Should All of Nepal Be Treated as Having the Same Earthquake Hazard?

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Abstract Current earthquake hazard maps for Nepal predict substantial variations in hazard within the nation, with noticeable differences between maps. We thus suggest that given present knowledge, all of Nepal may be better regarded as equally hazardous and perhaps vulnerable to much larger earthquakes than those currently known because of their long recurrence times. This proposal is based on the limitations of the historical earthquake record, the recognized deficit in seismic moment release, and GPS data showing a similar level of coupling along the arc. Support for using smoother maps can be had from analysis for Japan, which is also located on and parallel to a subduction boundary, showing that in some ways the hazard maps may be overparameterized, in that including too high a level of detail may lower the maps' ability to predict shaking. Treating Nepal's hazard as uniform and developing mitigation strategies accordingly may help reduce damage in future earthquakes.

Keywords Nepal · Earthquake hazard · Hazard mitigation

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1 Introduction

In February 2016, the Alexander von Humboldt Foundation organized a conference in Kathmandu on the topic of “Living under the threat of earthquakes: Short- and long-term management of earthquake risk and damage prevention in Nepal.” The conference sought to explore “future ways of perceiving risk, prevention of damage, and disaster management in all parts of society, administration, and politics in Nepal.”

Like many nations seriously threatened by earthquakes, Nepal is a developing nation in a seismically active plate boundary zone. It faces a major seismic hazard with severely limited resources available to mitigate it.

The steady subduction of the Indian plate beneath Eurasia has raised the Himalayas, Nepal’s primary asset. However, the subduction gives rise to major earthquakes. The conference occurred almost a year after the April 2015 M_w 7.8 Ghorka earthquake caused nearly 9000 deaths and damaged many buildings, including about 500,000 residences, temples and palaces forming part of a UNESCO World Heritage site, schools, and many public facilities. Damage is estimated at about 1/3 of Nepal’s GDP (Government of Nepal 2015). This enormous impact reflected the fact that Nepal is one of the poorest nations in Asia, with per capita GDP of about $750—derived largely from tourism, agriculture, and remittances from Nepalese working in other countries.

Based on studies prior to and after the Ghorka earthquake (Bilham et al. 2001; Bilham and Ambraseys 2005; Ader et al. 2012; Martin et al. 2015; Hayes et al. 2015), the 2015 earthquake was much smaller and caused much less intense shaking than larger earthquakes that occurred in the past and are expected to occur in the future. Hence existing earthquake hazard maps used to develop construction codes may substantially underestimate the future hazard. Moreover, much of the damage and deaths in 2015 reflected poorly constructed buildings, and similar buildings will perform even more poorly in future larger earthquakes (Goda et al. 2015).

Current earthquake hazard maps for Nepal predict substantial variations in hazard within the nation, with noticeable differences between maps, indicating substantial uncertainty in hazard estimates. This is not surprising given the limitations of the historical record in Nepal and the lack of knowledge of how strain from plate convergence is released in earthquakes. This paper explores the question of whether, given these uncertainties, all of the nation might be better regarded as equally hazardous and perhaps vulnerable to much larger earthquakes than those currently known, with long recurrence times. The paper is not a comprehensive review of data and previous work for Nepal, but merely notes some issues and suggests an approach that we think is worth considering.

2 Current Hazard Maps

Figure 1 shows three hazard maps for Nepal, all of which predict the shaking expected with 10% probability of being exceeded during 50 years, or on average once in 475 years. The predicted hazard varies from west to east, along the subduction zone.

The map predictions differ in both the level of detail and in some specifics. In particular, the GSHAP (1999) and Ram and Guoxin (2013) maps both show the center of the country, near 84°E longitude, the area of Pokhara, Nepal's second largest city, as having lower hazard than areas to the east and west. In contrast, Chaulagain et al. (2015) show this area as having higher hazard than its surroundings.

These differences reflect different choices among the many parameters required to develop a hazard map. Hazard maps require a wide range of assumptions about earthquake source locations, recurrence, and magnitudes, along with models of the resulting ground motion. As has been observed elsewhere, different plausible assumptions about key parameters yield quite different hazard maps (Newman et al. 2001).

Research is ongoing to address these issues. At present, however, given the differences between maps, two approaches could be taken. One is to try to decide which assumptions to prefer, and adopt the resulting map as preferable. Another is

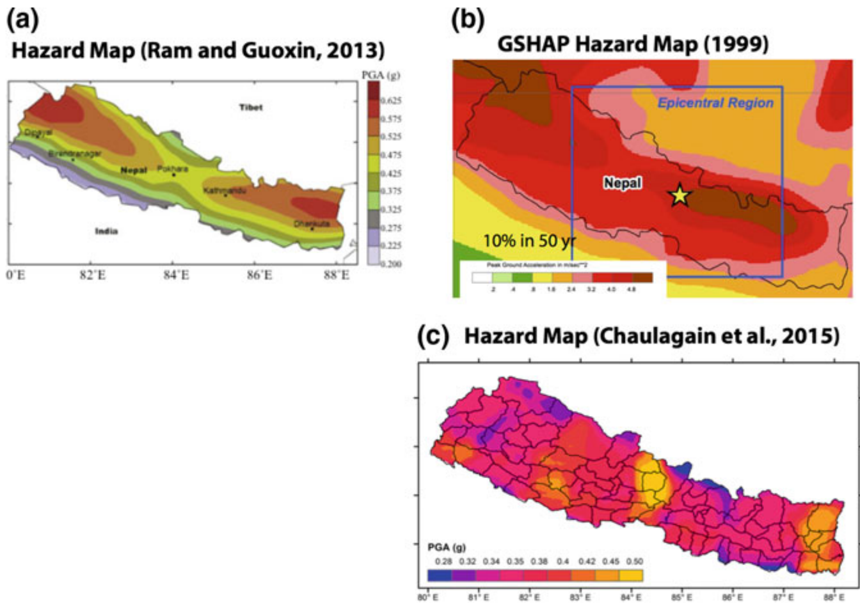

Fig. 1 Three earthquake hazard maps for Nepal: **a** Ram and Guoxin (2013), **b** GSHAP (1999), and **c** Chaulagain et al. (2015) that differ in both the level of detail and in some specifics

to assume that key parameters are sufficiently uncertain that making a smoother map, with less detail, may be more useful for predicting the future earthquake hazard.

