This document is the accepted manuscript version of the following article:
Kreibich, H., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Green, C., … Thieken, A. H. (2014). Costing natural hazards. Nature Climate Change, 4(5), 303-306. https://doi.org/10.1038/nclimate2182

Commentary:

Costing natural hazards

Heidi Kreibich[1], Jeroen C. J. M. van den Bergh[2,3], Laurens M. Bouwer[3,4], Philip Bubeck[1†], Paolo Ciavola[5], Colin Green[6], Stephane Hallegatte[7], Ivana Logar[8], Volker Meyer[9], Reimund Schwarze[9], Annegret H. Thieken[10]*

[1]GFZ German Research Centre for Geosciences, Section 5.4 Hydrology, Telegrafenberg, Potsdam 14473, Germany

[2]Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Edifici Cn, Campus UAB, 08193 Bellaterra, Spain and ICREA, Barcelona, Spain, and Faculty of Economics and Business Administration, VU University Amsterdam, The Netherlands

[3]Institute for Environmental Studies, VU University Amsterdam, The Netherlands.

[4]Deltares, PO Box 177 Delft, 2600 MH, Netherlands

[5]Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy

[6]Flood Hazard Research Centre, Middlesex University, Middlesex, HendonLondon, NW4 4BT, UK

[7]The World Bank, Sustainable Development Network, 1818 H Street NW, Washington, DC 20009, USA

[8]Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Überlandstrasse 133, 8600 Dübendorf, Switzerland

[9]Helmholtz Centre for Environmental Research - UFZ, Department of Economics, Permoserstraße 15, D-04318 Leipzig, Germany

[10]University of Potsdam, Institute of Earth and Environmental Sciences, Karl-Liebknecht-Strasse 24-25, D-14476 Potsdam, Germany

*Corresponding author. E-mail: kreib@gfz-potsdam.de

[†]Now adelphi, Caspar-Theyss-Straße 14a, D-14193 Berlin, Germany

The ‘cost assessment cycle’ – a proposed framework for the integrated cost assessment of natural hazards.

Reported costs of natural hazards are at historically high levels, and are increasing due to ever more costly events with wide-scale effects. The Thailand flood in 2011, for example, shut down scores of factories, damaging global car manufacturing and electronics industries. Typhoon Haiyan in the Philippines in 2013 caused many casualties and displaced thousands of people. Globally, natural hazards caused damage estimated at US$125 billion for 2013[1]. Property damage has doubled about every seven years over the past four decades[2].

But such assessments generally do not reflect the complete set of costs of natural hazards, which comprise direct, business interruption, indirect, intangible, and risk mitigation costs (see Box 1 for definitions). In fact, most assessments account only for direct costs, and even these are thought to be at least 50% higher than internationally reported[3]. Substantial indirect and intangible damage, caused for instance by disruptions of global supply chains or environmental and health impacts, are often neglected[3].

A better understanding of total costs and their physical and societal drivers is needed for efficient risk management[4,5]. Regions can be left under-protected unless all costs are considered. Optimal investment in risk mitigation requires that each measure is used up to the point where the marginal benefit of risk reduction is equal to the cost of achieving that reduction[6]. Investment in risk management will be suboptimal unless the total costs of natural hazards, including those of risk mitigation, are fully understood (see Supplementary Information).

Efficient risk management requires a comprehensive analysis of the probabilities of extreme events as well as of the various effects and associated costs that natural hazards evoke. A generally accepted framework is the 'risk management cycle', which describes the consecutive phases followed when aiming to reduce the impacts of hazardous events: emergency response; recovery and reconstruction; risk analysis; and risk reduction (Fig. 1).

Costs arise in all phases of the risk management cycle and need to be comprehensively assessed – more than they are at present – to improve risk management decisions. Such costs comprise those for damage (including recovery) and risk mitigation. Damage costs include direct, business interruption, indirect, and intangible costs. Risk mitigation costs arise due to emergency response, planning (including risk analyses), and risk reduction measures.

