Super Case Study

2

Fukushima Daiichi accident in 2011

Online Version

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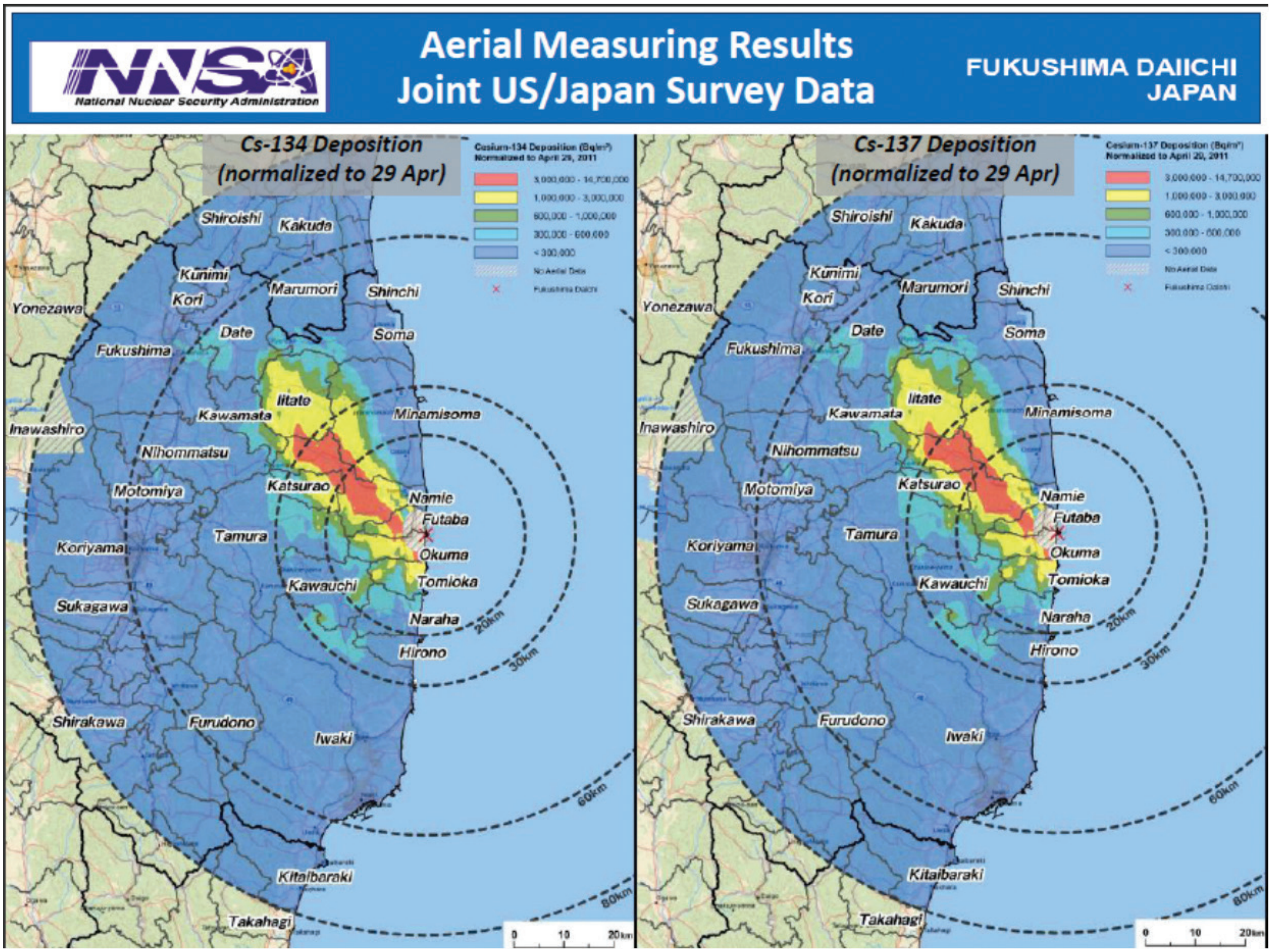
1 Introduction

This study focuses mainly on the Fukushima nuclear disaster; however, it also addresses the consequences of the tsunami, as both of them influenced the impacts and emergency management.

