optimal mitigation investment levels.

In support of our viewpoint, the aforementioned COAG *Natural Disasters in Australia* report recommends a paradigm shift to improve disaster mitigation in Australia (COAG, 2002). The two recommendations in the report can be connected to the earlier discussion of mitigation policy in this paper. First, the report suggests the systematic inclusion

of mitigation activities in a wide array of government and private bodies to achieve sustained resilience in Australian society. Moreover, other researchers confirm that the main need for hazard mitigation lies mainly with the vulnerable communities and individuals (Anderson-Berry and King, 2005). This inclusion ought to recognise changes in risk profile, vulnerability, and learning in time (that is, dynamic effects). Second, the report recommends ‘finding the right balance among mitigation, preparedness, response, relief and recovery activities’ and highlights the need to ‘recognize the investment and savings opportunities provided by mitigation’ (COAG, 2002, p. 10), implying that there is an ‘optimal’ point of disaster management spending.

Future research

The model created here makes a number of assumptions vis-à-vis the cost curves, including their shape (polynomial form and parameters) and their behaviour over time. In addition, these cost curves are assumed to emerge through an aggregation of the probabilities of differing levels of risk and the associated costs of a possible disaster. Future research is needed to test the validity of the assumptions and to develop empirically-based cost curves.

Correspondence

Sameer Prasad, 800 West Main Street, Whitewater, WI 53190, United States.
E-mail: prasads@uww.edu

Endnotes

¹ See <http://www.worldbank.org/hazards/> (accessed on 23 March 2013).

² See <http://www.emdat.be/database> (accessed on 23 March 2013).

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