In search of perfect foresight? –policy bias, management of unknowns and what has changed in science-policy since the Tohoku Disaster

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ABSTRACT

The failure to foresee the catastrophic earthquakes, tsunamis and nuclear accident of 2011, has been perceived by many in Japan as a fundamental shortcoming of modern disaster risk science. Hampered by a variety of cognitive and institutional biases, the conventional disaster risk management planning based on the 'known risks' led to the cascading failures of the interlinked disaster risk management (DRM) apparatus. This realization led to a major rethinking in the use of science for policy and the incorporations of lessons learned in the country's new disaster risk management policy. This study reviews publically available documents on expert committee discussions and scientific articles to identify what continuities and changes have been made in the use of scientific knowledge in Japanese risk management. In general, the prior influence of cognitive bias (e.g. over-reliance on documented hazard risks) has been largely recognized, and increased attention is now being paid to the incorporation of less documented but known risks. This has led to upward adjustments in estimated damages from future risks and recognition of the need for further strengthening of DRM policy. At the same time, there remains significant continuity in the way scientific knowledge is perceived to provide sufficient and justifiable grounds for the development and implementation of disaster risk management policy. The emphasis on 'evidence-based policy' in earthquake and tsunami risk reduction measures continues, despite the critical reflections of a group of scientists who advocate for a major rethinking of the country's science-policy institution, respecting the limitations of the current state-of-science.

Keywords: Science-policy interface; catastrophe risk management; uncertainty

1. INTRODUCTION

Global discourse on disaster risk management (DRM) increasingly emphasizes the importance of using science to inform policy formulation and implementation. The need for 'usable and useful' science is increasingly being emphasized in which solution-driven research is increasingly being called upon to inform disaster risk reduction.[1-4] More scientific knowledge and public awareness of scientific facts are generally assumed to help build safer communities. The technological solutions such as improved early warning systems, better building construction, and probabilistic risk assessments are promoted as means to achieve disaster risk reduction.[5] Given that scientific knowledge is built on testing theory through empirical observations and controlled experiments, it is generally expected that more science would contribute to the reduction in reducible uncertainty (i.e. epistemic uncertainty) and will lead to better understanding of known risks.[6]

The same, however, may not necessarily apply to irreducible uncertainty (i.e. aleatory uncertainty). Regardless of how advanced science may be, there is always a chance that the nature will surprise us with what Nassim Taleb called the 'Black Swan'—an extremely rare and never-before-seen event that cannot be anticipated with existing knowledge.[7] Moreover, continued failure to provide sufficient warnings for earthquakes suggests that the scientific knowledge in this area is hardly complete.[8-10] Despite the fact that practitioners and regulators demand clear and definite policy guidance to manage hazard risks,[11,12] there will always be a limit to our science, and therefore uncertainty will remain.[1]

[1] There are divergent views as to what is meant by terms such as uncertainty and unknowns. In this study, we adopt the distinction put forth by Walker et al. .[62] in which the notion of unknown or Black Swan is considered to represent the highest level of uncertainty found at the end of spectrum between complete certainty and total ignorance. Of course, such a distinction inevitably involves value judgements regarding what may be considered a satisfactory level of prior knowledge. A concept, such as for a society to 'foresee' an event, may therefore be thought of having a level of prior knowledge (and policy actions taken) deemed satisfactory in the eye of stakeholders involved.

At the first glance, the triple disasters of earthquake, tsunamis and nuclear accident appeared to be the epitome of such a Black Swan. Very few scientists or practitioners anticipated that multiple ruptures would cause a magnitude 9 earthquake off the coast of Tohoku, or that subsequent tsunamis would engulf the coast and paralyze the country's nuclear plant. These unprecedented events thus appeared to represent a defeat for science: the Headquarters for Earthquake Research Promotion had planned for an earthquake of magnitude 7.5 off the coast of Miyagi, based on an estimate of hazard that was some 150 times smaller than what actually took place.(13) On close examination, moreover, evidence began to emerge that a series of cognitive and institutional barriers led to the dismissal of other 'known' risks.(10,14,15) This led to the formation of an inquiry process in which investigatory scientific committees were formed to delve into the causes for failures in the science, and to consider major revisions in the country's DRM policy.