The second approach, which we explore here, is to assume that including too high a level of detail to describe past or future earthquakes may lower hazard maps' ability to predict future shaking. As we will see, there is considerable uncertainty in Nepal's earthquake history, and a good case can be made that earthquakes much larger than those assumed in the map development may occur. Hence what is known—or assumed to be known—from previous earthquakes may not completely show what will happen in the future.

3 How Detailed Should Hazard Maps Be?

Because earthquake hazard maps are forecasts, we can get insight from other forecasting applications. Forecasting something involves starting with a conceptual model of the process, implementing it—usually on a computer—to produce a forecast, and then comparing the forecast to what actually happens. Assessing how well this works involves looking at both stages, via operations called verification and validation. Verification asks how well the algorithm used to produce the forecast implements the conceptual model ("have we built the model right?"). Validation asks how well the model forecasts what actually occurs ("have we built the right model?").

Our focus here is on a validation issue: improved maps to forecast future shaking. The classic resolution-stability tradeoff (Parker 1977) tells us that more detailed a model is, the more sensitive it is to uncertainty, and thus the more likely it is to perform worse when assumptions fail. Hence the challenge is to seek an optimal level of detail.

This phenomenon arises in many applications and termed "overfitting" or "overparameterization." For example, given a set of observations at k distinct points in time, one can perfectly fit them with a curve described by k parameters, such as a polynomial of degree $k - 1$. However, a perfect fit to past data need not yield a good forecast—a good fit to future data. Figure 2 shows an example of using a model derived from past data to predict the future evolution of a function. A linear model fits the past data and predicts the future reasonably well, and a quadratic does both even better. However, an 8th order polynomial that fits the past data perfectly does a poor job of predicting the future. The more detailed model seems like it should be better because it matches the past so well, but imposing that level of detail makes the forecast worse.

This situation is common in both geophysical and other forecasting applications. Hence to forecast the future, the goal should be not to build the most detailed model, but instead one that is robust or stable in the sense that small changes in the uncertain model parameters do not dramatically change the model's forecasts (Parker 1977; Box 1979).

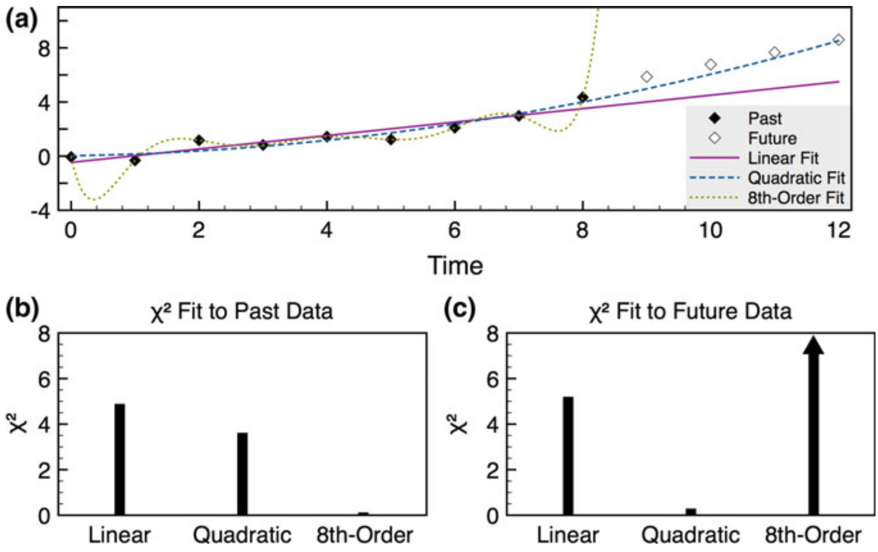

Fig. 2 Example of the effect of overparameterization on forecasting. A high order polynomial fits past data better than linear or quadratic models, but this more detailed model predicts the future worse than the simpler models (Brooks et al. 2016a)

In a hazard map application, one can think conceptually of the past data as containing both a "signal" of a long-term pattern of seismicity and shaking, and additional "noise", where the latter includes both details of past events that will not be repeated and errors due to inaccurate assumptions about what actually occurred. The more detailed a model we make, the more it is influenced by the noise, and, beyond some level of detail, the less likely it is to forecast the future well.

4 Hazard Map Uncertainties for Nepal

The limitations of available data pose limit how accurate an earthquake hazard map can be (e.g., Stein et al. 2012; Stein and Friedrich 2014). For Nepal, at least three issues are crucial:

(1) **The locations and magnitudes of major past earthquakes are not well known**. Figure 3 (Hayes et al. 2015) compares three different scenarios for the rupture length of major historical earthquakes from Kumar et al. (2006, 2010), Mugnier et al. (2013), and Bollinger et al. (2004, 2014). Solid rectangles show the overlap between scenarios, and dashes represent the disagreement between them, which can be taken as a measure of the present uncertainty. In general terms, longer ruptures would have corresponded to larger magnitudes, greater slip, and longer duration and higher intensity of shaking. Similarly, longer

