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The aftermath of the Fukushima nuclear accident: Measures to contain groundwater contamination

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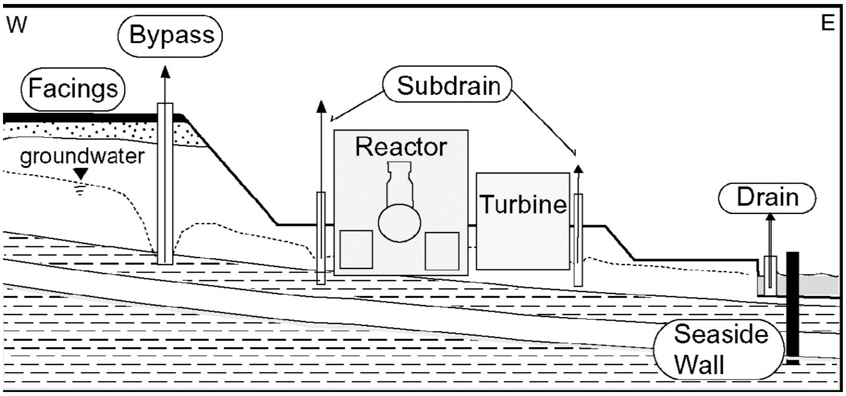
HIGHLIGHTS

- Measures are being undertaken to manage groundwater contamination in Fukushima.
- Methods focus on isolating the source and controlling the radionuclides migration.
- Wastewater is being temporarily held in tanks for treatment.
- Impervious walls inhibit the transport of contaminants toward the ocean.
- Paving and pumping further mitigate the dispersion of pollutants by water.

GRAPHICAL ABSTRACT



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ABSTRACT

Several measures are being implemented to control groundwater contamination at the Fukushima Daiichi Nuclear Plant. This paper presents an overview of work undertaken to contain the spread of radionuclides, and to mitigate releases to the ocean via hydrological pathways. As a first response, contaminated water is being held in tanks while awaiting treatment. Limited storage capacity and the risk of leakage make the measure unsustainable in the long term. Thus, an impervious barrier has been combined with a drain system to minimize the discharge of groundwater offshore. Caesium in seawater at the plant port has largely dropped, although some elevated concentrations are occasionally recorded. Moreover, a dissimilar decline of the radioactivity in fish could indicate additional sources of radionuclides intake. An underground frozen shield is also being constructed around the reactors. This structure would reduce inflows to the reactors and limit the interaction between fresh and contaminated waters. Additional strategies include groundwater abstraction and paving of surfaces to lower water levels and further restrict the mobilisation of radionuclides. Technical difficulties and public distrust pose an unprecedented challenge to the site remediation. Nevertheless, the knowledge acquired during the initial work offers opportunities for better planning and more rigorous decisions in the future.

1. Introduction

Environmental pollution, including contamination of water resources, have been one of the major concerns for authorities and the general public after the accident at the Fukushima Daiichi Nuclear

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Power Plant (FDNPP) in March 2011. The high magnitude earthquake and tsunami that followed shattered the defence walls and flooded the power plant in a few minutes. Seawater entered the reactors basement and caused a major failure of the entire system. Loss of power supply and the disruption of the cooling circuit led to a series of uncontrolled events, and the escape of large amounts of radionuclides. Thousands of square kilometres (km^2) of the prefecture of Fukushima and large parts of the Pacific Ocean were contaminated by the release of about 2% of the inventories of ^{137}Cs (caesium) and ^{131}I (iodine) from reactor units 1 to 3 (Granbow and Mostafavi, 2014). Additionally, numerical simulations by Morino et al. (2011) indicated that approximately 13% of the radioiodine, and more than 20% of the total caesium emitted from the power plant were deposited over land in Japan, whilst the rest was transported toward the ocean. As expected, rates of deposition were the highest in Fukushima, although emissions propagated to at least 14 prefectures within the island of Honshu. In this regard, atmospheric deposition largely contributed to radioactive contamination of soils in the coastal area whilst, groundwater constitutes a key component for the transport of radionuclides further into the sea. In effect, rainfall infiltration into the affected areas, leachate from the reactors, remobilisation of sediment-bound Cs, and subsurface mixing processes, all enhance the potential migration of radioactive elements into local aquifers and the dispersion of pollutants via groundwater. In this context, the management and ultimately the remediation of contaminated waters is critical for the protection of the environment and human health. The Act on Special Measures was promulgated soon after the accident to facilitate the reduction of environmental contamination and to accelerate the remediation of the Fukushima area (METI, 2011). Thus, the plant operator TEPCO (Tokyo Electric Power Company), with the support of research centres and academic institutions of Japan, is working on several strategies to cleanup and decommission the nuclear plant. The approach focuses on isolating the contamination source, at the same time that hazardous wastes accumulated are being treated on site. Some of the concepts are innovative, while other methods were extrapolated from the stabilisation of tunnels and shafts in the fields of civil and mining engineering. Nonetheless, the magnitude of the FDNPP accident and the scale of the associated contamination are unprecedented, raising concerns about the practical effectiveness and limitations of the implemented strategies. Due to the unique nature of the remediation works, it is important to recognise that there is a "learning by doing" curve, which requires a process of knowledge capture, especially the tacit knowledge represented by the experience of the teams involved (Hardie and McKinley, 2014). Substantial information has recently been published about the spatial distribution of contaminants in soils, and the impact of the accident on the marine environment (e.g. Matsuda et al., 2015; Mikami et al., 2015; Yu et al., 2015; Tateda et al., 2015). However, there is a notorious scarcity of reliable data about the remediation works and actions taken to manage radioactive contamination at Fukushima. Information about countermeasures to control pollution is largely being channelled through the media, with limited participation of the scientific community. This paper attempts to fill that gap by providing an overview of large-scale strategies being implemented to manage groundwater contamination and to mitigate the dispersion of radionuclides through hydrological pathways at the FDNNP. In particular, the study outlines those measures aimed at eliminating the source of groundwater pollution and intercept further radionuclide releases into the ocean. The manuscript is expected to be a reference not only for technical experts, but to also provide concise and clear information for the general public.

