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# Review on the need for inventories and management of reservoirs of POPs and other persistent, bioaccumulating and toxic substances (PBTs) in the face of climate change

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## Abstract

**Background** Large quantities of persistent organic pollutants (POPs) and other persistent, bioaccumulative and toxic substances (PBTs) like heavy metals have accumulated mainly over the last century in reservoirs, such as landfills, dump sites, contaminated sites, and mine tailings, as well as in environmental sinks like soils and sediments. Large floods in the past 20 years have demonstrated the mobilisation of POPs/PBTs from these reservoirs, underscoring the limitations of conventional technical safeguard measures like leachate and wastewater treatment or containment systems at landfills.

**Results** This study emphasises the need to develop inventories of POPs/PBTs in these reservoirs for the assessment of future risk of increased flooding triggered by climate change and for priority setting of remediation and securing measures. Further, sea-level rise should be included in these assessments as long-term risk for large areas that are likely to be permanently flooded in the coming decades and centuries. In addition, the risk of release of POPs and other PBTs by industries affected by Natural Hazards Triggering Technological Accidents (Natech) should be globally evaluated. The review emphasises the importance of conducting systematic assessments and inventories to understand the risk of these reservoirs for environmental pollution and human exposure. The releases and remobilisation of POPs/PBTs can lead to higher levels in food and drinking water with increased human exposure. In addition to fish, it is crucial to consider livestock grazing in flood plains and other areas affected by floods, and to include them in inventories and risk management.

**Conclusion** Based on these assessments, appropriate measures must be developed to eliminate or secure the respective reservoirs, following the precautionary approach. Whilst management measures have been initiated in affected areas (including affected feed/biomass), such as floodplains, there is a need to develop them more systematically. This review advocates for a comprehensive and precautionary approach to address the environmental challenges posed by climate change for POPs and other PBTs reservoirs, with an emphasis on increased flooding and sea-level rise. The substitution of POPs/PBTs in non-essential uses should be implemented to reduce future risks. A synergistic implementation of the Stockholm, Minimata, and Climate Convention can be used as frame for inventories and mitigation.

**Keywords** POPs, Heavy metals, Climate change, Flooding, Sea-level rise, Contaminated sites, Landfills, PBTs, Natech, Climate information and early warning system

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## 1 Introduction

Persistent Organic Pollutants (POPs) and other persistent, bioaccumulative and toxic substances (PBTs) have accumulated in landfills/dumps, stockpiles, contaminated sites, mine tailings, and in soils and sediments mainly over the last two centuries of industrial production and deposition [81, 315, 320, 348, 350, 351, 361, 362, 366, 367]. Primary pollutants are chlorinated, fluorinated, and other halogenated industrial chemicals or pesticides as well as unintentional POPs such as polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/PCDF) [92, 95, 212, 220, 241, 255, 351, 361, 362]. Furthermore, huge quantities of heavy metals—secured before for millions of years in the earth crust—have been mined and are now at the surface (technosphere, mine tailings, and deposits) with exposure risk for the wider environment [62, 65, 67, 79, 175, 216, 306, 310].

Reservoirs of POPs, heavy metals, and other PBTs present a high risk and management challenge for society and, if not adequately eliminated or secured, they are a threat to present and future generations.

In many industrial countries, chemical production wastes including POPs were largely landfilled or dumped until the 1970s and even 1980s [87, 94, 97, 115, 220, 296, 348, 362, 378]. In low- and middle-income countries, such production waste is still disposed mostly in dumpsites and landfills due to the limited or absence of destruction capacity [4, 61, 362, 363]. During the past 60 years brominated, chlorinated and fluorinated POPs and other PBTs have been increasingly produced [257, 283] and used in consumer goods [39, 40, 112, 121, 273, 316]. An assessment of registered chemicals estimated that approximately 590 of these chemicals are likely POPs considering the Stockholm Convention POP criteria [257]. As products containing these POPs/PBTs reach the end-of-life, these chemicals end up in the waste stream [307, 308, 316]. Most low- and middle-income countries have very limited adequate recycling, treatment, and destruction capacity, and many countries have relied heavily on landfills and dumps [12, 13, 362, 363]. Also, many high-income countries have disposed POPs containing municipal waste largely in landfills until recently and some countries, such as Australia, New Zealand, and the US with limited waste destruction capacity, still dispose POPs containing waste to landfills [46, 167, 184, 189, 362]. Therefore, municipal landfills are joining chemical landfills as reservoirs of POPs and other PBTs albeit at a lower pollution inventory for individual sites, but they represent a large overall inventory considering the hundreds of thousands of landfills including those that predate modern environmental regulations, and which do not have lining and caping systems and waste is not isolated from the surrounding environment [29].