Because budgets for risk management are limited, the choice of appropriate measures, the assessment of the costs and effects of such measures, and their prioritization are crucial for decision makers. Thus, cost assessments need to become an integral part of efficient risk management, with the aim to minimize the total costs related to all the risk management phases. Our vision for an integrated cost assessment in risk management is represented by what we call the 'cost assessment cycle' (Fig. 1). It is based on a comprehensive compilation and synthesis of currently available and applied methods for the cost assessment of natural hazards[7].

Natural hazard risk depends on climate variability, climate change, and changes in exposure and vulnerability[8]. Because of its dynamic nature, cost assessment should be a continuous process able to detect relevant changes in risk, and to initiate appropriate adaptation to changes[9]. The objective is to establish a systemic cost assessment framework.

We propose a four-phase continuous costing, as described below.

Phase 1: Contextualization. Cost assessments are purpose-oriented[10]. This means that cost assessments for a private company, a municipality, or a whole country differ in various aspects. It is important to define clearly the aim and scope of the assessment and the relevant hazards. Identifying system boundaries, such as spatial scale and time horizon, is also important as these will determine the required analysis and assessment of cost categories. The relevant cost categories are defined on the basis of preliminary assessments or expert judgments. Socio-economic aspects that might influence the system's recovery or response after a hazardous event are taken into account.

Potential risk mitigation measures and strategies can be identified through open dialogue with relevant stakeholders. The costs of these potential strategies are then assessed in the following step.

Phase 2: Cost assessment considering dynamics. Cost assessment is conducted for all relevant cost categories identified in phase 1. It aims to achieve comprehensiveness and avoid double-counting. Appropriate cost assessment methods are selected based on available overviews and guidelines[7]. Method selection depends on the specific properties of different cost categories and fields of application (e.g. investments in structural measures, land use planning, or insurance), as well as on relevant hazard types and sectors at risk. It needs to be decided whether it is necessary or helpful to include intangible costs in monetary terms, or whether they should be considered in a non-monetary or qualitative way, e.g. through multi-criteria approaches.

In order to account for changes in risk, scenarios for the future development of major risk drivers are created and used for assessing costs up until a specified time horizon. Potential changes in the cost estimates based on these scenarios are described, and their influence on the evaluation of risk mitigation measures (phase 3) is assessed. Uncertainties pertinent to the dynamic scenarios need to be quantified, clearly communicated, and taken into account in the decision-making process[11].

Phase 3: Decision support under uncertainty. Economic cost assessment supports the choice between alternative risk mitigation strategies. Cost assessment figures are integrated in decision-support frameworks, such as cost-benefit analysis, multi-criteria analysis, and robust decision making[11,12]. They assist decision makers in evaluating different risk mitigation strategies under uncertainty. The choice between alternative decision support frameworks and their associated decision rules, such as the weighting of evaluation criteria, should be made transparent to the decision makers. The choice made may substantially influence the results of an evaluation and the ranking of options.

When decision makers feel that uncertainties are too high to make a decision on pre-selected risk mitigation strategies, more detailed or precise cost estimates need to be achieved in putting more efforts on data collection and modelling (return to phase 2).

Alternatively, additional criteria, like robustness (performance of an option under different future scenarios), flexibility (ability to adjust a risk mitigation strategy according to future risk changes), and the precautionary principle (measures that are taken in the face of uncertainty to avoid harm to human health or the environment) can be considered in the evaluation of risk mitigation strategies[11,13].

