Article title: Integrating tsunami risk assessments in development planning: lessons from Western India

Authors: Richard Bradley[1], Serge Guillas[2], Garima Jain[3], Cassidy Johnson[4], Teja Malladi[5], Julia Wesely[6]

Affiliations: Department of Philosophy, Logic and Scientific Method, The London School of Economics and Political Science.[1], Department of Statistical Science, University College London[2], Indian Institute for Human Settlements[3], The Bartlett Development Planning Unit, University College London[4]

Orcid ids: 0000-0003-2184-7844[1], 0000-0002-3910-3408[2], 0000-0002-6080-6458[4], 0000-0001-7100-4699[5]

Contact e-mail: cassidy.johnson@ucl.ac.uk

Funder: NERC-AHRC-ESRC

DOI: 10.14324/111.444/000026.v1

Preprint first posted online: 17 December 2019

Keywords: tsunami, hazard, risk assessment, development planning, modelling, India, disaster, Environmental science, Environmental policy and practice, Statistics, Sustainable and resilient cities

Integrating tsunami risk assessments in development planning: lessons from Western India

Abstract

A natural, if idealised, picture of the role of risk assessments in planning sees decision-makers drawing on the risk projections provided by natural and social scientific models and fashioning policies or plans that maximise expected benefit relative to this information. In this paper we draw on our study of the use tsunami science in development planning in Western India to identify ways in which this idealised picture fails to reflect important difficulties encountered by both the science and policy domains, including the representation and communication of scientific uncertainty and the management of this uncertainty within the planning system. We highlight aspects of the management of these uncertainties pose pressing problems and make some suggestions as to how they might be resolved.

Key Words: tsunami hazard modeling, uncertainty, development planning, disasters, India.

Introduction

When scientists are able to predict the occurrence of a harmful event, such as the landfall of a tropical storm or eruption of a volcano at some time and place, decision makers can implement the optimal policy available to them relative both to this information and to what they know about the mitigatory effects of the policy. It is rare however that science can predict hazards with certainty, at least at the level of specificity required in order simply to pick the best policy option. Instead it typically offers predictions in the form of estimates, expectations or, more generally, probabilities for relevant event types and potential losses. In such cases optimal policy decisions are those that maximise expected overall benefit relative to the risk information provided by science and policy analysis. In this paper, we will set out an idealised picture of the integration of science into policy in which probabilistic hazard and outcome assessments play a central role. Having done so we will draw on the lessons of a recent project studying the use of tsunami science in disaster planning in Western India to illustrate ways in which this idealised picture fails to reflect important difficulties in integrating tsunami risk assessments into planning, including the representation and communication of scientific uncertainty and the management of this uncertainty within the planning system[i]. Acknowledging the body of literature in relation to uncertainties and hazard risk assessment (for example, Beven et al., 2018), our aim in this paper is to highlight that uncertainties come from all sides, not just from hazard modelling (which is well documented in the literature), but highlighting that there are also uncertainties within the political process of development planning and implementation. We aim to make some tentative suggestions as to how tsunami risks can be integrated into development planning in such circumstances.

1. **An Idealised Model of Science-Based Policy Making**

Let us start with an idealised picture of science-based policy making. Four aspects can be distinguished (see Figure 1 below): scientific modelling and hazard prediction (in blue); vulnerability analysis (in yellow); risk and welfare assessment (in green); and policy modelling, decision making and implementation (in red). At its core is a risk assessment: a specification for the hazard involved of the probability of the various possible impacts it could produce, such as loss of life, damage to property and infrastructure, and other economic losses. To obtain it, information must be drawn from both the (typically natural) scientific analysis of the hazard and the (typically social) scientific analysis of the exposure and vulnerability of the system of interest (a community, for instance) to the hazard. The former aims to provide a probabilistic prediction for relevant hazard event types; for example, the height and velocity of any tsunami wave that might eventuate. The latter brings together information about the state of the system and a model of the impact of the different hazard types on systems in such a state (for example, a loss function for property damage from flooding). Once values have been specified for different possible impacts, a risk assessment can be used to derive a full welfare evaluation of the estimated impact of the hazard.