Whilst in the frame of the Stockholm Convention POPs inventories are developed, e.g., for polychlorinated biphenyls (PCBs) in transformers and capacitors or PBDEs in electronic waste, the POPs disposed to landfills or in contaminated sites are normally not quantified with some exemptions like large pesticide landfills [234, 294, 349, 351]. Inventories of unintentionally produced POPs, such as PCDD/PCDF, are largely developed as release inventories for specific years [86, 354] and mostly do not consider the historic reservoirs and releases with a few exemptions [198, 289, 361], although the UNEP unintentional POP inventory toolkit contains a dedicated chapter on contaminated sites [311]. However, e.g., for PCDD/PCDF, PCBs or hexachlorocyclohexane (HCH) isomers, the reservoirs in soils and sediments are a main determining factor for today's exposure or exposure risk USEPA [198, 212, 348, 351, 361, 332].

Because of their high persistence, these compounds will not degrade in these reservoirs for extended timeframes probably for centuries and longer [361, 362]. Over these extended timescales, consideration needs to be given to the impacts of climate change in the next decades and centuries. A range of interlinks have been described between climate change and POPs in a review for the UN [322]. In the latter publication and in a review [207], the focus is rather on global flows and emphasises, e.g., the relevance of temperature on volatility or the impact on the Arctic and does not highlight flooding and remobilisation from landfills and other reservoirs [207, 322]. However, in a recent publication on chemicals, wastes, and climate change, UNEP stressed the relevance of flooding and the risk of release of POPs and other chemicals of concern [314].

The International Panel on Climate Change (IPCC) 6th Report concludes that the frequency and intensity of heavy precipitation events have likely increased at the global scale over a majority of land regions with good observational coverage due to climate change. Heavy precipitation has likely increased on the continental scale over three continents: North America, Europe, and Asia [149, 267]. Significant trends in peak streamflow have been observed in some regions over the past decades (high confidence) [149, 267] with associated extreme flooding events [51, 186, 209, 264, 368], whilst for some regions, the flooding risk decreases due to lower precipitation [20]. The recent report of the World Meteorological Organisation (WMO) highlights that climate change indicators reached record levels in 2023 with records broken for sea-level rise, ocean

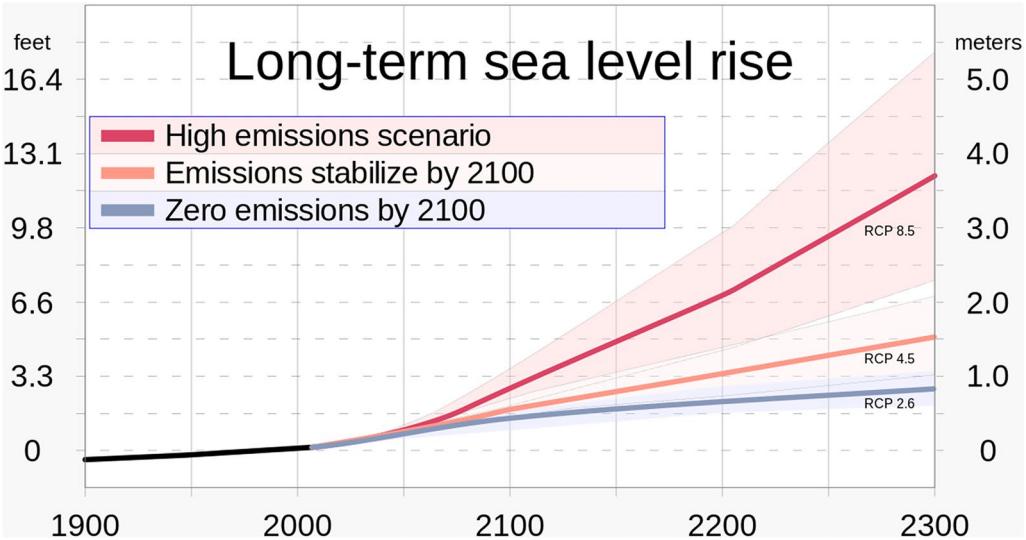


**Fig. 1** Long-term sea-level rise 1900–2300 considering three scenarios [208]

heat, antarctic sea ice loss, and glacier retreat [374]. Global hydrological models project a larger fraction of land areas to be affected by an increase in river floods than by a decrease in river floods (medium confidence) [149, 267]. There is persuasive evidence that the costs of extreme weather events, with flooding as a major contributor, have been exhibiting a significant upward trend [134, 325]. Furthermore, floods are amongst the most frequent natural hazards that trigger accidents in chemical infrastructures or oil and gas pipelines resulting in the release of hazardous materials/chemicals, fires, and explosions [233] and are above the capacity of treatment plants for wastewater and leachates. These increasing floodings in some regions pose also likely problems with the integrity of the containment systems, and likely increase the rate of future release from landfills [362] as well as increase the mobilisation of pollutants from soils and sediments [51, 375].