Phase 4: Monitoring. The continuous monitoring of the actual damage caused by natural hazards and the expenditures for their risk reduction should be put in place by the responsible authorities[14]. Although damage can only be recorded in the aftermath of natural hazard events, the expenditures for risk reduction can be collected continuously, e.g. on an annual basis across the multiple levels of the administrations involved. Such evaluations of damage and risk mitigation costs should be fed into national and international, open-access databases, in order to improve the evidence basis for decision making. These data may then be used to update, improve, validate and adjust cost assessment models and cost estimates, which serve as inputs for phases 2 and 3. Furthermore, new information on the expected development of the major risk drivers is used to update the cost estimates (phase 2). It should be verified regularly whether such new insights or other developments are leading to necessary adjustments in the decision context of risk management (phase 1). Updated cost estimates are used for a new evaluation of risk mitigation strategies (phase 3). If necessary, decisions are revised, and the chosen risk mitigation strategies are adjusted.

Making better, more informed decisions for natural hazard risk management will gain even more importance in view of global environmental change. So far, such decisions are hampered by biased and uncertain cost estimates. The proposed framework for integrated, continuous cost assessment in natural hazard risk management throughout the new cost assessment cycle could provide more efficient solutions. It initiates the continuous monitoring of all damage and risk mitigation costs associated with climatic and other natural hazards. This enables the early detection of inefficient or efficient risk mitigation strategies. The cost assessment cycle is linked to the risk management cycle, which has proven to be an effective framework for risk management[2]. The resulting new, extended framework would allow more integrated cost assessment and improved decision making for natural hazard risk management.

Acknowledgments The research was supported by the European Community's Seventh Framework Program through the Coordination Action Project 'Costs of Natural Hazards' (CONHAZ), Grant Agreement number 244159. This document reflects the authors' views only and not those of the European Community.

References

1. Munich Reinsurance Company, Overall picture of natural catastrophes in 2013 dominated by weather extremes in Europe and Supertyphoon Haiyan, press release, Munich, January 7, 2014.
http://www.munichre.com/en/media_relations/press_releases/2014/2014_01_07_press_release.aspx

2. ICSU - International Council for Science, A Science Plan for Integrated Research on Disaster Risk: Addressing the Challenge of Natural and Human-induced Environmental Hazards. (2008). http://www.icsu.org/publications/reports-and-reviews/IRDR-scienceplan/irdr-science-plan.pdf

3. UNISDR, Global Assessment Report on Disaster Risk Reduction 2013. (2013).
http://www.preventionweb.net/english/hyogo/gar/2013/en/home/download.html

4. Bouwer, L.M., Crompton, R.P., Faust, E., Höppe, P. & Pielke Jr, R.A. *Science* **318**, 753 (2007).

5. Hall, J.W., Brown, S., Nicholls, R.J., Pidgeon, N.F. & Watson, R.T. *Nature Clim. Change* **2**, 833–834 (2012).

6. Young, R.A. in Cost-benefit Analysis and Water Resources Management (eds Brouwer, R. & Pearce, D) (Elgar, Cheltenham, 2005).

7. Meyer, V., *et al. Natural Hazards Earth Syst. Sci.* **13**, 1351–1373 (2013).

8. Huggel, C., Stone, D., Auffhammer, M. & Hansen, G. *Nature Clim. Change* **3**, 694–696 (2013).

9. Goble, R. & Bier, V.M. *Risk Analysis* **33**, 1942–1951 (2013).

10. The World Bank, The United Nations, *Natural Hazards, Unnatural Disasters: the Economics*
of Effective Prevention (2010). https://www.gfdrr.org/NHUD-home