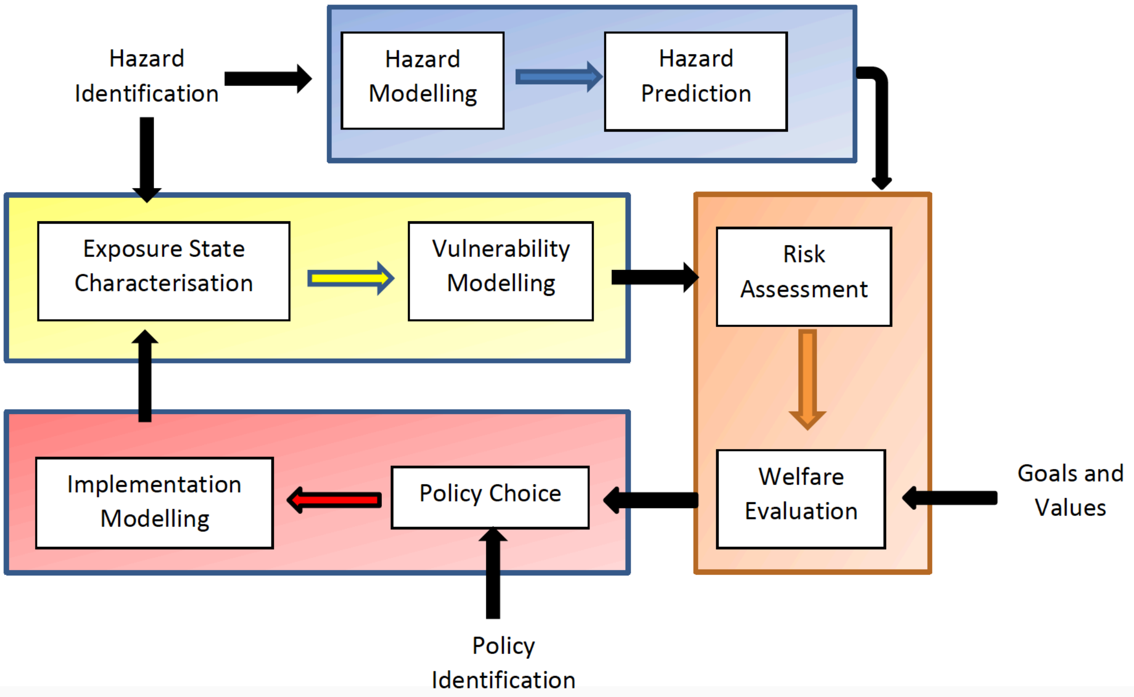

Figure 1: Hazard Mitigation Modelling

Policy decision making requires an evaluation of the kind above for each of the possible policies available to policy makers, and indeed for each policy in relation to interdependencies between different hazards and other needs. For this purpose, a third kind of analysis is necessary, namely of the effect of the implementation of the policy on the exposure of the target system. Here too uncertainty about the effect of a policy can often be captured probabilistically and an expected impact derived for each hazard and policy combination. With all of this in place, policy makers can in principle identify the policies with greatest expected benefit and implement them.

Our study of tsunami inundation hazard on the western coast of India revealed several aspects of this ideal picture to be unrealisable within current practices, including a probabilistic quantification of all uncertainties, a full welfare evaluation of the risks posed by tsunami inundations and a specification of a unified planning response to it. Our focus here will be on problems regarding the management of the various uncertainties at play which for convenience (and following van Asselt & van Bree, 2014 and Saunders et al., 2014) we divide into two main components: those relating to the modelling and prediction of tsunami hazards and their possible impacts, and those relating to the evaluation and implementation of development planning.

2. Scientific Uncertainty

Scientific uncertainty encompasses both hazard prediction and vulnerability analysis, though these two are currently typically conducted using rather different methods. Our purpose here is not to review this large body of literature, but rather to outline the very large uncertainty surrounding policy-relevant probabilistic predictions such as the severity and frequency of hazards and the potential losses and damages that they entail. It is important to recognise that this uncertainty can have a number of different sources. Some of it may derive from poor or sparse data, required to fix both the initial conditions of scientific models and the values of any parameters or indexes occurring in them. Other may derive from uncertainty about the models themselves: whether they correctly identify the main causal variables in target systems and the relationships between them and whether un-modelled factors (known and unknown deficiencies in the physics) have non-negligible effects on real outcomes. Both play a significant role in the assessment of tsunami hazard in the Indian subcontinent.

(a) *Sparse data*

The most recent large tsunami on the Indian subcontinent was in the Indian Ocean (in 2004) and was caused by an earthquake of magnitude 9.2. It occurred off the coast of Sumatra and killed over 10 00 people on the east coast of India and over 200 000 in the region. Although there is historical evidence of severe earthquakes in the Makran subduction zone off the coast of Pakistan and Iran and associated tsunami inundations on the west coast of India in earlier periods, this past knowledge is currently not influencing planning and decision-making (Heidarzaheh et al, 2008). The zone has shown little earthquake activity since a magnitude 8.1 earthquake in 1945 that generated a tsunami whose death toll was around 3000, but scientific studies suggest that the Makran remains capable of producing large-scale earthquakes. Yet little is known about its potential impact on the west coast of India.

While the existence of a tsunami hazard in the region is uncontested, obtaining a precise probabilistic estimate of the inundation risk that it poses and of the potential loss and damage on India and other countries is extremely difficult. One reason for this is the lack of, or gaps in, the data required for hazard and vulnerability assessments, regarding *inter alia* the determination of the location and severity of earthquakes, the propagation of resultant tsunami waves and inundation levels along the coast, and in knowledge of the built environment beyond coarse information gleaned from census data or satellite imagery, of the impact of the inundation on coastal communities and more generally on levels of economic and social welfare and, lastly, the efficacy of mitigatory policies targeting these effects.

Such data scarcity is in fact a structural feature of much natural hazard assessment because the most severe events - the ones that cause the greatest loss and damage in one event - are the least frequent. Earthquakes large enough to cause significant tsunamis are quite rare globally, occurring every decade or so. Tsunami hazard assessments making use of novel statistical approaches to represent fully the range of possible tsunamis (e.g. Guillas et al., 2018 for the U.S.A and Canada's Pacific Northwest region of Cascadia) rely on large amounts of prior investigation of the earthquake source of the tsunami, often unavailable outside developed countries. Regionally specific data is all the more sparse. For instance, there is a lack of high resolution sea floor elevation data (bathymetry) in the public domain. Imprecision in bathymetry results in much enhanced uncertainties in the tsunami heights at the shore (Liu and Guillas, 2017). To properly quantify hazard and subsequent risk, surveys would need to be done at key locations where the exposure is large. As a result, the physical and statistical models used to predict the location and frequency of such events and the vulnerability functions used to calculate losses and damages are calibrated against small data sets and have to be treated with some caution.

There are also numerous obstacles to gathering relevant evidence specific to western India. Accessing fault zones to obtain seismological measurements is often difficult, but for political reasons is particularly so in the case of the Makran subduction zone, as it spans across Pakistan and Iran, which are less open to sharing information. Bathymetric data for the West coast of India is not available at the resolution, and in a format that is most helpful to scientists for use in numerical modelling of the propagation of the wave. The most precise global bathymetry data set, The General Bathymetric Chart of the Oceans, has an insufficient resolution (around 900 m), and navigation charts do not continuously measure swaths of bathymetry, unlike modern multibeam sonars, and are often not carried out around locations of interest for the propagation or focusing of the wave, such as in creeks.