2. Location and geological setting

The FDNPP occupies an area of about 3.5 km^2 on the coastal area of Futaba, in the Prefecture of Fukushima, approximately 260 km (km) north of Tokyo. The site hosts six boiling water reactors apportioned in two groups: units 1 to 4 to the south, and units 5 and 6 to the north. The devastating tsunami of March 2011 caused severe damage and radioactive escapes from three operating reactors (R1–R3), and to a lesser extent it affected the neighbour R4, whose fuel had been previously removed. At the time of the incident, the remaining reactors (R5–R6), had been shut down for routine maintenance.

The nuclear plant sits on the alluvial deposits of the Hamadori belt, a stretch of Quaternary sand terraces that extend north–south between the Abukuma Granites to the west, and the Pacific Ocean to the east. The bedrock in the Abukuma Mountains is composed mainly of Early Cretaceous granitic rocks (Kubo et al., 2004). To the east, the granites are delimited by the Futaba Fault, a deep angle tectonic structure that separates the crystalline basement from the sedimentary deposits along the coast. More specifically, the FDNPP lies on a coastal terrace at an elevation of about 35 m above sea level ("level 35"), which was partly lowered to 10 m to build the reactor facilities ("level 10"). Auxiliary buildings and the port services were constructed at a lower bench "level 4", in proximities to the shoreline (Fig. 1).

Borehole data in the vicinities of the plant indicates that the Quaternary terraces are underlain by sediments of the Tomioka Group, from the Neocene. These deposits are constituted by a succession of marine to fluvial sediments dipping approximately 2° to the east. The Stratum I or Mid-sand consists of medium grain-size sandstones of crude to non-existing bedding that reach a maximum thickness of 20 m (Table 1). The hydraulic conductivity of the unit is estimated to range from 2 to 4×10^{-3} cm/s (Marui, 2014). The underlying unit (Stratum II or mud-layer), is constituted by the intercalation of silts and mudstones with a thickness in the order of 5 to 7 m. Pumice particles and tuffs are also present within the layer. An intercalation of sands and clays known as Stratum III or Alternating Strata lies beneath. The sandstones in this unit are light-coloured, quartz-rich, and contain angular fragments of chert that suggest a more rapid deposition within the marine basin. Both, the Stratums II and III provide the foundation for the reactors and buildings at the FDNPP. Sediments of the deeper Stratum IV comprise a sequence of mudstones and minor sands with a maximum thickness of 30 m. The upper member is coarse-grained although it becomes finer upwards. Bedding is uncommon, whilst the presence of rounded quartz would reflect the high maturity of the sediments. In contrast, the lower member of the Stratum IV is dominated by pelite and siltstones including some isolated sand lenses essentially massive. The basement of the sequence is constituted by mudstones, graywackes, and tuffs of the Tomioka Formation, from the Oligocene–Miocene. These sediments correspond to neritic and pelagic facies in a marine environment, with minor pyroclastites derived from atmospheric deposition.

Measurements at the nearby Tomioka weather station since 1981 indicate that on average, precipitation is in the order of 1550 mm/year (Japan Meteorology Agency, 2015). Considering that evaporation reaches about 700 mm/year, and that the estimated runoff coefficient for relatively flat areas with natural ground cover is in the range of 0.1 to 0.2, the superficial aquifer would receive between 540 and 695 mm of recharge from rainfall alone. Dewatering activities have artificially lowered piezometric heads below the base of the reactor buildings therefore, the bulk of the groundwater currently flows through the sandy layers of the Stratum III–Alternating Strata. This unit constitutes thus a leaky aquifer fed both from upper units as well as by inflows from the western margin of the premises.

Even when most of the radionuclide concentrations in groundwater were measured near the surface, anomalous levels of tritium (^{3}H) were detected up to 30 m below the base of the reactors. This suggests a high degree of hydraulic connectivity between shallow units. The migration of soluble species downwards and the potential contamination of deep aquifers must be managed not only by removing pollution at surface, but through the elimination of the relevant pathways that mix dissolved radionuclides with freshwater.

