

## The importance of accounting for equity in disaster risk models

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Societal efforts to understand and mitigate threats posed by hazards are often informed by complex disaster risk models. Despite research demonstrating the disproportionate effects of disasters on vulnerable groups, current risk modeling approaches lack robust methods to account for such equity concerns. Consequently, efforts to develop evidence-based disaster risk management interventions may lack awareness of differential risks in the settings where they are applied. Here, we draw on the relevant literature to develop a typology for characterizing current approaches to incorporating equity into risk modeling. Using this typology, we then evaluated 69 risk assessments conducted by major international development organizations. We found that only ~28% of risk models attempt a quantitative evaluation of the differential impacts of disasters and climate change. We then used an equity-sensitive approach to reconstruct a recent risk assessment and show that important elements are missed when equity is excluded in disaster risk modeling.

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Between 2005 and 2015, more than 1.5 billion people were impacted by disasters around the world. The societal impact, quantified in terms of economic losses, is estimated to have been approximately US\$1.3 trillion<sup>1</sup>. The representation of the severity of disasters in dollar amounts is routine practice in disaster risk management (DRM), where disaster risk models are used to assess their potential future impacts. Doing so allows for the identification of trends and costs associated with disaster damage to assets, production, and infrastructure, and subsequently, the design of appropriate interventions to mitigate disaster risk. However, this approach to modeling disaster risk can fail to adequately capture the full impacts of these events on people and communities. In particular, decades of research demonstrate that the extent of disaster impacts varies greatly for different populations living within the same affected area<sup>2</sup>. Differential disaster burden has been observed along wider axes of societal marginalization, such as income and social status<sup>3–8</sup>, age<sup>9–11</sup>, race<sup>12–14</sup>, gender<sup>15–19</sup>, and disability<sup>20–22</sup>. Increasingly, scholars are calling attention to the need for disaster and climate risk models to account for equity in order to better integrate these concerns into practice<sup>23</sup>. Failing to account for equity in the design of disaster mitigation efforts may unintentionally lead to policies that exacerbate them<sup>23</sup>.

Our investigation is guided by the following questions: (i) in disaster risk assessments conducted by major international development organizations, to what extent and in what ways are equity concerns taken into account? and (ii) at the level of the assessment, what are the implications of not taking equity into account? To address these questions, we first developed a typology for characterizing current approaches to incorporating equity in risk modeling. We then used this typology to analyze the largest global sources of disaster risk assessments available to the public—the World Bank Open Knowledge Repository, the Asian Development Bank, PreventionWeb, and the Inter-American Development Bank—for risk models created between 2010 and 2021 to understand current practices. We then performed a re-assessment of a prior earthquake analysis for Nepal<sup>24</sup> to compare the outputs of a risk assessment when equity is taken into account against when it is not. Overall, we find that contemporary disaster risk assessments do not adequately account for equity issues, despite available methods for doing so. We show that such methods can uncover the disparate impacts of natural hazards and bring attention to at-risk groups, which may improve both the allocation of emergency aid and the efficacy of risk management interventions.

### Related work and typology

Globally, DRM relies heavily on risk modeling to understand the nature and extent of disaster risk<sup>25</sup>. In this context, disaster risk is understood probabilistically as a function of hazard, exposure, and vulnerability—where hazard refers to the disaster phenomenon, exposure refers to the populations, infrastructure, and assets within the community of interest that may be affected by the hazard, and vulnerability refers to the community's susceptibility to damage and its capacity to cope with or adapt to disaster disturbances<sup>25–27</sup>. Information on disaster risk is typically created and communicated through projects called risk assessments, which aim to support the decision-making processes of a wide range of actors across the public and private sectors<sup>28</sup>. Such risk assessments are often conducted to have a reliable and comprehensive estimate of the potential costs of disaster events to better target, design, and implement risk reduction measures such as building retrofitting, land-use planning, or the design of disaster risk insurance programs<sup>29</sup>.