On the vulnerability side, there is limited data regarding informal settlements, which makes accurate vulnerability modelling more difficult in low and middle-income countries, like India for example. Informal settlements house 10-50% of urban dwellers in Indian cities – with typically a larger proportion in larger cities. Many studies show that informal settlements tend to be highly exposed to a range of hazards, including coastal areas exposed to tsunamis, because they are often located in areas declared unsuitable for development. The challenges these settlers face in these locations are often exacerbated by precarious living conditions, such as overcrowded housing and lack of basic infrastructure. The available data for understanding people's exposure and their capacity to respond to tsunamis is sparse. Basic demographic and socio-economic information from censuses, such as the number of people living in a neighbourhood and household, their gender and age, livelihoods and household income is not always reliable and is often aggregated at a ward level making it less helpful for assessments (see Chandramouli, 2014, for details on the India

Census data 2011). There is a myriad of complex reasons for the lack of data on informal settlements, often related to a political interest in keeping the status quo and a lack of clear institutional responsibilities for gathering data about informal dwellers. Roy (2005, 2009) even describes the processes of ‘unmapping’ where a lack statistics and maps provides precisely the flexibility for the state to change land uses, evict, and displace the urban poor.

Prior to the 2004 Indian Ocean tsunami there was a lack of local data on vulnerability to tsunamis in the region, and the consequent unpreparedness is thought to have exponentially increased the number of deaths from the tsunami. Since this event, systems for data gathering and communication of risks have improved. Nonetheless local impacts of tsunamis and other hazards require greater study (Suppasri et al., 2015). For instance, a major report (Byravan et al., 2010) on sea level rise in Tamil Nadu uses GIS and publicly available data to assess vulnerability to this hazard. However, the report calls for more detailed studies covering larger portions of the Indian peninsula and points to a need to incorporate the effects of climate change on sea-level rises. The Government of India’s Guidelines for the management of tsunami’s itself claims that detailed vulnerability studies are required for all areas (Government of India, 2010).

It is worth noting that the lack of data regarding conditions before a disaster can also impact recovery. The lack of local vulnerability data existing before 2004 Indian Ocean tsunami had particularly severe consequences for low-income coastal communities in the aftermath of the disaster. Salagrama (2006) for instance documents how the lack of information regarding the size, quality and location of houses and basic services as well as ownership structures that existed before the tsunami had a defining impact on the outcomes of relocation and in-situ reconstruction programmes.

(b) Modelling uncertainty and scientific disagreement

Data scarcity affects not only the characterisation of hazard types and sources and the specification of exposure and related vulnerability, it also contributes to uncertainty about the reliability of the natural and social scientific models underpinning hazard and vulnerability assessments and to corresponding disagreements within various scientific communities about the level of confidence in scientific projections that is mandated.

In this regard the current state of earthquake science is particularly worth of note, with the field undergoing a period of intense critical self-reflection and several of those working in it questioning the credentials of the probabilistic estimates for earthquake hazards supported by standard models (see for instance Mulargia et al., 2017, Stein et al., 2012, Stark, forthcoming)[ii]. The immediate origins of this critical reflection lie in the poor performance of seismic hazard maps. The fact that the recent Tohoku magnitude 9 earthquake occurred in a low hazard zone has attracted a lot of attention (for obvious reasons: the resulting tsunami killed 19,000 people and caused $200 billion of damage). In fact, all of the earthquakes in Japan since the 1970s causing more than 10 fatalities occurred in low hazard zones (Stein et al., 2012). The explanation for these failures is a matter of fierce debate. As mentioned previously, the underlying difficulty in resolving it is that the largest and most dangerous events occur very infrequently and so it is very difficult to test claims made about them. The recourse most often is to extrapolate from smaller magnitude events, though the theoretical basis for this is quite weak. The Gutenberg-Richter Law (G-R) governing earthquake occurrence is well specified for lower magnitude earthquakes, for instance, but more fundamental energy laws imply that it cannot hold at very high magnitudes. What is unknown is whether there is a maximum magnitude at which it holds or whether the relationship deviates smoothly from that postulated by the G-R law.

The theoretical foundations of probabilistic seismic hazard assessment are also under attack within the field for making assumptions in contradiction to what is known about seismicity and for a poor record in identifying the frequencies and magnitudes of earthquakes in specific locations: see, for instance, Stein et al. (2012) and Mulargia et al. (2017). These authors also question the widespread assumption in statistical modelling of earthquakes that their occurrence is governed by a stationary random process; an assumption that licenses projections based on frequencies of past occurrences. While modelling of this kind is pretty standard in hazard modelling, it is one that is underwritten neither by an accepted physical model, nor by the data. Less fundamentally, but perhaps more important in practical terms, the two most commonly used models in Probabilistic Seismic Hazard Assessment (PSHA) – the characteristic earthquake model and the Poisson process model – are both flawed. The former views earthquake occurrence as a cyclical activity in which elastic forces in a fault segment accumulate and are then released by an earthquake with a magnitude characteristic of that location. The model is at odds with the G-R law and not well supported by the data, though the lack of it makes decisive empirical refutation difficult. But the occurrence of earthquakes such as in Sumatra in 2004 and Tohoku in 2011 which ripped through several fault segments suggests that associating each segment with an upper magnitude of a characteristic earthquake is misleading. As for statistical modelling of seismic activity, this is typically done as a uniform Poisson process despite the fact that it is known that earthquakes are subject to clustering. In particular, Omori's law tells us that there is negative correlation between the magnitude of an earthquake and the time until the occurrence of another one and that the time before the next earthquake is positively correlated with the time since the previous one. No time-independent statistical model matches these correlations; nor for that matter is it consistent with the characteristic earthquake model. To accommodate clustering, fore- and aftershocks are sometimes removed from the data, but since these can be dangerous in their own right, this is hardly ideal.