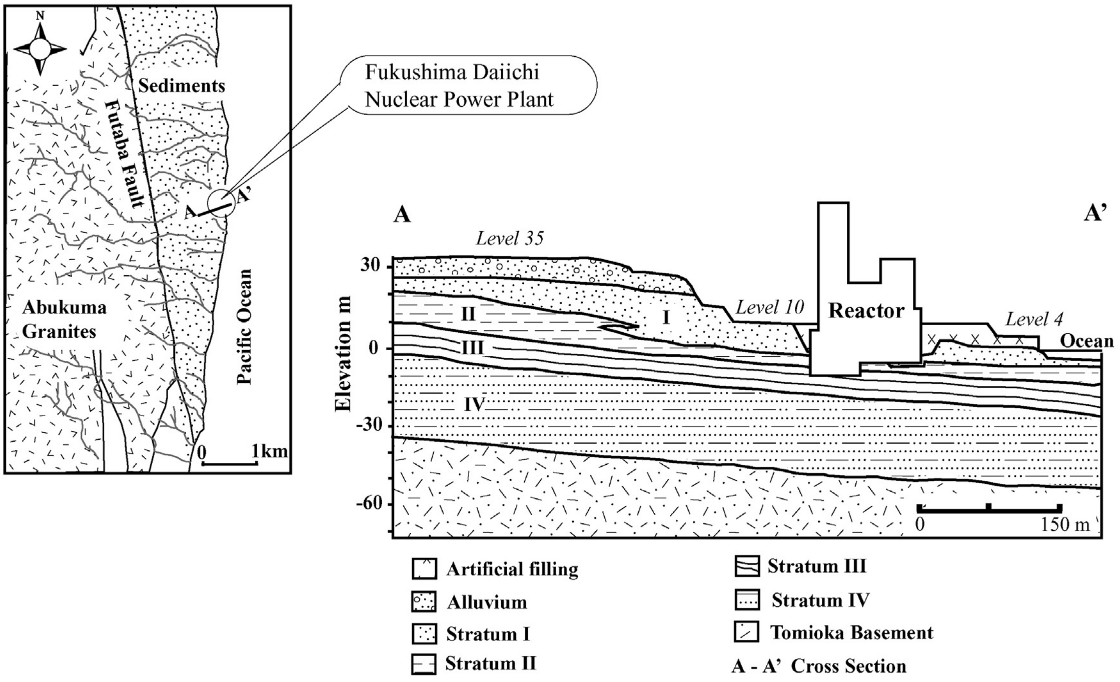

Fig. 1. Location and geological setting in vicinities of the Fukushima Daiichi nuclear power plant.

3. Results and discussion

Management of groundwater contamination and decommission of the Fukushima FDNPP rely on three basic policies: 1) to remove and treat existing contamination; 2) to isolate freshwaters from the contamination source; and 3) to prevent leakage of contaminated water. In this context, a number of large-scale measures are being implemented (Table 2):

- Storage tanks and water treatment
- Seaside impervious wall
- Ice wall
- Groundwater bypass
- Facings

3.1. Storage tanks and water treatment

The problem of groundwater contamination at Fukushima starts in the Abukuma Mountains. It is estimated that 400 m^3/day of fresh groundwater flows from the peaks overlooking the complex toward the reactor halls, where it mixes with contaminated waters generated from cooling operations (Coghlan et al., 2013). In line with the removal and treatment policy, contaminated water is pumped out and temporarily stored on site in approximately 900 tanks, each holding a maximum of 1000 m^3 (Fig. 2). Approximately 630,000 m^3 of water has been treated so far, whilst an additional 100,000 m^3 are waiting to be removed for further processing (TEPCO, 2015a). The tanks constituted an effective first response to contain the increase of radioactive water, but they are not devoid of limitations. In effect, tanks have a finite life span, whilst spills and leakage incidents are an ongoing problem (Fig. 3). In this respect, approximately 300 m^3 of highly radioactive effluents escaped to the ground in August 2013 (Jiji Press, 2013). Another 100 m^3 of water with beta particles exceeding 200 million Bq/L was discovered to leak from a storage tank in February 2014. Additionally, several other events are being disclosed by TEPCO on a regular basis. Measures such as replacing bolt joints with welded joints, installation of collection gutters, use of radiation-resistant pipes, tanks with double shell structures, and construction of breakwaters against typhoons and tsunamis, were all undertaken to minimize the risk of leakage and potential outflows into the shallow aquifers and ocean.

Tanks are expected to reach full capacity within 3 years. Since December 2013 however, their installation has expanded at a rate of 15 additional tanks per month. As a result, the total storage capacity by the end of 2015 would be close to 800,000 m^3. Tsunamis and potential releases to the ocean are the primary hazards that prevent the

Table 1
Stratigraphy of the superficial sediments in the Hamadori Belt.

Unit	Age	Maximum thickness m	Main lithology	Average hydraulic conductivity cm/s
Alluvium & terrace deposits	Quaternary	15	Mid to coarse sand with subordinated gravel — unconsolidated	–
Stratum I	Pleistocene	20	Massive mid-grain sandstone with subordinated siltstones	2 to 4×10^{-3}
Stratum II	Pleistocene	7	Mudstone and siltstones — minor pumices	1×10^{-6}
Stratum III	Pleistocene	8	Alternation of mid-grain sandstones and sandy siltstones	8.1×10^{-3}–2.4×10^{-4}
Stratum IV	Pleistocene	30	Pelites and siltstones with subordinated fine to coarse grained sandy layers on the top	Muddy part: 1.2×10^{-6} Fine-grained sandstone 5.1×10^{-3} to 10^{-4} Coarse-grained sandstone 4.4×10^{-3} to 6.2×10^{-4}
Tomioka Formation	Oligocene–Miocene	120	Graywackes, mudstones and minor pumice tuffs	–

Table 2
Outline of major strategies to control groundwater contamination at the FDNPP.