A central issue is that risk assessments, and the measurements they are based on, do not account for the disparate impacts of natural hazards, and may thus undermine policy efforts. This is especially true of measurements of asset losses—the monetary value of damage to physical assets—which are used extensively to quantify the cost of disaster events<sup>30</sup>. Reliance on this metric may be counterproductive to disaster responses for multiple reasons. First, it may lead policy makers to favor disaster risk reduction measures that minimize asset losses and neglect vulnerable populations with fewer assets<sup>29,31–33</sup> in the process. Second, the use of asset losses as the primary metric for estimating the potential costs of disasters is an incomplete measure of total impacts on populations. For example, although vulnerable groups tend to have fewer assets to lose, they also have fewer resources to recover their assets while maintaining pre-disaster consumption<sup>34,35</sup>. As such, they are also more likely to forgo consumption of food, health, or education, and to take longer to recover<sup>36,37</sup>. Third, prioritizing asset-loss reduction strategies may obscure the benefits of other disaster reduction measures, emergency preparedness or reinsurance for instance, which may reduce the long-term consequences of disasters on populations, even if they do not reduce direct asset losses<sup>33</sup>. Similar issues arise when looking at equity across other dimensions. While ex-post disaster assessments have documented the uneven distribution of impacts across gender, race, ethnicity, age, physical ability, wealth, and other categories, the analytical tools used for ex-ante risk analysis used to guide risk-reduction policy do not account for these disparities. Despite these limitations, there is a limited understanding of risk modeling approaches that quantify risk in a more equitable manner and how such approaches relate to one another.

To better characterize the current status of equity within disaster risk assessment practices, we developed a typology—ranging from Type 0 to Type 5—as shown in Table 1A. The increasing order of values in the typology generally reflects an increase in complexity for how the models attempt to take equity into account. Type 0 describes approaches that do not engage with equity considerations, as is characteristic of traditional asset loss-based analyses. In Type 1 approaches, discussion of equity is supported by descriptive statistics and/or qualitative understandings of group vulnerabilities, although the models themselves omit such information. Type 2 approaches are based on index-based models, such as those developed by Cutter et al.<sup>38</sup>. These approaches employ a risk index where equity factors—such as class/income, gender, and age—are considered parameters or social indicators in a vulnerability index. Type 3 and Type 4 approaches disaggregate risk by various social groups. In the former, the overall risk faced in a given geographic area is assigned according to the percent of the overall population that comprises these groups. In the latter, differential potential impacts of hazards are incorporated into the model by disaggregating by vulnerability. Finally, Type 5 approaches measure the utility of the consumption loss due to a disaster event based on the welfare loss model first proposed by Hallegatte and Vogt-Schilb<sup>33</sup>. This approach, which is currently only applicable to income, considers a welfare function that scales according to wealth, where each unit of consumption loss is worth more for the poor as compared to the rich. To our knowledge, no studies have quantified the prevalence of equity considerations in risk assessments or compared the effects of different risk modeling approaches on the corresponding results—the focus of the subsequent section.

### Results

Overall, our analysis of risk assessments commissioned by the major international development organizations between 2010 and 2021 revealed that relatively few studies incorporated equity

**Table 1 Summary of risk assessment review results.**

**A: Typology of approaches to inclusion of equity in disaster risk assessment.**

Approach	Description	Frequency
Type 0	No incorporation of equity concerns	39
Type 1	Qualitative/literature review/secondary sources	11
Type 2	Risk or vulnerability Indexes	8
Type 3	Differentiated exposure	8
Type 4	Differentiated vulnerability	0
Type 5	Welfare Loss	3

**B: Inclusion of equity parameters in risk assessments.**

Parameter <sup>a</sup>	Frequency
Class/Income	29
Gender	16
Age	15
Race	6
Ability/Disability	7

<sup>a</sup>Categories are not mutually exclusive as some risk assessments considered more than one parameter.

concerns beyond qualitative description. As shown in Table 1B, of the 69 assessments reviewed, only a minority (30) mentioned equity issues at all. Of these studies, 11, 8, and 8 assessments engaged in a Type 1, Type 2, and Type 3 analysis, respectively. Of particular interest to this work were economic status (29), gender (16), and age (15), as issues regarding race (6) and ability (7) were given little attention. No risk assessments adopted a Type 4 approach while three assessments, each supported by the World Bank, adopted a Type 5 approach. There does not appear to be a strong relationship between the purpose of risk assessments, the year in which they are conducted, or the part of the world they represent, and the incorporation of equity considerations. We note that our review focused solely on ex-ante assessments used to quantify potential future impacts, rather than ex-post assessments used to support recovery. Taken together, these findings suggest that the differential impacts of disasters on marginalized groups are generally not accounted for in disaster risk assessments meant to inform DRM programs. There are thus considerable opportunities for further development.

**Re-assessing a risk analysis to account for equity**

To understand the potential impacts of incorporating equity in risk modeling, we updated an existing earthquake risk assessment using these methods. The original analysis was conducted for Nepal<sup>24</sup> and included expected monetary loss and fatalities for a one in 500-year earthquake event by district, consistent with a Type 0 approach. Using simple techniques and publicly available data, we updated the results with a Types 3–5 analysis to uncover substantial disparities in the distribution of earthquake risk in the population.