The upshot of all of this is that, although precise predictions of the frequency and severity of earthquakes are generated by current seismic models, there is disagreement in the scientific community about the degree to which these predictions can be trusted, even for regions for which there is considerable seismic data. The uncertainty that it engenders is compounded by secondary uncertainties in the modelling of both tsunami inundations and of the vulnerability of communities to it. Although these fields display less in the way of fundamental disagreement about the status of basic modelling assumptions, the complexity of the processes being modelled means that the models used to determine the environmental, social and economic impacts of tsunamis inundations must of necessity omit some potential causal factors. This happens either intentionally because they are considered to have negligible or unpredictable effects (the 'known unknowns') or unintentionally because they simpy haven't been thought of (the 'unknown unknowns') Indeed when it comes to vulnerability assessments, one is confronted not so much with different models as a multiplicity of different concepts of vulnerability and ways of measuring it combined with a lack of precise models of how (measured) vulnerability factors relate to different kinds of losses (Løvholt et al., 2014). And while there has been important progress in the identification of tsunami vulnerability factors and development of methodologies for measuring them since the massive 2004 tsunami, there are still no common guidelines that are systematically employed in measuring tsunami vulnerability and choice of measures may be guided by availability of data as much as anything else.

Vulnerability studies for tsunami hazards can be separated into those that focus on the human environment, using social scientific methods, and those that target the built environment, using primarily engineering methods. Several methods for the assessment of both kinds have been developed in the last ten to twenty years and these identify numerous vulnerability factors, including exposure to tsunami waves, the warning capacity, building and infrastructure fragility, evacuation and emergency capacity as well as recovery capacity. The review of Gonzalez-Riancho et al (2015) suggests that while social vulnerability measurements differ amongst studies, they tend to agree on what factors require measurement: (i) human exposure, (ii) reception of warning messages, (iii) understanding of a warning messages, (iv) mobility and evacuation speed, (v) safety of buildings, (vi) difficulties in evacuation related to the built environment, (vii) societies coping capacity (viii) household economic resources, (ix) recovery external support and (x) expected impacts affecting recovery. But how these various vulnerability factors combine with hazard characteristics such as the acceleration, velocity and depth of potential tsunami waves to produce losses of various kinds and especially how physical and social vulnerability factors interact in this process is something for which a precise understanding is still lacking.
The overall situation is thus one of improving scientific understanding of the chain of events leading from earthquake occurrence and the propagation of tsunami waves through to the impacts on communities within their path and considerable residual uncertainty about the nature, scale and timing of these impacts. For the purposes of this paper, the main question is not whether these weaknesses in the scientific modelling of earthquake and tsunami occurrence and of their impacts on lives and livelihoods can be overcome in the medium to long term, but how policy makers should respond to the fact of disagreement and uncertainty within a scientific community about their projections arising from their models. This is an issue we return to below.

3. Uncertainty in the planning domain

Uncertainty regarding policy decision making is not simply a consequence of scientific uncertainty but has its source in a number of additional factors. Here we focus on the uncertainty arising from the process of implementing plans and policies and uncertainty regarding the values or goals that should be steering these choices.

(a) *Implementation Difficulties*

There are two major sources of uncertainty regarding the efficacy of planning instruments such as land use regulation: the fragmentation of the planning process and the fact that much development takes place outside of formal planning processes.

Fragmentation: The responsibility for managing the risks posed by tsunamis is shared by a large variety of agencies differentiated by level – federal, state, municipal, etc., and by domain – disaster response, land planning, port management, nuclear plant safety, etc. In India responsibility for dealing with disasters lies with the National Disaster Management Authority, but mitigation planning falls to a variety of agencies. For example, coastal land use planning is the responsibility of the Ministry of Environment & Forest[iii]. For this reason, familiar issues stemming from the lack of both vertical and horizontal integration in planning are found here. Federal plans require implementation through more detailed planning at state and municipal level for instance. When there is uncertainty about the degree to which this will be done, planners at the state level face a dilemma. Do they plan on the assumption of optimal implementation at the state and municipal level or do they plan on the basis of what they expect will in fact be the level of implementation? A similar dilemma faces the municipal planners when considering what policy instruments to employ in circumstances in which they are unsure as to how individuals will respond to planning decisions. There is little merit for instance in managing land use through a formal system of planning permissions if people simply bypass them.

There is much evidence of these problems in the literature. Evaluating post-disaster recovery after the Indian Ocean tsunami, a report by the UN, World Bank and Asian Development Bank (2007) revealed the fragmentation of reconstruction responsibilities between NGOs and (local) government and attributed to them poor calibration of the speed of the reconstruction projects and financial flows. Fragmentation manifested itself in failures such as housing being reconstructed without basic infrastructure (water, sanitation, electricity and access roads); or projects taking one phase (e.g. the construction) into account, without thought or agreement regarding institutional responsibilities for the other project phases (e.g. maintenance). Some institutional support arrangements were not only fragmented, but largely absent. Although the state provided technical support for large infrastructure problems, there was no adequate support mechanism at village or district level to ensure good quality buildings.

Many authors reflecting on disaster risk management since the Indian Ocean tsunami criticise the notion of a uniform planning agent and call for better networking, collaboration, coordination, integration (or similar terms) to reduce institutional fragmentation. The major advances in tsunami vulnerability modelling since the Indian Ocean tsunami offer great potential for improving planning. However there has so far been little integration of this information into planning (Løvholt et al., 2014). The national guidelines on tsunami management suggest that the weak enforcement and compliance of town planning byelaws, development control regulations and building codes in the coastal areas are one of the critical gaps that remain (Government of India, 2010). During a project workshop in May 2017 in Bangalore, participants emphasized the need for different departments, such as port authorities and fisheries to engage with each other and discuss town-planning schemes.