The great east Japan earthquake (GEJE), with a magnitude of 9.0, occurred off the north-east coast of Japan at 14.46 local time on 11 March 2011. It caused a tsunami that resulted in the deaths of approximately 18 500 people and initiated the nuclear disaster at the Fukushima Daiichi nuclear power plant (FD NPP), with approximately 150 000 people receiving evacuation orders (NAIIC, 2012; IAEA, 2015a; Callen and Homma, 2017).

Figure 1. *The area affected by radiation.* ***Source****: US Department of Energy, 2011.*



At the FD NPP, with six reactors, units 1–3 were in operation whereas units 4–6 were shut down because of maintenance or refuelling works. The reactors of units 1–3 were shut down automatically by the reactor protection systems when the ground motion was detected, in accordance with the design. However, the earthquake damaged the external electric power supply lines, and then the tsunami wave, with a height of more than 14 m, flooded most of the emergency diesel generators, causing a complete station blackout. This severely affected the cooling function of the operating reactors as well as of the spent-fuel-cooling pools. Cooling of the residual power of the reactors was maintained thanks to systems regulated by batteries that stopped after some hours. As cooling could not be restored from external sources, severe damage from fuel melting occurred to the reactor cores of units 1–3. Oxidation of metal parts of fuel by steam at high temperature generated large amounts of hydrogen, and the containment vessels were breached because of an increase of pressure far beyond what they were designed to cope with. Hydrogen explosions were produced in the reactor buildings of units 1, 3 and 4, damaging structures and equipment and injuring personnel. In unit 2, an explosion in the containment building was produced. This resulted in large amounts of radionuclides, although less than 10 % of the amount from Chernobyl (Steinhauser et al., 2014), being released into the atmosphere and deposited on land in the following days, causing severe contamination in the area to the north-west of the FD NPP (Figure 1) and on the ocean. Large and direct releases of highly radioactive water into the sea were also produced from a trench at unit 2, with a peak at the beginning of April 2011. An assessment of different published estimates made by the International Atomic Energy Agency (IAEA, 2015b) indicates ranges between 7 and 50 PBq and between 90 and 700 PBq for the atmospheric releases of the key radionuclides ^{137}Cs and ^{131}I, respectively (excluding uncertain early estimates).

2 Description of the main consequences of the event

The combined effects of natural and man-made disasters had severe consequences that were not recognised in the preparedness phase. Cascading and lasting effects have been observed.

2.1 Main consequences for the environment

The releases resulted in the contamination of the surrounding terrestrial (and freshwater) environment through deposition processes and interception by vegetation (IAEA, 2015c). Soil deposition density maps of gamma-ray-emitting radioactive nuclides are supplied by Yoshida and Takahashi (2012), Saito et al. (2015) and the IAEA (2015b), and on the dedicated website of Japan Map Center (JMC, 2019), with values of several MBq/m^2 for ^{137}Cs and ^{134}Cs within the restricted area of 20 km around the FD NPP. The resulting dose rates in the areas around the FD NPP led the Japanese Government to define a deliberate evacuation area extending up to 55 km in the north-west direction, in addition to the restricted area (IAEA, 2015a). Eight years after the accident, the areas where it is expected that the residents will have difficulties in returning for a long time cover 337 km^2 extending to about 40 km in the north-west direction with a width of about 10 km (Reconstruction Agency, 2019; JMC, 2019).

The possible biological effects of radiation and its ecological impacts over time among non-human species following the FD NPP accident have been intensively studied (e.g. Steen and Mousseau, 2014). However, no impact on populations or ecosystems have been reported (IAEA, 2015b), i.e. the releases from the Fukushima Daiichi accident are unlikely to have caused any substantial harm to animals and plants. Special attention was paid to characterising the radioactive contamination in north-eastern Japan (e.g. Imamura et al., 2017), which is mostly covered by forest (c. 70 %). Recent studies (e.g. Manaka et al., 2019) have supported the view that contaminated forests have entered a steady-state phase of ^{137}Cs cycling. In rivers, Somboon et al. (2018) reported values up to 22 000 Bq/kg in riverbed sediments and 2 000 Bq/kg in flood plain deposits 7 years after the accident.

Radionuclides were also found in seawater and marine organisms through deposition to the sea surface and runoff of seawater used to cool the reactors, plus leakage of wastewaters from damaged containment structures (IAEA, 2015b). The Institute for Radiological Protection and Nuclear Safety (IRSN) reported that radionuclide concentrations were stable in the marine environment close to the nuclear power plant (within a 30 km radius) 5 years after the accident, and radioactive caesium concentrations had fallen to levels close to those observed prior to the accident more than 200 km from the FD NPP (IRSN, 2016).

