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

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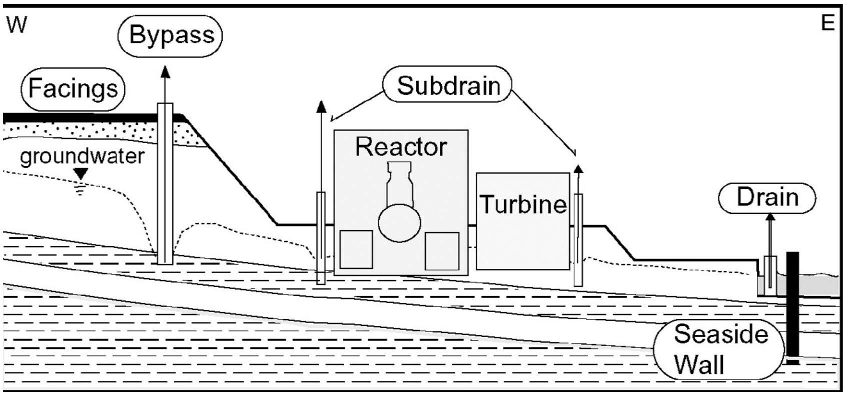
HIGHLIGHTS

- 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.