We first disaggregated previously modeled fatality rates by either differentiated exposure (Type 3 approach) or by both differentiated exposure and vulnerability (Type 4 approach). As shown in Fig. 1, the latter approach revealed notable differences in fatality rates for all groups, which were not identified in the initial risk assessment. For example, modeled fatality rates of the bottom economic quantile were twice that of the highest, and mortality rates for adults between ages 5 and 60 were sharply lower than other categories. On the other hand, the former analysis uncovered stark differences in fatality rates for caste types and income groups. This is likely because many caste types in Nepal are geographically clustered and are thus differentially exposed to earthquake hazards. While we do not identify a strong relationship between caste

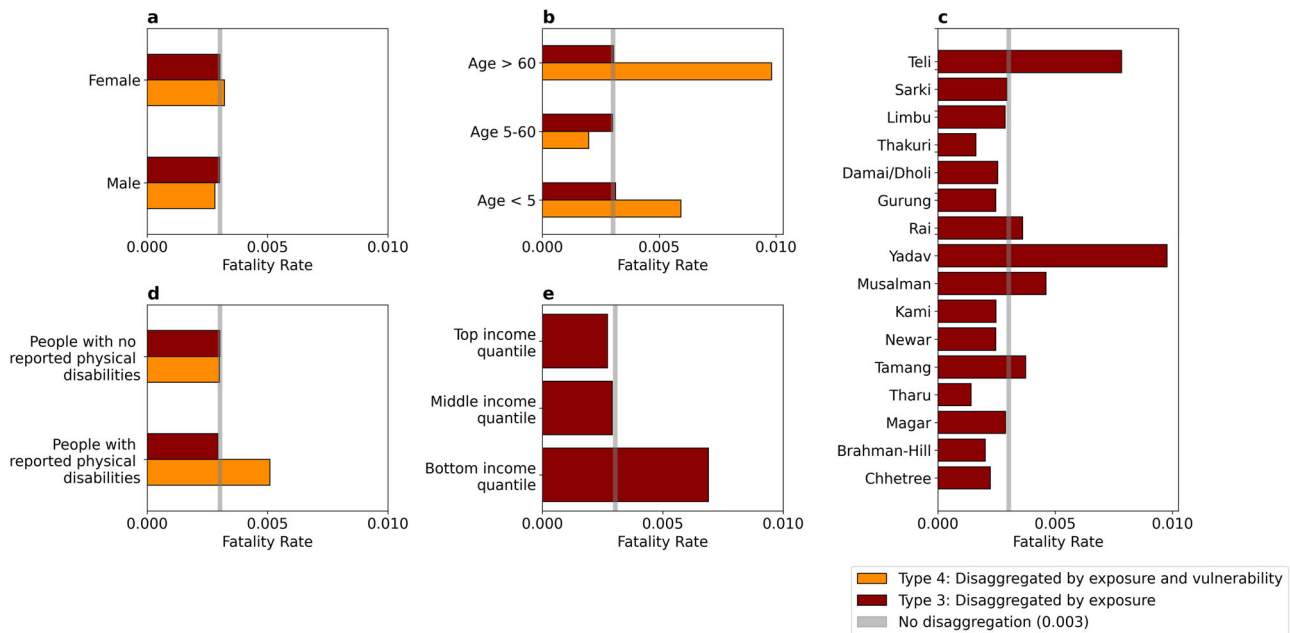
rank and exposure, such distinctions are nonetheless important for DRM planning.

For our Type 5 analysis, we recalculated expected monetary loss using the equity weights approach presented by Kind et al.<sup>39</sup> and Hallegatte et al.<sup>40</sup> This approach redistributes disaster losses based on average income per district to account for the higher welfare impact that each dollar of consumption loss has on low-income individuals. Figure 2 displays the results for total unweighted losses (Type 0 approach). In this analysis, we find that losses increase as average incomes increase so that the highest losses are concentrated around the urban and relatively prosperous Kathmandu region. However, when losses are weighted by income (Type 5 approach), this trend is reversed and impact is greater in rural areas (Fig. 3). This finding suggests that welfare impacts are higher in districts with lower average income—an intuitive, but critical, finding for DRM that the original risk assessment obscured.