Policy	Major measures	Status
Remove & treat contamination	Collecting water in tanks on site	Ongoing
	Water purification in trenches	Ongoing — when required
	Purification by multi-nuclide removal equipment (ALPS; KMPS)	Ongoing
	Capture of Sr from leakage	Under investigation
Isolate freshwater from the contamination source	Seaside impermeable wall	Completed
	Ice wall	Ongoing — mountain side completed
	Groundwater bypass	Ongoing
	Bore rehabilitation	Completed
	Subdrain system	Ongoing
	Facings	Ongoing (>80% completed)
Preventing leakage	Replacing steel horizontal tanks	Ongoing
	Replacing bolt-joint tanks	Ongoing
	Increasing tanks' number and storage capacity	Ongoing
	Installation of leakage detecting systems	Under investigation
	Reinforcement of patrols in tanks' area	Completed
	Runoff rerouting and installation of gutters and drainage channels	Ongoing
	Breakwaters and buildings' reinforcement	Completed

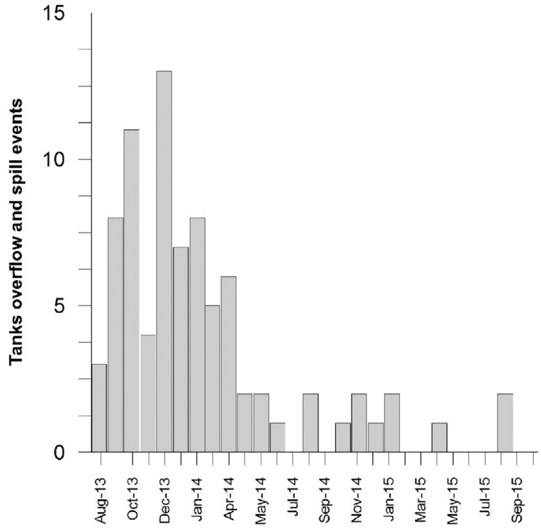

Fig. 3. Reported events related to leakage or overflow of storage tanks.

installation of tanks near the coast. Thus, only the highlands west of the plant are considered appropriate for the storage. As expected, constrains on the available space means that the number of tanks cannot grow indefinitely. In this regard, additional actions are required to equilibrate the amount of contaminated waters with the storage capacity of the tanks. Public anxiety and strong opposition from local fisheries have typically precluded direct releases into the ocean, highlighting the need to rapidly implement additional clean-up works that reduce the volumes of waste water being generated. As it will be discussed in the following sections, shut-off walls and a dewatering bore network would restrict groundwater inflows into contaminated areas and therefore, contribute to maintain the long-term storage capacity of the site. Additionally, higher efficiency in the purification process is being tested with new technologies such as ALPS (advanced liquid processing system), and KMPS (Kurion mobile processing system). The ALPS units are designed to accelerate the purification of a broad range of contaminants in the stored waters, whilst the KMPS system is especially relevant for the removal of ^{3}H. Both systems are still under trial after a

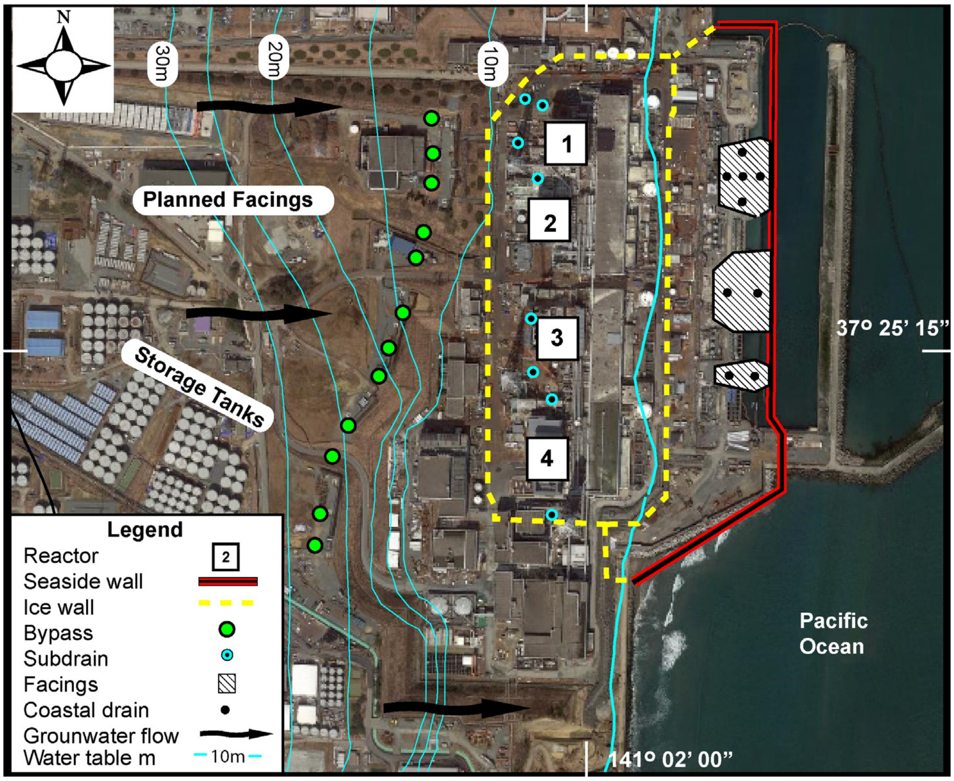

Fig. 2. Plan view of storage facilities and engineering works to contain radioactively contaminated groundwater.

number of setbacks and technical difficulties that put the initiative at stake on several occasions. Even though the challenges to reach full-scale operations remain, recent changes in the adsorption materials has largely improved the removal capacity of more resilient nuclides such as ^{60}Co, ^{129}I, ^{125}Sb, and ^{106}Ru (TEPCO, 2015b). Removal of nuclides below detection limits would eliminate the long-term toxicity of the wastes and open the possibility for the transfer of waters offsite, while research for disposal in a deep geological repository progresses.

