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Renewed soil erosion and remobilisation of radioactive sediment in Fukushima coastal rivers after the 2013 typhoons

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Summer typhoons and spring snowmelt led to the riverine spread of continental Fukushima fallout to the coastal plains of Northeastern Japan and the Pacific Ocean. Four fieldwork campaigns based on measurement of radioactive dose rates in fine riverine sediment that has recently deposited on channel bed-sand were conducted between November 2011 and May 2013 to document the spread of fallout by rivers. After a progressive decrease in the fresh riverine sediment doses rates between 2011 and early spring in 2013, a fifth campaign conducted in November 2013 showed that they started to increase again after the occurrence of violent typhoons. We show that this increase in dose rates was mostly due to remobilization of contaminated material that was temporarily stored in river channels or, more importantly, in dam reservoirs of the region during the typhoons. In addition, supply of particles from freshly eroded soils in autumn 2013 was the most important in areas where decontamination works are under progress. Our results underline the need to monitor the impact of decontamination works and dam releases in the region, as they may provide a continuous source of radioactive contamination to the coastal plains and the Pacific Ocean during the coming years.

A large soil radioactive pollution plume covering ca. 3000 km² with ¹³⁷Cs contamination exceeding 100 kBq.m⁻² formed across Fukushima Prefecture, in northeastern Japan, following Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident¹⁻². As radionuclides are strongly sorbed by fine particles, they are likely to be redistributed on hillslopes and supplied to the rivers, in association with the particles mobilized and transported by erosion processes³. Dispersion of radioactive material along rivers may lead to an increase in the radiation external exposure of populations living in downstream plains even though those areas were relatively spared by initial radioactive fallout⁴. In addition, the transfer of contamination to the food chain and particularly to fish and rice may also affect human activities in this region⁵, where agriculture and fishing represent important sectors of activity. As continuous river monitoring was lacking in this region during the months that followed the accident, alternative tracking methods were developed to quantify the dispersion of radioactive sediment along rivers. An original method consisted in using the spatial pattern of radioactive fallout (i.e., the variable ^{110m}Ag: ¹³⁷Cs activity ratio) in soils to track the export of riverine sediment⁶. However, due to the rapid decay of ^{110m}Ag (half-life of 250 days), this technique can no longer be used. Another technique consisted in measuring radioactive dose rates (dominated by cesium – both ¹³⁴Cs and ¹³⁷Cs – gamma emissions) on soils and fine sediment that appeared to have recently deposited (i.e., mud drapes on channel-bed sand) along rivers draining the main radioactive pollution plume. A previous study based on four fieldwork campaigns conducted twice a year after the summer typhoons and the spring snowmelt in 2011–2012 showed that the succession of those hydro-sedimentary events led to the rapid dispersion of radioactive material along coastal rivers draining the main contamination plume⁷. However, this study showed that radioactive dose rates in riverine sediment decreased dramatically in May 2013 across the entire region. Those findings suggested that the upstream sources of contamination in paddy fields may have dried up. As several violent typhoons occurred in the region during summer in 2013, a fifth fieldwork campaign was organized in November 2013 to investigate their potential impact on renewed soil erosion and sediment dispersion across the region. We used local ground dose rate measurements



to estimate whether fresh sediment drape deposits were more or less contaminated than local soils. We compared them to the dose rates measured during the previous campaign (i.e., May 2013) to document an entire annual cycle (i.e., comprising the succession of summer typhoons and spring snowmelt) of sediment dispersion in Fukushima coastal catchments draining the main inland radioactive fallout plume⁷ (Fig. 1).

Results

Occurrence of typhoons in 2013. During autumn in 2012, neither typhoon nor heavy rainfall event (with daily cumulative precipitation exceeding 60 mm) occurred across Fukushima region. In contrast, two violent typhoons (i.e.; Man-Yi and Wipha) led to heavy rainfall (70 to 90 mm/day) in the region during autumn in 2013 (Fig. 1a). Consequently, the dam located on Mano River had to be opened on October 16, 2013⁸ and was still open during our sampling campaign in early November 2013. According to our on-site observations in the field, Takanokura dam was closed whereas Yokokawa dam on Ota River was opened in early November in 2013 (Fig. 1b).