A second key risk factor for pollutant reservoirs is the rise of sea level. The IPCC has been found to have underpredicted sea-level rise, as part of its general "understatement of existential climate risk" [281]. Recent data show that the upward trend is non-linear and accelerating [25, 374]. The long-term perspective estimated by NASA for 2300 is between 0.8 m (Zero Emission by 2100) and up to more than 5 m sea-level rise for the high-emission scenario [208], Fig. 1). This will inevitably result in permanent flooding and erosion of coastal areas which most often host banned industrial sites as well as present active industry. Landfills and contaminated sites in many of these threatened areas have so far been given little attention, but are expected to be compromised by these changes with associated releases and pollution risk [29, 211].

The current paper reviews the major reservoirs which need to be considered for an assessment of increasing flooding and sea-level rise and the experiences of mobilising POPs/PBTs by flooding. It highlights the importance of better understanding the potential and risk of releases of POPs and other PBTs from reservoirs. The study emphasises the importance of urgently developing

**Table 1** Water solubility of POPs listed in the Stockholm Convention with higher water solubility and selected chlorobenzenes [274, 348], and POPs Review Committee documents of respective listed POPs)

| Compound | Water solubility (20 or 25 °C) |
|---|---|
| PFOA | **4.14 mg/L** |
| PFOS | **519 mg/L** |
| PFHxS | **1.400 mg/L** |
| HCBD | **3.2 mg/L** |
| α-HCH and β-HCH | **0.25 mg/l and 1.44 mg/L** |
| γ-HCH (lindane) | **7.4 mg/L** |
| PCP | **15 mg/L** |
| HCB | 0.005 mg/L |
| PeCB | **0.55 mg/L** |
| 1,2,4,5-TeCBz | 2.18 mg/l |
| 1,2,3,4-TeCBz | 7.8 mg/l |
| 1,2,3-TeCBz | 18 mg/l |
| 1,2,4-TeCBz | 30 mg/l |

Bold are water solubilities of listed POPs with water solubility above 0.25 mg/L

national or regional inventories of these reservoirs, and of assessing the flooding and release risks considering the impact of climate change scenarios. The study stresses that related impacts on the safety of food and drinking water should be considered and assessed. Finally, the assessment concludes on needs for modifying disposal policy and developing policies for securing and remediation of landfills and contaminated sites with high risk of release by increased fluvial flooding and coastal flooding by sea-level rise (Fig. 1). As recently pointed out by the European Environment Agency, extreme sea levels have increased at many locations along European coastlines, due to increases in mean local sea levels. These ongoing increases will amplify the frequency of 1-in-100 years' historical extreme events, by exposing most locations to critical conditions already with a sea-level rise value above 10 cm. Without better coastal protection, the projected sea-level rise would increase the frequency of extreme high coastal water levels by a factor of 10 in most European coastlines prior to 2050, with differences depending on the location and the future climate scenario [73].

## 2 Materials and methods

### 2.1 Selection of pollutants

The scope of this paper covers the most persistent pollutants including POPs listed in the Stockholm Convention and heavy metals. POP persist in reservoirs like landfills or soils in the scale of centuries [16, 361]. Heavy metals are "perfectly persistent" and even more extended time scales need to be considered for their containment and release risk. Both pollutant classes pose a risk for human health and biota when they are distributed to the environment [292, 366, 367]. Therefore, release need to be avoided and minimised. For these pollutants, a time horizon of centuries needs to be considered for the assessment and release risks from reservoirs. Therefore also climate change scenarios of centuries become relevant which is in particular true for the sea-level rise. Considering the high-emission szenario for greenhouse gases (Fig. 1), the sea will likely flood large coastal and possibly inland areas including the related landfills and contaminated sites already in the next two centuries (Fig. 1; Climate [45]).

### 2.2 Selection of reservoirs

For POPs and heavy metals, the major reservoirs - landfills, soils, and sediments - were considered. For heavy metals, additionally, the mine tailings and related dams were considered as a major reservoir and climate change risk. The study also considered radioactive reservoirs due to their high risk and relevance if they get flooded and eroded.

### 2.3 Screening of information

For searching studies, Google Scholar was used with further assessment by Science Direct and PubMed. For the selection of papers, keywords were used for the search including "persistent organic pollutants", "POP", "heavy metals", "mine talings", "Natech", and selected individual POPs.

The review has assessed also relevant national and international databases, reports, and websites for context and evidence, in particular for the selected case studies where the information was frequently not included in peer-reviewed publications.

### 2.4 Selection of case studies

As case studies, prominent large POPs contaminated sites have been selected where information on quantities of disposed waste or amount of POPs in the sediments of a river were available. These case studies can demonstrate the risk and potential future relevance in relation to the quantities of the respective POPs.