3.2. Seaside impervious wall

Cracks in the reactor foundations combined with potentially inefficient methods for collecting cooling water most certainly led to direct radionuclide inputs to the local aquifer and subsequent transport to the coastal ocean via submarine groundwater discharge (Charette et al., 2013). Although offshore waters are safe with respect to international standards for radionuclides in the ocean (Buesseler et al., 2012), public concerns about Cs levels in marine products remain high. In this regard, the seaside impervious wall constitutes a fundamental measure to block the flow contaminated water into the ocean. After more than 3 years of work, a steel–pipe barrier has been completed along the shoreline in front of reactors 1 to 4 to intercept surface runoff and groundwater outflows from the alluvium and the sandy beds of the Alternating Strata (Fig. 4). Each pile is connected with a sealing rubber to improve the shutoff of the wall. Furthermore, a group of abstraction bores informally known as “drains” were installed at regular intervals on the coastal plain of “level 4” to prevent the embankment and consequent rise of the water table. The amount of pumped water is approximately 100 m^3/day, although the system is able to abstract up to about 800 m^3/day if required (TEPCO, 2015c). Dewatering has been more challenging in vicinities of Reactor 2, where piezometric levels rose up to 8 cm/day following the wall construction. Soils heterogeneity and a local reduction in the aquifer transmissivity might be the reason behind the observed changes. Abstracted water is temporarily held in the storage tanks for purification, and it will be eventually drained to the sea upon water quality verification.

Long-term data will be necessary to properly assess the effectiveness of the seaside wall, which became fully operational in late October 2015. Nevertheless, some inferences can still be made. At a first glance, changes in piezometric levels and radioactivity contents suggest that the barrier could be an effective mechanism for ocean protection. In effect, water levels in the drains rose up to about 1 m during and after the wall completion due to the interception of groundwater flows toward the ocean (TEPCO, 2015d). In addition, seawater at the “shallow draft quay” monitoring point within the plant port exhibited a steady reduction in ^{137}Cs concentrations after April 2012, period mostly concomitant with the placement of the steel pipes in the shoreline. Further drops in radionuclides were recorded in the last trimester of 2015, possibly as a result of the wall closure (Fig. 5). Similarly, the figure shows that fish with radioactivity levels exceeding permissible levels for human consumption (100 Bq/kg) have steadily declined from about 58% of the sample population in 2012, to almost none after April 2015 (Fisheries Agency of Japan, 2015). Nevertheless, the evidence about the wall performance is not definitive. The radioactivity in fish has declined at a different rate than radionuclide concentrations in seawater. The fact that ^{134}Cs and ^{137}Cs in fish, particularly in bottom-dwelling species, remained elevated for a long time, supports the hypothesis that a source of continue contamination might lie in the seafloor (Buesseler, 2012). Furthermore, a few seawater samples still show radioactivity contents higher than the WHO (2011) guidelines of 10 Bq/L, while some ^{137}Cs increases have been recorded in the coastal waters of stations T-1 and T-2, on the boundaries of the power-plant (NRA, 2015). This suggests that radioactive elements might still be transported into the FDNPP waters to be later dispersed by coastal currents. Radiocaesium would selectively adsorb to organic matter or certain clay minerals (Vejsada et al., 2005; Sakai et al., 2015). As such, it could adhere to granular materials and be mobilised either by aeolian or hydrological processes. In this regard, there may be radiocaesium storage within catchments in forests, floodplains and hillslopes that may be remobilised and contaminate downstream areas, even areas that did not receive fallout or may have been decontaminated (Evrard et al., 2015).

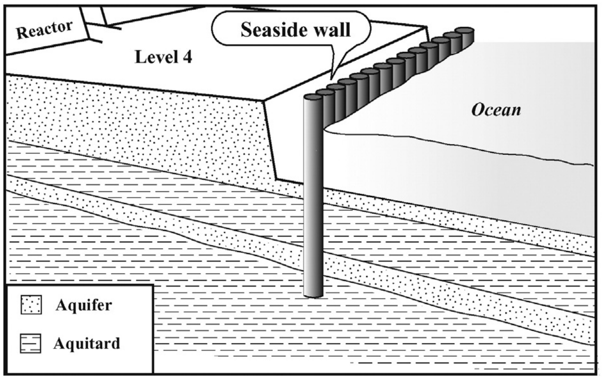

Fig. 4. Schematic representation of the seaside wall along the shoreline of the nuclear plant.