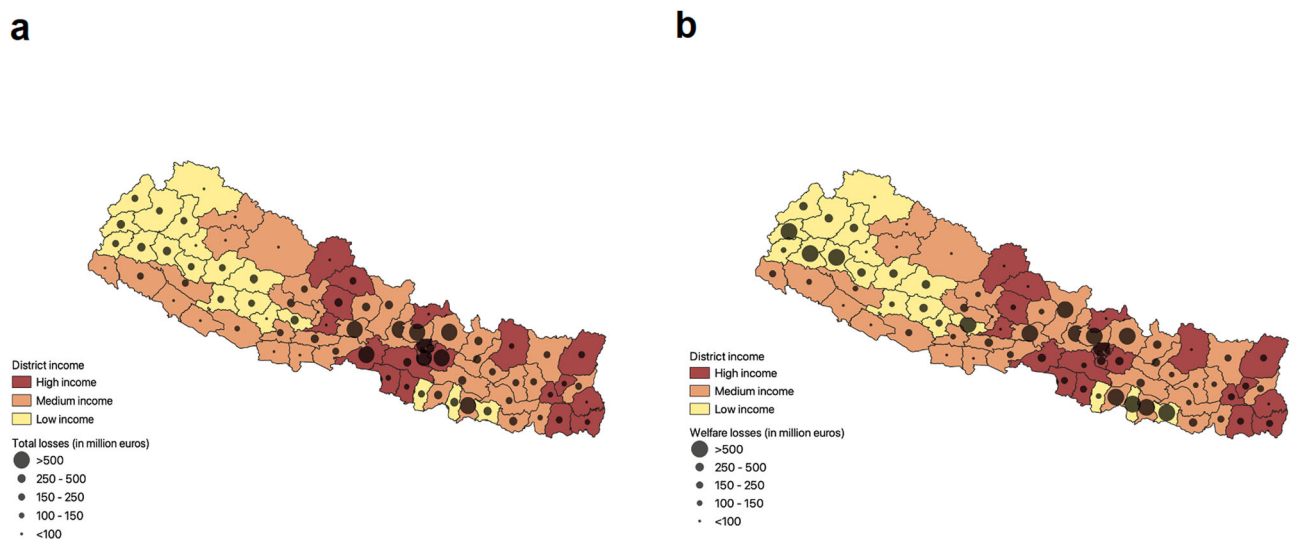
**Discussion**

Our findings demonstrate that, on the whole, contemporary disaster risk modeling practices do not adequately account for equity issues stemming from the differential impacts of natural hazards on marginalized groups. Few studies we examined considered these disparate impacts, and most that did, did so qualitatively. In addition, none of them accounted for differential vulnerability and only three accounted for welfare losses. We have also shown that there are straightforward methods available for doing so, with data that is currently available for many parts of the world, and that these methods can uncover disparities in the potential impact of hazard events on different groups that are elided by conventional approaches. While there is a need to further develop more sophisticated means of conducting equity-aware risk assessments, our results demonstrate that the potential aggregate effects of not accounting for equity across the large portfolio of studies that we surveyed are considerable and detrimental. In the worst case, risk assessments in their current form may prioritize investments in risk reduction in the wealthiest communities simply because they have more and higher value assets exposed, over less affluent areas where welfare losses would in fact be higher.

In the assessments we have evaluated, differential disaster risks experienced by marginalized groups can be the result of different exposure, vulnerability, or both. Disaggregating risk impacts through higher-order approaches (e.g., Types 3 and above), as we



**Fig. 1 Disaggregated fatality rates.** **a–e** Previously modeled fatality rates disaggregated by differentiated exposure (Type 3 approach, red) or by both differentiated exposure and vulnerability (Type 4 approach, orange). Both a Type 3 and Type 4 approach were used to disaggregate fatalities by **a** gender, **b** age and **d** disability. A Type 4 approach was used to disaggregate fatalities by **c** caste type and **e** income. Although the income analysis is technically a Type 3 approach, in practice it is a Type 4 approach as building vulnerability, which is included in the Type 3 analysis, is strongly correlated with income. The gray line depicts no disaggregation (0.003).