Informal planning: Municipal planners face a dilemma when considering what policy instruments to employ in circumstances in which they are unsure as to how individuals, companies and other institutions will respond to planning decisions. As mentioned previously, if people simply bypass planning permissions, there is little merit in managing land use through a formal system of planning. Ignoring this uncertainty - for instance by not recognising informally settled areas and insisting on top-down policy making - can lead to poor policy outcomes[iv]. There is considerable evidence of these effects of non-compliance. In Ainuddin et al's (2014) examination of the public perception of the enforcement of building codes in Pakistan, which is highly prone to earthquakes, they found that awareness of the risk and of the building code was very low, and compliance with the regulations hardly existed, rendering the code practically useless. Sheth et al. (2006) note that coastal zone regulation, which requires structures to be at least 500m from the shore, is not complied with in Kerala, despite the announced commitment by governments, something that they argue needs to be recognised in emergency planning[v]. The ineffectiveness of top-down building codes and land use plans can also manifest itself in very slow speed of implementation, which cannot keep up with the actual speed of (informal) urban growth. This problem affects not only private households, but also businesses and public buildings and infrastructure. Implementation uncertainties associated with these top-down approaches are not confined to levels of awareness, but include issues like corruption and generally insufficient compliance and enforcement of laws.

(b) Evaluative Uncertainty

Uncertainty regarding the efficacy of policy instruments filters through to evaluation since decision-makers find it difficult to decide on a particular course of action if they don't know to what extent it will fulfill its objectives and when (within which government period, with what kinds of trade-offs, etc.,). A second source of uncertainty concerns the policy goals themselves. These can be varied: saving lives, avoiding economic damage, protecting the most vulnerable, maximising the welfare of the greatest number, early recovery, etc. And very different policies may be optimal depending which goals are to have priority. For good practical reasons, the work of particular agencies has to be guided by a reasonably concrete and narrow set of goals. Integrated Coastal Zone Management in India, for instance, balances mitigation of the impact of disasters with the promotion of economic development, environmental protection and improvement of the livelihood of coastal communities. These goals often pull in different directions and no framework exists for systematically weighing these goals against each other. In practice, the objectives are not always clearly spelled out in advance of policy decision making.

Planning briefs emphasise the importance of taking a holistic approach to disaster risk management which recognises that disaster impacts, and those of mitigation policies, have to be embedded within a broader planning framework for achievement of wider goals, such as economic development and social equality. A clear policy framework would require consideration of the costs and benefits of designing and implementing a policy now versus transferring the economic and political costs of implementing them to the future, which is particularly challenging for the management of low-probability, high impact events like tsunamis. For example, a strict implementation of the coastal buffer zones would have a detrimental economic effect on the tourism sector, mining and local fisheries and would therefore be a rather unpopular measure. It would likely face strong opposition or be ignored and fail, if it were deployed as a single policy and not accompanied by other measures to, for example, support alternative livelihoods or facilitate transport to the coast.

These issues pale in significance in the face of what is perhaps the most important problem for coherent policy evaluation, the near total absence of systematic evaluations of the welfare impact of policy intervention options let alone more comprehensive assessments that take into account non-welfare considerations. Although sophisticated risk studies for multiple hazards in parts of India have been produced by consultants, there is little evidence of them serving as the basis for policy making or of such analyses being conducted by, or for, planning authorities. For instance, consultants for UNDP recently (2014) compiled a risk and vulnerability analysis for Visakhaptnam in Andhra Pradesh (a good example of what should be done). However, although it led to other such reports being prepared for other cities, there is little evidence that this document has been integrated into local planning. As for welfare assessments of the consequences of policy interventions (or lack of them), they are simply not done at all in any kind of systematic way. In other words, policy is made in the absence of any attempt to estimate the aggregate impact on human welfare of disasters or of the possible actions aimed at mitigating these impacts.

4. Integrating tsunami risk assessments in development planning: Lessons

The conclusion of our examination of the use of science in tsunami planning in India is that in practice the integration of science within policy making falls far short of the ideal picture that we sketched out at the beginning. It is doubtful that the explanation for this lies in the particular features of the region or type of natural hazard under consideration. Given this, the question that must be posed is whether the ideal picture should be abandoned, or significantly modified, in the face of these 'realities' or whether it should continue to serve as a model to guide reform of planning systems and the integration of science within them. We suggest a bit of both. In conditions of severe scientific uncertainty regarding hazard and risk projections, both what scientists communicate and how scientific information is integrated into policy will need to be reconsidered. On the other hand, the basic constituents of the ideal picture – policy analysis based on probabilistic hazard and risk assessment and comprehensive welfare evaluations of policies – will remain important and should continue to serve as a model. The concluding section develops these claims and their implications and makes some recommendations, providing examples from practices in other contexts.

On the ideal picture, to pursue optimal policies in the face of natural hazards policy makers need to know what the effect is of implementing these policies. For this they need probabilistic estimates of hazard frequencies and severities and of the impact on lives and livelihoods of catastrophic events, which in turn requires knowledge of the vulnerability of the system to such events. In our and similar studies the requisite probabilistic estimates for tsunami inundation are obtained by modelling its seismic sources and the subsequent propagation of tsunami waves. But these estimates are highly uncertain because (i) the earthquake science on which the source modelling is based is contested, (ii) sparsity of data makes the calibration of model parameters difficult and (iii) the models idealise in important ways. Similarly, even given reliable probabilistic characterisations of the hazard, the medium to long term impact of hazard event types on social and economic systems is very difficult to gauge, in part because it depends on how people respond to them and in part because of the sparsity of data concerning the exposure state. No doubt scientific work will reduce many of these uncertainties over time, but important decisions will have to be taken in the meantime.