Radioactive dose rates in fresh drape sediment deposits compared to soils. Although dose rates should systematically decrease in soils and sediment because of physical decay of radiocesium and occurrence of soil erosion between successive campaigns, we observed an increase in dose rates in fresh riverine sediment at 76% of the sites

where measurements were conducted in November 2013 compared to the situation in May 2013 (Fig. 2). This illustrates the occurrence of soil erosion and/or remobilization of contaminated material stored in the alluvial plains or in dam reservoirs during the strong typhoons that affected the region during autumn in 2013. This increase is particularly clear in upper parts of Nitta and Mano River catchments and in coastal plains of all investigated catchments (Fig. 2b).

Evolution of radioactive dose rates in fresh drape sediment deposits between May and November 2013. Comparison of radioactive dose rates between fresh sediment deposits in rivers and nearby soils provides indications on the processes that controlled the dose increases mentioned in the previous section (Fig. 3). In Mano River catchment, the spring snowmelt in 2013 led to a clear dilution and dispersion of the radioactive contamination to the Ocean (Fig. 3a). Then, the autumn typhoons led to the supply of fresh material to the river in the entire catchment. However, radiation doses associated with those fresh sediment deposits remained generally lower than in nearby soils, except in the coastal plains (Fig. 3b). This dispersion of contaminated material to the Ocean was also observed in the Odaka River catchment. In the Nitta River catchment, material conveyed by the river across the coastal plain to the Ocean in May 2013 was strongly contaminated, whereas contamination of sediment was much lower in the riverine deposits than in nearby soils in the