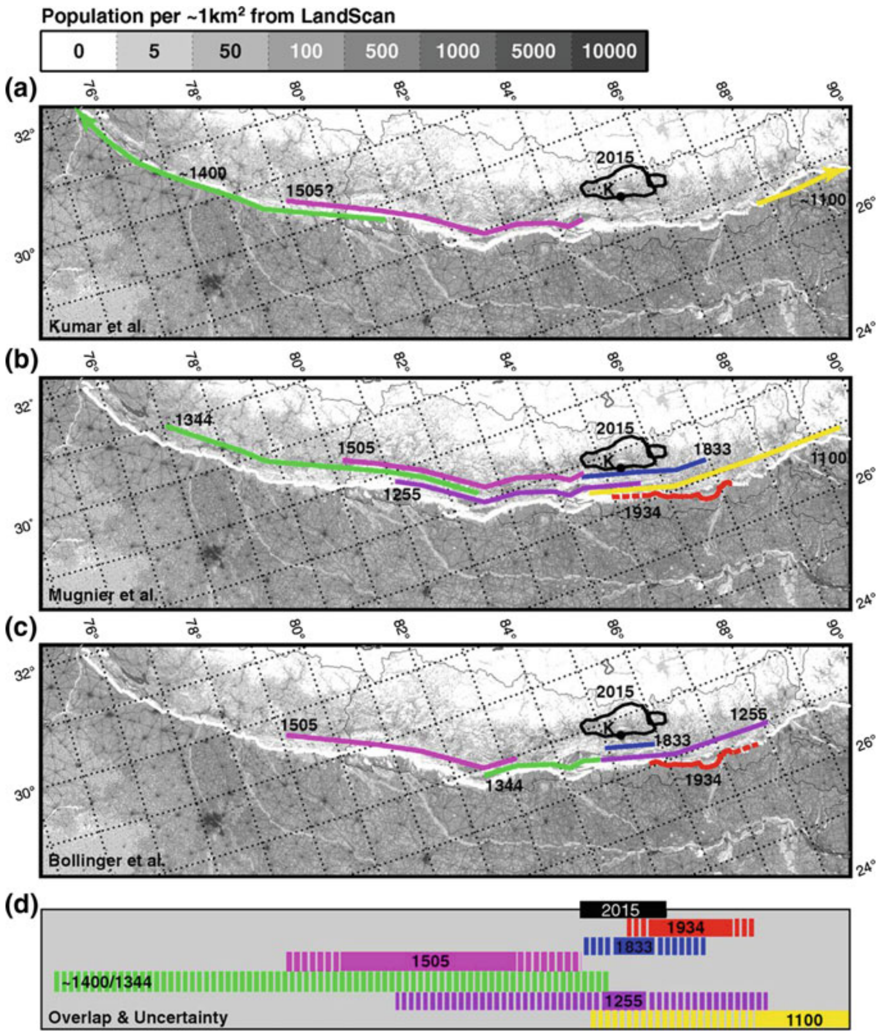

Fig. 3 Source region of the 2015 earthquake (*black polygon*, *K* Kathmandu) compared with published scenarios for rupture in earlier major earthquakes (*colored solid lines*). The back-ground image in shows population density. *Solid lines* show where estimated rupture areas for a given earthquake overlap, dashes represent disagreement (Hayes et al. 2015)

ruptures place more locations closer to the fault, and thus exposed to stronger shaking. For example, the central area west of the 2015 earthquake rupture would have been much more strongly shaken for some scenarios of the 1255 and 1505 earthquakes than for others. Thus the locations and magnitudes of future large earthquakes—and the resulting shaking—are difficult to reliably infer, even if future earthquakes were similar to past ones, which need not be the case.

(2) **A seismic moment deficit suggests that earthquakes much larger than observed in the past few hundred years may occur.** Bilham et al. (2001) noted that the inferred seismic moment release over the past few hundred year is substantially less than would be expected from the geodetically observed convergence rate across the Himalayan front, suggesting a moment release deficit that may be made up in future earthquakes larger than known to date (Fig. 4). This view is supported by subsequent analyses (Bilham and Ambraseys 2005; Ader et al. 2012; Stevens and Avouac 2016) and is being explored by paleoseismic studies that are developing a much longer time series and thus better estimates of long-term seismic slip rates (Kumar et al. 2006, 2010; Mugnier et al. 2013; Bollinger et al. 2014).

(3) **GPS data for Nepal are consistent with future great earthquakes**. These data (Fig. 5) show no significant variation in coupling along the arc, defined as the fraction of plate convergence accumulated as slip deficit. Though compiled before the 2015 earthquake, the area that ruptured in that earthquake does not show stronger coupling. In contrast, at oceanic subduction zones, GPS data show variations in coupling, and stronger coupling often indicates the locations of future large earthquakes (Moreno et al. 2010; Loveless and Meade 2011; Protti et al. 2014). The difference in coupling patterns between Nepal and

