Ocean and Coastal Management 153 (2018) 176–192

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Hydro-sedimentary model as a post-accidental management tool: Application to radionuclide marine dispersion in the Bay of Toulon (France)

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ARTICLE INFO

Keywords:
Hydro-sedimentary modelling
Radionuclides
Marine dispersion
Bay of Toulon
Las river

ABSTRACT

The coastal city of Toulon, located in southern France, is the homeport of the French navy's nuclear-powered vessels, and is the largest nuclearized harbour in Europe. Therefore, an accidental release of radioactive material would have major consequences for the marine ecosystem and the economy of the region. A hydro-sedimentary model is presented to better understand the dispersion of a hypothetical release of radionuclides and to gain insights into the potential effects on the surrounding ecosystem, especially on sea sediments. The aim of the model is to provide the foundation of a management tool for experts and stakeholders in decision making in case of an accidental release. We simulate a numerical radionuclide discharge in the military harbour under several climatic conditions and we compute ^{137}Cs, which might have substantial impacts on the marine ecosystem, and ^{239}Pu for its high affinity for solid phase. Results show that wind conditions and solid discharges from the Las River are the primary influences on sediment-bed contamination, and the hydro-sedimentary dynamics following the first days of release have an important influence on the distribution of radionuclides.

1. Introduction and motivation

Coastal areas are vulnerable regions and are very sensitive to impacts due to their proximity to major urban areas and the potential effects from associated pollutants (e.g. Nicholls and Hoozemans, 1996; Tiquio et al., 2017). The need to develop predictive tools is of critical importance in order to assess the potential effects from an accidental release of nuclear material, particularly long-lived radioisotopes (Duffa et al., 2016; Vives i Batlle et al., 2018).

The Fukushima Daiichi Nuclear Power Plant (NPP) accident of March 11, 2011 has highlighted this stake when between 3.5 and 27 PBq (10^{15}Bq) of caesium-137 (^{137}Cs) were released directly into Pacific Ocean (UNSCEAR, 2013), leading to the largest radioactive contamination of the marine environment since the beginning of the nuclear age. About 12 PBq of ^{137}Cs were released into atmosphere (Chino et al., 2011) which produced an areal deposition on watersheds assessed between 1 and 3 MBq·m^{-2} (Ueda et al., 2013). In July 2011, ^{137}Cs concentration in coastal waters off Japan reached values 10 000 higher than prior the accident (Buesseler et al., 2011). The radionuclides concentration in seawater decreased exponentially with time after the release due to radioactive decay and transport/mixing by currents. Radioactivities thus decreased by a factor of about 10^3 following a 30 km radius from the input location and by a factor of few dozens to couple hundreds within few weeks of the accident (Vives i Batlle et al., 2014) and dissolved Cs activities ranged from few Bq·m^{-3} to ca. 1000 Bq·m^{-3} in North Pacific Ocean surface layer in April–May 2011 (Aoyama et al., 2016). However sedimentary contamination level remained high one year after the accident with for example ^{137}Cs activities ranging from 18 Bq·kg-dry^{-1} to 1.12 kBq·kg-dry^{-1} in surface sediment (0–1 cm) in the offshore region of the facility (Ambe et al., 2014). Despite weak affinity of Cs for the particulate phase in marine environment, Otosaka and Kobayashi (2013) assessed the ^{137}Cs activity in the upper layer (0–3 cm) of sediment sampled 100 km away from the Fukushima Daiichi NPP to be more than 50 Bq·kg^{-1} (in comparison with 3–4 Bq·kg^{-1} before the accident). Wada et al. (2013) reported that highest Cs concentrations in marine products (as fishes, invertebrates, seaweed, surf clams) were found in shallower waters and areas next to the nuclear facility. In some benthic species, Cs concentrations were frequently above the regulatory limit (100 Bq·kg$_{wet}$$^{-1}$), showing a continuous uptake of radioactive Cs through the benthic food web. This bottom sediment contamination highlights the affinity of some radionuclides for the particulate phase, due to adsorption and bonding effect

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https://doi.org/10.1016/j.ocecoaman.2017.12.026
Received 25 September 2017; Received in revised form 6 December 2017; Accepted 25 December 2017

of sediments.