By reviewing publically available documents from these expert inquiry discussions and peer-reviewed scientific research, this study identifies what continuities and changes have been observed in the use of scientific knowledge in post-Tohoku earthquake and tsunami risk management. In particular, the study examines three key questions: i) what cognitive, technical and institutional factors have been attributed to the failure in the use of science? ii) what policy measures have been subsequently taken to rectify the perceived shortcomings in the use of the science? iii) what are the broader lessons we can learn from the debates over perceived failures of science in DRM policy-making?

We find that there are at least two opposing interpretations on the root causes of the failures. On the one hand, the issue has been framed as the failure of 'science' in which solutions are proposed to rectifying technical problems such as inaccurate underlying assumptions used in modeling probabilistic risk assessments; on the other hand, the issue has also been framed as the failure of 'science-policy' institution in which criticisms were expressed on the nature of national earthquake research policy agendas. These contrasting views reflect a fundamental debate regarding the treatment of uncertainty in DRM policy-making, and how a society may make inherent trade-offs in accepting the notion of residual risk.

Overall, the study finds that critical reflections on the use of science do not seem to have led to major rethinking and restructuring of science-policy agenda on this topic in Japan. Though debates are ongoing, an emphasis on 'evidence-based policy' in earthquake and tsunami risk reduction measures seems to continue in Japan and significant upward adjustments have been made to the official estimated damages from earthquakes in areas such as Nankai and the Tokyo metropolitan regions in 2013.(16,17) Further revisions in official estimates are also expected in regions such as the Japan Trench and the Kuril Kamachatka Trench in the Pacific regions by March 2017.(18) Municipalities are now debating how best to incorporate revised estimates into their local DRM planning.

2. BACKGROUND: THE HISTORY OF EARTHQUAKE AND TSUNAMI SCIENCE AND THE SCIENCE-POLICY INTERFACE IN JAPAN

Located on the ring of fire, Japan has suffered frequent earthquakes and tsunamis, causing significant human and economic loss. Since the first official monitoring of earthquakes began in 1875, earthquake and tsunami science has been promoted as part of national scientific agenda in the country. Following a magnitude 7.9 earthquake in the Kanto region in 1923, the country's first institute dedicated to seismology— the Earthquake Research Institute—was established in 1925 as part of the University of Tokyo.(19) Similarly, the Disaster Risk Prevention Institute was established in the Kyoto University in 1951 following the Fukui earthquake of 1948.(20) The topic of earthquake prediction became an important national scientific project following the Nigata earthquake of 1964, in which the first 4 Year Plan on Earthquake Prediction was released for years 1965 to 1968.(21) This plan promoted improved understanding of the country's seismic activity based on initial collaboration among national university institutes and four government bodies in which the first-year budget of 516 million yen was allocated for measurement of seismological activities, earth crust movement and identification of active faults.[21]

In the 50 years that followed, a number of scientific advisory bodies were established to inform the country's earthquake and tsunami risk management policy. These include (but are not limited to) the Coordination Committee for Earthquake Prediction (established in 1969 to exchange scientific information on research and observation), Prediction Council for Areas Under Intensified Measures against Earthquake Disaster (established in 1979 to advise the metrological agency of catastrophic earthquake possibilities), Earthquake Research Committee within the Headquarters for Earthquake Research Promotion (established in 1995 to provide long-term evaluations of probabilistic earthquake risks) and various committees established under the Center Disaster Prevention Council (CDPC)—the nation's central body of development of disaster risk management plan headed by the prime minister.[9,22,23] Table I shows the content and budget allocated for earthquake prediction plans in Japan from 1965 - 2008.