11. Kunreuther, H., *et al. Nature Clim. Change* **3**, 447–450 (2013).

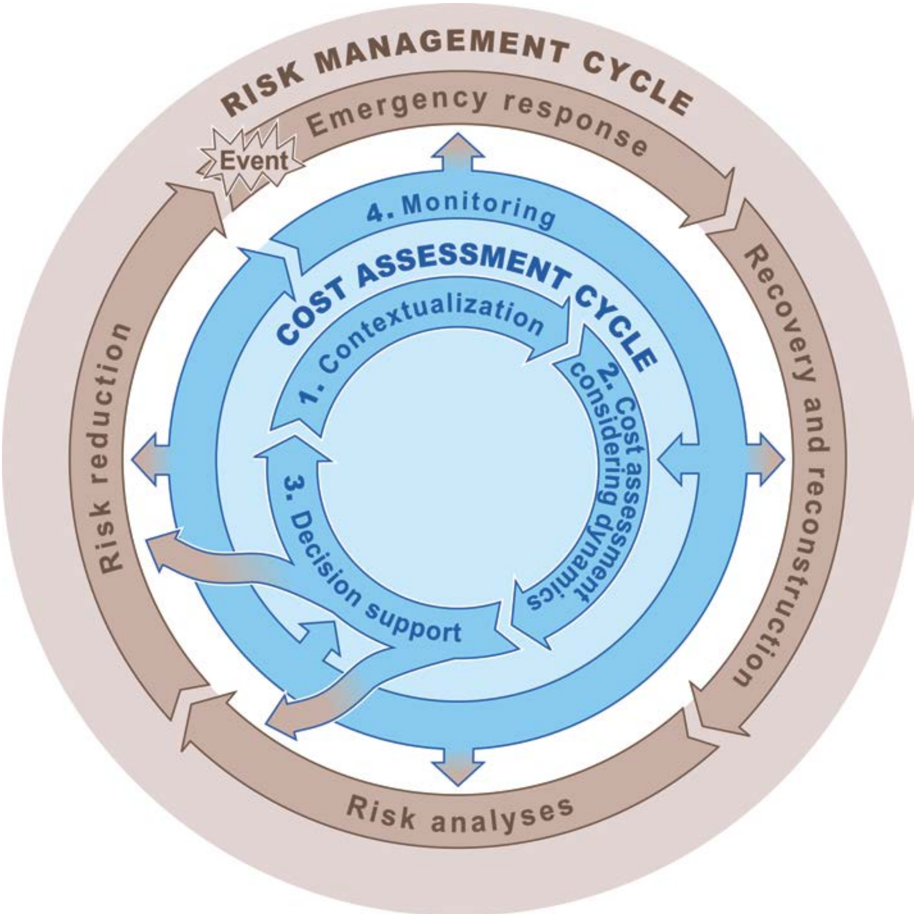
12. Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E. & van Deursen, W.P.A. *Clim. Change* **115**, 795–819 (2012).

13. Iverson, T. & Perrings, C. *Global Environ. Change* **22**, 161–177 (2012).

14. A Comparative Review of Country-level and Regional Disaster Loss and Damage Databases. (UNDP, New York, 2013).

15. Parker, D., Green, C. & Thompson, C.S. *Urban Flood Protection Benefits: A Project Appraisal Guide.* (Gower, Aldershot, 1987).

Figure 1 The proposed framework for integrated, continuous cost assessment in natural hazard risk management throughout the new cost assessment cycle.



Box 1 – Definitions of cost categories: Definitions of cost categories differ between communities dealing with different types of hazards. The following terminology is largely based on the classification of costs introduced to the flood damage literature by Parker *et al*. (ref. 15). New aspects are the addition of risk mitigation costs, as well as considering business interruption costs as a separate cost category (see Supplementary Table S1). The reason for choosing this classification is that these cost categories require different cost assessment methods[7].

Direct costs are damage costs that occur as a result of the direct physical impact of a hazard on humans, economic assets, or any other object. Examples include the destruction of buildings, contents and infrastructures, or the loss of life.

Business interruption costs occur in areas directly affected by the hazard. Business interruptions take place if, for example, people are not able to carry out their work because their workplace is either destroyed or made inaccessible. They also occur if industrial or agricultural production is reduced due to water scarcity.

Indirect costs occur inside or outside of the hazard area, often with a time lag. They are induced by either direct damage or business interruptions. Examples are negative feedbacks to the wider economy, such as the production losses of suppliers and customers of the companies directly affected by the hazard.