## 3 Results and discussion

### 3.1 Landfills/dumps and production sites as major reservoirs of POPs/PBTs and experiences with releases

A large proportion of historic POPs have been disposed in landfills [94, 97, 115, 220, 296, 348, 351, 362] or remain in contaminated sites [92, 361, 363]. Associated with the location of chemical productions adjacent to rivers are related waste deposits close to rivers [87, 127, 156, 344, 378]. Chemical landfills can contain 1000 s to 100,000 tonnes of POPs waste [87, 348, 362, 378]. Therefore, these waste deposits can be a source of large environmental pollution when flooded. In addition, large quantities of POPs listed in the Stockholm Convention including polychlorinated biphenyls (PCBs), POPs pesticides, brominated POPs (PBDEs, HBCD, HBB), and short-chain chlorinated paraffins (SCCPs) as well as fluorinated substances (PFAS including the listed PFOS, PFOA, PFHxS and related substances) have accumulated in municipal landfills over the last six decades of use and deposition [121, 184, 189, 221, 232, 362].

Over extended time frames, landfill engineering systems, including basal and capping liners together with gas and leachate collection systems, will inevitably degrade and lose their ability to contain contamination [254, 362]. Climate change is likely to result in higher temperatures, increasing the volatilisation of semi-volatile and volatile compounds. In some areas, higher sunlight (UV) exposure with longer periods of low rainfall may enhance

drying or desiccation of surface (or liner) caps, increasing erosion and cap failure resulting in higher infiltration of precipitation into waste deposits and increased leaching [18, 362]. Where climate change causes an increase in the frequency and magnitude of rainfall events and increased fluvial and coastal flooding, it imposes risks on the integrity of landfill containment systems and may result in increased leachate generation and the probability of landfill erosion and waste release [29, 183, 362]. Therefore, climate change and warming will cause higher levels of hazardous substances release into ground or surface water, thus ultimately contaminating drinking water reservoirs, rivers, lakes, and the larger environment.

The POPs releases from landfills and other deposits and storages are triggered in part from the specific physicochemical properties of the POPs category, in particular with respect to water solubility and volatility and the characteristics of their respective landfill setting [362]. Some POPs/PBTs are moderately-to-highly water soluble (Table 1), such as the fluorinated POPs (PFOS, PFOA, PFHxS) (Table 1) and other per-/polyfluorinated alkylated substances (PFAS), HCHs isomers and hexachlorobutadiene (HCBD), and can be released in relevant concentrations. In addition, low water-soluble POPs like PCBs, hexachlorobenzene (HCB) (Table 1), and PCDD/PCDF are a major pollution challenge if flooding mobilise waste reservoirs in landfills. A number of cases have been documented linking POPs releases to flooding and flooding risk and some are shortly introduced here.

#### *3.1.1 Experience with POP pesticide deposits and releases at former production sites*

For some pesticide production sites, large POPs reservoirs have been generated from disposal of production wastes. POPs waste in individual deposits can reach 1000 s to 100,000 tonnes with a related risk of release, in particular when such sites are flooded. Experiences have been documented in particular for HCHs and for DDT.

*3.1.1.1 Production sites of HCHs and related release risk* Between 4 and 7 million tonnes of HCH waste isomers (α-HCH, β-HCH, and δ-HCH) have been deposited/dumped around former lindane (γ-HCH) production sites. As α-HCH and β-HCH are listed as POPs, HCH waste isomers are the single largest POPs stockpiles, with the largest share disposed in Europe [348, 351]. Isomers of HCH exhibit moderate-to-high water solubility (mg/L) (Table 1) and moderately high vapour pressure and can therefore enter the environment by leaching into ground and surface water and by volatilisation into the atmosphere [87, 378]. This migration has, over time, turned some HCH waste deposits into POPs contaminated megasites with much larger pollution footprints in groundwater and soil than the original landfill/dump [87, 350, 378]. In the case of the Elbe River where four lindane/HCH production sites are located (Bitterfeld, Magdeburg, Hamburg in Germany, and Spolana in Czech Republic) strongly increased HCH levels above regulatory limits were observed in fish after the 2002 flooding downstream the production site in

**Fig. 2** Groundwater treatment plant (850 $m^3$/h) for remediation of DDT, chlorinated organics, arsenic, and mercury from a production site in Italy [237]

Bitterfeld (released via the Mulde river) [106, 107]. Also, in Hamburg approx. 400 km downstream of Bitterfeld, the HCH levels in fish increased significantly after the 2002 flood, revealing an increased HCH contamination by flooding. However, the HCH levels and isomer pattern in the fish in Hamburg had a different time trend over the years compared to the pattern upstream near Bitterfeld [106] indicating that the increased contamination in River Elbe fish in Hamburg did not mainly stem from releases from Bitterfeld. The source was most likely deposits from the former Lindane/HCH production in Hamburg where residues from the Lindane/HCH production and from recycling of HCH waste have been disposed to different landfills [115, 276].

For rivers close to Spanish and Indian HCH deposits from lindane production, the surface water concentrations were in the ug/L range at times without specific precipitation [87, 156]. For the Spanish site (with more than 100,000 tonnes of HCH stored in landfills), it was estimated from measurements that at least 130 kg HCH isomers are released into the Gallego river per year even without specific flooding impact [87]. One major HCH landfill has been relocated (180,000 $m^3$) a few km to a new landfill with liners to protect the Gallego river [225].