3.3. The ice wall

A second impervious barrier informally known as the ice wall is being constructed around the reactors to intercept groundwater fluxes to and from the buildings. Artificial ground freezing (AGF) appeared 150 years ago in the coal mines of South Wales, and is particularly widespread in civil and mining engineering, as well as for the containment of hazardous waste in environmental projects (Andersland and Ladanyi, 2004; Vitel et al., 2015). A successful test was initially carried out in March 2014, opening the way for a large-scale design which is scheduled to be in use until 2020. Thus, the purpose of the structure is twofold: it prevents groundwater from the uplands from reaching the basement of the reactors where radioactive water is accumulated; at the same time, a restricted groundwater inflow translates into a gradual decline of water levels and the consequent reversal of hydraulic gradients inside the walls. The reactors basements are thus kept isolated, and contaminated water is prevented from flowing out of the buildings.

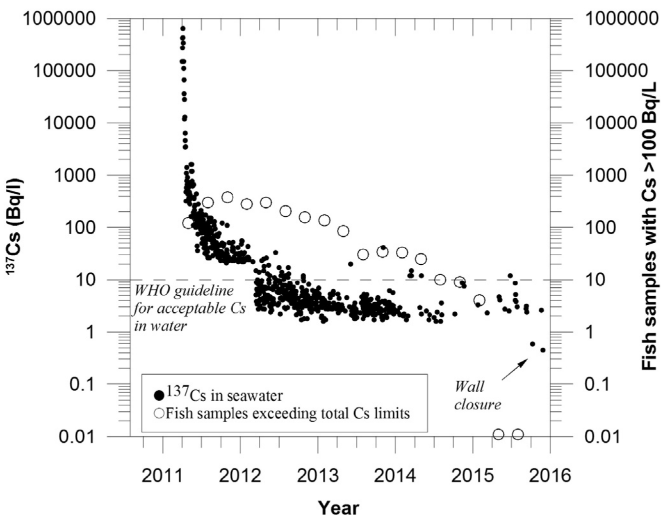

Fig. 5. Evolution of ^{137}Cs concentrations in seawater (after TEPCO, 2015f) and fish in the coastal waters of Fukushima (modified from Fisheries Agency of Japan, 2015). Note: lower density of points after 2014 due to increase in ND (not detected) ^{137}Cs measurements.

The wall will extend for over 1500 m to enclose the perimeter of the reactors in a design that freezes the surrounding ground to a depth of 30 m (Fig. 6). A row of underground pipes are vertically installed at a space interval of 1 m, and a calcium–chloride refrigerant is circulated through a double tube system that generates a permafrost layer on the surrounding soils. Once the refrigerant begins circulating, pore water readily turns to ice reducing the ground permeability whilst increasing the strength and stiffness of the sediments. Maximum ice growth would occur about a month after the commencement of freezing.

Due to the complexities associated with construction, the wall is being developed in stages. Work focused mainly on the land-side of the structure to prioritise the reduction of groundwater inflows into the buildings. Following the completion of this section a new phase of drilling has been initiated in October 2015 to install the first freezing pipes on the coastal margins of the system.

The frozen wall is expected to play a critical role in the control of groundwater contamination, as it is estimated that once it is fully operational, the volumes of water reaching the reactors will be reduced to less than 30 m^3/day. Despite promising expectations, the full-scale application of the technology remains uncertain. Onsite experiments by TEPCO showed that stratification and sediments' heterogeneity affect heat conduction and consequently, create a variable ice distribution in the porous media. Typically, saturated sands freeze faster and achieve a more effective strength than fine-grained materials such as silt and clays, usually devoid of interstitial water. Additionally, the intensive energy consumption required to attain freezing may be prohibitively expensive and eventually unsustainable over the long-term. At an estimated annual cost of 2 billion yens (~$17 M), running the system will put great pressure on the available resources. On a more optimistic note however, it is argued that once the frozen soil achieves its designed thickness thermal conduction approximates a steady state and therefore, the system can be operated at a reduced rate. This is in line with numerical simulations that indicate that upon freezing, maximum power is no longer necessary and cooling elements can be switched to maintain the temperature (Simmaker, 2015). Expanding the debate, a significant decline of water levels inside the ice barrier might enhance the compaction of clay beds in the Stratum II and promote in land subsidence. Subsidence has been noticed along the Pacific coast due to crustal deformation and soil liquefaction caused by the Tohoku earthquake (Imakiire and Koarai, 2012). As expected, sediments desaturation may lead to an increase in the ground effective stress and soil fracturing. Thus, even relatively modest subsidence can cause structural failure and further damage to buildings. At this stage, there is no compelling evidence to quantify such a risk. However, soil mechanical properties are intrinsically linked to the history of the land and therefore, it is critical to carefully monitor the soil dynamics to early detect any potential deformation around the reactors.

In summary, the large scale of the operations means that several uncertainties remain in place, but yet, the ice wall raises high hopes for a drastic reduction in the inflows to the reactors.

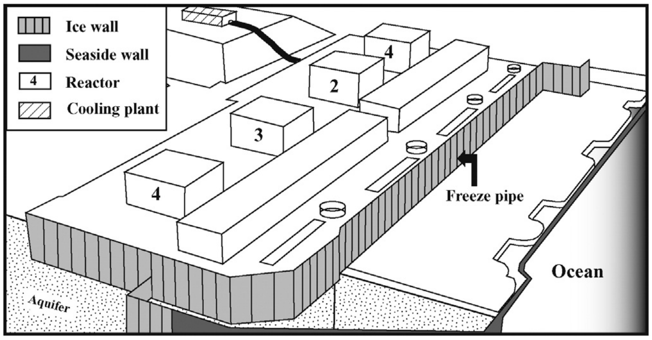

Fig. 6. Overview of the wall barriers around the nuclear reactors.