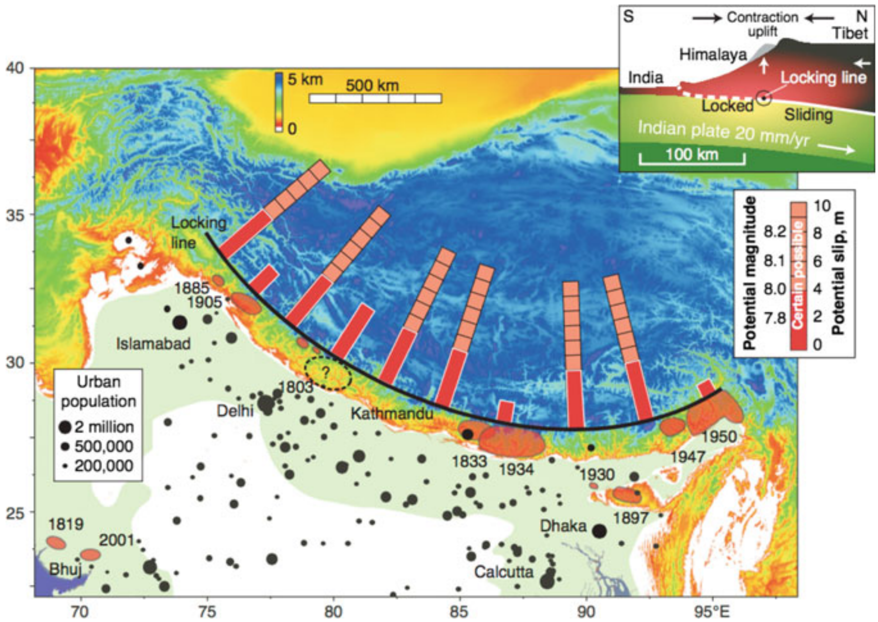

Fig. 4 Estimated potential for slip in future earthquakes along the Himalaya. *Red segments of bars* show the potential slip that accumulated since the last recorded great earthquake, or since 1800. The *pink portions* show possible additional slip permitted by the limited historic record (Bilham et al. 2001)

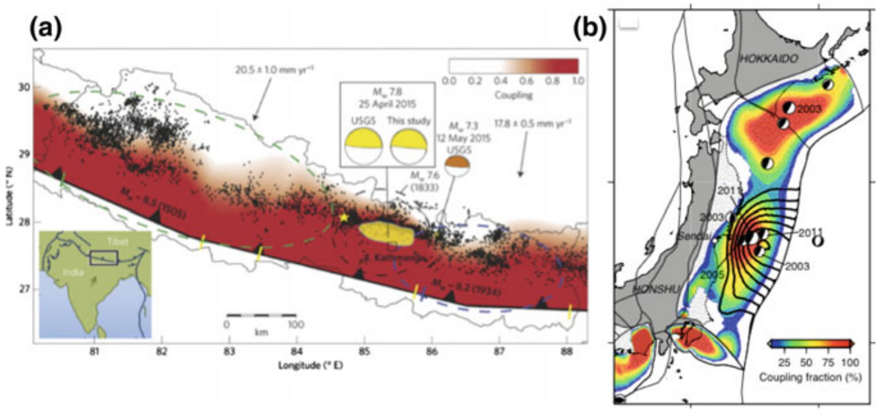

Fig. 5 **a** Coupling fraction across Nepal, showing no significant variation along the arc, including the area of the 2015 earthquake (Avouac et al. 2015) **b** Coupling along northern Japan prior to the March 2011 Tohoku-oki earthquake (*colors*), and coseismic slip in this earthquake (*contours*). The ~400 km-long region estimated to have slipped ≥ 4 m corresponds to an area of the subduction zone interface that was coupled at $\geq 30\%$ of the plate convergence rate, with peak slip near a region coupled $\geq 80\%$ (Loveless and Meade 2011)

oceanic subduction zones could reflect a difference between continental and oceanic subduction, or some aspect of the data and analysis. Alternatively, it might indicate that the entire arc is strongly coupled and could rupture in an earthquake or earthquakes much larger than observed to date, releasing the accumulated moment deficit.

The possibility of much larger earthquakes, which would rupture larger areas along the subduction zone, favors treating the seismic hazard as uniform along the zone, given our limited knowledge. This amounts to saying that because the entire country is in a similar tectonic situation, the hazard might well be viewed as uniform.

5 Insights from Japan

Although the issues just discussed suggest that smoother—possibly uniform—hazard maps may be better for Nepal, we presently lack a long enough record of shaking observations to explore this possibility qualitatively. However, this possibility is also suggested by analyses we conducted for Japan, which is also located on and parallel to a subduction boundary (Fig. 6). For Japan, we have the advantage that a 510-year-long record has been compiled (Miyazawa and Mori 2009), giving the largest known shaking on the Japan Meteorological Agency (JMA) instrumental intensity scale at points within Japan from 1498 to 2007. Hence we compared these observations to both the Japanese national hazard maps and smoother versions of these maps (Brooks et al. 2016a, b).