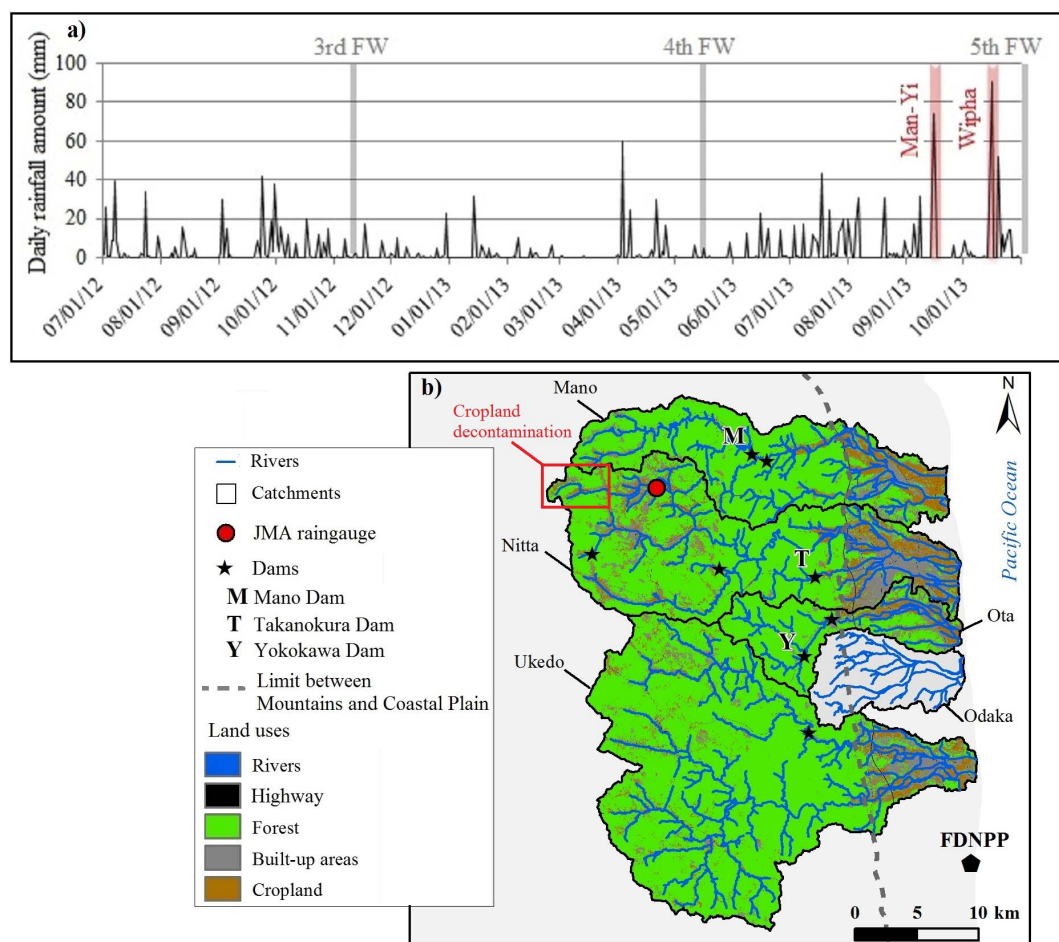


Figure 1 | (a) Rainfall measured at the Japan Meteorological Agency raingauge located in the upper part of the Nitta catchment, and occurrence of Man-Yi and Wipha typhoons during autumn in 2013. (b) Land use map of the investigated coastal catchments (with the exception of the Odaka River catchment). FW stands for fieldwork campaign and FDNPP stands for Fukushima Dai-ichi Nuclear Power Plant. The results of the first four FW campaigns are described in previous publications⁶⁻⁷. Location of the main dams and the ongoing decontamination works taking place in the area is also indicated. This original map was created using ArcGIS 10 software.

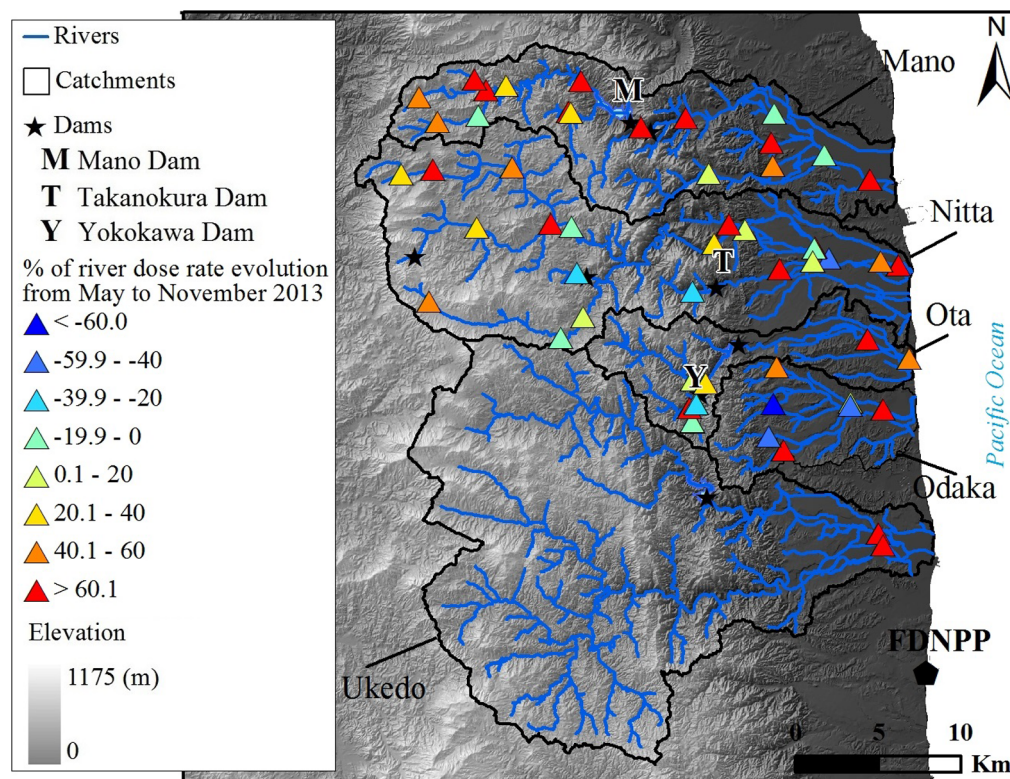


Figure 2 | Percentage of change in radiation dose rate measured above river sediment from May to November 2013. FDNPP stands for Fukushima Dai-ichi Nuclear Power Plant. This original map was created using ArcGIS 10 software.