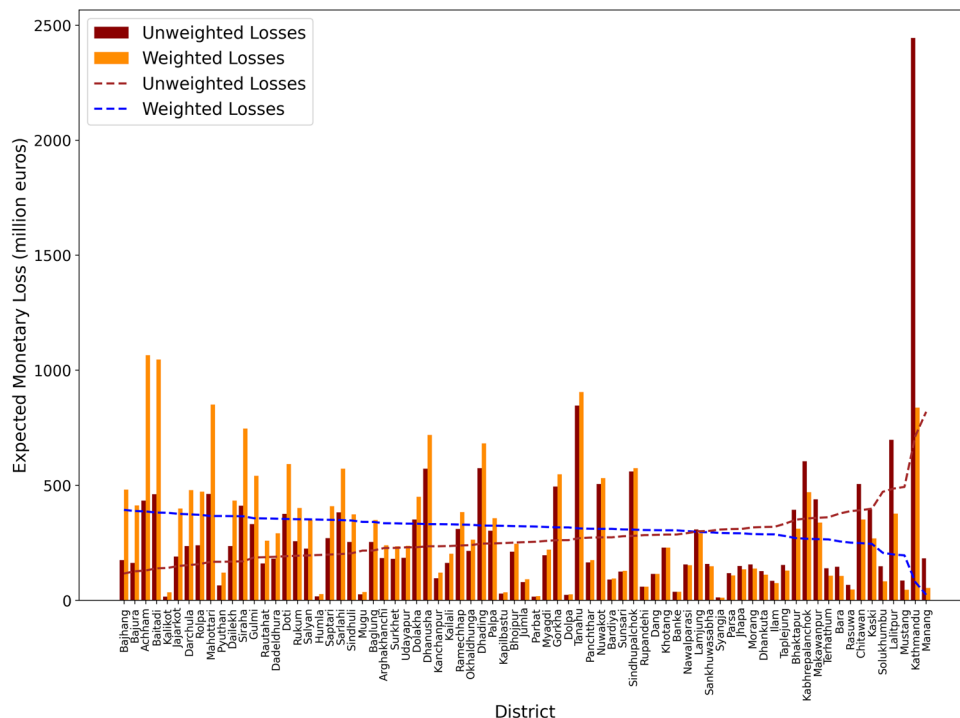


**Fig. 2 Welfare and total losses by district and income level in Nepal for a 1 in 500-year earthquake (in million euros).** **a, b** Comparison of a Type 0 and Type 5 approach to an earthquake risk assessment initially conducted for Nepal. **a** Total losses (Type 0 approach) for a 1 in the 500-year earthquake by district (high-income districts are red, medium-income districts are orange, low-income districts are yellow) in Nepal and **b** welfare losses (Type 5 approach) for the same event. Total losses are lowest for the poorest districts and highest for the wealthiest ones. By comparison, welfare losses are highest for the poorest districts, and lowest for the wealthiest ones. District-level losses—both total and welfare—are displayed as proportional black circles.

have argued, can both bring attention to groups that are more at risk and uncover potential causes of this differential risk. This stands to improve disaster risk management interventions in two ways. First, it would allow interventions to better identify the communities towards which risk reduction interventions would have the most impact. Second, it would support the design of more effective interventions appropriate for the specific communities affected (e.g. gender or disability-informed design<sup>41</sup>). Furthermore, it would appear that incorporating equity into

disaster risk modeling would be relevant across all phases of the disaster cycle, from mitigation to post-disaster recovery.

A frequent response to calls for a more detailed examination of disaster and climate change’s disproportionate impacts on marginalized people is to point to a lack of disaggregated data or the prohibitive costs of collecting it. Recent work has identified the existence, or nonexistence of data, as itself an issue of equity<sup>42</sup>. Our findings speak to this point in two ways. First, the scale of analysis is important. Despite the limited availability of microdata



**Fig. 3 Expected weighted and unweighted losses by the district in Nepal for a 1 in a 500-year earthquake (in million euros).** From left to right, the districts are ordered by average income where Bajhang has the lowest average income and Manang has the highest. Unweighted losses (red; brown line of best fit) are lowest for the poorest districts and steadily increase for the wealthiest ones. When the analysis considers weighted losses (orange; blue line of best fit) as per the Type 5 welfare-loss approach, this phenomenon is reversed. In this analysis, the poorest districts experience the greatest losses, which decrease with average district income.

in Nepal, the current work was still able to engage in a Type 5 analysis, albeit simplified, using what data was available. A Type 5 analysis would ideally employ household-level data to redistribute disaster loss based on income per household. In Nepal, much of the necessary data describing disparate disaster impacts does not exist at the household level. However, we demonstrate here that district and provincial-level data can be derived from census data, which are available in many areas, enabling a simplified approach. In the absence of household data, we thus redistributed disaster losses based on average income by district for a variation of the welfare loss approach which was still informative in its own right. Second, and despite this, it is clear that disaggregating exposure (Type 3), without associated incorporation of group-specific vulnerability (Type 4), may in some cases yield misleading results, and is likely best for highlighting groups affected by disproportionate exposure or physical building vulnerability but not social vulnerability. However, the vulnerability models needed for this form of analysis are often unavailable, pointing to the need for further work to develop context-appropriate vulnerability models in disaster-prone locales.