Under prevailing weather conditions, more than 80 % of the atmospherically released radionuclides were estimated to have gone offshore from Japan, followed by deposition in the Pacific Ocean (Morino et al., 2011) and in other parts of the world. The global atmospheric transport and deposition of radionuclides released from Fukushima have been documented (e.g. Christoudias and Lelieveld, 2013). The long-term consequences of the releases on the environment are considered to be insignificant (IAEA, 2015b).

2.2 Main consequences for the population

The most disruptive consequences were the evacuation orders to the population around the FD NPP. Whereas the evacuation as a result of the earthquake and tsunami was obvious – more than 460 000 people were displaced to about 2 400 shelters throughout Japan – the one prompted by the nuclear disaster might not have been (Hasegawa et al., 2016). Evacuation orders around the FD NPP were issued on 11 March, successively increasing the radius from 2 km to 3, 10 and then 20 km (IAEA, 2015a; METI, 2017). Sixty patients from hospitals and nursing homes died from complications related to the evacuation (NAIIC, 2012). This continuous increase of distances did not foster trust in the authorities. Moreover, iodine thyroid-blocking tablets were not distributed within the 10 km emergency zone despite the available stocks (Callen and Homma, 2017).

Evacuated people received compensation and support for establishing their lives outside their home towns. Similarly to Chernobyl, psychiatric problems as well as psychosocial issues such as stigma or discrimination from the public emerged (Maeda et al., 2018). Radiological consequences were limited; e.g. there were no early radiation-induced health effects on humans (workers or the public). The radiological consequences in countries other than Japan appeared negligible (Masson et al., 2011; Behrens et al., 2012).

As a long-term consequence, disaster-related deaths (DRDs) were reported. A DRD is defined as 'a death caused by the deterioration of underlying medical problems due to poor medical access or illnesses arising from poor living environments, such as temporary shelters, in a disaster' (Ichiseki, 2013). By 31 March 2013, 2 688 people died in shelters or temporary houses (Ichiseki, 2013). By the end of 2018, this number had increased to 3 701 deaths (Nippon.com, 2019). The figures do not distinguish whether the DRD is a direct effect of the tsunami or the evacuation from the nuclear power plant accident. However, they clearly demonstrate the importance of long-term medical care after such a disaster.

Consequences were also investigated by a study called Fukushima Health Management Survey coordinated by the Fukushima Medical University (Yasumura and Abe, 2017) that reports the following information. The basic survey aims to estimate the external radiation dose exposure of 2 050 000 inhabitants. At 31 March 2018, 567 810 persons had answered the questionnaire. Results based on estimates show that 62.2 % had received doses below 1 mSv and only 15 persons were exposed to values above 15 mSv, with a maximum of 25 mSv.

Several specific studies were launched as well. One focused on thyroid cancer occurrence in 360 000 children who were under 18 years old when the accident occurred. The preliminary baseline screening campaign conducted from 2011 to 2014 showed 116 and 71 thyroid cancer cases in the first and second rounds for children. However, the frequency of occurrence of thyroid cancer is similar to that in non-exposed children (Yamashita et al., 2018). From 2017 onwards, evacuation orders were lifted in several villages, allowing the population to return to their homes. The official number of people throughout Japan still living in temporary housing is about 54 000 (Nippon.com, 2019). It was reported that, by January 2019, approximately 32 000 of Fukushima's roughly 42 000 evacuees still lived in other prefectures. This shows that many of the evacuees still have not returned. Indeed, the choice of returning or not is dependent on several factors: some are linked to the post-accident policy with financial incentives and constraints; others can be linked to age, family status, professional status (Fassert and Hasegawa, 2019).

The population's trust in authorities is indeed a key for success in emergency management and long-term rehabilitation (see for example IAEA, 2015a). In Fukushima, however, the local population was faced with 'chaotic mishandling of the Fukushima crisis', as reported by Abe (2015). The delayed information about release and statements such as 'The radioactive fallout does not have any immediate health effects' worried the public (Tateno and Yokoyama, 2013, p.2). To build trust, risk communication may play an important role. It helps in explaining the consequences of the accident and enhances the capability of local actors to make informed decisions and, finally, understand the authorities (Perko, 2015).

