EconDisCliCha (2019) 3:23–38
https://doi.org/10.1007/s41885-018-0032-7

ORIGINAL PAPER

Flood Proofing Low-Income Houses in India: an Application of Climate-Sensitive Probabilistic Benefit-Cost Analysis

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Received: 13 February 2018 / Accepted: 4 May 2018 / Published online: 31 May 2018

Abstract Poor communities in high risk areas are disproportionately affected by disasters compared to their wealthy counterparts; yet, there are few analyses to guide public decisions on pro-poor investments in disaster risk reduction. This paper illustrates an application of benefit-cost analysis (BCA) for assessing investments in structural flood proofing of low-income, high-risk houses. The analysis takes account of climate change, which is increasingly viewed as an important consideration for assessing long-term investments. Specifically, the study focuses on the Rohini river basin of India and evaluates options for constructing non-permanent and permanent residential structures on a raised plinth to protect them against flooding. The estimates show a positive benefit-cost ratio for building new houses on a raised plinth, while the ratio is less than one for demolishing existing houses to rebuild on a raised plinth. Climate change is found to significantly affect the BCA results. From a policy perspective, the analysis demonstrates the potential economic returns of raised plinths for 'building back better' after disasters, or as a part of good housing design practice.

Keywords Probabilistic cost benefit analysis · Flood risk · Climate change · Building back better · Low-income housing · India

JEL C44 · C53 · I38

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Introduction

During the past decade there has been a marked improvement in the availability of risk information and analyses for disaster risk reduction (DRR), but many of the poorest and most vulnerable countries have been left behind (World Bank 2016). As poor communities are disproportionally affected by disaster events in terms of human and economic losses (relative to income), DRR analyses can be especially beneficial (Hallegatte et al. 2016). The Sendai Framework and the International Panel on Climate Change have highlighted the importance of pro-active DRR, especially in the face of climate change (IPCC 2012; Shamsuddoha et al. 2013; UNISDR 2015); yet, DRR still receives low priority on the part of many governments and on the international development agenda (Watson et al. 2015). As spending on DRR can be costly, and often competes with many other investment needs in developing countries, an assessment of the benefits and costs can provide valuable input to private and public policy decisions (Michel-Kerjan et al. 2013; Mechler 2016).

The application of benefit-cost analysis (BCA) for appraising DRR investments is standard practice within organizations such as the US Federal Emergency Management Agency (FEMA), the UK Department of Environment, Food and Rural Affairs (DEFRA) as well as other multi-lateral institutions, such as the World Bank and Asian Development Bank (Smith et al. 2017). At the same time, it is recognized that BCA has major challenges, including the choice of a discount rate, placing a value on human losses and explicitly considering the distribution of the benefits, risks and responsibilities (Shreve and Kelman 2014). Moreover, the World Bank (2016) has brought attention to the proprietary nature of risk assessment models in developing countries, and subsequently another challenge is acquiring data on the hazard, exposure to the hazard and vulnerability of exposed assets and people (Handmer et al. 2017). Still another challenge is how climate change will alter these hazards in the future, especially given the lack of data from weather monitoring stations in developing countries needed to downscale global climate models to the local level (Hochrainer et al. 2009). Partly because of the methodological and data challenges, there have been limited applications of climate-sensitive probabilistic BCA for DRR in the developing world and specifically in rural and poor areas (Kull et al. 2013).

This paper describes the application of a climate-sensitive probabilistic BCA in a developing country context. The study focuses on flood risk in India's Rohini River Basin and assesses the economic costs and benefits of raising high-risk houses on a plinth under different climate-change scenarios. Residential houses in this area are characterized by two main construction types: kutcha houses are constructed mainly of mud and are highly vulnerable to floods, and pucca houses are constructed mainly of brick and are less vulnerable. Our analysis investigates the benefits and costs of two options: i) constructing new kutcha and pucca houses with a one-meter raised plinth and ii) demolishing and replacing existing kutcha and pucca houses with a one-meter raised plinth. Based on a probabilistic approach, losses are distinguished according to different return periods, and the study quantifies the impacts climate change may have in altering these losses. We use as input for our analysis data from a previous project in this region (Risk to Resilience Study Team 2009) including loss distributions as well as climate change projections. From a methodological view, the value of this analysis is its demonstration – in a data-scarce context - of an assessment of the benefits and costs of changing building practices taking account of stochastic flood events under conditions of climate change. The methodology can be useful in an iterative process where results and policies are updated as new data and knowledge become available.

This discussion is organized as follows: We begin in the following section with a description of probabilistic BCA methodology for DRR. Afterwards we introduce the case study region and describe the application of the BCA methodology to kutcha and pucca houses within our case study region. Subsequently, we discuss limitations of our approach as well as possible ways forward and, finally, summarize and discuss policy implications.