This paper focuses solely on one type of equity—distributional equity. We do this by demonstrating the importance of characterizing the differential impacts of disasters on marginalized communities and offering pathways for doing so. However, as argued by Klinsky et al.<sup>23</sup>, efforts to include equity in climate and disaster risk models may also seek to consider two other forms of equity: procedural and recognition. First, efforts to incorporate procedural equity could include the participation of vulnerable communities in the design and execution of the assessment or peer review by local experts<sup>43</sup>. Our initial document analysis included identifying concerns for procedural equity but reporting on these activities was rare and potentially inconsistent across the risk assessments we reviewed. This in itself is a meaningful result,

as it suggests the need for proper reporting on participation and the process for conducting a risk assessment. Second, risk modeling processes could also inform work to achieve recognition equity through greater efforts at characterizing non-economic losses such as psycho-social impacts of disaster, damage to cultural heritage, discontinuation of childhood education, and displacement. Finally, designers of risk assessments need to help decision-makers address potential tradeoffs between reducing overall levels of risk and equitable distribution of such risks. Though not always present, such tradeoffs can be an important concern<sup>44</sup>.

**Conclusion**

Despite some preliminary work in the academic literature, considerable effort is needed to develop techniques that better account for equity in disaster risk modeling. The use of our typology to evaluate contemporary assessments confirmed that few studies incorporate equity considerations. Our re-assessment of a case study in Nepal found that traditional methods conceal disparities in the distribution of earthquake risk for diverse groups. Consequently, failing to account for equity may hamper the findings, conclusions, and policy options of current studies and DRM practices. International agencies such as development banks and the United Nations are major funders of these models. Just as important, they are leading voices in the broader community of practice that designs and implements risk assessment processes in the international development community. They are therefore well positioned to influence the sector. Scientists and researchers from academia and other institutions can drive such adoption through further development and refinement of techniques for conducting risk assessments that account for equity. While improving the models themselves does not resolve the

underlying structural issues that produce inequitable outcomes during disaster mitigation and recovery, equity-aware models are an important tool toward this goal.

## Methods

**Part I: Risk assessment review.** Risk assessments were sourced from the World Bank, the Asia Development Bank, the Inter-American Development Bank, and PreventionWeb—major international financial institutions, organizations, and regional banks that fund and produce risk assessments. The majority of assessments (~47%) were sourced from the World Bank Open Knowledge Repository<sup>45</sup>, in part because the Global Facility for Disaster Reduction and Recovery (GFDRR)<sup>46</sup>—a global partnership between the World Bank, the United Nations, and other major donors—is one of the central funders and producers of risk information. Since 2010, GFDRR has funded at least 80 disaster risk assessments at the regional, national, or subnational levels around the world, which are publicly available in the official open-access repository and widely used to inform the development and disaster literature<sup>47,48</sup>. The Asia Development Bank, PreventionWeb, and Inter-American Development Bank accounted for ~31%, ~13%, and ~7% of the risk assessments in our dataset, respectively. The Inter-American Development Bank is an international financial institution that focuses on development finance in Latin America and the Caribbean<sup>49</sup>. The Asia Development Bank is a regional bank that supports projects that create economic and development impacts<sup>50</sup>. Risk assessments are integral to the work of both organizations, although their access is governed by their respective open-access policies. Managed by the UN Office for Disaster Risk Reduction, PreventionWeb is a knowledge-sharing platform focused on disaster risk reduction (DRR) and which thus offers knowledge products and services to facilitate DRR work, including risk assessments<sup>51</sup>.

Two searches were conducted in the repositories. In the first, the search terms ‘disaster “risk assessment”’, ‘climate “risk assessment”’, and ‘climate “vulnerability assessment”’ were specified in the World Bank Open Knowledge repository. These search terms yielded few results in the remaining repositories and the research team instead specified “disaster risk assessment”, “climate risk assessment” and “climate vulnerability assessment” in them. In the second search, relevant documents were discovered using the hierarchical categorization and tags in the repositories as was applicable. For the World Bank Open Knowledge repository, this began with *Economic and Sector Work Studies*, then narrowed to *Sector/Thematic Studies*, and further narrowed to *Risk and Vulnerability Assessments*. For the Inter-American Development Bank, documents were filtered first by *Type* and then *Topic*, where *Types* included *Technical Notes*, *Working Papers*, *Co-publications*, and *Annual Reports*, and *Topics* included *Disaster Risk Management* and *Natural Disaster Risk Management*. Similarly, for the Asian Development Bank, each search term was specified independently and with the filters *Publications* and *Institutional Documents*, and using the website hierarchy beginning with *What We Do*, then *Projects & Tenders*, and finally, *Documents*.