Table I. Historical foci and funding for earthquake prediction research in Japan

Period	Total funding allocation (in million yen)	Of which to national universities (in million yen)	Content
1st (1965-1968)	1,072	444	Development of observation network, establishment of university curriculum and departments, analysis of rust movements

2nd (1969-1973)	3,478	867	Understanding of earth crust movement through continuous observation; establishment of regional observation centres within national universities
3rd (1974-1978)	12,832	3,023	Further promotion of observation plan, strengthening of data analysis and interpretation
4th (1979-1983)	31,099	8,574	Observational focus on both long-term and short-term predictions. Longer-term prediction is aimed at identifying location and magnitude while shorter term prediction is aimed at identifying timing of earthquakes.
5th (1984-1988)	30,029	8,540	Continued focus on both long-term and short-term prediction.
6th (1989-1993)	36,319	9,502	Continued focus on both long-term and short-term prediction with use of GPS and other satellite technology.
7th (1994-1998)	78,650	11,983	Continued focus on both long-term and short-term prediction with further attention be paid to high risk areas such as the Tokai region.
1st* (1999-2003)	73,650	9,517	Understanding mechanisms of crust activity leading to earthquake occurrence, improvement of crust activity monitoring system, development of simulation and observation capacity of crust activity
2nd*(2004-2008)**	29,587	-	Continuation of research foci: Understanding

	mechanisms of crust activity leading to earthquake occurrence, improvement of crust activity monitoring system, development of simulation and observation capacity of crust activity

*Revised plan on monitoring research for earthquake prediction

** Earthquake prediction plan has been merged with volcanic eruption prediction plan as of 2009

Source: MEXT[24]; SSJ[25]

Though the transparency of these scientific advisory discussions is achieved through open documentation of discussions on most occasions, the limited openness of these advisory committee systems to wider academic and civil society participation has been frequently criticized by a number of scholars.[8,26] Furthermore, the way in which science was used by these advisory committees has been repeatedly questioned. At the national level, earthquake and tsunami risk management measures are typically designed and evaluated based on what are called 'assumed hazard scenarios' based on the latest scientific knowledge. At the start of scientific advisory meetings, therefore, scientists and practitioners discuss what is known and unknown about current earthquake risk in a particular area. The committee then selects an assumed earthquake scenario of a particular magnitude, based on which tsunami simulations are conducted and risk management policies are designed. Given that much is unknown about specific scientific mechanisms of earthquake occurrence, the use of 'assumed hazard scenarios' itself has been criticized for its limited scientific foundation.[8,13,27]

The DRM system, based on decades of earthquake and tsunami prediction research, failed to anticipate the catastrophic hazards of a magnitude 9 earthquake followed by dangerous tsunamis that occurred on

March 11, 2011. The results were cascading failures of unprecedented magnitude: in what has been described by many as the country's most severe crisis in the modern history, nearly 20,000 people identified dead or missing and the nation's critical infrastructure, including the Fukushima Daiichi nuclear power plant was severely impaired.[28] In response, the largest-ever disaster-response operation in Japan was immediately launched with a total of 107,000 maritime, ground and air personnel, 541 aircraft and 59 ships.[29] The catastrophic disaster was seen by many to be a failure of science, which led to the formation of an inquiry process to draw major lessons learnt in the use of scientific risk information.

3. METHODS AND DATA

To identify key debates regarding the use of scientific information in earthquake and tsunami risk management in post-2011 Japan, we reviewed the transcripts of investigatory committee meetings for 2011 Tohoku earthquake and tsunami and studied how scientific assessments have been updated for both Nankai Trough and Tokyo inland earthquake preparation (see the Appendix for the list of committee meetings reviewed). In addition, this study also identified scientific discussions on this topic in both English and Japanese languages through online search. While a complete review of this topic is beyond the scope of this article, we have focused on identifying the opinions expressed by researchers at leading domestic institutions and academic societies on earthquake and tsunami risk assessment, including the Earthquake Research Institute and Seismological Society of Japan.

4. RESULTS

4.1. Has Science Failed?

While diverse professional opinions were expressed on the root causes of their failures, these generally converge into the following two interpretations. One interpretation—which we call 'the failure of science' perspective—primarily perceived the heart of the issue to be the lack of scientific capacity. Scientific understanding on the underlying hazards was insufficient and DRM system designed based on limited knowledge led to catastrophic failures. Therefore, solutions to be prescribed are also technical and scientific in nature.

The other strand of interpretations—which we call 'the failure of science-policy institution' perspective—instead contended that the root causes stemmed more fundamentally from issues of science-policy process; how the country's earthquake and tsunami scientific research agendas were formulated to provide solutions to the threats posed by these hazards. The sense of urgency created by an imminent threat of major earthquakes and tsunamis, together with unfounded faith in the ability of science to deliver solutions, led to the silencing of open debate and constructive skepticism. The outcome was an eventual mis-application of science in the formulation of DRM policy. Therefore, the solutions they prescribe include a major rethink and further engagement of scientific community in the country's DRM policy making. The following section briefly summarizes key arguments put forth by these two interpretations.