Methodology

Probabilistic Benefit-Cost Analysis

Table 1 shows the steps involved in carrying out a probabilistic BCA. The methodology begins by identifying the options for mitigating risk (step 1), after which the risk without DRR is estimated (step 2) with either a forward-looking or backward-looking approach depending on whether risks are estimated with a catastrophe model or with a statistical analysis of past events, respectively (Kull et al. 2013). The term 'risk' is understood here as a probabilistic representation of potential losses. Risk can be formally represented through loss distributions or loss exceedance probability curves as discussed below. The loss distributions can be derived by relying on historical data that is analyzed using extreme value theory (see Embrechts et al. 1997) or with modeling approaches that simulate potential hazards on an exposed area (Grossi and Kunreuther 2005). Step 3 estimates the risk, taking account of the DRR option, which yields the net risk reduction. Combining the net risk reduction with the costs of the DRR intervention and other benefits (step 4) yields the benefit/cost ratio for public sector investments, or net present value for private investments (step 5).

As already indicated, one popular way to express risk in Steps 2 and 3 is with a loss exceedance probability (EP) curve. An annual EP curve indicates the probability p that *at least* \$L is lost in a given year. Figure 1 illustrates an EP curve, where the x-axis shows the magnitude of the loss in monetary terms (e.g. in US dollars) and the y-axis depicts the annual probability that losses will exceed this amount. With an EP curve, the analysis can show how DRR investments perform under changing risks triggered by future hazard occurrence (for a full discussion and examples see Grossi et al. 2005). Climate change can lead to an increase in the frequency and/or severity of the hazard, which is indicated in Fig. 1 as a shift of the EP curve to the right. A decrease in risk due to a DRR intervention is indicated with a shift of the EP curve to the left.

Table 1 A five-step approach for carrying out a probabilistic BCA

Step 1	Identify DRR investment options (hazards, sectors, location and time-frame)
Step 2	Estimate risk before DRR investment • A forward-looking approach is based on a catastrophe model incorporating hazard, exposure and vulnerability • A backward-looking approach is based on a statistical evaluation of past disasters
Step 3	Estimate risk after the DRR investment, and the benefits of the DRR investment as the net reduction in risk
Step 4	Estimate project costs and additional benefits associated with projects other than direct risk reduction
Step 5	Estimate the net present value (NPV) or benefit-cost ratio (B/C) by aggregating all costs and benefits estimated in Steps 3–4.

Source: Authors' adaptation from Kull et al. (2013)

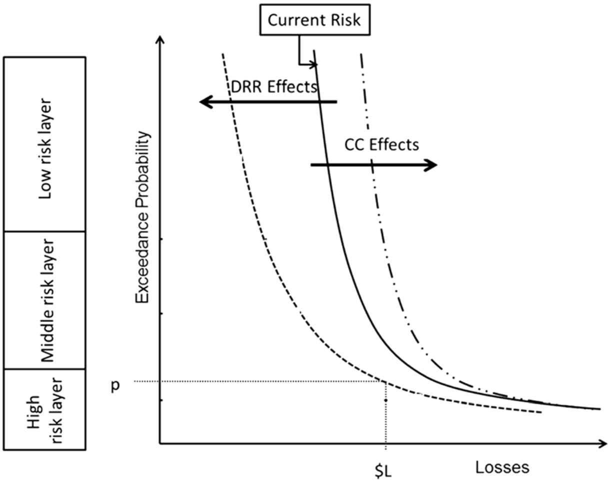

Fig. 1 The EP curve according to risk layers and showing DRR and climate-change (CC) effects

As a way of measuring and presenting risk, an EP curve has several advantages. First, it contains the necessary information for calculating standard statistical risk measures, such as the expectation, median, variance, standard deviation as well as lower and upper partial moments (Pflug and Römisch 2007). Second, it is possible to provide clear measures for those extreme high-loss events represented in the 'tail' of the distribution - such as 'value at risk', 'expected shortfall', 'conditional value at risk', and 'probable maximum loss'. Third, and finally, different layers of risk can be distinguished along the EP curve: a low-risk layer includes frequent less severe events; a middle-risk layer includes more severe events; and, a high-risk layer includes high impact events that occur at low frequency (Linnerooth-Bayer and Hochrainer-Stigler 2015). In this way, frequent and infrequent events are denoted, which may be of particular interest to stakeholders who are concerned about the occurrence of extreme or catastrophic events (Mechler et al. 2014). Some risk management measures (see UNISDR 2015 for a general introduction) may only be cost effective or even feasible for the low-risk layer (e.g. household structural mitigation measures, such as a raised plinth); some more effective or feasible for the medium-risk layer (e.g., insurance), and some appropriate to the high-risk layer (e.g., large-scale public structural measures such as embankments, or a national catastrophe fund). Hence, portfolios of risk management measures, including risk reduction and risk transfer, can be tailored to specific current and future risks (Hochrainer-Stigler and Pflug 2012).