2.3 Main consequences for critical infrastructures

Several types of critical infrastructure (CI) were affected by the disaster. Among them, the sudden loss of about 10 % of power generation capacity on 11 March and the eventual shutdown of all 50 nuclear power plant units in Japan by 2012 caused a deficit of 30 % of the electricity supply that could not be closed immediately (Komiyama, 2017). This initially caused shortages in the supply to citizens, resulting in rolling blackouts that were implemented in March to April 2011 in the Tokyo and Kanto area, followed by mandatory reductions in power usage from July 2011 onwards to avoid unplanned blackouts during summer months (Komiyama, 2017)
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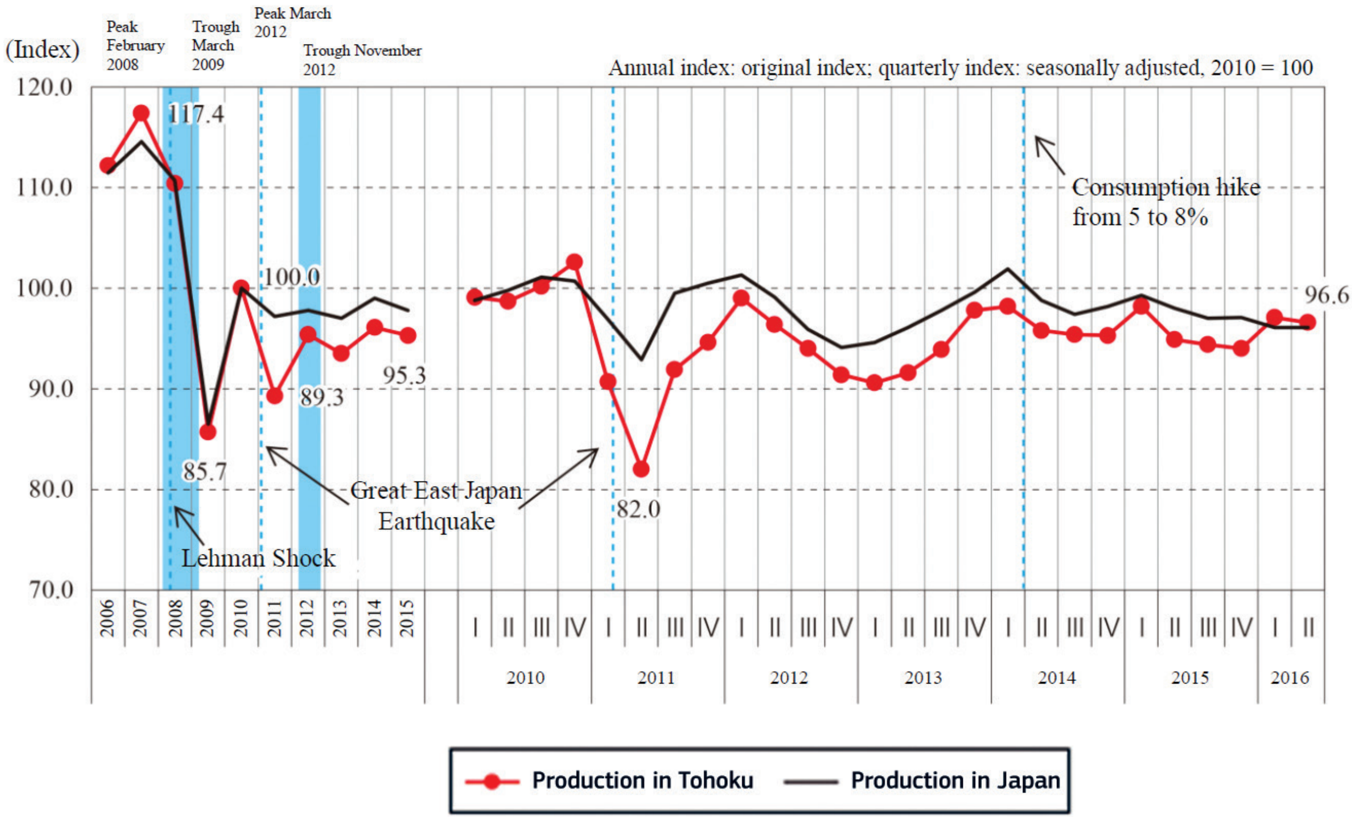
Immediate consequences to CI were caused by the earthquake and tsunami. They affected, for example, regional airports, seaports, many motorways, the Tohoku Shinkansen (high-speed railway) and nuclear plants. The Sendai airport north of Fukushima was closed for 6 days and not available to bring in rescue personnel directly after the earthquake (Kadri et al., 2014; Holguín-Veras et al., 2014). The problems at the airports resulted in the need for more intensive ground transport to deliver goods, and in particular food, to the affected areas. However, owing to shortages at local petrol stations, delivery of needed products was delayed or even impossible (Shimizu and Clark, 2015). Besides the shortage of petrol, impacts on the logistics sector also reduced the capacity for fast response (Holguín-Veras et al., 2014). Communication lines were disrupted, by either damage or loss of power, thus affecting critical communication between the national and local governments, as well as between governments and first responders (Shimizu and Clark, 2015). The medical sector, one of the most important sectors in case of a crisis, was heavily affected by the disaster. Six hospitals that were assigned as primary radiation emergency hospitals were nearly unable to function owing to physical damage, location in an area where evacuation was proposed or lack of personnel (Hasegawa et al., 2016).