4.2. How and Why Science Has Failed

The 'failure of science' views were frequently voiced within and outside of expert investigatory groups, in which technical failures have been identified as primary causes. The specific issues identified include but are not limited to: i) limited capacity to observe earthquake and tsunami mechanisms and over-reliance on past scientific records for probabilistic risk assessment; ii) limited tsunami early warning capacity to provide timely and accurate warning information following a catastrophic earthquake and; iii) limited civil engineering and spatial planning which were designed to fail safely above design thresholds. Related issues such as the failure of risk communication, evacuation drills, and other emergency protocols were also identified.

One issue frequently raised was the over-reliance on past earthquake and tsunami observations as benchmark for future risk estimation. Through three years of scientific committee deliberation from 2003-2005, the expert committee on Japan Sea and Chishima Trench estimated earthquake and tsunami damage based on the following eight types of observed events: i) magnitude 8.4 earthquake off the coast of Etorofu Island, ii) magnitude 8.3 earthquake off the coast of Shikotan island; iii) magnitude 8.3 off the coast of Nemuro and Kushiro; iv) magnitude 8.2 off the coast of Tokachi and Kushiro; v) magnitude 8.6 earthquake with 500 year return period; vi) magnitude 8.4 off the coast of north Sanriku; vii) magnitude 8.2 earthquake off the coast of Miyagi and viii) magnitude 8.6 earthquake of Meiji Sanriku.(30)

Four observed events with limited evidence of its return cycles were noted as 'needing further attention' but excluded from evaluation. These are i) Jogan earthquake of 869; ii) Keicho earthquake of 1611; Enpo earthquake of 1677 and ii) Showa Sanriku earthquake of 1933.(30) The strict use of model-based hazard risk assessment was seen as to the cause of this omission:

> "The use of model-based assessment, in a strict sense, requires sizable data. But in some cases we have one or two data points that are clearly indicating the occurrence of a large tsunami. These cases are prone to being omitted: 1611 Keicho tsunami or [1677] Enpo Tsunami for example. We discussed these pieces of evidence but we eventually omitted them since we could not model them very well." (author's translation)(31,p.6)

The disciplinary divide was seen as another contributing factor to this omission. In general, it has been customary for those with an engineering background to assert that earthquake risk assessment should be based on the use of past observations. Geologists, on the other hand, believe that there is a need to incorporate potential risk with the use of geological information. As one scientific advisor describes:

> "This strip of seafloor experienced three tsunami earthquakes over the past 400 years. These earthquakes were generated by a common geological mechanism known as subduction zone, and they are the same along the Japan Sea Trench from North to South […].[We] therefore arrived at a conclusion that it is geologically likely that same type of earthquakes may happen anywhere in this area. Civil engineers on the other hand, assessed risk based on the principle of 'largest recorded incidents.' They assumed that those areas experiencing [earthquakes] will experience them in the future while those that haven't will not […]. Especially in the second advisory discussion, I repeatedly inquired why this potential was not properly recognized. But my criticism unfortunately remained unheeded." (author's translation)[32,p.24]

Given disaster risk policy and plans are designed based on the concept of assumed hazards, severe under-estimation of these assumed earthquake scenarios led to the cascading failures of DRM measures. One key technical failure, which contributed to the large loss of life, was the inaccuracy of the initial earthquake magnitude and tsunami height estimates released by the Japan Meteorological Agency (JMA). Both earthquake magnitudes and tsunami heights were repeatedly revised in the first hours of their occurrence, hampering swift evacuation and creating confusion among responders and residents.