This has a number of important implications for the integration of hazards and risk modelling into planning. Firstly, it is crucial that the uncertainty surrounding scientific predictions be adequately communicated both to decision makers and to those exposed to the hazards. This is often not done in anything other than informal terms, a fact that carries significant dangers. In particular, there is a risk that policy makers will draw on these predictions as if they are ‘certain’ and that, as a consequence, they and the public have more confidence in the measures based on them than is appropriate. This can have tragic consequences: many of the coastal areas struck by the tsunami caused by the 2011 Tohoku magnitude 9 earthquake were protected by seawalls designed for magnitude 7.5 or 8 earthquakes, for instance, which hazard maps of the time indicated to be the largest that could be expected in these areas. The confidence that officials and residents had in these sea defences played a role in the failure to evacuate in time. A similar failure of science-based policy was also a factor in the 2011 disaster in Japan when a tsunami caused the breakdown of the Fukushima nuclear plant (Mochizuki and Komendantova, 2017).

The failure to fully assess and communicate scientific uncertainties also carries a longer-term risk of loss of confidence in science itself, in reaction to the effects of poor science-based policy making. Indeed, expressions of scepticism about the scientific claims purportedly underpinning policy proposals is now common place in political discourse. To address it, it is not sufficient to simply enumerate uncertainties; their implications for the success of policy initiative also needs to be explained so as to avoid both overreactions to risk and its opposite, complacency deriving from the failure of the risks materialise in the past.

> *Example*: The GITEWS-TEW project (Spahn et al., 2010) suggests that, in preparing for emergency situations, uncertainties regarding tsunami hazards be openly communicated to those who are vulnerable to them. This involves education and awareness raising initiatives to explain how analyses are made and how much valuable time it costs to achieve certainty about a potential upcoming tsunami (time that could be spent evacuating the affected site). While repetitive false alarms might result in people taking them less seriously (and hence not evacuating), understanding why ‘false alarms’ come about counter-acts this and helps to maintain trust in official warning services.

Secondly, there is a need for methods and institutions that support policy decision making by helping policy makers to understand scientific uncertainty and its implications, by providing technical support and putting scientific findings into context. In the case of natural hazards, support needs to extend beyond analysis of the risks that they generate, to the expected impact of any policy responses and to the uncertainties around this impact. Ideally such support should be based on a measure of scientific (un)certainty that reflects the weight of evidence underpinning policy-relevant projections and which determines the level of confidence policy makers should have in the decisions based on them (see below).

> *Example:* The UK Scientific Advisory Group for Emergencies (SAGE) draws members from science, industry and government in accordance with the type of emergency. Once a Cabinet Office Briefing Room has been installed for response and/or recovery, SAGE can be activated to provide analysis, assessments, evaluations or expert opinion on an evolving situation and its plausible implications, policy options and their pros and cons. Experts from natural and social sciences ideally draw upon pre-established advice, but even in situations that are new and unexpected, the imperative is to highlight the known risks, uncertainties, and debates in the field, often in the form of scenario or policy option papers.

Thirdly, decision tools need to be developed that allow decision makers to calibrate their choice of actions to the degree of uncertainty surrounding policy-relevant predictions. There is a growing literature on decision making under conditions of severe uncertainty that is potentially of help here, but as yet applications to natural hazards are sparse. A full survey of this literature is beyond the scope of this paper, but it is worth at least noting that two commonly expressed, if extreme, views seem inadequate[vi]. The first is that the rule of maximisation of expected benefit is the only normatively sound decision rule and hence that scientists simply must do their best to quantify the uncertainties probabilistically, however difficult this might be. The second is to say that in conditions of severe scientific uncertainty policy makers should make no use of probabilistic predictions at all, but should base their decisions on analyses of possible scenarios, perhaps by seeking to protect social and economic systems against the worst-case scenario. Both these views squander scientific information. The first does so by ignoring the differences in confidence that scientist have in predictions that are based on agreed scientific theory concerning events for which data is plentiful from those of the kind examined in this paper. The second by refusing to use probabilistic projections even if they incorporate the best scientific judgement available, simply because these judgements are not certain.

Improved decision rules seeking to avoid these extremes will need to draw on methods for assessing the state of scientific understanding and which can be used to inform the confidence judgements allowing discrimination between situations in which precise probabilistic projections can be relied upon and those in which they cannot (Bradley et al, 2017).

> *Example*: Assessment Reports produced by the Intergovernmental Panel on Climate Change periodically summarize the present state of knowledge about climate change, its impacts, and the prospects for mitigation and adaptation. These reports implement an innovative approach to characterizing and communicating scientific uncertainty, involving reporting both probabilities for events and a qualitative notion of confidence, the latter required to convey a qualitative judgement about the level of evidence and scientific understanding that backs up a given finding (Mastandrea et al, 2010).

Let us turn finally to the evaluative inputs to planning and policy making. On the ideal picture sketched at the outset, policy making that responds to natural hazards will be based on a full welfare evaluation of all potential mitigatory actions, informed by a risk assessment that recognises both the range of hazards and the trade-offs between mitigation of these hazards and pursuit of other development goals. We observed that this is rarely, if ever, done in response to tsunami hazard. But without these kinds of assessments, resources devoted to the improvement of the scientific understanding of natural hazards will not necessarily lead to improvement in social and economic prospects. Indeed, it will be hard even to say whether such improvements have been obtained or not and whether more might have been achieved by pursuit of alternative policies.