2.4 Main consequences for the economic sector

The GEJE and tsunami event caused severe and long-lasting damage to the physical capital stock, infrastructure and supply chains in the affected regions and far beyond. The Japanese Cabinet Office estimated the total damage at USD 210 billion (4 % of Japan's gross domestic product), of which USD 129 billion was direct damage to buildings and facilities such as housing, offices and plants and USD 43.5 billion was for transport infrastructure, lifeline utilities and critical infrastructure such as electricity, water and communication (Ranghieri and Ishiwatari, 2014). The energy sector was one of the most severely affected by the disaster. With respect to agriculture, fisheries and forestry, in 2011 the capital stock was affected by about USD 29 billion and the total cultivated area for agricultural crops in the affected Tohoku region declined significantly (TBETI, 2016).

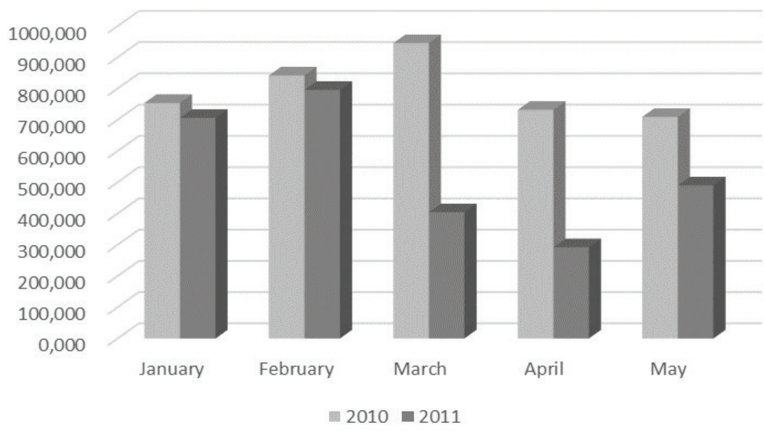
Figure 2 *shows how the GEJE-event affected industrial production of the Tohoku region compared to the level of industrial production from all over Japan.* ***Source****: TBETI, 2016.*



The damage to the tourism industry amounted to USD 8.7 billion (IBRD, 2012). On the financial markets, the Nikkei Index (Tokyo Stock Exchange) fell by almost 5 % for a brief period while the yen depreciated based on the expectation that Japanese investors would repatriate cash to cover the costs of the disaster (Ranghieri and Ishiwatari, 2014).

Japan is the second largest manufacturer in the world and is known for key materials (e.g. Japan provides 60 % of the world's supply of silicon, which is used as raw material for semiconductor chips) and for its high technical precision and quality in key industries such as the automotive and electronics industries (Park et al., 2013). Such key primary industries are also located in the affected region of Tohoku. Compared with the whole industrial output of Japan, the region of Tohoku is especially strong for information and communications equipment (15.2 % of the national total), and electronic devices and circuits (13.8 %), which makes this region an important manufactural hub (TBETI, 2016). Figure 2 shows how the GEJE event affected industrial production in the Tohoku region compared with the level of industrial production from all over Japan.

Figure 3. *Motor Vehicles Production in Japan (year-on-year-comparison),*
Source: *De Souza, 2011.*



The disruptions in the industries of the Tohoku region led to severe and prolonged interruptions in the national and global automotive supply chain, mainly caused by the lack of energy and the unavailability of a transport network as first-order effects, and the short supply of preliminary parts as a second-order effect (Ono et al., 2015). First and foremost, in March 2011, there was an immediate and strong decline of 57 % in the production of motor vehicles in Japan, as illustrated by Figure 3 (De Souza, 2011, based on data from the Japanese Automobile Manufacturers' Association). The drop in production reached 60 % in April 2011 and it recovered slightly in May 2011.