Thus, the sediment bed has the potential to act as a contaminant source and radionuclides trapped in bottom sediments may re-enter the water column due to seabed remobilization under energetic hydrodynamic conditions such as waves or storms, or due to bioturbation (promoting sediment mobility) and diffusivity of pore-water and advective flux from water-sediment interface (Vives i Batlle et al., 2018). Aldridge et al. (2003) reported that the bottom sediment and re-salting plutonium (Pu) from the mud-patch off the coast of Sellafield, Ireland was the main $^{239\ 240}$ Pu source in Irish Sea. Consequently, the fate of radionuclides in marine system is tightly linked to both hydrodynamic and sedimentary dynamics, thus, it is essential to take into account both the dissolved and particulate phases of radionuclides to understand the spatiotemporal evolvement of radionuclides and assess the environmental risk in radioactively contaminated areas.

Previous studies have shown the reliability of ocean model to simulate dissolved radionuclides dispersion. Following the Fukushima Daiichi NPP accident, numerical modelling was used to assess the amount of ^{137}Cs released (i.e. Bailly du Bois et al., 2012; Estournel et al., 2012) and several studies focused on radionuclides dispersion in the marine environment (i.e. Choi et al., 2013; Estournel et al., 2012; Masumoto et al., 2012; Nakano and Povinec, 2012; Povinec et al., 2013). Using a dispersion model, Min et al. (2013) demonstrated that the large atmospheric ^{137}Cs deposit combined with weak ocean currents led to a significant contamination of the seabed after Fukushima accident and highlighted the importance of an accurate hydrodynamic model to estimate radiological activities.

While many studies focussed on dissolved radionuclide contaminations or on the water/sediment exchange, very few concern the dispersion through hydro-sedimentary processes. Aldridge et al. (2003) used a hydro-sedimentary model to identify and quantify the mechanisms responsible for the redistribution of $^{239/240}$Pu in the Irish Sea, highlighting the necessity to include sedimentary processes. Vives i Batlle et al. (2008) developed a multi-compartment model (comprised of seawater, colloids, suspended load, and sediment) to represent the radioactivity in each compartment and investigate the interplay of flows between them, without, however, identifying contaminated areas. Since numerical models appear to be a valuable part of post-accidental management tools (Iosjpe et al., 2009; Wada et al., 2013), the inclusion of the sedimentary compartment in tridimensional dispersion models is essential to estimate the future of radionuclides in marine system, as pointed out by Duffa et al. (2016).

In this work, we aim to set up a hydro-sedimentary model to compute the dispersion of a hypothetical accidental input of radionuclides into the Bay of Toulon. We compute ^{137}Cs, which might have substantial impacts on the marine ecosystem, and ^{239}Pu for its high affinity for solid phase. As the homeport of nuclear-powered vessels, Toulon is the largest European nuclearized harbour and the need to identify contaminated areas in case of accidental release obviously arises. A hydro-sedimentary model allows a mechanistic interpretation of the dispersion processes and an accurate assessment of the temporal and spatial evolution of the contamination. Besides enhancing our understanding of several processes with a multidisciplinary point of view, the model is incorporated within the framework of management and restoration policy, aiming at assisting decision makers and stakeholders.

In this manuscript, a radionuclide discharge into the militarized harbour is simulated and its radiological consequences are studied by estimating the modeled contaminated areas.

2. Study area

Toulon is located in South of France, along the Mediterranean coast. The semi-enclosed Bay of Toulon is divided into two basins by a seawall (Fig. 1). The Little Bay (LiB) shelters the military and civilian harbours and is connected to the Large Bay and the open sea through a channel. This channel is crucial for exchanges and circulation of water bodies within the whole Bay. As described by Dufresne et al. (2014), the circulation is wind-driven, with several episodes of either upwelling or downwelling according to the wind direction, which has also been described at other locations on the French Riviera such as Cassis (Albérola and Millot, 2003) and Marseille (Pairaud et al., 2011).