While ground-shaking was ongoing on March 11, 2011, the first estimate of earthquake magnitude—of 7.9 – was made at 14:49 pm. Approximately one hour later at 16:00, JMA revised its magnitude estimate to be 8.4. Their estimate was again revised upward at 17:30 pm to be 8.8. It was not until two days later on March 13 when the final estimate of 9.0 was ultimately released. [33] Given that speed was emphasized over accuracy in tsunami early warning, the JMA released its first wave of warning 3 minutes after the initial tremor. This initial early-warning was based on their 7.9 magnitude estimate, which severely underestimated tsunami heights: initial reports forecasted waves of 6 m in Miyagi prefecture and 3 m in Iwate and Fukushima prefectures respectively. As one expert explains:

> "Unfortunately, we do not have any technical means, even based on the best of seismological science, to estimate a magnitude 9 earthquake accurately within 2-3 minutes of its occurrence. [An accurate estimate] requires at least 10-15 minutes. JMA nonetheless is of an opinion that a first wave of warning should be released within 2-3 minutes. In the future, we hope to minimize the risk of under-estimation by taking necessary measures such as an upward adjustment, when we immediately know that an earthquake magnitude may have exceeded a magnitude of 8, especially for those areas where such risk is presumed to be high." (author's translation) [32,p.17]

The JMA magnitude estimation, which uses a seismograph, is known to become unreliable when earthquakes of a magnitude larger than 8 strike. However, JMA failed to share such critical information outside its agency.

Another technical issue identified in the review committees was the design failure of coastal sea walls. A practitioner says:

> "The sea wall against Nankai earthquake in Suzaki, for example, is also designed for a magnitude 8 earthquake. It is assumed the sea wall can protect residents up to this level. But above that, residents should evacuate. We more or less know which areas are dangerous according to hazard maps. But such thought processes go on only within our heads. Residents will think the presence of sea wall, in and of itself, would protect them. They would never imagine a possibility that if a large tsunami beyond design threshold occurs, sea wall itself will collapse. Such cognitive gap in fact led to large damage and losses [in Tohoku] […]. A lesson learnt is that we can't easily set design standards, else people may face a catastrophe." (author's translation).[31,p.30]

In addition, many deaths were reported in designated evacuation areas in Tohoku, since the selection of evacuation areas was made based on smaller earthquake and tsunami risk estimate. In Kesennuma city, where the country's tsunami evacuation practice originally began, for example, 60% of deaths in tsunami risk areas was found in the city's designated evacuation areas.[34] These technical failures were largely seen as an immediate threat to public trust on the country's disaster management measures, for which appropriate measurements should be taken to strengthen the use of accurate science.

A swift revision of the nations' earthquake and tsunami defense systems was thus called upon based on revised and upward estimates of existing earthquake and tsunami risks. Technical remedies proposed by the expert committees included: i) the use of ancient historical texts, tsunami deposits and other archeological information to further understand the mechanisms and evidence of past earthquake and tsunamis; ii) expansion of the direct observation network covering ocean floor crustal movement; iii) further scientific studies to understand the mechanisms which lead to simultaneous occurrence of ocean trench quakes and tsunami earthquakes. With improved scientific information, earthquake and tsunami hazard assumptions are to be revised for the "largest-possible mega earthquake and tsunami…from every possible angel."[35,p.8] In somewhat of a contradiction, the Cabinet office also highlights the need to be aware of the possibility that actual damage may exceed that assumed in risk modeling.

Though what technically may constitute the "largest-possible mega earthquake and tsunami" is to be deliberated in the Headquarters for the Earthquake Research Promotion, the CDPC presented an outline of revised earthquake and tsunami defense planning in Japan on September 28, 2011, in which a portfolio of structural and policy measures were proposed which addressed both frequent (> 100+ yrs) and rare (one in 100s or 1000 yrs) tsunamis. For frequent but more minor tsunamis structural measures are to be promoted, whereas a combination of improved land-use planning, evacuation and early warning measures are to be taken to manage the risk of extremely rare but catastrophic events.[35,36]

This 'two-level' thinking—accounting for both frequent and rare events—is not only used in the reconstruction plan of Tohoku regions but also extended to preparedness plans in the rest of the country. The assumed scenarios of the much-dreaded Nankai trough earthquake, for example, have been revised based on the three year deliberation of the Committee for Modeling the Nankai Trough Megaquake. Table II shows summary of revised damage estimate for Nankai Megaquake.