3.4. Groundwater bypass

Inflows into the reactors are being further reduced by pumping groundwater out of level 35, on the mountain side of the power plant. The system, known as groundwater bypass, consists of 12 bores that intercept clean groundwater flowing downhill, and reroute it around the facilities before it interacts with contaminated waters accumulated in the reactors. Collected water is temporarily held in the tanks to confirm that it is of acceptable quality for release into the environment. Bypassed groundwater is essentially natural water therefore, it was agreed with local fisheries that discharges to the ocean may take place under stringer concentration limits such as 1 Bq/L for Cs, 1500 Bq/L for ^{3}H, and 5 Bq/L for total β. Strontium levels are required to be below 10 Bq/L as per the WHO (2011) guidelines. Distrust and concerns about the potential spread of the contamination at sea were eased by requesting independent parties such as the Japan Chemical Analysis Centre and the Japan Atomic Energy Agency (JAEA) to monitor water quality before any release. Recent measurements of radionuclides in discharge waters at the plant port indicate a close match between data collected by the plant operator and external parties, with values well within the established permissible levels (Table 3). Further confidence is added by tracer and simulation studies on long-term dispersal of ^{137}Cs in the near-shore environment (e.g. Dietze and Kriest, 2011; Behrens et al., 2012). Findings from these investigations indicated that the Pacific Ocean around Fukushima is stirred by energetic, fluctuating currents on various scales, all contributing to an effective dispersion of the contaminated body of seawater. Unlike contamination of soils on land, vertical and horizontal mixing rates in the ocean are fast, diluting the contaminant signal quite rapidly, particularly where the Oyashio waters move south and interact with the offshore meandering of the Kuroshio Current (Buesseler et al., 2011).

At full operation, the bypass diverts approximately 80 m^3/day of the flow toward the reactors, at the same time that alleviates the pressure for long-term storage space into the tanks.

An additional pumping system, the subdrain, serves as a complement to prevent water from flowing in/out of the reactors. Twenty seven abstraction bores damaged by the tsunami were rehabilitated, whilst an additional 14 wells were installed all around Units 1 to 4 to further dewater the basement of the buildings. Groundwater abstraction successfully commenced in September 2015 at 20 bores. Again, the water is kept in storage until third-party tests confirm that it has been treated to stringent standards, and only then it is discharged into the port area adjacent to the plant. Once fully operational, the subdrain alone is expected to reduce the total daily accumulation of water by approximately 200 m^3 (TEPCO, 2014).

Due to the proximity of the wells to the reactors, radioactive contents in the abstracted groundwater are occasionally high. Peaks up to 8800 Bq/L for ^{137}Cs, and 10,000 Bq/L for gross β were occasionally detected at some of the subdrain outlets during mid-2015 (TEPCO, 2015c). These elevated radionuclide concentrations imply that waters from the subdrain system require more intensive monitoring and treatment than their bypass counterparts before any release can be considered.

Preliminary results suggest that the contribution of the subdrain could have been overestimated. Numerical simulations predicted that groundwater levels on the coastal side of the reactors would decline up to about 1 m. In contrast, water levels were observed to decline an average of 0.2 m, significantly less than the expected rates. It can be argued that conceptual models are inherently based on simplifications of the real system, which can hardly mimic local heterogeneities and the entire anisotropy of the aquifer. Nonetheless, it is still early to make generalisations, as the system is not working at full capacity. In addition, groundwater measurements are preliminary and subject to revision therefore, longer term observations will be necessary to reliably assess the effectiveness of the subdrain.

Table 3
Radionuclide concentrations in discharged waters from the bypass system during the second semester of 2015 (after TEPCO, 2015e).

	2 August		27 August		24 September		22 October		19 November		Operational target
	TEPCO	Third parties	TEPCO	Third parties	TEPCO	Third parties	TEPCO	Third parties	TEPCO	Third parties	
Discharge (m^3)	2520	2660	2660	2660	2670	2670	2330	2330	2170	2170	
^{134}Cesium	0.71	0.56	0.72	0.81	0.67	0.73	0.63	050	0.78	0.64	1
^{137}Cesium	0.63	0.71	0.53	0.55	0.58	0.55	0.67	0.58	0.57	0.57	1
Total β	0.89	0.52	0.80	0.49	0.90	0.59	0.68	0.54	0.85	0.51	5
Tritium	140	130	130	140	170	190	160	160	140	140	1500

Units: Bq/L.