Estimating Flood Risk Taking Account of Climate Change

There is a great deal of experience in estimating climate-sensitive EP curves, but mainly in developed countries (Kull et al. 2013) and for risks occurring at a large scale (Ward et al. 2017). The lack of climate-sensitive BCA in a localized developing country context can be partly explained by the general lack of data required for the estimates (World Bank 2016). As noted earlier (Table 1), the risk of losses from climate extremes in a specific region can be estimated either with a statistical analysis of past events (via extreme value theory, see McNeil et al. 2015) or with a catastrophe model (Grossi and Kunreuther 2005; Woo 2011). The catastrophe model approach is typically more data intensive, while a statistical analysis is useful if empirical data on losses is available but detailed information on the risk is missing.

In more detail, a catastrophe model requires precise and spatially explicit information of the local hazard, exposed elements (e.g. housing types) and their vulnerabilities. Conceptually, a catastrophe model consists of at least four components: hazard, exposure, vulnerability and losses (Grossi and Kunreuther 2005). The hazard component estimates the frequency and severity of future events at a specified location based on either historical and/or engineering information, e.g. by simulating potential flood events to increase the number observations. The exposure component requires detailed spatial information on the elements at risk (e.g. houses or infrastructure) as well as vulnerability functions that relate hazard intensity to damage. In contrast to a catastrophe model, a statistical approach depends entirely on historical data (for example, losses over a given time horizon) making use of extreme value theory (EVT) statistics that take account of 'fat-tailed' distributions to estimate an EP curve (Embrechts et al. 1997; McNeil et al. 2015). EVT-based statistics circumvent the problem that standard statistical distributions (such as a normal distribution) underestimate extreme events.

An advantage of the statistical approach compared to a catastrophe modeling approach is the lessened data requirements; however, a catastrophe model is spatially explicit and more capable of accounting for climate change impacts. Catastrophe models typically take climate change into consideration by calibrating the (flood) hazard model to changes in weather patterns (e.g. precipitation), and thus estimating changes in flood frequencies or intensities (for an advanced modeling application on the global scale see Ward et al. 2017). A statistical approach, by contrast, focuses on past events without attention to future contributions of climate change. Our analysis takes a hybrid approach, as will be explained below, by estimating the probabilistic loss distribution based on historical loss data and adjusting for climate change based on proxies for changes in the frequency and severity of the flood hazard.

Case Study: Flood Risk Reduction in the Rohini River Basin

The Rohini River originates in Nepal and flows through the Indian state of Uttar Pradesh, dividing two districts, Gorakhpur and Maharajganj. Because of the flat terrain, even small deviations from the natural flow of water can cause large-scale and long-term flooding. In addition to the annual small-scale seasonal flooding, the area has also been affected by major floods in the past (1954, 1961, 1974, 1993, 1998, 2001, 2007) and also recently in 2017. To mitigate flood risk, national and state authorities have relied primarily on structural flood defenses in the form of embankments. The local population has developed coping strategies, such as keeping boats in reserve for transport during flood periods (Hochrainer et al. 2011). The Rohini basin is primarily rural, where livelihoods are largely based on agriculture.

The housing in the case study region is typical of housing throughout rural India: *kutcha* houses (non-permanent construction) are built with local organic materials, such as mud or adobe; *pucca* houses (permanent construction) are built with bricks or stones, thus increasing their durability; and *semi-pucca* houses (semi-permanent construction) use a combination of mud, brick and stone. In general, kutcha dwellings are constructed by the owners and local unskilled masons; whereas pucca dwellings are constructed by hired craftsmen using simple construction tools (Okazaki et al. 2012). The advantage of kutcha housing is that materials are cheap, readily available and relatively little labor is required for construction. Generally, these houses are constructed on a mud foundation, which in some rare cases may be raised. *Pucca or semi-pucca* dwellings (the most common non-engineered buildings in India) are, on the other hand, relatively more expensive to construct as they require pricier materials and more labor. Like kutcha houses, pucca houses are also sometimes constructed on a raised plinth.

In the Rohini basin approximately 55% of houses are constructed with brick, which is the most flood resilient material; 16% of housing is semi-brick and 29% of housing is constructed with mud or adobe (Moench et al. 2009). The cost of constructing a pucca house (1500 USD)[1] is more than the average annual income (500–700 USD) of local inhabitants (see Table 2). During the 1998 flood 43% of houses surveyed were completely destroyed, while this number dropped to 21% in the 2007 floods. In both occasions, mud and semi-brick homes suffered the most damage in the region (Kull et al. 2008).

Probabilistic BCA for Raised Plinths According to the 5-Step Approach

Identifying DRR Investment Options (Step 1)

The first step in the estimation approach is to identify the options for reducing risks to residents in the Rohini basin. Besides plinths to raise houses, there are a range of low-cost, small-scale and minimally structural interventions to protect the lives and property of those living in flood-prone areas such as the Rohini basin (Kull et al. 2008). These include, among other measures, 'water-thirsty' plants such as banana and bamboo to absorb water, bitumen to damp-proof timber and bamboo posts and/or walls to strengthen timber. The building guidelines for India also mention such measures as strengthening structures with bamboo (BMTPC 2010).