Table II. Revised estimate of Nankai Trough Earthquake and tsunami damage

	Earthquake magnitude	Inundation area	Number of deaths/missing	Housing damage (fully destroyed)
Revised estimate	9.0	1,052 km2*	323,000**	2,386,000***
Previous estimate as of 2003	8.7	-	24,700****	940,200 *****

*Assuming proper functioning of sea walls and gates

**Earthquake movement on the land with tsunami (case 1) with the windspeed of 8m/s at late night during winter time.

*** Earthquake movement on the land with tsunami (case 5) with the windspeed of 8m/s in the evening during winter time.

**** Damage estimate for 5 am.

***** Damage estimate for 6 pm.

Source: Cabinet Office[37]

As a result of the aforementioned technical revisions proposed, the estimate of economic losses for Nankai trough megaquake has now risen to 220 trillion yen (i.e. approximately twice the national budget). The estimated areas expected to experience JMA intensity scale of weak 6 or more has tripled to 71,000 square kilometers.[38] Tsunami heights have also been revised upward, with expected wave heights in the prefectures of Ehime, Oita, Miyagi and Kagoshima tripling up to 13-17 m. Given the economic losses of the Kobe and Tohoku earthquake of 1995 and 2011 were a mere 10 trillion and 17 trillion yen respectively, the public release of this revised loss due to 'largest-possible class of earthquakes' was received with much surprise. Some practitioners and residents expressed concerns that investors and businesses may relocate due to high perceived risks.[39] Local deliberations are ongoing to revise and update local DRM plans accordingly.[40]

Other technical aspects being discussed in the revision of the earthquake countermeasures include but are not limited to: an appropriate role of media in delivering accurate information and mitigating the risk of compulsive hoarding[41]; improved supply-chain management for critical items including medical supplies[41-45] and fuel[46,47]; enhanced communication networks between fire fighters, police officers and self-defense forces[46]; further coordination and collaboration with volunteer and private sector organizations[48-50]; an adoption of wider risk financing mechanisms such as bonds and earthquake insurance.[49] Many of these lessons have been incorporated into the revised preparedness plans for both Nankai and Tokyo Megaearthquakes.

4.3. How and Why the Science-Policy Process Failed

While the national earthquake and tsunami policy revision incorporated technical lessons learned into revised policy measures, different opinions were also expressed on more fundamental issues, including the use of science in DRM policy formation. Scientific communities questioned the direction of the nations' research agenda, and the manner in which scientists are called up to answer questions that go beyond the limits of the science.

These voices contended that a fundamental re-thinking of the science-policy process should be pursued, while accepting and communicating the limits of science and practice:

> "The fundamental flaw is the conventional mind-set of crisis management. Crisis management [as practiced conventionally] talks only about what to do in case 'assumed' scenarios occur. But we of course can't assume [everything]. Crisis management should be about what to do when our assumptions fail. But we can't write such things [in disaster management plans] […]. In that sense, we can't really address 'new levels' of disaster risk." (author's translation)[31,p.43]

According to this view, the limitation was the assumption that DRM planning had prior knowledge of prevalent hazards in the area. However, we know without doubt that our prior knowledge has limitations:

> "Our current earthquake science depends on the use of physical observational data. The accumulation of physical observational data spans less than 100 years. Historical records may go back some 1,500 years. Tsunami deposits some 5000 years. It is important that historical information be uncovered through tsunami deposit assessments, etc. But the accuracy and richness of information obtained through such means hardly matches that of the existing physical observations." (author's translation)[26,p.160]

Hence, the adoption of official concepts such as the 'largest possible class' of earthquakes was received with skepticism by scientists. In advisory meetings, priority was given to strictly following an administrative schedule, which gave an impression that insufficient time was devoted to scientific discussions on the nature of, and methods to estimate, such largest possible earthquakes[26]. Although the use of improved science was advocated, publically released final documents also failed to elaborate on what is unknown, uncertain or of limited scientific understanding:

> "What in the end is 'science' or 'scientific' [information]? Is it possible for us to 'consider all possibilities from every angle' as suggested by the technical investigation committee on lessons learned? The number of models described in the report for the committee for modeling assessment was a mere five for strong motion and 11 for tsunami. Can we for certain conclude that '[we have] considered all possibilities?'" (author's translation)[26,p.162]

Others contended that a more fundamental cause may be traced to the institution of science-policy process on this topic:

> "The estimated probability of '99% that a magnitude 7-class earthquake will occur over the next 30 years' sounds, in common sense, 'almost certain'. It therefore cannot be supported by many academic members of the seismological society including myself. I am in shock to discover that this kind of estimate had been proposed and used in an actual disaster risk management plan. […]. The real problem lies in the fact that the contents of national government-led research projects have not been sufficiently explained to the broader scientific community and that their responsibility remains unclear." (author's translation)[27,p.69]

Systemic issues with research agenda, planning and evaluation were also identified:

> "The short-term nature of evaluation and project-based research implementation have prevented scholars' from devoting the early years of their careers, often the most capable, to solving more challenging questions based on outside-the-box thinking. Well defined evaluation criteria favor the quantity of research over its quality. Researchers have therefore avoided those topics that cannot be easily validated with short-term observational data, such as mega-

earthquakes with extremely long return periods. We were also too focused on arriving at a scientific consensus on long-term earthquake risk evaluation." (author's translation)[51,p.127]

Based on these perspectives, fundamental issues may be traced to the way in which scientific information was used selectively to promote earthquake and tsunami risk agendas, and how significant research funds were channeled for earthquake prediction. The practical needs of disaster risk management were prioritized over scientific rigor, such as speedy planning over deliberation, language of certainty over uncertainty, notions of scientific competence over scientific limitation.

Proposed solutions hence include revisions of scientific research agendas[8,27]; incorporation of uncertainty and limits of science as a basis for policy discussions[26,52]; more open discussions beyond the existing advisory institutions, along with better documentation of internal advisory discussions.[26] Critical revision in the mind-set of scientists are also called for, in which scientists should pay closer attentions to DRM policy content, media coverage and how science is used and misused to informing dominant discourse and assumptions.[13]

5. DISCUSSIONS

Science-policy scholar Roger A. Pielke warns that the perceived role of science as 'the servant of interest-group politics' threatens democracy, causing the 'diminishment of science as a resource for policy-making.'[53,p.10] Under what he refers to as the linear-model of science-policy interaction, neither policy makers nor scientists take a full responsibility for navigating the ways science and policy interests are linked. In a demand-driven linear model, scientists, receiving generous public research funds, focus on the narrow production of basic scientific knowledge to provide specific policy answers to a chosen topic. It is believed that this newly acquired basic science will naturally flow downstream to applied research and eventual uptake by policy community. Such a science-policy interface is prone to external pressure and manipulation as the provision of research fund is typically linked to the 'preexisting political agenda.'[53,p.144] When policies are formulated in a top-down manner, this linear model leaves little room for citizen engagement and genuine democratic dialogue on the issues at stake.

The science-policy interface of earthquake and tsunami risk management reviewed in this article seems to resemble such a linear model of interaction. While the sense of urgency was created by the extraordinary circumstances of the post-disaster muddle, science was ultimately made to service the defined goal of re-establishing public trust in the country's DRM policy—even when scientists themselves questions their capacity to deliver such goals.

From the viewpoint of the 'failure of science', the basic scientific research promoted under such linear-model was inadequate at informing society of the true risks prior to the 2011 earthquake and tsunami. If data gathering, the early warning system, and engineering and land-use capacities and resources had been better, and if the updates of scientific information had been carried out in a timely manner, they would have reduced damage and losses significantly. The remedy to rectify the short-fall of science is, therefore, to strengthen scientific capacity. Better guided research with a clearer mandate to serve policy demands is needed to target knowledge creation which will be of real use for reduction earthquake and tsunami risks on the ground.

From the view point of the 'failure of the science-policy process', the real culprit is the demand-driven linear-model itself. The country's seismology and tsunami science were promoted to serve narrowly defined goals of safety and disaster risk reduction. If discussions of uncertainty and unknowns had been prioritized over what little is known of seismological risk; if more democratic discussions had taken place outside the advisory systems, and if citizens had been more aware of the risks of unknown possibilities, we would have reduced damage and losses significantly. The remedy to rectify these short-falls of science-policy process is, therefore, to ensure that policymakers respect the scientific need for deliberation of unknowns and uncertainty, while scientists engage fully with policymakers, providing constructive criticisms. Citizen engagement will also be important, and the proper use of science should encourage the public to not blindly accept what is assumed, but act independently and quickly in case of an unexpected catastrophic event.