The business interruptions caused the bankruptcy of more than 650 private companies within one year, and 88 % of these Japanese firms were located outside the Tohoku region, i.e. they were indirectly affected by supply chain problems (IBRD, 2012). A large proportion of highly specialised Japanese small and medium-sized enterprises produce goods overseas, which led to notable ripple effects through supply chains around the world. Taking Toyota as an example, the GEJE caused the shutdown of domestic factories in March 2011 and they slowly recovered to an operational level of 50 % in April and May. Toyota's overseas factories were initially unaffected but dropped to an operational level of 20 % for lack of parts between mid-April and May. Both domestic and overseas factories reached an operational level of 70 % in June 2011 (Ono et al., 2015). The disruptions spilled over to other countries in the region. Farther away, GM, Ford and Chrysler closed their plants in the USA (Park et al., 2013). Opel in Germany and Renault in France saw interruptions in production, too (De Souza, 2011). One reason for the high vulnerability of the supply chain for motor vehicles, but also for electronic equipment, was the highly specialised single-source strategy of major Japanese car makers such as Nissan and Toyota (Abe and Ye, 2013). In addition to this, there was a very low level of inventory and operational flexibility because of just in time production .

2.5 Main consequences for the cultural heritage

The 2011 earthquake and tsunami had severe impacts on the cultural heritage sector. Immediately after these events, the Agency for Cultural Affairs launched two programmes to rescue/recover the affected cultural heritage and prevent the occurrence of further damage (e.g. demolition, theft, abandonment): the Cultural Property Rescue Programme, which focused on movable heritage assets; and the Cultural Properties Doctor Dispatch Project, which focused on immovable heritage assets (ICOMOS, 2014). Besides the normal difficulties involved in cultural heritage stabilisation and rescue operations during post-earthquake scenarios, the damage to the FD NPP introduced additional challenges. The defined evacuation zones made it difficult to get information about the damage to cultural heritage in those areas and perform heritage recovery/rescue operations. Moreover, the seriousness of the situation was further intensified because Japanese cultural institutions did not have, at the time, cultural heritage protection procedures or guidelines for scenarios involving radiation-contaminated areas. According to the maps provided by the Institute of Disaster Mitigation for Urban Cultural Heritage (R-DMUCH, 2012), of the many immovable assets of the Fukushima prefecture that were affected by the earthquake (which include 127 buildings and 65 historic sites; Kikuchi, 2015) only three appear to be located in the original evacuation zone (the Kannondo stone Buddhas, the Daihizanjitoku Temple and the Idagawa memorial (stone) monument in Minamisōma). Accordingly, conservation and repair measures for these heritage assets could not be implemented right after the event. In terms of the consequences to movable heritage assets, the available data provide a more detailed description of how the post-disaster situation was addressed. The areas that were evacuated because of the radiation levels have four public museums as well as several storage facilities housing archaeological artefacts excavated by local governments. Although these facilities did not sustain major damage due to the earthquake, it was critical to undertake actions to rescue the heritage assets they housed to avoid further damage or thefts. However, these actions were unable to start before August 2012.

By October 2013, close to 4 000 boxes (60 × 44 × 15 cm) of heritage assets were rescued from the evacuated areas. By then, the Shirakawa storage facility was already nearly full, even though a large number of heritage assets remained in the evacuated areas (Kikuchi, 2015). Furthermore, at the time, the whereabouts of heritage assets that were privately stored or owned remained mostly unknown, thus precluding the ability to get a clear picture about the amount of work that still had to be done. Finally, it is noted that, since the Shirakawa facility provides only (temporary) storage, heritage assets formerly in museums were no longer on display. However, Sano and Yamamoto (2013) state that a selection of the rescued heritage assets is displayed in annual exhibitions to keep the memories of these events alive and to reconnect the people who were evacuated from Fukushima with their home towns.