Many other options exist. Large-scale, structural, collective measures, such as embankments, have been the dominant DRR measure in India for reducing the flood hazard (Kull et al. 2013). In addition, DRR can focus on reducing exposure by relocating houses in high-risk areas or restricting future settlement. Because of their potential for a high benefit-cost ratio in comparison with large, collective structural measures, our analysis focuses on raised plinths as a small-scale, vulnerability reducing measure. Shreve and Kelman (2014) suggest that B/C ratios for small-scale and minimally structural interventions, including household infrastructure changes, compare favorably to large-scale infrastructure projects. Hallegatte (2014) also calculates higher B/C ratios (4 to 36) for small-scale infrastructure measures but points out that the (sometimes immense) value added of low investments in small-scale DRR approaches can depend on large-scale measures being already in place. Counterexamples also exist, for example, for flood management along Pakistan's Lai River (Kull et al. 2013). Given the wide range of loss mitigation measures, this analysis should be viewed as only one part of a holistic treatment of flood risk, which would assess a full range of mitigation options and compare their costs and benefits.

We confine our analysis thus to assessing only one type of DRR measure, raising pucca and kutcha houses on a one-meter high plinth. Specifically, we evaluate two options: i) demolishing and replacing existing residences with a raised plinth, and ii) building new homes or homes destroyed by a flood on a raised plinth (i.e., building back better). As seen in Table 2, the estimated cost of constructing a standard-sized pucca house (1500 USD) is significantly

[1] All monetary values shown are in 2010 USD.

Table 2 Construction cost, lifetime, and additional cost of raising homes on a one-meter plinth

	Kutcha house	Pucca house
Cost of construction	150 USD	1500 USD
Lifetime	5 years	25 years
Cost of one-meter raised plinth addition to newly constructed house	25 USD	25 USD

Source: Moench et al. 2009, all monetary values are in 2010 USD

greater than a standard-sized kutcha house (150 USD). In both cases the additional cost of constructing a new house on a raised plinth is approximately equivalent (25 USD).

Estimating the Risk Before the DRR Investment (with and without Climate Change) (Step 2)

As previously discussed, risk, expressed as an EP curve, can be estimated either with a statistical analysis of past loss events or with a catastrophe model. Neither approach, however, is fully applicable in the Rohini basin due to the lack of historical loss data and information on the exposure and vulnerability of both housing types. To circumvent data limitations, this analysis takes a hybrid approach by scaling losses to an early study of the flood hazard conducted in this region (Kull et al. 2008). This early study examined two flood events (1998 and 2007) and provided detailed loss information. Return periods for the two events were estimated from a hazard model from which an EP curve was derived. In more detail, in Kull et al. (2008) frequencies of the past flood events were estimated based on the ARNO rainfall-runoff model, which uses parametric descriptions of primary hydrological processes at the basin scale in order to predict water flows (Todini 1996). The flood-inundated areas for selected return periods were estimated based on the HEC-RAS (Hydrologic Engineering Center – River Analysis System), where water flow from the ARNO model was used as an input parameter. In this way, estimates were derived for return periods for the 1998 and 2007 flood events as well as for a no-loss event scenario (Kull et al. 2008). From this information we estimated a truncated Pareto distribution (see also Hochrainer-Stigler et al. 2011). Finally, based on available information on losses to kutcha and pucca houses from these events (Kull et al. 2008), we assessed risk in the current period (2015) for both housing types. As shown in Fig. 2, risk in the current period is expressed in the form of a loss exceedance probability curve.

Turning to future risk, the challenge is to include climate change in the risk estimates. For this purpose, our analysis assumes that changes in drivers of the flood hazard, specifically changes in precipitation, can serve as a proxy for changes in flood losses for the previously estimated two return periods. Precipitation data from 1976 to 2006 obtained from the nearest weather station, the Bhairawa Airport, provides the baseline case (more data was not available). The weather station records rainfall for each dekad (10-day period). These estimates are combined with results of the IPCC A2 and B1 downscaled scenarios of daily precipitation for 2030 for the case study region, which were taken from Opitz-Stapleton et al. (2008). The A2 and B1 storylines are generally considered the worst- and best-case scenarios, respectively, and therefore qualitatively represent the range of climate outcomes (new data from the representative concentration pathways are not yet available for the Rohini basin). In more detail, based on data from Opitz-Stapleton et al. (2008) for the A2R1 and B1R3 scenarios (considered to be most representative for the region) we estimated a (heavy-tailed) gamma distribution to obtain