In total, this returned 901 unique documents (Asia Development Bank: 285; PreventionWeb: 125; Inter-American Development Bank: 67; World Bank: 424) for the relevant time period. Selection of documents within the scope of the study was based on the following inclusion criteria: (1) the document must have been a multisectoral disaster risk assessment conducted to inform international development planning; (2) the document must have included a primary analysis; (3) the analysis must have been principally quantitative; and (4) the document must have been published between the years 2010 and 2021 (inclusive). After

evaluating the 901 search results on the basis of the criteria described above, 69 out of the 901 items were found to satisfy the inclusion criteria, while the remaining 831 items did not. The 69 assessments were distributed among the research team (6 individuals) for individual analysis. Any questions, discrepancies, and areas of uncertainty encountered by any individuals were flagged, and then later discussed at the next meeting until a resolution was reached.

For the risk assessments that incorporated equity ( $N = 30$ ), we engaged in a classification process to document the specific ways that equity concerns and differential risk (i.e., on the basis of race, class/income, gender, disability, and age) were or were not represented. This consisted of reviewing the assessments again, but this time, with a particular focus on these elements. The results of this exercise revealed that among those assessments that mentioned equity, there were varying levels of engagement in the ways this was done. Informed by our results, we were able to develop a typology to characterize these different levels of engagement based on the methods used (see Table 1B).

Once individual analysis for all 69 items was complete, a Quality Assurance and Quality Control (QA/QC) phase ensued. The purpose of this phase was to evaluate the level of variability in reporting between individual assessors in order to address major discrepancies and/or adjust the analysis framework if needed. This QA/QC encompassed ‘spot checking’ of all 901 items that had been identified during the search process to confirm the decision to include or not include in the analysis. This spot check was performed on ~26% of assessments ( $N = 18$ ) that had been included in the analysis, and ~10% of search results that did not satisfy the inclusion criteria ( $N = 83$ ) and had thus been excluded. All QA/QC assessments were in agreement with the original assessments. Minor adjustments in reporting practices were applied to avoid future inconsistencies.

**Part II: Nepal risk assessment.** In order to demonstrate different approaches to incorporating equity in risk assessments, we re-analyzed a risk assessment conducted for Nepal using equity-informed methods. We first disaggregated risk across different axes of societal marginalization, such as gender and age. We also applied a welfare loss approach using equity weights<sup>59</sup> to redistribute earthquake impacts and account for the household-level welfare, as opposed to asset, losses.

The original study was a multi-hazard risk assessment for Nepal, conducted at a district-level resolution<sup>24</sup>, for the purpose of understanding and guiding risk reduction decisions. The study provided the estimated number of fatalities and the number of buildings damaged and destroyed at the 100- and 500-year earthquake hazard level. Key inputs into such estimates included the number of different building types per district, the physical vulnerability of these building types, and earthquake shaking intensity maps. For our additional analysis, we focused only on the 500-year earthquake hazard level.

To re-analyze estimated earthquake fatalities, we disaggregated fatalities by income, gender, age, disability, and caste. We first disaggregated only on the basis of exposure, (Type 3) and when category-specific vulnerability models existed, we disaggregated by both exposure and vulnerability (Type 4). For disaggregation by exposure only, we calculated the number of fatalities per group for each district using formula 1:

$$F_{i,d} = \frac{N_{i,d}}{N_{\text{total},d}} F_d \quad (1)$$

whereby  $F_{i,d}$  is the number of fatalities for group  $i$  (e.g. people below a certain income level) in district  $d$ ,  $N_{i,d}$  is the number of people belonging to group  $i$  in district  $d$ , obtained from the census

data<sup>52</sup>,  $N_{\text{total},d}$  is the total population in district  $d$ , and  $F_d$  is the number of fatalities in district  $d$  according to the initial risk assessment. The number of fatalities per district ( $F_d$ ) is available from the initial risk assessment.

Some population groups have well-documented differential earthquake fatality rates. This enabled us to propagate disaggregated exposure to disaggregated vulnerability, using odds ratios of fatalities obtained from the literature. An odds ratio ( $OR_i$ ) indicates how much more likely a person from group  $i$  is to experience death compared to a person from the reference group 1. We applied these odds ratios to calculate the fatalities by group without adjusting the total number of fatalities ( $F$ ). Formula 2 shows the derivation where  $FR_i$  is the fatality rate of group  $i$ .

$$\begin{aligned} F_{i,d} &= N_{i,d} FR_i = N_{i,d} OR_i FR_1 \\ F_d &= FR_1 N_{1,d} + \sum_{i=2} OR_i FR_1 N_{i,d} \\ \frac{F_d}{FR_1} &= N_{1,d} + \sum_{i=2} OR_i N_{i,d} \\ FR_1 &= \frac{F_d}{N_{1,d} + \sum_{i=2} OR_i N_{i,d}} \\ F_{i,d} &= N_{i,d} OR_i \frac{F_d}{N_{1,d} + \sum_{i=2} OR_i N_{i,d}} \end{aligned} \quad (2)$$