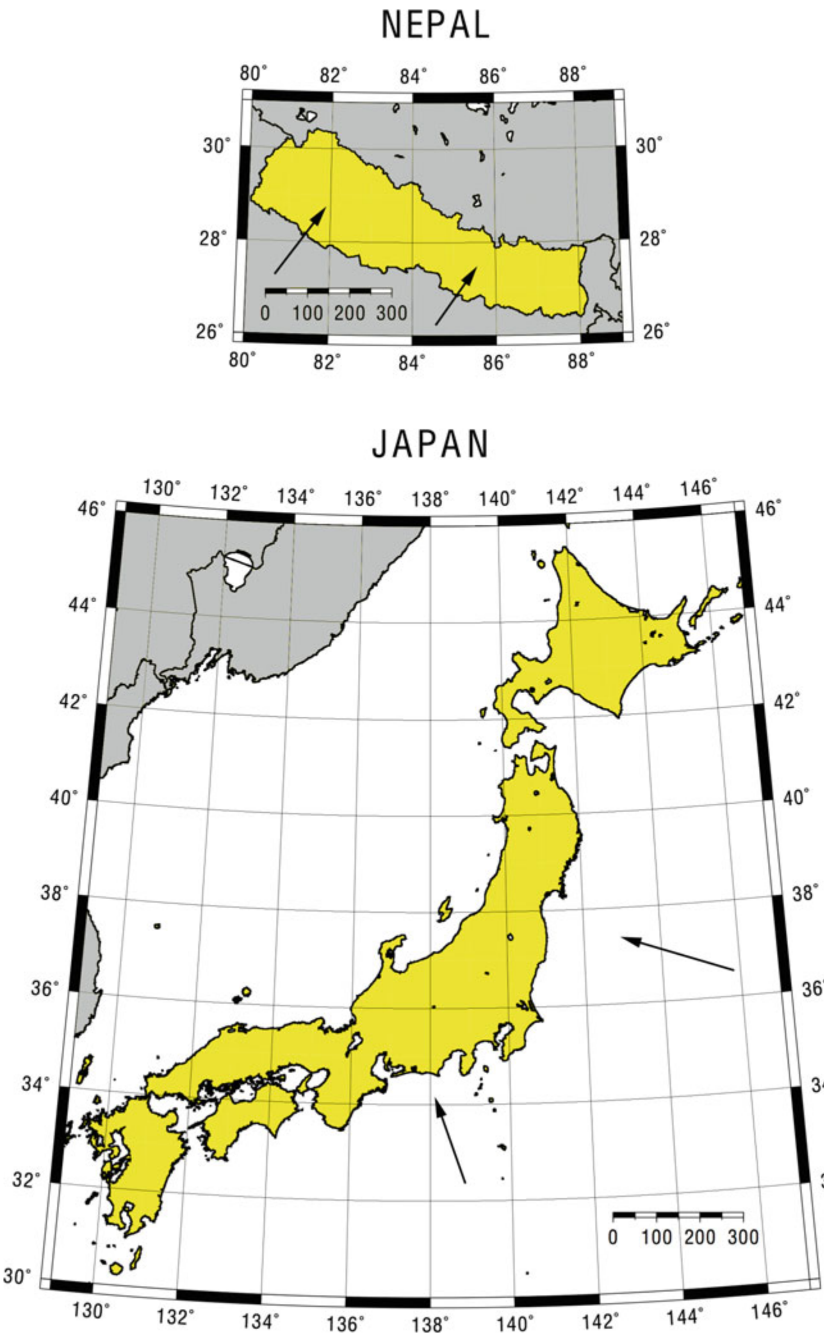

Fig. 6 Comparison of the geometry of Nepal and Japan, both of which are located on and parallel to a subduction boundary, making models of uniform hazard within them worth considering

6 Methodology

Our approach was based on similar issues in weather forecasting. Weather forecasts are routinely evaluated to assess how well their predictions matched what actually occurred. A key part of this assessment is adopting agreed metrics for "good" forecasts, so forecasters can assess how well different forecasts performed. Over the years, this process has improved forecasting methods and results, and yielded much better assessment of uncertainties.

Figure 7 shows an example, comparing the predictions of two models for the probability of rain at some place to the fraction of the time it actually rained. The National Weather Service forecasts are pretty accurate. However, a local television station's forecasts are less accurate, because they predict rain more often than actually occurs. Knowing how a forecast performs is useful: the better it has worked to date, the more we factor it into our daily plans.

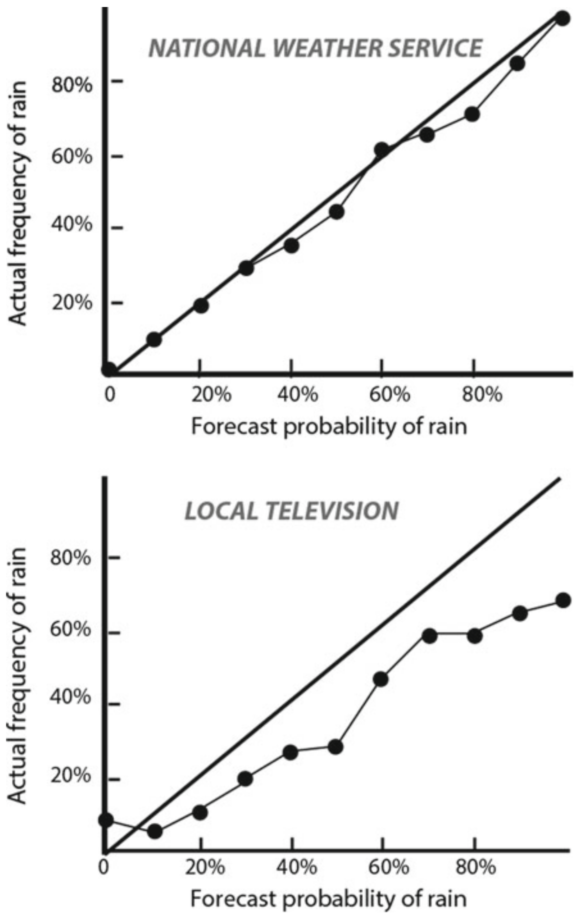

Fig. 7 Comparison of the predicted probability of rain to that actually observed in National Weather Service and a local television station's forecasts (Stein et al. 2015, after Silver 2012)

Similar analysis can be done for earthquake hazard maps, with two differences. One is that rainstorms happen often, so the predicted and observed frequency of rain at one place can be compared directly. However, large earthquakes are infrequent, so most places will not have experienced major shaking. To get around this, we can compare the maximum observed shaking over years of observations at many sites on the map to the predicted shaking at those sites (Ward 1995).

The second difference is that we can use several measures, or metrics, to assess how well a map performed. This is because the predictions of most seismic hazard maps are given in terms of probabilities. Maps are made for a return period of T years, and the value shown at a point on a map is a level of shaking which, during t years of observations, has a probability p of being exceeded once. T, t, and p are related by $p = 1 - \exp(-t/T)$ (Field 2010). This equation (Fig. 8a) shows that a map with a 475-year return period gives the level of shaking that should be exceeded at 10% of the sites in 50 years and at 63% of the sites in 475 years. Plots like Fig. 8b, c shows at which sites shaking exceeded the mapped value, which are the ones above the 45° line along which the observed and predicted shaking are equal.

