Environmental Pollution 240 (2018) 125–139

Contents lists available at ScienceDirect

Environmental Pollution

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

Investigating the metal contamination of sediment transported by the 2016 Seine River flood (Paris, France)☆

Marion Le Gall [a,*], Sophie Ayrault [a], Olivier Evrard [a], J. Patrick Laceby [b], David Gateuille [c], Irène Lefèvre [a], Jean-Marie Mouchel [d], Michel Meybeck [d]

[a] Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 (CEA/CNRS/UVSQ), Université Paris-Saclay, Domaine du CNRS, Avenue de la Terrasse, 91198 Gif-sur-Yvette Cedex, France
[b] Environmental Monitoring and Science Division, Alberta Environment and Parks, 3115-12 Street NE Calgary, Alberta, Canada
[c] Laboratoire de Chimie Moléculaire et Environnement, Université Savoie Mont-Blanc, 73376 Le Bourget du Lac Cedex, France
[d] Milieux Environnementaux, Transferts et Interactions dans les hydrosystèmes et les Sols (UPMC/CNRS/EPHE), UMR 7619, Université Pierre et Marie Curie, 4 place de Jussieu, Paris Cedex, France

ARTICLE INFO

Article history:
Received 25 August 2017
Received in revised form
16 April 2018
Accepted 18 April 2018

Keywords:
Fallout radionuclides
Trace elements
Lead isotopes
Fingerprinting

ABSTRACT

Fine sediment transport in rivers is exacerbated during flood events. These particles may convey various contaminants (i.e. metals, pathogens, industrial chemicals, etc.), and significantly impact water quality. The exceptional June 2016 flood of the Seine River (catchment area: 65 000 km^2, France), potentially mobilized and deposited contaminated materials throughout the Paris region. Flood sediment deposits ($n = 29$) were collected along the Seine River and its main tributaries upstream (Yonne, Loing and Marne Rivers) and downstream of Paris (Oise and Eure Rivers). Fallout radionuclides (^{137}Cs, ^{7}Be) were measured to characterize the sources of the material transiting the river, while trace elements (e.g. Cr, Ni, Zn, Cu, As, Cd, Sb, Pb, Tl, Ag) and stable lead isotopes ($^{206}Pb/^{207}Pb$) were analyzed to quantify the contamination of sediment transported during the flood. In upper sections of the Seine River, sediment mainly originated from the remobilization of particles with a well-balanced contribution of surface and subsurface sources. In the upstream tributaries, sediment almost exclusively originated from the remobilization of subsurface particles. In Paris and downstream of Paris, recently eroded particles and surface sources dominated, suggesting particles were mainly supplied by urban runoff and the erosion of agricultural soils. The highest metal concentrations and Enrichment Factors (EF) were found in the sediment collected in the Loing, Orge and Yvette upstream tributaries. Although these inputs were diluted in the Seine River, an increase in elemental concentrations was observed, progressing downstream through Paris. However, EFs in sediment collected along the Seine River were lower or in the same range of values sampled over the last several decades, reflecting the progressive decontamination of the urbanized Seine River basin.

1. Introduction

Trace elements are naturally found in the environment, although at low background levels, as they are released by natural processes such as bedrock weathering or volcanic eruptions. However, anthropogenic activities may supply excessive quantities of metals and metalloids to the environment (Elbaz-Poulichet et al., 2001; Coynel et al., 2009; Resongles et al., 2014). In particular, large amounts of metals and metal compounds are released by industrial, domestic and agricultural activities (Suthar et al., 2009; Le Pape et al., 2012; Rosolen et al., 2015). In urbanized catchments, atmospheric fallout associated with anthropogenic activities provides one of the main pathways of soil contamination (Nriagu, 1989; Pacyna and Pacyna, 2001). Once emitted into the atmosphere, trace elements are transported and deposited through wet and dry fallout on soils where they may accumulate and be stored over long periods (Bindler et al., 2009; Bur et al., 2009). These hazardous compounds may be preferentially bound to fine particles (i.e. <63 μm) (Blake et al., 2003; Owens et al., 2005) and they may subsequently be delivered to the riverine environment by processes such as soil leaching or soil erosion (Nystrand et al., 2012; Mileusnić et al., 2014; Zheng et al., 2016). The temporal dynamics of

☆ This paper has been recommended for acceptance by Joerg Rinklebe.
* Corresponding author.
E-mail address: sophie.ayrault@lsce.ipsl.fr (M. Le Gall).

https://doi.org/10.1016/j.envpol.2018.04.082
0269-7491/

contaminants released by erosion processes are not well understood in urbanized catchments characterized by extensive impervious surfaces.

Although sediment and associated metals may accumulate in the river channel during low flow periods, they are mainly re-suspended and transported during flood events. Therefore, significant amounts of metals may be exported by rivers during very short periods (Cobelo-Garcia et al., 2004; Carter et al., 2006; Ollivier et al., 2011). Accordingly, the monitoring of flood events with high-temporal resolution sampling is essential to better understand trace element dynamics at the catchment scale (Cánovas et al., 2008). Studies based on robust flood monitoring remain scarce and, to the best of our knowledge, they were mainly restricted to small catchments impacted by former mining activities (Coynel et al., 2007; Turner et al., 2008; Resongles et al., 2015). The sampling of lag deposits may constitute an effective strategy to overcome the lack of sediment monitoring during extreme events (Lepage et al., 2016). Representative of the fine material transported by the flood and deposited during the falling limb (Olley et al., 2012), lag deposits are similar to fresh floodplain deposits originating from various catchment sources (Du Laing et al., 2009). Currently, there is a lack of data regarding the impact of flood events on water and sediment quality in large urbanized catchments (Baborowski and Einax, 2016). Furthermore, the determination of metal contents together with the identification and quantification of sediment sources during flood events are necessary for understanding their transfer at the catchment scale. Indeed, identifying both spatial and temporal sources of sediment is essential to interpret sediment contamination levels and evaluate the resilience of major urbanized catchments. This important distinction may be resolved by combining several sediment source tracers (Bradley and Cox, 1990; Krüger et al., 2005).