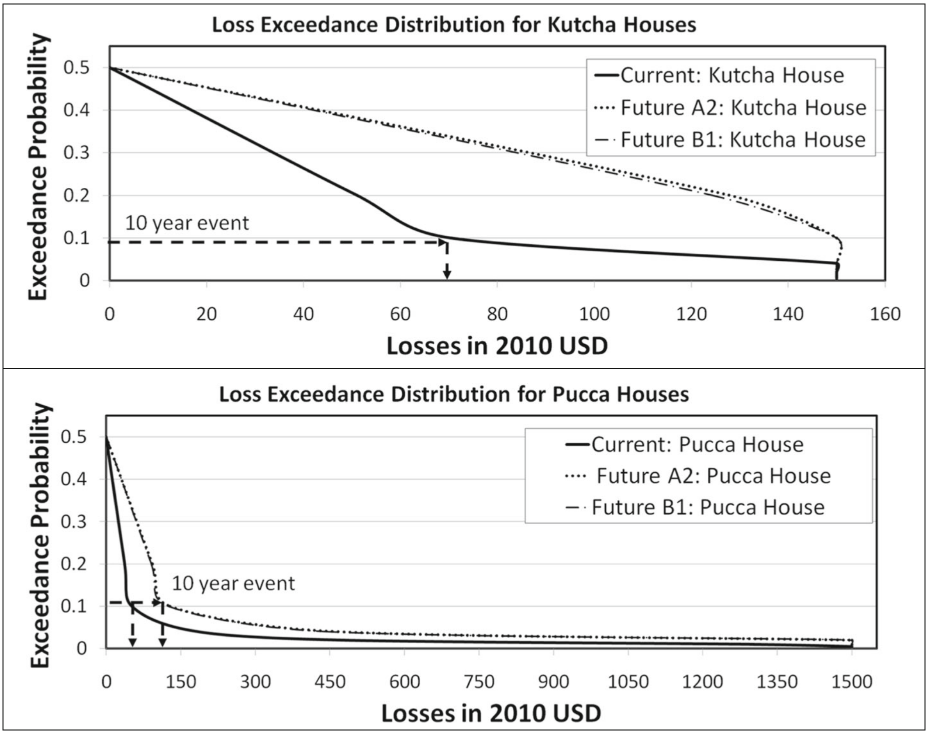

Fig. 2 Present (2015) and future (2030) EP curves for Pucca and Kutcha Houses

rainfall distributions using maximum likelihood techniques for each dekad until 2030. The adjusted precipitation patterns serve as a proxy to estimate changes in flood risk by changing the return periods for the aforementioned two loss events. Figure 2 summarizes the results for step 2.

As shown in Fig. 2 for the current period (2015) a 10-year flood loss event (or an event that happens on average every 10 years, or with an annual probability of 10%) would cause losses of about 70 USD to a kutcha house, and in 2030 this same event would result in a full loss (150 USD). For pucca houses the situation is less dramatic. Flood events with a 10-year return period would cause losses of about 50 USD today, which would increase to around 127 USD for the A2 scenario and 124 USD for the B1 scenario. While these figures have large margins of error, the important point is that climate change, according to this analysis, can have significant impacts. It should be noted that the A2 and B1 scenarios differ very little in their impact, which is explained by the near-term analysis (2015 and 2030). The impacts would be more differentiated for a longer term analysis (e.g. 2050, see Stapleton et al. 2008). Still, for kutcha houses, in contrast to more stable pucca houses, the effects of climate change are already visible for low-return period events.

Estimating Risk After the DRR Investment, and the Benefits (Net Reduction in Risk) (Step 3)

As noted in Table 1, the direct benefits of the DRR investment can be calculated as the difference in estimated losses after the investment compared with the estimated losses before the investment. For both the current period and taking account of future climate scenarios (Fig. 2), raising houses on a one-meter plinth is expected to reduce the vulnerability of kutcha and pucca houses in the region. Vulnerability reduction estimates assuming a raised plinth were taken from the study by Kull et al. (2008), which estimated the change in return periods for different housing structures. These estimates were used to calculate the decrease in absolute losses given the kutcha and pucca loss distributions for the current and future scenarios (as shown in Fig. 1).

Figure 3 shows the breakdown of risk reduction into different return periods. Based on current climate conditions, the raised plinth is expected to decrease the annual average loss (AAL) of kutcha houses by about one third, from 26 USD to 8 USD. The AAL prior to flood proofing is estimated at 47 USD given the A2 scenario, and 46 USD given the B1 scenario. The expectation after flood proofing is that the AAL is reduced to 26 USD under the A2 and B1 scenarios, respectively. This probabilistic analysis indicates that the flood proofing options, in terms of raising houses on a one-meter plinth, offer larger gains for the frequent events, especially taking account of a changing climate.