3.5. Facings

The flat lands and slopes around the nuclear plant are being covered with an asphalt layer or facings that restrict rainfall recharge and contribute to a general reduction of the water table. The ultimate purpose of the strategy is to minimize seepage and prevent thus, any rainwater from being mixed with the contamination plume. The facings are especially suited to the plateau of level 35, which constitutes the main area of recharge for the local aquifers. As a first step, wide areas of the premises were cleared and paved, although the removal of large volumes of debris and stripping of the contaminated topsoil make the works challenging to the least. How much soil must be removed is still under debate. Section soil samples from Kawamata, in the northern part of the Fukushima prefecture, showed that approximately 80% of the deposited radiocaesium and ^{131}I were adsorbed in the upper 2 cm of soil (Kato et al. 2012). Similarly, Matsuda et al. (2015) indicated that radioactive Cs from 71 sampling sites around the FDNPP remained within 5 cm of the ground surface at most locations. In some cases however, temporal changes to the depth profiles have been observed after several years, in which maximum Cs concentrations moved toward deeper soil horizons (He and Walling, 1997). Rodent burrows, fractures, texture and lithological variations are all factors that can alter the soil profile and the distribution of ^{137}Cs within the aquifers. Radionuclide concentrations in fish could also suggest the ultimate migration of radionuclides to the marine environment. In this line, Niimura et al. (2015) indicated that the ^{134}Cs and ^{137}Cs emitted by the accident fell into the ground as a granular material which does not become ionic and therefore, would not be available to be adsorbed into soils. This has important implications in relation with climate and the trapping capacity of the sediments. Chartin et al. (2013) demonstrated that both rainfall and snowmelts result in a progressive mobilisation of sediment-bound radiocaesium to the Pacific Ocean in Fukushima. Runoff rates and the washout of granular material could accelerate with the snowmelts of spring and the typhoons that arrive in late summer. Thus, the facings also mitigate erosion and would further delay the migration of contaminated soils downstream. Work by Yamazawa and Hirao (2012) showed that most of the airborne radioactive deposition was released after March 14, 2011. No significant deposition would currently take place. Nevertheless, the facings constitute an additional barrier against potential fallouts from unexpected blasts or due to gradual emissions from cracks in the reactors.

Given the porous nature of the surface, the asphalt is typically laid on top of a well compacted aggregate, with a geotextile fabric underneath. Sediments accumulation and clogging of the pore spaces reduce the pavement porosity and further restrict infiltration into the subsoil. Laboratory testing found that the permeability of the surface decreases to around 30–50% after approximately 30 years (Argue, 2004). In contrast, the asphalt may also deteriorate due to gradual water seepage, soil movements or vehicle traffic. Small cracks and potholes, soil deformation, and a rising water table all reduce the facings strength and enhance percolation of rainwater. Therefore, regular inspections and a maintenance schedule similar to conventional roads are essential to maximise the performance and life span of the materials. As with any impermeable surface, the paving translates into higher runoff during storm events. Overland flow is being managed by local interspacing of permeable materials such as pebbles, and the installation of additional gutters and trenches.

To be extended over a total of 2 km^2, the effects of the strategy is expected to be seen over the medium-term, at least 2 to 3 years after completion. Groundwater flow simulations indicate that facings alone may not produce immediate effects, but they are expected to play a major role to supplement the other countermeasures (METI, 2013).

4. Summary and conclusions

We discussed a number of large-scale measures undertaken to manage groundwater contamination at Fukushima after the earthquake and tsunami on March 11, 2011. Damage of the reactors permitted the infiltration of radionuclides into local aquifers, and their ultimate transport to the coastal ocean by groundwater. Contaminated water is being currently held in tanks for posterior purification. Advanced technologies such as the ALPS and Kurion systems are being implemented to accelerate the cleanup of radioactive wastes in the tanks. Nevertheless, space constrains, the limited life-span of the containers, and the continuous risk of leakage means that the storage can only be considered temporary. The use of tankers stationed at sea and the construction of an underground repository have been evaluated as long-term measures to store contaminated water, but their feasibility is not conclusive. Thus, it became imperative to prevent further contamination of fresh groundwater and its dispersion into the surrounding environment. A number of strategies were devised to restrict groundwater influx to/from the reactors, and to intercept outputs into the ocean. An impervious wall has been built along the coast, in front of the reactor buildings. The structure is complemented with a network of abstraction bores that reduce the volumes of water reaching the shoreline. A steady decrease in ^{137}Cs in seawater at the plant port would suggest the system is effective. However, some caution is required, as a source of continue contamination might still lie in the nearby catchments or the seafloor. Additional flows will be precluded by a second impervious wall surrounding the reactors. The principle is to circulate a fluid coolant through underground pipes so as to freeze the ground and to form a continuous ice barrier. The technology has long been used in civil and mining engineering and therefore, appears to be suitable for the containment of hazardous wastes. Its main drawback is the intensive energy consumption and hence, the high costs of maintaining long-term frozen conditions. Other strategies to isolate the pollution source consist of diverting clean groundwater on the land side of the power plant before it mixes with waters accumulated in the reactors. Supplementary bores were installed in vicinities of units 1 to 4 to induce drawdowns and further reduce inflows to the facilities. The effectiveness of the system remains dubious as the decline in piezometric levels has been limited, probably due to aquifer transmissivities greater than expected.

An asphaltic lining is also being built to control soil erosion and the effects of climate, especially in relation to snowmelts and the frequent typhoons that hit the region in summer. The impervious surface restricts rainfall infiltration, provides protection against the unlikely fallout of airborne particulates, and more importantly, minimizes the potential transfer of sediment-bound radionuclides downstream. The effects of the facings would be visible 2 to 3 years after completion.

Significant uncertainties remain about the effectiveness of the adopted measures. Even though some of the techniques were previously tested in other disciplines, the scale of the contamination, public distrust, and the political demand for a rapid solution pose an unprecedented challenge to the site remediation. It is anticipated that the experience being gained during mitigation procedures will contribute to optimise the described measures, and lead to the development of new techniques for the control of groundwater pollution in the area.

Conflict of interest

The authors declare that they have no conflict of interest that could impact or bias their work.

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