The landfill of chemical waste of Juraj Dimitrov Company (CHZJD) in Vrakuna (borough of Bratislava/Slovakia) is another deposit of HCH and other chemical waste, which has a high risk of impacting the surrounding environment [235, 350]. Storage of chemical waste began in 1966 until 1979 and in 1980, the entire landfill was covered with an inert material of about 2–6 m. At the time of disposal, there was no interference between waste and groundwater level in the area of the landfill. However, after damming of the Danube for the Gabčíkovo power plant in 1996, the groundwater level rose in the whole area between Gabčíkovo to Bratislava. Since 1996, regular leaching of waste to the groundwater takes place, meaning 30 years of active distribution of contamination into soil and groundwater and to the environment [192]. The contamination plume is spread over 5.5 km from the landfill and permanently threatens the largest drinking water reservoir in Slovakia and Central Europe—the Žitný Ostrov—with the capacity of water supply for 15 million people [347, 350]. Increased flooding of the Danube results in increased release from this landfill, and the Environmental Ministry of Slovakia has submitted the case as national priority to the United Nations Department of Economic and Social Affairs as a priority activity for the implementation of the Sustainable Development Goals (SDGs) [305].

For all HCH disposal sites, the impact of high precipitation and the implications of contaminant release caused by flooding have not yet been sufficiently assessed.

*3.1.1.2 Experience with DDT production and related release and release risk* Similarly to HCHs, also DDT production has resulted in large DDT waste deposits [237, 378, 382]. A former DDT production facility, located on a tributary to the Lago Maggiore, Italy, contaminated the lake with DDT, arsenic and mercury [22, 237]. A large water treatment plant was constructed at the end of the 1990s to prohibit the infiltration and further spread from the area [237]. The plant functioned successfully and minimised discharges of contaminants from the production site to the river (and lake) during normal day-to-day operations. In October 2000, however, a heavy flood occurred and lake waters exceeded the maximum flooding level of about 2.5 m for 10 days, the highest levels in the twentieth century [237]. During this period, DDT residues were transported from contaminated soils and river sediments into the lake. This was confirmed by the increase of DDT content in water and sediments in Baveno Bay and in the flowing river downstream of the chemical plant [237]. Another study compared DDT concentrations in the soft tissues of zebra mussels at several sampling stations after 2001 with those collected at the same sampling stations in the preceding years [22]. The results confirmed increased DDT pollution due to transport from contaminated sediments and soils still present on the closed chemical factory site. The assessment of the flooding event and further work revealed that the capacity of the first groundwater treatment plant (400 $m^3$/h) was too small to cope with heavy rain events and it had been necessary to enlarge the plant to a capacity of 850 $m^3$/h in a second construction stage in 2001 [22, 237], Fig. 2).

This case highlights the technical challenge of retaining pollutants during flooding events, since water treatment systems cannot cope with the huge water volumes during flooding. The case also demonstrates that an assessment of releases from contaminated production sites and related reservoirs urgently needs to include the releases during flooding and consider flooding in securing and remediation measures (see also the section "Release of PCDD/PCDF from contaminated chemical production sites and landfills").

*3.1.1.3 Experiences with mobilising POPs pesticide wastes in low- and middle-income countries* Stockpiles from unused and expired pesticides are a problem in low- and middle-income countries in Africa [63], South-America [296], but in particular in the Eastern Europe, Caucasus, and Central Asian (EECCA) region [294, 295, 349].

It has, e.g., been found that a large quantity of POP pesticides was deteriorated and distributed through the devastating flood of 2010 in Pakistan, which hit almost every province with associated contamination of the environment [117]. Further, various small-scale flash floods have

led to the release of an unknown quantity of POPs and other pesticides that enter the aquatic system and are distributed to soils and sediments with associated risks [117].

Furthermore, the releases of POPs and other pesticides from obsolete pesticide deposits in Kyrgyzstan have impacted the surrounding population and led to a significantly increased risk of health problems in pregnant women and newborns [294, 295].

#### 3.1.2 Experience with deposits of HCB, PeCBz, and HCBD at organochlorine production sites

HCB and HCBD are formed as unintentional by-product in organochlorine solvent productions with 1000 s of tonnes of deposited POPs waste for single factories [151, 191, 311, 362, 386]. These landfills and contaminated sites have impacted or are impacting rivers with HCB and the more water-soluble HCBD and PeCB [126, 127, 312].