The most direct way to assess how well a map is doing is using the fractional exceedance metric $M0 = |f - p|$, where p is the predicted fraction of sites where shaking is higher than the mapped value, and f is the actual fraction of such sites. If f is close to p, $M0$ is small, and by this metric the map did well. $M0$ measures how well a probabilistic map does what it's supposed to do. However, this measure doesn't consider the size of the differences between the observed and predicted shaking, which is also important. To see this, consider two different hazard maps.

In Fig. 8b, the predicted and observed fractions p and f are both 10%, so $M0 = 0$ and the map is perfect by this metric. However, many points are far from the 45° line, which is bad. Points far above the 45° line show underpredicted shaking, that would have exposed buildings to major damage. Points far below the 45° line show overpredicted shaking, that would have caused structures to be overdesigned and thus wasted resources. Viewed this way, the map did poorly.

Conversely, in Fig. 8c, the predicted and observed fractions are 10% and 20%, so $M0 = 0.1$, showing that by this metric the map didn't do well. However, most points are close to the 45° line, so the maximum actual shaking generally plots close to that predicted—which is good. The shaking wasn't significantly underpredicted or overpredicted, so in this sense the map did well.

How close points are to the 45° line is described by the squared misfit metric, $M1$, which measures the difference between the predicted and observed shaking, summed over all the sites. The map in Fig. 8b does well as measured by the $M0$ metric and poorly by the $M1$ metric, whereas that in Fig. 8c does poorly by the $M0$ metric and well by $M1$. Each metric measures different aspects of a map's performance. $M1$ measures something the hazard map isn't designed to do, but is like a visual comparison of a hazard map to the shaking that occurred (e.g., Geller 2011).

Using several metrics to measure hazard map performance makes sense. In general, assessing any system's performance involves looking at multiple aspects. This concept is familiar in sports, where players are evaluated in different ways. For

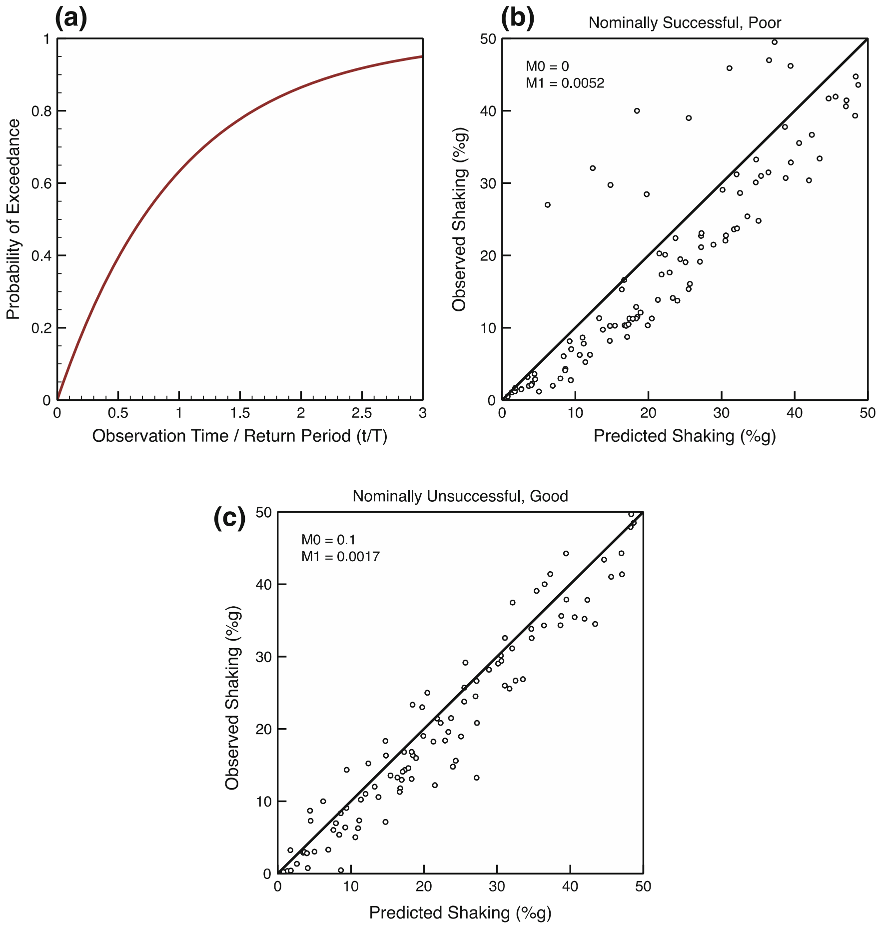

Fig. 8 **a** Assumed probability *p* that during a *t*-year-long observation period, shaking at a site will exceed a value that is expected on average once in a *T*-year return period. **b**–**c** Comparison of the results of two hazard maps. That in **b** is nominally successful as measured by the fractional exceedance metric, but significantly underpredicts the shaking at many sites and overpredicts that at others. That in **c** is nominally unsuccessful as measured by the fractional site exceedance metric, but better predicts the shaking at most sites (Stein et al. 2015)

example, how good a baseball player Babe Ruth was depends on the metric used. In many seasons Ruth led the league in both home runs and in the number of times he struck out. By one metric he did very well, and by another, very poorly. Similarly, a baseball player may be an average hitter, but valuable to a team because he is an outstanding fielder.

The short time period since hazard maps began to be made poses a challenge for assessing how well they work. If, during the 10 years after a 10%-in-50-yrs map was made, large earthquakes produced shaking at 40% of the sites that exceeded the predicted values, the map may not be performing well. However, if no higher shaking occurred at these sites in the subsequent 465 years, the map would be performing as designed. Given this problem, various studies examine how well maps describe past shaking. Although looking backwards in time—hindcasting—is not the same as evaluating a forecast with observations after the forecast was made, it gives useful insight.