The results shown in Fig. 3 require some further explanation. It was calculated that a 10-year flood event for a kutcha house would cause losses of about 70 USD, and raising a house with a one-meter plinth would decrease losses by around 77% (Kull et al. 2008). This would mean a reduction in losses for a kutcha house of 47 USD, which we consider to be the DRR benefit. The remainder (23 USD), which we call residual risk, would be lost during such an event even given the raised plinth. As seen in Fig. 3, a one-meter plinth was found to reduce the risk of damage to kutcha houses during a 5-year flood event to zero, bringing a gain on

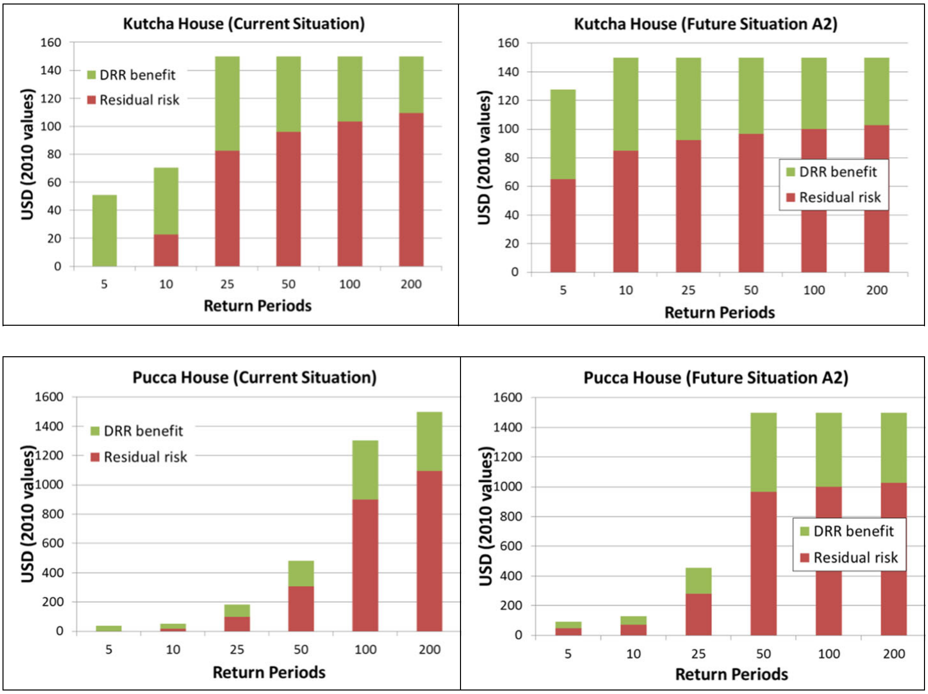

Fig. 3 Reduction in disaster damage (in USD) at selected return periods for the A2 scenario (above: kutcha house; below: pucca house, left current climate, right future 2030 period)

average to each house of approximately 50 USD, a third of the housing value. The same plinth will reduce damage in the future by approximately 61% (A2) and 63% (B1) during a 5-year flood event, bringing an average gain to each Kutcha house of approximately 65 USD (A2) and 63 USD (B1). Given an already low risk to pucca houses from frequent flood events, a one-meter plinth fully mitigates the risk of damage from a 5-year flood event; yet the estimated gain is only 37 USD in the current climate or 2.4% of housing value. Under the A2 and B1 scenarios, disaster risk reduction gains are estimated to be approximately 45 USD (for the 5-year event). While the full value of the average pucca house is lost in the case of a 50-year flood event given the A2 and B1 scenarios, constructing pucca houses on a raised plinth reduces these damages by approximately 36% (A2) and 35% (B1), bringing an average gain to each pucca house of 534 USD (A1) and 538 USD (B1).

Estimating Project Costs and Additional Benefits other than Direct Risk Reduction (Step 4)

As noted earlier (Table 2), the cost of constructing a one-meter high plinth is 25 USD for both kutcha and pucca houses. If the house is demolished for the purpose of plinth retrofitting, the cost of construction would be additional, or 150 USD for a kutcha house and 1500 USD for a pucca house. Apart from the costs and benefits discussed above, there are, however, additional benefits to raising houses on a plinth other than the economic savings from reduced risk of house collapse. Most important, raising houses can contribute towards saving lives since intact houses do not collapse on the residents, and house roofs serve as temporary refuge during floods. At least 20 people were killed due to wall and ceiling collapses during heavy rains in Uttar Pradesh in 2008 (IANS 2008). Various methods have been proposed for including lifesaving impacts in benefit-cost analyses, including what is called the value of statistical life (VSL), which places a value on risk reduction (Viscusi 2008). All approaches, however, are controversial since ultimately they put a price tag on life, which can be different for different income groups and countries. For example, Cropper and Sahin (2009) suggest that the VSL be scaled according to a country's per capita income relative to the USA (see as an application Sadeghi et al. 2015). As another co-benefit, seismic activity is prevalent in the region, and there are simple house-strengthening measures that could be tied to the plinth (Arya and Gupta 2010). Additionally, houses on a raised plinth avoid crawling creatures from entering the structure, and they are less susceptible to backflow of sewage into the toilets. Other social welfare considerations for constructing or retrofitting houses with raised plinths include the value to governments of lessened post-disaster relief payments and the ensuing fiscal benefits.