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3 Lessons learning and learned

Public investigations and hearings were launched in many countries, as were stress tests for more realistic and severe worst case scenarios, beyond design basis. Risk regulation and governance have been revised. Preparedness remains of utmost importance

Following the FD NPP accident, the status of existing plants was reviewed in many countries around the world, and particular stress tests initiated (OECD/NEA, 2017; European Union, 2012, 2013). In the European Union, 132 units in 17 countries were considered targets for stress tests. Positive and negative issues were identified and solutions proposed for problems, which had to be implemented by national authorities. In France, for example, stress tests are called complementary safety assessments (évaluations complémentaires de sûreté), as their purpose is to challenge NPP design assumptions with more extreme natural hazard threats. It is a complementary approach to the usual safety demonstration approach required for the licence of design and operation, in the sense that it should address 'beyond design basis' scenarios. Those beyond design basis scenarios could lead to cliff-edge effects in critical equipment and safety functions (especially loss of cooling and electricity) and would then lead to a severe accident and radiological release to the environment.

In the USA, studies were carried out to investigate the current status of safety regulations for NPP. Among them, a comprehensive study on Lessons learned from the Fukushima nuclear accident for improving safety of U.S. nuclear plants was performed by an independent Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants (2014). It provided recommendations for improvements in both plant status and emergency management.

In Japan, the national system of nuclear regulation and competent authorities was changed. On 15 August 2011 and on 11 December 2011, a cabinet decision and a recommendation from the Advisory Committee for the Prevention of a Nuclear Accident, respectively, proposed to separate regulatory functions with respect to nuclear safety, security, safeguards, radiation monitoring and radioisotope regulation from promotional functions (IAEA, 2015a,d). This decision is in line with the objective of establishing and improving safety culture worldwide (IAEA, 1998).

In Europe in particular, the need for decision-making with limited information was recognised. Response in the very early phase in Japan was dominated by missing information on potential radioactive releases and their consequences. In this respect, the available predictions from the national System for Prediction of Environmental Emergency Dose Information (Chino et al., 1993) were not used by decision-makers owing to the lack of source term estimates due to the loss of power on site at the FD NPP (IAEA, 2015e). In Europe, the ongoing discussion about cross-border harmonisation and advice in the very early phase of the emergency resulted in concerted action by the Heads of the European Radiological Protection Competent Authorities and the Western European Nuclear Regulators' Association, proposing a concept to deal with cross-border emergency management in the early phase (HERCA-WENRA, 2014). To deal with missing and uncertain information in the early stages of an accident, they proposed to characterise the need for early countermeasures, such as evacuation, sheltering and iodine thyroid blocking, by four key parameters. They selected risk of core melt, containment integrity, wind direction and time of release as factors that are sufficient to initiate countermeasures. Thus, depending on the plant status, weather and start of release, areas for early phase countermeasures are proposed and are applicable all over Europe and worldwide.

As trust and communication were considered essential, work on this topic is ongoing. Practical recommendations on risk communication can be found from Perko (2015) and Tateno and Yokoyama (2013). They conclude that timely and clear information is key for success. The public should feel that authorities care about them in the best possible way.

Provisions related to failure in CI, e.g. power or medical supplies, were addressed in many countries. Providing uninterruptible power supplies to services such as hospitals, first response centres, internet and phone services, and data centres (exempting them from rolling blackout schedules is recommended) was identified as important (National Academies of Sciences, Engineering and Medicine, 2016). It was also recognised that a response centre for a disaster should not be built in a location that is likely to be affected by a disaster: the designated off-site centre by Fukushima Daiichi had to be abandoned, as air filters were not installed by design and it lacked a reliable power supply (JNES, 2013).

The catastrophic natural disaster in Japan clearly highlighted the vulnerability of global supply chains. There are a couple of lessons learned that can be drawn from this event and are integrated in current supply chain risk management practices. A first measure relates to the preparedness of a business, which requires a business impact analysis and a business continuity plan. To this end, risk managers should work with realistic worst case and multi-hazard scenarios and establish a response plan that includes preparation, training and permanent communication with key decision-makers. Risk and crisis managers should be always aware of the fact that even the worst case can be an overly optimistic scenario if boundary conditions are wrongly considered (IBRD, 2012).

With respect to the supply networks of a company, suppliers should be part of the contingency plans and also prepare for the unexpected, especially in generic skills and organisational capabilities. As the case studies of Park et al. (2013) highlight, firms that were heavily affected by the disaster now regularly visit their suppliers to develop strategies for emergencies together with them. In addition, the need to become less dependent on energy provision and availability of critical parts was recognised. As the study of Ono et al. (2015) illustrates, Japanese supply chain managers (in manufacturing businesses) see a need for an increase in the decentralisation of domestic procurement, a need for further expansion of their overseas procurement and the importance of multiple sourcing. Finally, the application of network risk management procedures is also of high importance.