These contrasting views reflect tensions common in science-policy process. On the one hand, a policy process often demands factual information that is certain and accurate; scientific deliberation on the other is frequently characterized by uncertainty and unknowns.(11,12) Questioning and revising of underlying assumptions are fundamental to the process of scientific learning, which may not be amenable to a linear process of policy planning and implementation. The existing literature on risk governance shows that a probabilistic knowledge of hazards alone is hardly sufficient in properly managing the risk of natural disasters (54,55) and an active engagement of scientific community is an essential pre-requisite for successful risk governance.(56-60)

In their influential work on disaster risk management 'knowing better and losing even more, ' White et al.(55, p.81) identified five possible reasons why economic loss from natural disasters continue to rise globally despite our improved scientific knowledge of the subject. It is either: i) knowledge is 'flawed by areas of ignorance'; ii) knowledge is 'available but not used effectively'; iii) knowledge is used but in an 'ineffective manner' iv) knowledge is 'used effectively but it takes a long time to have an effect' and v) knowledge is used but the effect is 'overwhelmed by increases in vulnerability and in population wealth and poverty. Their critical observations reflects the complexity in the ways scientific information must be produced, disseminated, and used to properly inform disaster risk management policy. As this study illustrates, a society may, in fact, never have flawless knowledge of catastrophic risk, and DRM policy must accept the presence of residual risk and be built on the appreciation for the limit of science. Rather than to strive for flawless knowledge, a society may learn to be resilient by properly understanding, and planning based on such limits.

6. CONCLUSION

By reviewing publically available documents from expert committee discussions and scientific articles, this study identified what has been perceived as the cause of failure in use of scientific knowledge in post-Tohoku earthquake and tsunami risk management in Japan. We found that there are at least two opposing views on the root causes of the failures. On the one hand the 'failure of science' perspective saw the limitation of science as the major cause of DRM policy failure, for which further investment into research and better incorporation of scientific information were seen as the remedy. On the other hand, the issue has also been framed as the failure of the 'science-policy' process in which criticisms were expressed more broadly on the formulation of the national earthquake research policy agenda and limited engagement with the larger scientific community. Although debates are ongoing, an emphasis on 'evidence-based policy' in earthquake and tsunami risk reduction measures remains and significant upward adjustments have been made in estimated damages from expected earthquakes in the rest of the country such as Nankai Trough. Overall, these criticisms have led to a limited rethinking and restructuring of science-policy agenda on this topic in Japan.

Global policy discourse on DRM increasingly emphasizes the use of science in informing policy formulation and implementation. Within wider areas of climate risk management and development, improved science-policy linkages are called on to providing the many answers needed to solve complex and inter-related problems.[(61)] In deliberating how science should be used to inform policy in the future, this study indicates that is important not only to examine how science is being used at present, but more broadly how the science-policy interface is formulated and what other influences are present or absent across and within the science and policy communities. As the debate on the use of science in disaster risk reduction continues, active engagement of scientific community will be increasingly called upon to co-define and co-design solutions. Clearly communicating the best of, and the limit of, scientific information will be therefore crucial in these efforts. The debates on this topic in Japan highlight tensions and pitfalls common in linking DRM science-to-policy-making. While appreciating our cognitive and policy biases, it is ultimately up for a society to decide what level of risk it is willing to accept—such discussions inherently demand open-mindedness on the part of all stakeholders involved. In these processes, science should neither be perceived as a source of perfect foresight, nor a servant of vested interests.

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Appendix

List of committee discussions reviewed

Committee name	Session duration
Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the '2011 off the Pacific coast of Tohoku earthquake'	May 28-September 28, 2011 (12 sessions)
Committee for Modeling the Nankai Trough Megaquake	August 28 2011 to July 31st 2015 (51 sessions)
Committee for Modeling the Tokyo inland earthquake	May 11 2012- July 31 2015 (35 sessions)
Working Group on Countermeasures for the Nankai Trough Megaquake	April 20, 2012-April 25, 2013 (16 sessions)

Working Group on Countermeasures for the Tokyo inland earthquake	April 25, 2012-December 10, 2013 (19 sessions)