Intangible costs refer to damage to people, goods and services which are not easily measurable in monetary terms because they are not traded on a market. All cost categories described before may be tangible or intangible costs (Table S1). Intangible costs include, for instance, costs associated with environmental impacts, health impacts, and impacts on cultural heritage.

Risk mitigation costs are part of the total costs of natural hazard risk management, and are thus considered an essential cost category. The direct costs of risk mitigation refer to any costs attributed to research and design, the set-up, operation and maintenance of infrastructure, or other measures for the purposes of risk mitigation. The indirect costs of risk mitigation relate to any secondary costs (externalities) occurring in economic activities or localities that are not directly linked to such infrastructure investment. The intangible costs refer to any non-market health or environmental impacts of risk mitigation measures, such as environmental damage due to the development of a structural risk mitigation measure.

Supplementary table S1. Cost categories including examples adapted from Parker, D., Green, C. & Thompson, C. S., *Urban Flood Protection Benefits: A Project Appraisal Guide* (Gower, Aldershot, 1987).

<table>
<tr><th></th><th></th><th>Tangible costs</th><th>Intangible costs</th></tr>
<tr><td rowspan="3">Damage costs including recovery costs
arise during and after an event, as well as during the recovery phase</td><td>Direct costs</td><td>• Physical damage to assets:
– buildings
– contents
– infrastructure</td><td>• Loss of life
• Health effects
• Loss of environmental goods</td></tr>
<tr><td>Business interruption costs</td><td>• Production interruption because of destroyed machinery</td><td>• Ecosystem services interrupted</td></tr>
<tr><td>Indirect costs</td><td>• Induced production losses of suppliers and customers of companies directly affected by the hazard</td><td>• Inconvenience of post-flood recovery
• Increased vulnerability of survivors</td></tr>
<tr><td rowspan="2">Risk mitigation costs
arise due to emergency response, planning (including risk analyses), and risk reduction</td><td>Direct costs</td><td>• Design and set-up of mitigation measures
• Operation and maintenance costs</td><td>• Environmental damage
- due to development of mitigative infrastructure
- or due to a change in agricultural practices</td></tr>
<tr><td>Indirect costs</td><td>• Induced costs in other sectors</td><td></td></tr>
</table>

Total cost minimization approach

The total cost (*C*) of risk management depends on risk mitigation costs and expected damage costs, as formalized in equation 1. Expected damage costs (*ED*) are the sum of direct, business interruption, indirect, and intangible damage costs, which depend on the extent to which the different selected risk mitigation measures are applied (*x ,y,…n*), such as the height of a levee. *ED* is decreasing in *x* and *y*. Risk mitigation costs ($c_{i,}$ $i=1,2,..n$) are the sum of the costs of all selected risk mitigation measures. The total cost minimization approach in the case of two selected risk mitigation measures, with the cost c_1 of measure 1 rising in *x* and the cost c_2 of measure 2 rising in *y*, reads as follows:

Minimize $C(x,y) = c_1(x) + c_2(y) + ED(x,y)$. (1)

The first-order conditions are:

$\partial C(x,y)/\partial x = dc_1(x)/dx + \partial ED(x,y)/\partial x = 0$; (2)

$\partial C(x,y)/\partial y = dc_2(y)/dy + \partial ED(x,y)/\partial y = 0$. (3)

These conditions can be rewritten as:

$dc_1(x)/dx = - \partial ED(x,y)/\partial x;$ (2a)

$dc_2(y)/dy = - \partial ED(x,y)/\partial y$. (3a)

These conditions mean that for each measure the marginal cost of the measure has to be equal to the marginal benefit, i.e. the avoided expected damage costs due to this measure. This implies that an incomplete accounting of costs and benefits, for example, only direct expected damage or only measure 1 will not satisfy these optimality conditions and thus lead to a deviation from the global optimum.

This example of two selected risk mitigation measures easily extends to the case of *n* risk mitigation activities, which demonstrates the need of comprehensive cost-effectiveness and cost-benefit analysis of mitigation measures in the risk management cycle.