Toulon is surrounded by rugged hills that influence meteorological conditions, particularly rainfall and wind intensities and directions. Three different climatic categories have been described for the area (Tiné et al., 1981). Calm weather occurs 20% of the time and is characterised with low wind intensity (< 5 m·s^{-1}). Windy conditions arise from two directions: the Mistral, a cold north-westerly wind that blows 40% of the time, and the East Wind, which is warmer and more humid. Originating offshore, the East Wind is usually accompanied by clouds, rain and swell, and blows less frequently during the summer. The fall and winter seasons are characterised by a succession of strong Mistral and East Wind events. These two wind conditions are the main forcings of the hydrodynamics of the Bay (Dufresne et al., 2014). The Northern Current, of flow rate of about 1 Sverdrup (10^6 m^3 s^{-1}), governs the North Western Mediterranean circulation along the coast, with little influence within the Bay. The tidal current is weak since the mean tidal range is low, *i.e.* approximately 20 cm (Albérola et al., 1995; Millot et al., 1981).

Two small rivers flow into the Bay of Toulon. The Las River flows in the western area of the town and its watershed ($\sim$60 km^2) is partly natural, partly urban. The outlet is located at the back of the LiB, in the military harbour. The Eygoutier River has an urban watershed of $\sim$70 km^2 and flows into the Large Bay. For both rivers, the base flow is characterised by very low discharge (10 m^3 h^{-1}) and is interrupted by short and intense storm flows (Dufresne, 2014; Nicolau et al., 2012). The flood periods depend on local rainfall and are mainly observed during winter season. Dufresne (2014) assessed the water and sediment discharge through 18 months *in situ* measurement in the Las River and concluded that about 85% of the sediment yield happens during flood events, which occur 30% of the time, and is mainly composed of cohesive sediment (90%). The solid discharge is usually insignificant at base flow and ranges between 2 and 5 kg s^{-1} during flood events (Dufresne, 2014).

The seabed of the LiB is mostly covered with cohesive sediment. Fine particles are predominant in the surface sediment layer, with median grain size value ranging between 10 and 60 μm with a median value of 27 μm (Tessier et al., 2011). Previous work (Arnaud et al., 2002) has also characterised the sediment bed of the LiB, as being composed by more than 40% of fine particles ($D < 63$ μm). Historic data also mentions the silting up of the LiB and Toulon's harbour with rivers mud (Tiné et al., 1981). The sand ($D > 63$ μm) fraction increases near the artificial beaches on the northern side of the Large Bay, where the 2 mm fraction is more important. Some coasts, more exposed to waves and swell, also have a coarser grain size. Therefore, the fine sediment fraction is lower outside the Large Bay, near Cape Sicié, where it represents no more than 10% (Arnaud et al., 2002). According to Tessier et al. (2011) the average annual sedimentation rate is 0.21 ± 0.05 cm per year in both LiB and Large Bay.

Some studies have shown the important sediment contamination of the Bay with metals (Dang et al., 2015a, 2015b; Tessier et al., 2011), with suspected pollutants being exported from the LiB to the open sea. Tessier et al. (2011) have analysed surface sediment core samples from both Little Bay and Large Bay basins, and concluded that contaminants from the LiB are exported to the Large Bay through hydrodynamic processes. Duffa et al. (2011) have used a hydro-sedimentary model to show that a contamination in the Little Bay might remain significant due to its semi-enclosed configuration. Therefore, the fate of an accidental radionuclide contamination event would largely depend on the hydrodynamic and sediment dynamics between the LiB and the open sea.

Besides being France's largest naval port, there are other economically important activities that take place in the Bay of Toulon. Tourism