4 Consequences for emergency management

In addition to preplanning of all possible actions – including communication – in the preparedness phase, training should enhance skills for adaptation to the unexpected. Continuity plans should widen their scope with regard to cascading and lasting effects, to foster resilience within territorial and supply chain perspectives.

Many authors have addressed the need to better prepare for such an emergency; in particular, to prepare evacuation routes well in advance, to define how to deal, for example, with hospitals, elderly care homes, prisons or members of the general public with disabilities (physically impaired/deaf/blind) in the area at risk. Furthermore, there is a clear need to inform the population well in advance about the risk and the proposed management plan in case of an emergency. In the long term, healthcare services and measures to prevent social disruption have to be strengthened.

Initiated in the frame of the European stress test on nuclear power plants, the European Commission launched a study to review, in particular, cross-border emergency management arrangements in Europe (ENCO, 2014). The study highlighted several gaps in existing arrangements and provided recommendations for all EU Member States. Among them, harmonisation of criteria, cross-border communication and integration of nuclear emergency management into civil protection mechanisms are some aspects that still are not fully implemented.

Several countries in Europe initiated reflections on their emergency management preparedness. Among them, the German Radiation Protection Commission issued a catalogue with many considerations for improvement based on lessons learned after Fukushima (Strahlenschutzkommission, 2015). One demanding part of this was realised in 2014 with the new definition of preparedness-planning zones for evacuation, sheltering and iodine thyroid blocking. Planning distances were generally increased as, in the new assessments, International Nuclear and Radiological Event Scale (INES) 7 source terms (IAEA, 2008) were considered, unlike what had been done before (Strahlenschutzkommission, 2014). Similar work was performed in Sweden, where the Swedish Radiation Safety Authority (SSM), together with other agencies and stakeholders, reviewed emergency-planning zones and emergency-planning distances for early-phase countermeasures, which led to a revision of the planning zones (SSM, 2017). In France, several changes to emergency management were conducted at several levels. The government established a new national plan to respond to a nuclear crisis. Local emergency response plans were updated to integrate the effects of severe natural hazards on response. Strategies to improve robustness include strengthening on-site safety equipment to resist extreme hazard impacts, such as electricity backup with diesel generators or new emergency centres, and are complemented by resilience strategies to rely on more flexible capabilities to face unexpected situations.

Besides operational consequences, at least in Europe, several research projects started to address gaps from Fukushima. Among them, the Prepare (Innovative integrated tools and platforms for radiological emergency preparedness and post-accident response in Europe) (Raskob, 2017) project, completed in 2016, and the Confidence (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs) project (Confidence, 2019), completed in 2019, supported the development of methods and tools that will be used operationally in Europe and worldwide, e.g. as part of the JRODOS (Java based Real-time On-line Decision Support) system (Ehrhardt and Weis, 2000; Ievdin et al., 2010). The resilience of society was also addressed as important for emergency management preparedness.

5 Conclusions

The cascading chain of events in Fukushima demonstrated the need for preparedness for compound events, beyond design basis, that are extremely unlikely but with high impact. The station blackout of the Fukushima Daiichi nuclear power plant could not be managed by the means foreseen in the preparedness phase. Decision-making with high levels of uncertainty resulted in decisions that are regarded as questionable in hindsight, but were probably inevitable given the exceptional chain of events with the earthquake, tsunami and meltdown of reactor cores.

The high number of deaths caused by the earthquake and tsunami is extremely unfortunate; however, more than 3 000 disaster-related deaths might be the result of a lack of preparedness for the long-term effects of such a combined disaster. The social disruption resulting from evacuation, and stigma resulting from fear of consequences of radiation, are key impacts on evacuees in the provinces around the power plant.

The most affected CI in Japan was the energy sector, with the stepwise shutdown of all nuclear power plants following the accident. Economic consequences were numerous and affected not only Japan but the global economy.

Gaps identified and lessons learned were manifold, particularly in the areas of nuclear safety and emergency management. Among them, proper preparedness at all levels even for very unlikely events can be regarded as a key driver of successful emergency management. In particular, the need was again highlighted to prepare for low-probability, high-impact events – such as Chernobyl and Fukushima, which were accidents with the highest INES rating and an extremely low probability.

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