A detailed assessment of the pollution risk and remediation challenge has been documented in Kalush (West-Ukraine), where more than 11,000 tonnes of HCB waste from a carbon tetrachloride/tetrachloroethene manufacturer have been dumped in a landfill site very close to the Sivka River [191]. A Joint United Nations—EU Commission Environmental Emergency Response Mission visited the site in early 2010 to evaluate the risk of leaching into Sagopiv River, a tributary of the Dniester River which is a major water resource of West Ukraine and Moldova [312]. The barrels had completely corroded over the 20 to 40 years of disposal and partly released HCB and PeCB into the groundwater and surface water [191]. For the prevention of further leaching into water, it was decided to excavate the waste together with contaminated soil and export it to Poland for destruction in incinerators [191, 365].

Also, an HCB deposit in Czech Republic from organochlorine industry adjacent to the Elbe River containing 80,000 drums of "HCB waste" along with approximately 4 million tonnes of other wastes with subsequent leaching of the waste into the Elbe resulted in high concentrations of HCB accumulated in sediments downstream of the production and landfill area [126, 127]. Similarly, an HCB/HCBD waste deposit from a chlorinated solvent and chloralkali production in Austria is releasing these POPs into groundwater and surface water with increased release risk from floods from the river Gurk [82], Land [179].

Systematic assessments of such sites have not been performed for most countries, but considering the degradation of the containment systems such as metal drums [191] need to be urgently performed, including the release risks from flooding.

#### 3.1.3 Experience with mobilising of PCBs from reservoirs

More than 50% of the 1.3 million tonnes of PCB produced have been disposed to landfills [30]. The Swiss government screened their rivers for PCB contamination and compiled more than 1,000 fish data to establish levels of PCB contamination in rivers [261, 383, 384]. For two rivers (Saane and Birs), fish were frequently found above EU food limits for dioxin-like PCBs. For the Saane River, the source of the contamination was a landfill (La Pila) containing more than 20 tonnes PCBs (mainly in corroded condensers) distributed within 300,000 $m^3$ waste [383]; CSD [53]. This site is regularly flooded after heavy rain events with associated PCB releases [384]. The landfill is under remediation (CSD [53]) with an estimated cost of approx. 250 million Swiss Francs [304].

Without flooding, PCBs migrate only slowly out of landfills as documented by a study at a site in Poland, where PCBs (mainly tri- to tetraCBs) migrated up to approximately 50 m from the disposal site [101].

The flood in Pakistan in 2010 has displaced or washed away PCB-contaminated equipment with associated pollution risk [117].

PCBs have also been used and released in mines as hydraulic fluids, and large volumes have been released underground during the use of PCBs largely before the 1980s [58]. The flooding of mines and pumping of water result in current PCB releases from mines with related contamination of surface waters where the mine water is released [59, 60, 371].

#### 3.1.4 Experience with mobilising of PFOS, PFOA, PFHxS, and other PFAS from reservoirs

Per- and polyfluoroalkyl substances (PFAS) are highly persistent under environmental conditions including landfills, as they contain perfluorinated chains that only degrade very slowly, if at all, and are therefore called "forever chemicals" [23, 32]. Meanwhile, three groups of PFAS are listed in the Stockholm Convention, including PFOS, PFOA, and PFHxS and related compounds, where related compounds mean those PFAS which can degrade to PFOS, PFOA, or PFHxS [317]. The largest share of PFAS produced in the last 60 years has ended as waste in landfills in impregnated carpets, textiles, paper, or car shredder residues [48, 184, 362, 388]. The accumulated amounts of PFAS disposed to landfills are a great threat to the surrounding environment, since perfluorinated PFASdo not degrade in landfills or groundwater and many of them are water-soluble and are leaching from landfills and dumpsites [33, 103, 174, 184, 238, 240]. Since a large share of PFAS is included in side-chain fluoropolymers which degrade over decades to centuries

[359, 360], landfills of the last 50 years are long-term PFAS reservoirs.

Landfills with a particularly high PFAS reservoir and release are those from PFAS production which can contain thousands of tonnes of PFAS waste. For the production of the approx. 96,000 tonnes of PFOS/PFOSF, it is estimated that 26,000 tonnes of production waste have been generated which were frequently landfilled [220, 228]. Up to now only, for the detailed assessment of the 3 M PFAS production site in Minnesota, the crucial role of landfills from PFAS production for pollution has been documented [220]. Also, the use of PFAS in productions (e.g., leather, paper, textile, and chromium plating) and associated landfills have generated deposits with high release and pollution potential. A well-documented case is the PFAS pollution from a factory producing leather shoes with PFAS impregnation. The related disposal of production waste has resulted in human exposure of the surrounding community via drinking water. A fine of 110 million USD has been set by court for the shoe producer, and approx. 50% had to be paid by the PFAS producer due to a second court decision [195, 336]. Due to the risk of such deposits, the Conference of Parties of the Stockholm Convention recommended already 2010 a systematic assessment of deposits of POP-PFAS waste from producers and users when PFOS was listed in the Stockholm Convention [309]. There is no documented case of a landfill from PFAS production or a landfill with high amounts of deposited PFAS that has been excavated with further PFAS destruction. Therefore, it is likely that almost all landfills from disposal of PFAS waste still exist and continuously release PFAS to groundwater and possibly surface water. These landfills need a priority assessment including flooding and related release risk.