Integrated assessment is currently only widely used in one area of environmental policy; in the assessment of climate change and potential mitigatory and adaptive policies. But there is no reason (other than cost) why such assessments should not be conducted in support of policy response to natural hazards. It must be recognised, of course, that everything we have said about scientific uncertainty will carry through to welfare assessments. Additional uncertainties arise, as we noted earlier, from the fragmentation of the political and planning systems and the difficulty of anticipating how actors outside the formal system will respond to policies. If policy making is to be sensitive to implementation uncertainties the image of the 'unified planning agent' assumed in standard planning approaches must be dispensed with. Failure to do so can lead to false confidence in the efficacy of policy interventions and a loss of public confidence in public authorities when unintended negative consequences of the policies arise.

There are recognised ways of addressing such problems, such as more holistic planning methods that set agencies local goals that cohere with an integrated strategy for managing disasters that in turn is embedded in broader development planning (although few states are able to achieve this ideal). It is also possible to model people's responses to policy initiatives and draw on this information in assessing different policy options. But measures taken to reduce policy implementation uncertainty, like those taken to reduce scientific uncertainty need to be coupled with a recognition that the problem is not going to disappear any time soon and that methods of policy evaluation sensitive to such uncertainty still need to be developed.

Funding Information: Research for this paper was supported by a cross-council NERC-AHRC-ESRC grant (NE/P016367/1).

References

Ainuddin, S., Kumar Routray, J., & Ainuddin, S. (2014). People's risk perception in earthquake prone Quetta city of Baluchistan. *International Journal of Disaster Risk Reduction, 7*(C), 165-175.

Arputham, J. (2008). Developing new approaches for people-centred development. *Environment and Urbanization*, *20*(2), 319–337.

Baud, I., Pfeffer, K., Kuffer, M., Sliuzas, R., & Karuppannan, S. (2010). Understanding heterogeneity in metropolitan india: The added value of remote sensing data for analyzing sub-standard residential areas. *International Journal of Applied Earth Observation and Geoinformation,12*(5), 359-374. 14

Beven, K J, Aspinall, W P, Bates, P D, Borgomeo, E, Goda, K, Hall, J W, Page, T, Phillips, J C, Simpson, M, Smith ,P J, Wagener, T and Watson, M. (2018) Epistemic uncertainties and natural hazard risk assessment – Part 2: What should constitute good practice?, *Natural Hazards and Earth System Science*, 18(10): 2769-2783, https://doi.org/10.5194/nhess-18-2769-2018

Bradley, R., C. Helgeson, and B. Hill (2017). Climate change assessments: Confidence, probability, and decision. *Philosophy of Science* 84 (3), 500–522.

Bradley, R. (2017). *Decision Theory with a Human Face*. Cambridge University Press

Byravan, S., Rajan, S.C., & Rangarajan, R. (2010). Sea Level Rise: Impact on Major Infrastructure, Land and Ecosystems Along the Tamil Nadu Coast.
Chandramouli, C. (2011). *Census of India 2011. Provisional Population Totals*. New Delhi.
Gilboa, I. and M. Marinacci (2011). Ambiguity and the Bayesian paradigm. In *Advances in economics and econometrics,* tenth world congress, Volume 1.
Gopinathan, V., Roy, R., Guillas, S. & Dias, F. (2017). Uncertainties in the 2004 Sumatra-Andaman source through nonlinear stochastic inversion of tsunami waves. *Proceedings. Mathematical, Physical, and Engineering Sciences, 473*(2205), 20170353.

Guillas, S., Sarri, A., Day S.J., Liu, X., Dias, F. (2018). Functional emulation of high resolution tsunami modelling over Cascadia, *Annals of Applied Statistics*, *12* (4), 2023--2053. doi:10.1214/18-AOAS1142.

Gonzalez-Riancho, P., Aliaga B., Hettiarachchi S., Gonza´lez M., and Medina, R. (2015). A contribution to the selection of tsunami human vulnerability indicators: conclusions from tsunami impacts in Sri Lanka and Thailand (2004), Samoa (2009), Chile (2010) and Japan (2011). *Nat. Hazards Earth Systems Sciences*, 15, 1493–1514.

Heidarzadeh, M., Pirooz, M. D., Zaker, N. H., Yalciner, A. C., Mokhtari, M., & Esmaeily, A. (2008). Historical tsunami in the Makran Subduction Zone off the southern coasts of Iran and Pakistan and results of numerical modeling. *Ocean Engineering*, *35*(8-9), 774-786.

Liu, X., Guillas, S. (2017). Dimension reduction for Gaussian process emulation: an application to the influence of bathymetry on tsunami heights. *SIAM/ASA Journal on Uncertainty Quantification*, 5(1), 787-812.

Løvholt F., Setiadi, N.J., Birkmann, J., Harbitz, C.B., Bach, C., Fernando, N., Kaiser, G., Nadim, F. (2014) Tsunami risk reduction – _are we better prepared today than in 2004? I*nternational Journal of Disaster Risk Reduction, 10*(A), 127–142. http://dx.doi.org/10.1016/j.ijdrr.2014.07.008

Mastrandrea, M. D., C. B. Field, T. F. Stocker, O. Edenhofer, K. L. Ebi, D. J. Frame, H. Held, E. Kriegler, K. J. Mach, P. R. Matschoss, G.-K. Plattner, G. W. Yohe, and F. W. . . Zwiers (2010). Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. Technical report, Intergovernmental Panel on Climate Change (IPCC).

Mitlin, D. (2014). Politics, Informality and Clientelism – _Exploring a pro-Poor Urban Politics. 34. ESID Working Paper. Manchester.

Mochizuki, J., & Komendantova, N. (2017). In Search of Perfect Foresight? Policy Bias, Management of Unknowns, and What Has Changed in Science Policy Since the Tohoku Disaster. *Risk Analysis*, *37*(2), 219–230.