7 Results

Using this approach, we compared the 510-year-long record of earthquake shaking to both the Japanese national hazard map (JNH) and smoother versions (Fig. 9). The smoothest version is a uniform hazard map with hazard at all sites set equal to the median of the JNH map. Using the misfit metric $M1$, the JNH map did better than

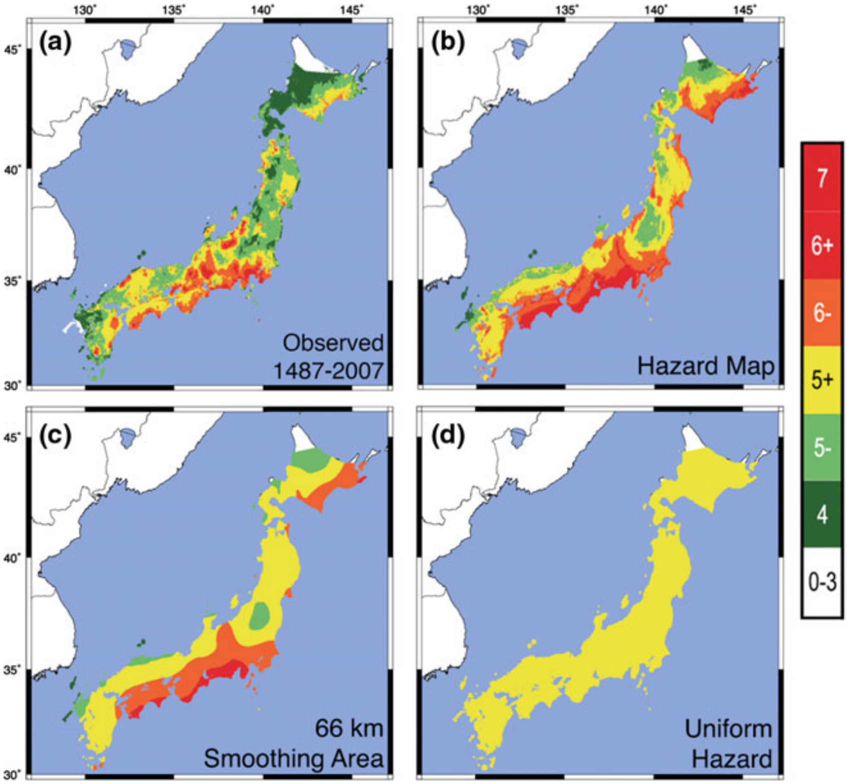

Fig. 9 **a** Map of largest known shaking on the Japan Meteorological Agency intensity scale in 510 years (Miyazawa and Mori 2009). **b** Probabilistic seismic hazard map for 975 year return period (J-SHIS 2015) **c** Smoothed hazard map derived by smoothing **b** over 66-km window (Brooks et al. 2016a). **d** Uniform hazard map derived by smoothing **b** over all of Japan (Brooks et al. 2016b)

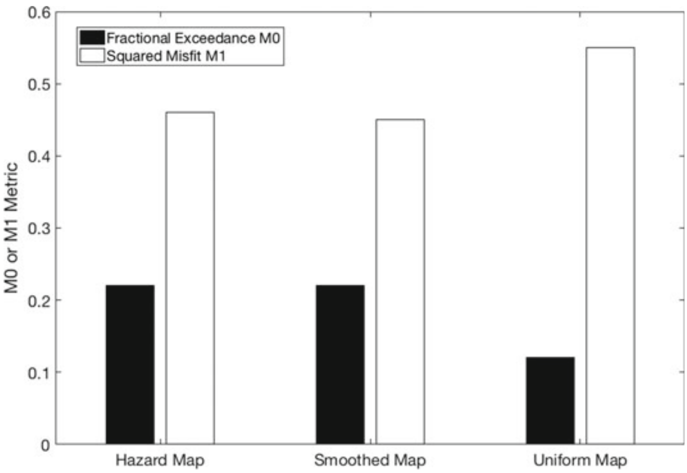

Fig. 10 Performance of the three hazard maps for Japan shown in Fig. 9, as measured by the fractional exceedance metric M0 and squared misfit metric, M1

the uniform map (Fig. 10). This is because *M*1 depends mostly on similar the patterns are in space, which is what we see when we compare two maps. However, as measured by the *M*0 metric, the uniform hazard map did better. This is because *M*0 depends mostly on how similar the average predicted and observed shaking levels are, and it turns out that the maps systematically overpredicted the observed shaking.

The uniform map averages over the whole country, so all the details are lost. An intermediate approach is to smooth the hazard map over different areas, which removes some but not all detail. The fractional exceedance metric *M*0 generally improved as the smoothing area increases, consistent with the observation that smoothing over all of Japan produced uniform maps that performed better than the JNH map as measured by *M*0. As measured by the *M*1 metric, map performance improved somewhat up to about 50–100 km of smoothing and then decreased substantially with further smoothing.

The observation that different maps do better by one metric and worse by another reflects the fact that a map's performance has multiple aspects, and so using several metrics to measure it makes sense. M0 is more sensitive to average shaking levels, whereas M1 is more sensitive to spatial variations. It seems that although the JNH maps are designed to predict shaking levels that should be exceeded at a certain fraction of the sites, the process by which their parameters are chosen tends to make the mapped shaking more closely resemble the maximum observed.

Our point is not that the Japan results would directly apply for Nepal. These results are for a particular area and for a particular set of maps and data. Rather, we think they indicate the value of doing similar analyses for Nepal. For this purpose, a long historical shaking dataset would be very valuable. We suspect that the results would favor smoother maps and—especially for longer return periods—higher hazard levels.