For PFOS and PFOA, high exposure and contamination of residents around contaminated sites, including landfills, have been documented [220, 336, 379]. Contamination and exposure to PFOS and PFOA are frequently related to groundwater pollution and related exposure via drinking water [220, 336]. Livestock, fish, and vegetables can get contaminated by PFAS released from landfills and contaminated sites [27, 188, 379], which can be accelerated by precipitation.

Systematic assessments of PFAS-contaminated sites have started in some countries. The USEPA conducted a systematic monitoring of 36,000 drinking water and groundwater samples [139]. Currently, the USEPA has an ongoing project to analyse 150 landfills in New York State as sources of PFAS groundwater contamination to protect humans from exposure [338]. And a methodology has been proposed to develop inventories of presumed PFAS-contaminated sites considering that PFAS contamination can be assumed around three types of facilities: (1) fluorinated aqueous film-forming foam (AFFF) discharge sites, (2) certain industrial facilities, and (3) sites related to PFAS-containing waste. More than 57,000 presumptive contaminated sites have been compiled [255]. This approach has also been applied by a Journalist Consortium to Europe with an inventory of 17,000 sites with known PFAS contamination and additional 21,000 presumptive contamination sites [47, 293].

For all landfills and contaminated sites that contain a relevant PFAS reservoir, the risk of flooding and dispersal to the wider environment should be assessed for the individual sites. The assessment of long-term release and contamination potential of larger PFAS deposits likely results in the need of excavation and destruction measures.

#### *3.1.5 Release of PCDD/PCDF from contaminated chemical production sites and landfills*

PCDD/PCDF have a low water solubility, and their release potential from landfills or other hot spots is relatively low if not oily leachates, dissolved organic matter or DNAPLs facilitate the release [113, 115, 363]. However, flooding of deposits containing PCDD/PCDF, such as organochlorine production sites or fly ash deposits from incinerators [19], can release particle-bound PCDD/PCDF by mobilising contaminated soils, fly ashes or wastes. The flooding of the Spolana factory (Czech Republic), which formerly produced 2,4,5-T, released PCDD/PCDF and mercury during the Elbe flood in 2002 when the area was flooded [217, 258]. A systematic assessment of chemical production sites and related landfills/dumps with former high generation and deposition of PCDD/PCDF containing waste (e.g., [115]) and related risk of flooding is missing.

### 3.2 Reservoirs of heavy metals and experience with increased release due to climate change

Heavy metals represent a relevant group of persistent pollutants, characterised by their inability to degrade naturally, making them exceptionally durable in the environment. Whilst they can be toxic to both humans and wildlife, the degree of toxicity varies depending on factors such as their oxidation state. For example, chromium VI is known to be highly toxic, whilst chromium ions in lower oxidation state exhibit lower toxicity. Some heavy metals, like lead and mercury, are consistently highly toxic as all oxidation states pose risks to both humans and wildlife [5]. Furthermore, there are radioactive reservoirs from mining, nuclear bomb testing and in the technosphere which pose a high risk [3, 154, 253].

On a global scale, efforts to address the impact of heavy metals on the environment and human health are gaining momentum. The Minamata Convention, established by

the United Nations Environmental Programme in 2013 [310], specifically targets mercury pollution, reflecting the international community's recognition of the seriousness of heavy metal contamination [125]. Additionally, UNEP is actively involved in addressing lead and cadmium as part of its global effort to control pollution [318]. The global relevance of heavy metal-contaminated sites has been highlighted by reviews conducted by organisations like the Blacksmith Institute, which have identified heavy metal-contaminated sites as amongst the most critical environmental challenges [204].

It is worth noting that addressing heavy metal contamination involves not only understanding the existing contaminated sites but also identifying potential sources of human exposure. These reservoirs of heavy metals require comprehensive inventories, and their associated risks need to be assessed, especially in the context of climate change impacts like flooding [42, 153, 291]. Some major reservoir types and case studies include mine tailings and related dams, contaminated floodplains and coastal sediments, as well as industrial soils, and landfills, which serve as examples of environments where heavy metal mobilisation and spread can be of concern [2, 31, 268, 389].

#### *3.2.1 Mine tailings and related dams*

Mine tailings, also known as mining waste deposits, represent a potential source of heavy metals and other environmental contaminants [34, 80]. These deposits are byproducts of mineral extraction and processing and may contain heavy metals, such as lead, mercury, cadmium, arsenic, and chromium, amongst others [391]. In the context of climate change, mine tailings pose an additional concern due to the effects associated with rising temperatures and extreme weather patterns [201]: Climate change can lead to increased precipitation and intense storms [35]. This can result in the leaching of heavy metals and other contaminants from mine tailings into nearby water sources, posing a significant risk to water quality and aquatic ecosystems [272, 287, 356, 390]. Additionally, these extreme weather events can lead to an increase in river and reservoir levels, potentially causing overflows in mining waste deposits, releasing substantial quantities of toxic substances into the surrounding environment [239]. Higher temperatures can also impact the stability of mine waste deposits by causing glacier melt and accelerated ice thaw in mountainous regions. This can increase water flow in these areas and exert pressure on the structures of mine tailings [218].