Mulargia, F., Stark, P. B., & Geller, R. J. (2017). Why is probabilistic seismic hazard analysis (PSHA) still used?. *Physics of the Earth and Planetary Interiors*, *264*, 63-75.
Government of India (2010). National Disaster Management Guidelines: Management of Tsunamis, August 2010, New Delhi. 15

Osuteye, E., Johnson, C. & Brown, D., (2017). The Data Gap: An analysis of data availability on disaster losses in sub-Saharan African Cities, *International Journal of Disaster Risk Reduction*, *26*, 24-33
Patel, S., Baptist, C., & D'Cruz, C. (2012). Knowledge is power -informal communities assert their right to the city through SDI and community-led enumerations. *Environment and Urbanization*, *24*(1), 13–26.

Roy, A. (2005). Urban Informality: Toward an Epistemology of Planning. *Journal of the American Planning Association*, *71*(2), 147–158.

Roy, A. (2009). Why India cannot plan its cities: Informality, insurgence and the idiom of urbanization. *Planning Theory*, *8*(1), 76–87.

Salagrama, V. (2006). *Post-tsunami rehabilitation of fishing communities and fisheries livelihoods in Tamil Nadu, Kerala and Andhra Pradesh*. Report prepared for the International Collective in Support of Fishworkers, Kakinada.

Saunders, W. S. A., Prasetya, G., Leonard, G. S., & Beban, J. G. (2014). A Methodology for Integrating Tsunami Inundation Modelling into Land Use Planning in New Zealand. *Planning Practice & Research*, *7459*, 1–18. http://doi.org/10.1080/02697459.2014.987441
Sheth, A., Sanyal, S., Jaiswal, A., & Gandhi, P. (2006). Effects of the December 2004 Indian Ocean tsunami on the Indian mainland. *Earthquake Spectra*, *22*(3), 435-473. http://doi.org/10.1193/1.2208562

Spahn, H., Hoppe, M., Vidiarina, H. D., & Usdianto, B. (2010). Experience from three years of local capacity development for tsunami early warning in Indonesia: challenges, lessons and the way ahead. *Natural Hazards and Earth System Sciences*, *10*, 1411–1429.

Stark, P. B. (forthcoming). Pay No Attention to the Model Behind the Curtain. In: Saltelli, A & Guimaraes Pereira, A. (eds): Significant digits: responsible use of quantitive information.

Stein, S., Geller, R. J., & Liu, M. (2012). Why earthquake hazard maps often fail and what to do about it. *Tectonophysics*, *562–563*, 1–25.

Sudmeier-Rieux et al., (2015). Opportunities, incentives and challenges to risk sensitive land use planning: Lessons from Nepal, Spain and Vietnam. *International Journal of Disaster Risk Reduction*, *14*, 205–224.

Suppasri, A., Goto, K. ,Muhari, A., Ranasinghe, P., Riyaz, M., Affan, M., Mas, E., Yasuda, M. & Imamura, F. (2015). A Decade After the 2004 Indian Ocean Tsunami: The Progress in Disaster Preparedness and Future Challenges in Indonesia, Sri Lanka, Thailand and the Maldives. *Pure and Applied Geophysics*, *72*(12), 313–334.

United Nations, World Bank, & Asian Development Bank. (2007). *Tsunami affected region. India- Two Years after*. United Nations Development Program (2014). "Hazard, risk and vulnerability: analysis (HRVA), City of Visakhapatnam, Andhra Pradesh," draft report available at http://www.gvmcdm.org/data0/RMSI_draft.pdf

van Asselt, M. B. A., & van Bree, L. (2011). Uncertainty, precaution and risk governance. *Journal of Risk Research*, *14*(4), 401–408.

---

[i] This project, entitled *Tsunami Risk for the Western Indian Ocean: Steps towards the Integration of Science into Policy and Practice* and funded by three UK research councils, included statisticians, geophysical scientists, urban planners and a philosopher. This interdisciplinary project team conducted field work and scientific modelling and facilitated a stakeholder workshop in Bangalore in May 2017 which drew experts from local and national authorities in charge of hazard planning at various locations over the Indian coastline.

[ii] The definition of tsunamigenic earthquakes characteristics is also undergoing some questioning, with the inversion of past events showcasing a lack of coherence in the values of the parameters describing the intensities of the generation (Gopinathan et al., 2017).

[iii] The complexity of this is outlined in the National Disaster Management Authority's "Guidelines for the Management of tsunami's" (2010) which indicates that the main stakeholders in tsunami risk management are the Ministry of Earth Sciences, and the Department of Science and Technology and its scientific and technical institutions like Indian Meteorological Department, Indian National Centre for Ocean Information Services, National Institute for Ocean Technology, Integrated Coastal Area and Marine Management Directorate, Centre for Earth Science Studies, etc. involved in establishing and operating India's Tsunami Early Warning System, tsunami modelling, paleo-tsunami studies, and coastal zone land use planning. It also identifies other major stakeholders involved in coastal zone land use planning, vulnerability reduction, immediate response, rescue and recovery including the Ministry of Environment & Forests, Ministry of Urban Development, Ministry of Housing and Urban Poverty Alleviation, Ministry of Information and Broadcasting, Ministry of Panchayati Raj, Ministry of Rural Development; State Governments and Union Territory Administrations along the coast and the islands; coastal development authorities, coastal municipalities and panchayati raj institutions, Indian Navy, the Coast Guards, NGOs and the corporate sector.

[iv] Roy (2009), for instance, argues that *"planning of Indian cities cannot be understood as the forecasting and management of growth. Instead, urban planning in India has to be understood as the management of resources, particularly land, through dynamic processes of informality." (p. 80)*

[v] A similar point was made in the project workshop in May 2017 by a State Officer from the Kerala Disaster Management Authority, who told us that 27 multiple-cyclone shelters had been set up at the coast, and two state-wide mock-drills were performed in 2011 and 2016 to assess preparedness in recognition of the fact of continued habitation of these areas.

[vi] For surveys, see Gilboa and Marinacci (2011) and Bradley (2017