mountainous part of the catchment (Fig. 3a). In November 2013, the supply of freshly eroded and contaminated material was clearly observed in upper parts of the same catchment (Fig. 3b). In upper parts of the Ota River catchment, source of contamination material seems to have dried up (Fig. 3a–b). It might have accumulated behind Yokokawa dam, where the presence of a thick sequence of strongly contaminated material was shown to have deposited⁶. However, the occurrence of the Yokokawa dam release in autumn 2013 led to the

clear dispersion of part of this strongly contaminated material to the coastal plains (Fig. 3b). Finally, in the Ukedo River catchment that was initially fully located within the restricted area and where we only had access – from May 2013 onwards, deposition of strongly contaminated material was documented in November 2013, which shows that this river draining the most contaminated part of the radioactive plume also provides a continuous supply of radioactive sediment to the Ocean (Fig. 3b).

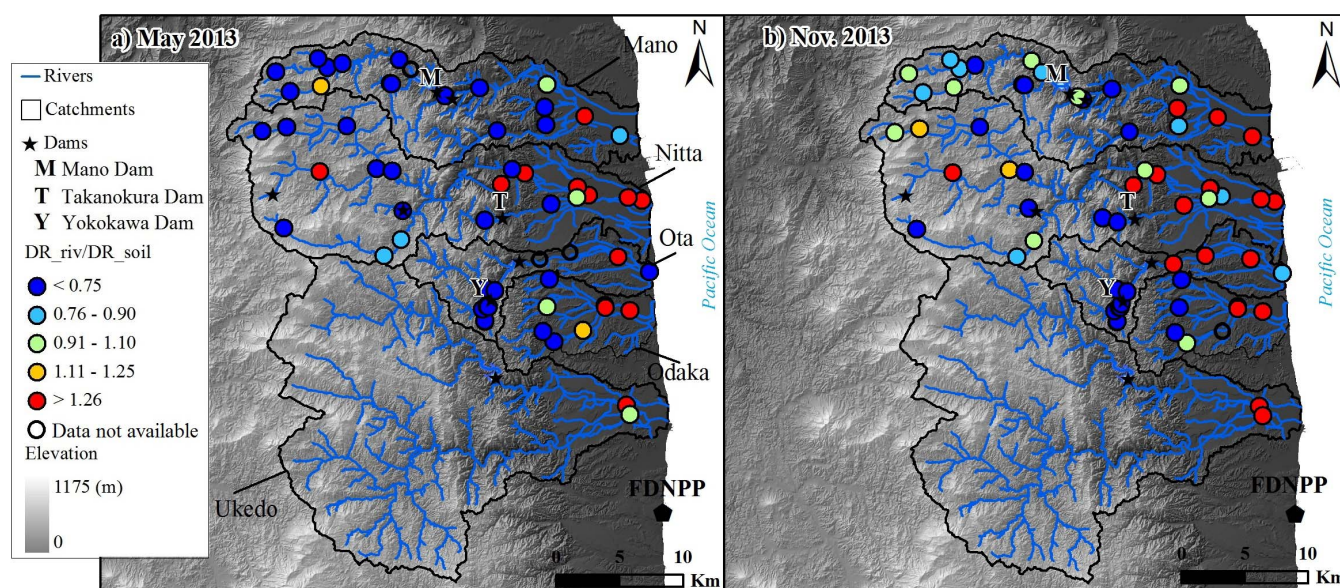


Figure 3 | Ratio between dose rates measured in fresh riverbed sediment (this study) and in nearby soils (MEXT⁹ and NRA¹⁰ data) along rivers draining the main contamination plume in a) May 2013 and b) November 2013. FDNPP stands for Fukushima Dai-ichi Nuclear Power Plant. This original map was created using ArcGIS 10 software.