Estimating the Benefit-Cost Ratio or Net Present Value (Step 5)

The final step of the analysis is to estimate the benefit-cost ratio (B/C), or in this case the net present value of the plinth investment (since we have confined the analysis to only the economic benefits and not the full social benefits as discussed above). Assuming a project lifespan of 25 years for pucca houses and 5 years for kutcha houses, the 'demolish and build back with a plinth' option is generally found *not* to be cost effective. As shown in Table 3, the most cost effective option is constructing new pucca houses on a one-meter plinth (without demolishing) under the A2 climate scenario with a B/C ratio of over 18 (5% discount rate),

Table 3 Estimated B/C ratios for raising kutcha and pucca houses on a one-meter plinth

	Current	A2 (2030)	B1(2030)	Current	A2 (2030)	B1 (2030)
Discount rate	Kutcha House					
	With demolition			Newly constructed		
5%	0.44	0.53	0.53	3.11	3.70	3.69
10%	0.39	0.46	0.46	2.73	3.24	3.23
15%	0.34	0.41	0.41	2.41	2.87	2.86
	Pucca House					
	With demolition			Newly constructed		
5%	0.18	0.30	0.30	11.06	18.47	18.27
10%	0.12	0.20	0.20	7.20	12.03	11.90
15%	0.34	0.41	0.41	5.16	8.61	8.52

12.4 (10% discount rate) and 8.6 (15% discount rate). The least cost-efficient option is demolishing pucca houses and re-building them on a one-meter raised plinth, with a B/C ratio of 0.2 (5% discount rate), 0.1 (10% discount rate), and 0.3 (15% discount rate). As one can see, the B/C ratio is sensitive to the choice of the discount rate as well as the potential impact of climate change.

Raising newly constructed pucca houses on a one-meter plinth is therefore the option with the highest estimated B/C ratio, ranging from 5.2 to 18.5. Although significantly lower, raising newly constructed kutcha houses on a one-meter plinth also exhibits positive B/C ratios ranging from 2.4 to 3.7. The option of 'demolishing and building back' houses on a raised plinth has B/C ratios less than one for both housing types.

The B/C estimates for newly constructed homes, therefore, range from around 2 to 18 and compare favorably with B/C estimates for other types of DRR measures in developing countries, including large-scale structural measures. Woodruff (2008) estimates B/C ratios ranging from 2 to 44 for improved flood forecasting and raising floors in homes and significant lower numbers compared to 0.01 to 0.64 for structural floodwalls; in the Philippines, Burton and Venon (2009) report a benefit-cost ratio of 24 for a footbridge, 4.9 for a large scale structural sea wall, and 0.7 for a levee. As already indicated, Hallegatte (2012) also calculates higher B/C ratios (4 to 36) for small-scale infrastructure measures. For flood management along Pakistan's Lai River, Kull et al. (2013) report benefit-cost ratios of 1.3 for floodplain relocation, 1.6 for a warning system, 8.6 for river improvement, 9.3 for a retention pond, and 25.0 for combining the latter two.

Finally, it should be noted that the benefits of raised plinths are not evenly distributed across all types of floods, but are more pronounced for the less intensive, high frequency events. For either house type, flood-proofing alone is not an effective measure against catastrophic flood events. In the case of a 200-year flood, the average damage to a pucca house is estimated to be above 1000 USD both for the current and future climate change scenarios. To reduce these higher risk layers, additional mitigation measures and risk transfer mechanisms, such as insurance, may be necessary.

Limitations

The scope of this analysis has been limited to the economic value of raised plinths as a low-cost vulnerability-reducing measure. The analysis has not accounted for additional benefits of raised plinths, including saving lives or coupling with seismic mitigation measures. Moreover, the analysis has not evaluated alternative flood DRR measures, such as embankments for reducing the hazard or regulations to reduce exposure. While the analysis takes account of climate change, it does not consider socio-economic and technological advances, nor does it account for indirect effects of disaster events (Cavallo et al. 2013).

Apart from the limitations regarding the scope of the study, there are large uncertainties in the DRR estimates mainly due to data limitations. The probabilistic EP curve was based on only two past events and corresponding return periods, and the analysis could be improved by applying more advanced catastrophe modeling approaches that can take account of unprecedented flood events. However, this would require a spatially explicit map of building types and corresponding vulnerability functions. Furthermore, climate change effects were estimated based on weather stations outside the region using only one flood model as described in Moench et al. (2009). This could be further improved with ensemble runs using a multitude of different global climate model simulations as well as local flood modeling approaches that capture the epistemic uncertainty (IPCC 2012). Additionally, climate change impacts were considered only with regard to changes in the selected return periods which neglects possible changes in the frequency of extreme precipitation events and their duration over several dekads. The interested reader should refer to Beven and Hall (2014) for a comprehensive discussion of the treatment of uncertainties within climate change modeling approaches.