8 Implications for Hazard Mitigation

The goal of hazard maps is to reduce losses in future earthquakes via choosing an appropriate level of hazard mitigation, primarily via earthquake-resistant construction. The total cost of earthquakes to a community is the sum of the expected loss in future disasters and the cost of mitigation. Conceptually, estimating the loss depends on the estimated hazard, because the expected loss is the sum of the loss in individual future earthquakes multiplied assumed probability. A probabilistic hazard map includes this information in the shaking levels it predicts with different probabilities.

The total cost to a community of earthquakes depends on the amount of mitigation, shown schematically by the U-shaped curve in Fig. 11. If a community undertakes no mitigation, it has no mitigation costs (left side of the curve) but will expect high losses—so it makes sense to invest more in mitigation. Increased mitigation should decrease losses, so the curve goes down. Eventually, however, the cost of more mitigation exceeds the reduction in losses, and the curve rises again—the additional resources required would do more good if invested otherwise. The optimum amount of mitigation is the “sweet spot” at the bottom of the curve.

Such graphs are schematic ways to guide our thinking, rather than precisely computed equations, for two major reasons. First, there are large uncertainties in our ability to assess the earthquake hazard—our focus here—and the resulting losses. As shown in Fig. 12, inaccurate hazard and loss (damage) estimates would produce nonoptimal mitigation. Thus it would be unrealistic to claim we can actually find a single optimum strategy. Moreover, even without these uncertainties, mitigation is unlikely to be less than optimal because of limited resources and other societal needs for these resources. This is true even for developed nations, and

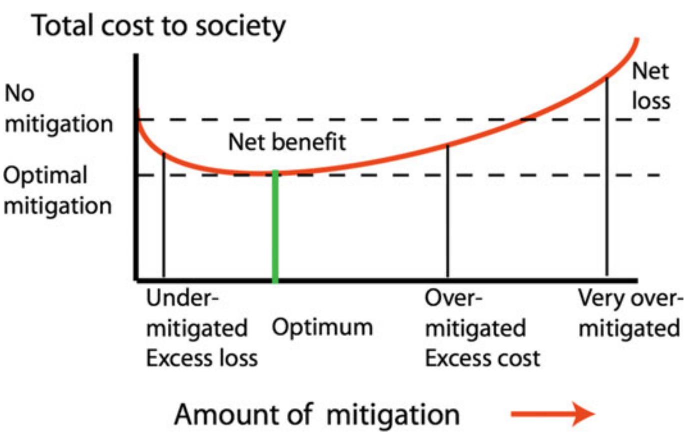

Fig. 11 Curve showing how the total cost to society of earthquakes depends on the amount of mitigation. The optimal mitigation level minimizes the total cost, the sum of the expected loss and the mitigation cost (Stein and Stein 2012)

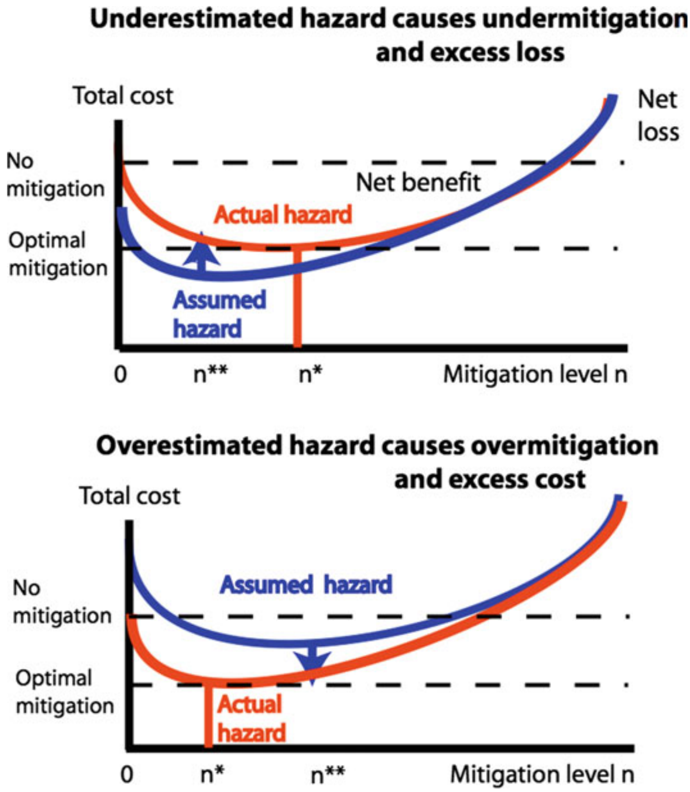

Fig. 12 Comparison of total cost curves for two estimated hazard levels. For each, the optimal mitigation level, $n*$, minimizes the total cost, the sum of expected loss and mitigation cost. If the hazard is assumed to be described by one curve but actually described by the other, the assumed optimal mitigation level causes non-optimal mitigation, and thus excess expected loss or excess mitigation cost (Stein and Stein 2013)

especially the case in developing nations like Nepal. However, so long as the total cost is below the loss for no mitigation, less-than-optimal mitigation is better than none.

9 Conclusions

We suggest that given present knowledge, all of Nepal may be better regarded as equally hazardous and perhaps vulnerable to much larger earthquakes than those currently known, with long recurrence times. It seems worthwhile exploring alternative hazard maps, ideally with a long historical shaking dataset, and using new geological data as they become available. We suspect that the results would favor smoother maps and—especially for longer return periods—higher hazard levels.

Nonetheless, we would not expect any hazard map to perform perfectly. Aspects of future earthquakes may behave differently from past earthquakes, the details of which are only partly known. Some of the assumed details of future earthquake behavior will differ from what actually occurs. Nonetheless, improved maps could help in choosing better mitigation strategies. Hazard maps, like any natural-hazard forecasts, do not need be perfect—or even that good—to be useful in making policy (Stein and Stein 2014; Field 2015). The better they are, the more effectively they can be used.

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