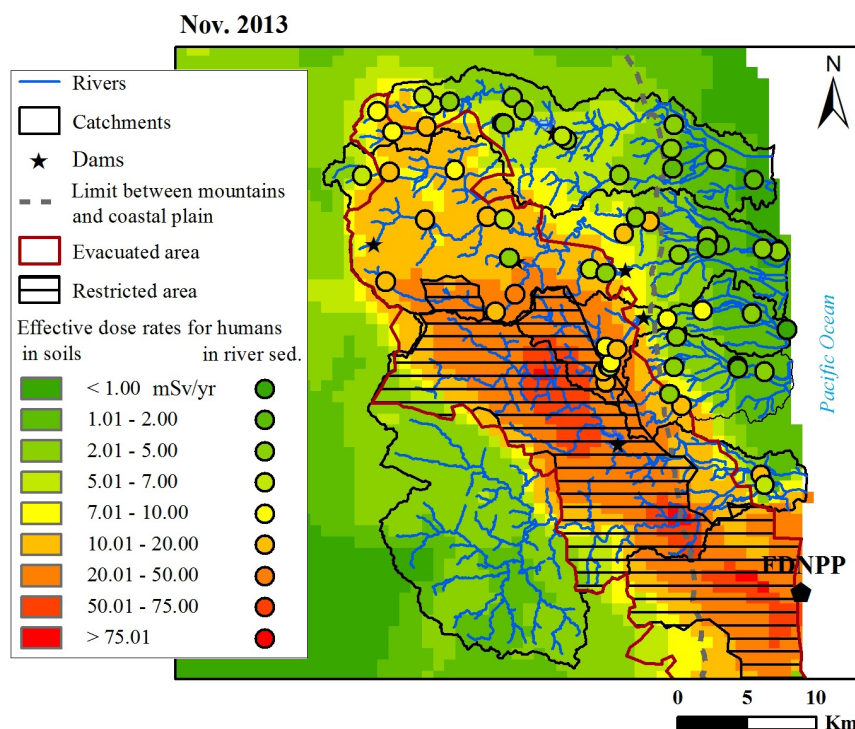


Figure 4 | Effective external dose rates for residents (mSv/yr) measured in riverbed sediment deposits compared to those measured on nearby soils (data from NRA¹⁰). FDNPP for Fukushima Dai-ichi Nuclear Power Plant. This original map was created using ArcGIS 10 software.

Discussion

Impact of dam releases and importance of typhoon rainfall intensity. Our results clearly demonstrate that the occurrence of dam releases is the major factor controlling dispersion of contaminated sediment in Fukushima coastal catchments equipped with this type of structure. Contrary to fresh soil erosion events and resuspension of radioactive material accumulated in reservoirs, remobilisation of material already stored in the river channel and its dilution with riverbank material depleted in fallout radionuclides is not sufficient to generate a large increase in radioactive dose rates to exceed the one emitted by nearby soils. The comparison of fallout dispersion in catchments equipped with a dam (i.e., Mano and Ota River catchments) and in an undammed catchment (i.e., Nitta River catchment) illustrates this different behaviour (Fig. 2). In the Nitta River catchment, dispersion of contaminated material to the Ocean is continuous throughout the year during both the spring snowmelt and the summer typhoons (Fig. 2). In contrast, in the Mano and Ota River catchments, this dispersion is clearly controlled by the occurrence of dam releases and was much more evident in November than in May 2013. Moreover, the occurrence of dam releases is driven by a complex cycle of water filling in the reservoirs, which is logically related to the rainfall occurrence throughout the year. The occurrence of heavier rainfall in 2013 may therefore explain the necessity to open dams, contrary to the situation observed in 2012 characterised by lower rainfall amounts (Fig. 1a).

Sources of freshly eroded material. The occurrence of fresh sediment supply from soil to rivers is reflected by the preferential delivery of fine particles concentrating radioactive contamination to the watercourses. The contamination level in fresh riverine sediment deposits supplied by recent erosion events is therefore expected to be higher than the corresponding dose rate in nearby soils. During the period of investigation, this phenomenon could only be demonstrated in upper parts of the Nitta River catchment and, to a lower extent, in upper parts of the Mano River catchment during the

November 2013 survey (Fig. 3b). The clear supply of freshly eroded soil material to the river was mostly evident in the uppermost part of the Nitta River catchment, in Iitate village, where decontamination operations were under progress during our last fieldwork campaign (Fig. 1b). Those works consist in the removal of vegetation and topsoil and their storage in big bags. During those operations, soil is left bare and exposed to the erosive action of rainfall (see pictures in Appendix A), which likely explains the enhanced erosion documented after the 2013 typhoons in this area. This behaviour was not found in other parts of the investigated zone, which confirms the limited occurrence of soil erosion in abandoned paddy fields, at least for the range of daily rainfall cumulative amounts (ca. 60–100 mm/day) documented during this study.