Uncertainty in the estimates highlights the potential of an iterative process where results and policies are updated as new data and knowledge becomes available (see IPCC 2012 and more specifically Mochizuki et al. 2015 and Schinko et al. 2017). Our re-analysis of previous data to perform a probabilistic and climate-sensitive BCA of risk reduction measures for low-income housing can be seen as a possible starting point for further investigating and reducing relevant uncertainties. The vulnerability of the very poor to flood events remains high, and despite large uncertainties, approaches for 'building back better' may provide a viable way to address the DRR goals set out in the Sendai Framework for Risk Reduction (UNISDR 2015).

Summary and Policy Implications

This analysis has demonstrated the potential benefits and costs of raising newly constructed kutcha and pucca houses in the Rohini basin on a one-meter plinth as part of good design practice. The raised-plinth measure targets the poor and will become progressively more cost effective as climate change increases flood hazards. Since kutcha and pucca housing types, with variations, are found widely throughout India and East Asia (India Census 2011), the results are relevant for wider applications and are especially topical for governments and donor organizations intent on implementing the concept of 'building back better' after disasters destroy private physical infrastructure (India Climate Dialogue 2017; UNISDR 2015).

Taking account of large uncertainties, the estimates indicate that options involving demolition are likely not to be economically cost effective, while raising houses at the time of their construction appear to be cost-effective at all discount rates. The value of flood proofing is significantly increased taking account of climate change. As indicated before, from a methodological view, the value of this analysis is its demonstration – in a data-scarce context – of a probabilistic assessment of the benefits and costs of changing building practices taking account of climate change. According to the World Bank (2016), risk assessment models in developing countries are frequently proprietary, and data is lacking on the hazard, exposure and vulnerability. This assessment partially circumvents the lack of data by combining scarce historical data on losses with a statistical and physical flood model to estimate flood return periods. With scarce data, large uncertainties exist, and the results should be viewed as indicative rather than definitive. The results can be viewed as baseline estimates useful within an iterative risk management framework that takes account of emerging data.

Despite the large uncertainties, the analysis signals the importance of assessing small-scale and minimally structural interventions, in this case the benefits and costs of constructing kutcha and pucca houses with raised plinths, as good building practice. The probabilistic analysis shows that flood proofing will become more important in reducing the risk of frequent flooding (especially for structurally weak kutcha houses). While losses at the higher return periods cannot be reduced substantially by this structural option, alternative disaster risk management options, such as risk transfer, are needed in order to cope with the intense flood events in the region today and in the future.

From a public policy view, the analysis demonstrates the potential return on investing in pro-poor hazard resilient housing as part of post-disaster reconstruction, climate adaptation and economic development. However, given the limited cash income and prevalent poverty in the case study area, as well as the limited access to credit, even low-cost flood-proofing measures can be unaffordable. Since raised plinths and other DRR measures have payoffs for regional and national public authorities that traditionally provide relief after disasters, the government, after further assessing the benefits and costs, might consider policy interventions that support this DRR intervention.

For this purpose, India’s National Building Code has formal provisions and informal guidelines for non-engineered buildings, defined as those that are spontaneously and informally constructed in the traditional manner without any or little intervention by qualified architects and engineers. Despite these provisions, however, the codes and guidelines remain recommendatory documents of good engineering practices, and their implementation depends upon numerous agencies and owners of the buildings. As pointed out by UNCRD (2008), the disaster management policies of India and many other governments in developing countries contain few concrete steps to support preventive actions for the safety of buildings: development plans do not require consideration for safety from hazards; settlement planning and development legislations have no provision to attend to hazard safety concerns, and the building by-laws of municipalities and corporations are silent about earthquake and flood resistance in buildings. Aimed at seismic safety, but also relevant for flood safety, Okazaki et al. (2012) recommend the following reforms for improving the resilience of non-engineered buildings in India:

- Guidelines and codes for natural disaster safety should be simpler and disseminated widely and properly to homeowners, builders and craftsmen.
- Awareness raising programs should be conducted in relevant communities;
- Quality control or inspection should be instituted by local authorities;
- Certification programs for masons/ craftsmen are needed to ensure the quality of the construction.

In addition to these public administration measures, the Indian authorities might also consider market measures, such as providing subsidies to render newly constructed homes more resilient to floods. Importantly, donor organizations and NGOs have numerous ways of influencing local communities to support resilient housing. Ultimately, the extent to which regulations, awareness raising campaigns, inspections, certifications and subsidies are enlisted to implement vulnerability-reducing measures, such as raised plinths, should depend on their relative value compared to other DRR and non-DRR interventions. This analysis has demonstrated a methodology for making these comparisons.

Acknowledgements Part of this work was supported by the Global Facility for Disaster Reduction and Recovery (GFDRR) as a background paper for the "Natural Hazards, Unnatural Disasters" report (UN 2010). The authors would like to acknowledge the contribution of Howard Kunreuther and Erwann Michel-Kerjan at the Wharton Risk Center to earlier versions (Hochrainer-Stigler et al. 2011) our paper is partly based on. Open access funding provided by International Institute for Applied Systems Analysis (IIASA).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

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