We applied odds ratios to differentiate by vulnerability for gender, age, and disability<sup>53</sup>. No data exists to include differentiated fatality rates of caste types and income groups. However, the unequal distribution of fatalities across castes and income groups observed in Fig. 1 reflects both uneven exposure and the increased vulnerability of building types occupied by these groups. For instance, there is a strong negative correlation between income and building vulnerability, with lower-income households tending to occupy unreinforced masonry buildings highly vulnerable to earthquakes<sup>54</sup>.

The use of equity weights has been used in several studies to account for the fact that the same unit of loss has different household-level welfare impacts, which vary with socio-economic status. For example, a \$100 loss for a low-income household has a larger impact than the same loss for a high-income household. Equity weights are a method to weigh disaster impacts in such a way that the loss is redistributed according to income in order to better represent the actual welfare impacts<sup>39</sup>. These adjusted losses can then be used in a cost-benefit analysis to minimize welfare loss on the entire population, rather than asset-loss which tends to prioritize asset-rich communities. Equity weights are just one component of welfare loss<sup>39</sup>. Other components of welfare loss, such as risk aversion, require the consideration of household-level financial information (e.g., savings, insurance, government assistance, and access to loans). Ideally, such information should also be considered in a full welfare-based approach (e.g., Hallegatte et al.<sup>40</sup>, Markhvida et al.<sup>32</sup>). For equity weights, there are no consensus on the use in cost-benefit analyses for disaster risk management<sup>39</sup>. In this project, we just applied equity weights to show how welfare loss is distributed very differently than asset losses.

The original risk assessment we replicated did not include estimated earthquake losses. We, therefore, estimated these using standard practice earthquake risk and loss analysis combining shaking intensity<sup>24</sup>, the distribution of each building type per district<sup>52</sup>, their corresponding fragility curves<sup>24</sup>, and their estimated replacement cost. For each building type, a fragility curve relates earthquake shaking intensity to the estimated damage state<sup>55</sup>, which is then converted to overall percent replacement cost using Lagaros et al.<sup>56</sup> Estimated replacement values of buildings in Nepal were obtained from Huizinga et al.<sup>57</sup>,

and disaggregated to different building types based on estimates from Wagenaar et al.<sup>58</sup> These asset-losses were then used to calculate equity-weighted losses using formula 3 and described in detail in Kind et al.<sup>39</sup>

$$EWL_d = L_d \left( \frac{I_d}{I_{\text{mean}}} \right)^{-y} \quad (3)$$

whereby  $EWL_d$  is the equity-weighted loss in district  $d$ ,  $L_d$  is the loss in district  $d$ ,  $I_d$  is the mean income in district  $d$ ,  $I_{\text{mean}}$  is the mean income in the entire study area and  $y$  is the elasticity of marginal utility of income.  $y$  was set to 1.2 based on Kind et al.<sup>39</sup> and income data per district was obtained from the Central Bureau of Statistics<sup>52</sup>.

### Data availability

Data used to generate the risk assessments for Nepal can be downloaded from the Asian Disaster Preparedness Center ([https://www.adpc.net/igo/category/ID276/doc/2013-b271ym-ADPC-NHRA\\_Report.pdf](https://www.adpc.net/igo/category/ID276/doc/2013-b271ym-ADPC-NHRA_Report.pdf)); the shape file for Nepal can be downloaded from the Stanford Digital Repository (<https://purl.stanford.edu/zs816cx6985>).

### Code availability

The code generated for the current study is available in a publicly available code and data repository: <https://doi.org/10.5281/zenodo.8306840><sup>59</sup>. Data preparation and graphing for Figs. 1 and 3 were completed in Python version 3.10.12. These figures can be recreated using these scripts.

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R.S.: supervised, conceptualization, methodology, formal analysis, writing—original draft, writing—review & editing, project administration. D.L.: supervised, conceptualization, methodology, formal analysis, writing—original draft, writing—review & editing. M.K.: formal analysis, writing—original draft, writing—review & editing. D.W.: conceptualization, methodology, formal analysis, visualization. C.L.: formal analysis, visualization. S.J.: formal analysis, writing—review & editing, visualization.

### Competing interests

The authors declare the following competing interests: Following the completion of this study, yet prior to its publication, the first author, R.S., has taken on a consulting role to the World Bank's Global Facility of Disaster Reduction and Recovery on a related project. The other authors have no competing interests to declare.

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