Exposition of local populations to external radiations. When converting the dose rates (in $\mu\text{Sv/h}$) measured in the field into effective external dose rates for residents (mSv/yr)⁸, the delineation of the restricted and evacuated areas in November 2013 logically corresponds to the zones exceeding a 10 to 20 mSv annual threshold of cumulative external dose emitted by the soils (Fig. 4). When applying the same conversion to the fresh sediment deposits, we see that the corresponding annual dose rates remain in the same range as in soils, except at a minimum of 5 sites surveyed along the Nitta, Ota and Ukedo River sections flowing across the coastal plains. The local and temporary presence of comparatively strongly contaminated sediment deposits in these areas should therefore be considered carefully by local authorities to manage fishing and recreational activities along the entire course of those coastal rivers.

Refining the model of contamination dispersion at the catchment scale. The seasonal cycle showing the succession of fresh sediment supply from soils to the rivers during typhoons and the subsequent dispersion of contaminated material during the spring snowmelt described previously⁶ was partly confirmed in 2013. Our results demonstrated that the upstream contamination source was temporarily disconnected from the river because of the



abandonment of the paddy fields found in this area and the associated growth of vegetation protecting the soil against erosion. However, these new results now clearly demonstrate that removal of vegetation during decontamination of paddy fields led at least temporarily to the re-connection of these sources to the rivers in upper parts of the Nitta River catchment. Consequently, the impact of those decontamination works and the associated dispersion of radioactive contamination to the coastal plains and the Pacific Ocean should be monitored during the coming years. More importantly, the impact of dam releases should also be followed up as the accumulation of radioactive material in reservoirs may provide a perennial supply of radioactive sediment to the coast in future. Studies involving the collection of sediment cores in those reservoirs should therefore be conducted in order to quantify the amount of radioactive material accumulated behind dams and to better evaluate their potential release in downstream inhabited and cultivated areas.

Methods

Fieldwork was conducted in the accessible parts of the Mano R., Nitta R., Ota R., Udaka R. and Ukedo R. catchments in early November 2013. The campaign was organized after the typhoons that occurred in the region. Radiation dose rates were systematically measured in the field using a radiometer (LB123 D-H10, Berthold Technologies; detection threshold $> 0.1 \mu\text{Sv/h}$) directly above fresh sediment drape deposits (generally thick of 5–10 cm) and directly above nearby soils along rivers (i.e. in a 10 to 20 m wide area along rivers). All dose rates are given in Supplementary Material (Supplementary Table). Results of the previous fieldwork campaigns are described in another publication⁷.

The changes of dose rates measured above river sediment between May and November 2013 (in %; Fig. 2) were calculated based on dose rates of May 2013 decay corrected to November 2013 using the theoretical decay equation proposed by the NRA¹⁰. In contrast, dose rates in soils used for calculation of the ratio displayed on Fig. 3 (i.e., ratio between dose rates measured in fresh riverbed sediment and in nearby soils, in May and November 2013) were extracted from soil dose rate maps computed based on a set of 2200 soil locations prospected under the authority of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in June and July 2011⁹, and then decay corrected based on successive MEXT and NRA measurements (those of March 2013), and on the theoretical decay equation provided by both institutions (Supplementary Figure 2)¹⁰. We chose to use them as representative local soil values, as they remained systematically within the range of values measured on-site with our radiometer during both May and November 2013 field surveys. Considering that potential residents are not permanently exposed to radiation, effective external dose rates for residents (mSv/yr) in November 2013 (Fig. 4) were calculated from dose rates measured in November 2013 ($\mu\text{Sv/h}$) according to the following relationship proposed by the Japanese Ministry of Environment¹¹: $0.23 \mu\text{Sv/h} = 1 \text{ mSv/yr}$.

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Author contributions

O.E. and Y.O. designed research and wrote the main manuscript; C.C. and H.L. conducted spatial analyses; O.E., C.C., H.L. and O.C. conducted field measurements. I.L. and S.A. participated to the redaction and reviewed the manuscript.

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