Sediment sources may be identified by combining ^{137}Cs and ^{7}Be measurements. Cesium-137 ($t_{1/2} = 30$ years) is an artificial radionuclide originating from thermonuclear tests (1950–1960s) and the Chernobyl accident in Northwestern Europe. Predominantly fixed to fine particles, ^{137}Cs discriminates between material eroded from the soil surface, exposed to atmospheric fallout, and from subsurface soils, sheltered from ^{137}Cs fallout (He and Walling, 1997; Motha et al., 2003). Beryllium-7 ($t_{1/2} = 53$ days) is a short-lived cosmogenic radionuclide, supplied to the soil surface by precipitation, that discriminates between recently eroded particles, tagged with ^{7}Be and older re-suspended particles, depleted in ^{7}Be (Dominik et al., 1987; Taylor et al., 2013). Using these radionuclides, the relative contribution of four different sources (i.e. recently eroded surface and subsurface, re-suspended surface and subsurface) to sediment may be quantified and interpreted in terms of contamination levels using elemental concentrations (Evrard et al., 2016).

In this study, sediment sources and metal contamination levels were investigated during an exceptional flood event that occurred in June 2016 in the Seine River basin, France, representative of the industrialized areas of Northwestern Europe. This catchment, with approximately 16 million inhabitants, drains the Megacity of Paris and concentrates more than a third of the French heavy industries, leading to the coexistence of major anthropogenic pollution sources, including metal contamination (Meybeck et al., 2004; Grosbois et al., 2006; Thévenot et al., 2009). Although the June 2016 flood mainly affected the upstream tributaries with a return period >50 years for the Loing tributary, the flood propagated along the Seine River with return periods estimated to be 10–20 years in Paris and 2–5 years in its downstream section near Poses. This flood was unprecedented, with the largest inundation in the Paris city center since the extreme flood event in 1910. In this context, stakeholder concerns arose regarding water quality, especially metal contamination. Furthermore, in the framework of the candidacy of Paris to host the 2024 Summer Olympics, the Seine River should be of sufficient water quality to hold the nautical competitions. The potential environmental impact of such major flood events needs to be investigated. Sediment metal contamination levels reached during this major flood need to be compared to historical data, and the sources of this contamination need to be investigated (i.e. contribution of recently eroded particle from impervious urban areas *vs* remobilized particles deposited on the riverbed during the last several decades). Accordingly, ^{137}Cs and ^{7}Be measurements were combined with the analysis of metal concentrations (Cr, Ni, Zn, Cu, As, Cd, Sb, Pb, Ag, Tl) and stable lead isotopes (^{207}Pb/^{206}Pb) in lag deposits collected in the catchment to investigate the urban sediment contamination and the spatial and temporal variations of their sources during the June 2016 flood event in the Seine River basin, France. In addition, Predicted No Effect Concentrations (PNEC) were used to examine the potential toxicity of these contaminants on the environment.

2. Material and methods

2.1. Study area

The Seine River basin (65 000 km^2) is located in Northern France and is characterized by homogeneous relief, geology and climate properties. The underlying bedrock is mainly sedimentary (~93%) with the predominance of carbonate rocks (chalk, limestone) while silicate rocks (7%) are restricted to the upstream Morvan area. Five main tributaries drain into the Seine River: the Aube (4750 km^2), the Yonne (11 250 km^2) and the Marne Rivers (13 160 km^2) flow into the Seine upstream of Paris, whereas the Oise (16 900 km^2) and the Eure Rivers (6017 km^2) flow into the Seine downstream of Paris (Meybeck, 1998).

The land use is heterogeneous, with 25% of the catchment area dedicated to agricultural production and 40% to industrial activities. Agriculture is predominant upstream of Paris, whereas industrial activities are located near and downstream of Paris. With a mean population density of 250 inhabitants km^{-2}, varying from 15 inhabitants km^{-2} in rural areas to a maximal value of 27 000 inhabitants km^{-2} in the Paris conurbation, 23% of the French population lives in the Seine River catchment, which only covers 12% of the French surface area. The variations in land use, industrial activities and population density lead to variable anthropogenic pressures.

To investigate the spatial and temporal variations of metal contamination in sediment transported during the May 26 to June 4, 2016 flood event, attention focused on the flood sediment deposits collected along the Seine River ($n = 16$) (from Bray-sur-Seine, upstream of the Yonne confluence, to Poses, the river mouth, 200 km downstream of Paris). Sediment deposits were also collected along the main tributaries ($n = 13$), just before their junction with the Seine River: the Yonne, the Loing, the Orge, the Yvette and the Marne Rivers upstream of Paris and the Oise and the Eure Rivers downstream of Paris (Fig. 1).

2.2. Flood characteristics

From May 26 to June 4, 2016, a stationary low pressure system over France induced moderate although continuous rainfall during three days, from May 29 to May 31. This precipitation followed a particularly wet spring season. Soils were saturated and the additional rainfall first generated overflow of small rivers such as the Loing and Yvette. The upstream Loing tributary quickly reacted to heavy rainfall and several towns were flooded on June 1, with more than 4000 people evacuated in the city of Nemours. Although this