In some cases, these events can promote increased erosion, resulting in a higher risk of dam failures in mine tailings, leading to the release of large amounts of waste into the surrounding areas. Fourie [98] highlighted that the presence of high water content in tailings and the resulting water action (erosion, seepage, and overtopping) is a primary factor in tailings dam failures. Lin et al. [187] pointed out that erosion by water flow can damage both the visible structure and the unseen foundations, and rainfall can damage the soil and wash it away by runoff, potentially causing dam failures in mine tailings.

Over the years, several significant incidents of contamination caused by mine tailings have been reported worldwide in relation to extreme weather events. One of the most notable examples was the Mount Polley Open Pit Copper and Gold Mine Disaster in Canada in August 2014. It resulted from a partial breach of the tailings pond dam at the mine, releasing 17 million cubic metres of water and 8 million cubic metres of slurry contaminated with heavy metals into Polley Lake and its surroundings [136]. The dam breach itself was not directly related to extreme weather events, but it has been noted that weather conditions, such as heavy rains, may have contributed to the weakening of the dam and increased pressure on the structure [136]. The Mount Polley disaster had severe ecological and environmental consequences in the area, affecting local bodies of water and causing damage to aquatic ecosystems. Investigations and assessments were conducted to understand the extent of contamination and its impacts [136].

Another significant event related to extreme weather events was the Baia Mare Cyanide Spill in Romania in 2000. This incident involved a cyanide spill into the Someș River caused by a gold mining company. The contaminants reached the Tisza and Danube rivers, resulting in significant fish mortality in Hungary and Yugoslavia. It was considered one of the worst environmental disasters in Europe since the Chernobyl incident [252]. The causes of the Aurul dam breakage were partially due to heavy rains and the rapid snowmelt, causing the water level in the pond to rise [15, 252]. This rise was quicker than the planned growth of the dam, which was intended to increase gradually over time through continuous construction [36].

These incidents and an assessment of 147 dam disasters have shown that heavy precipitation was the primary reason for dam failures [247]. The increasing impact of climate change and more frequent extreme weather events will eventually lead to more dam failures in the future and need to be considered in dam assessments and new dam constructions [248]. Preventing, monitoring, and mitigating the risks associated with mine tailings are essential to protect the environment and human health in the future [248].

#### 3.2.2 Landfills

Landfills are host to a wide variety of waste, including municipal and industrial solid waste. Within this mixture of refuse, heavy metals and metalloids that threaten both human health and the environmental surroundings are present in relevant concentrations [165]. They originate from various sources, such as industry, electronic wastes, car shredder wastes, paints, and everyday objects like batteries and thermometers, and contain significant amounts of heavy metals, including mercury, lead, and cadmium [49].

Improper waste disposal has become a global issue, especially in developing countries, where open dumps are a common sight [84]. In these areas, the heavy metals present in the waste have the potential to leach into the soil and groundwater, posing a threat to public health and the environment [138]. The lack of sealing and lining measures, coupled with the absence of leachate control systems, significantly contributes to this problem [84, 202].

Climate change adds a new dimension to landfill management and the associated issue of heavy metals and POP releases. As climate change triggers extreme weather events, such as torrential rains, landfills become more susceptible to releasing heavy metals and metalloids into the surrounding environment. Floods can carry heavy metals out of landfills, contaminating rivers and soils [138, 277]. A groundwater level increase and accelerated erosion can also expose these contaminants [68, 153].

In addition to heavy metals and POPs, flooded and eroding landfills can be significant sources of plastics in the environment, including rivers and marine areas [29, 66, 381].

Rising sea levels represent another critical factor that can exacerbate heavy metal contamination in landfills, especially for landfills located in coastal areas [380]. These landfills may experience more frequent and severe flooding due to rising sea levels, leading to the transport of heavy metals and other contaminants into marine water bodies, posing an additional risk to water quality and marine ecosystems [380]. The intrusion of saline water can also accelerate the release of heavy metals by promoting chemical processes that dissolve contaminants in groundwater, increasing their mobility and transport through soils and aquifers, worsening the contamination of water sources and surrounding ecosystems [1].

Faced with this complex issue, it is necessary to implement effective landfill management measures and climate change adaptation strategies to address the growing threat of heavy metal pollution in these sites. This requires a comprehensive approach that encompasses both prevention and emergency response to safeguard public health and protect our valuable natural resources [68].

#### 3.2.3 Reservoirs of radioactive wastes

Radioactive waste is a by-product of various human activities, such as nuclear energy generation, nuclear medicine, and nuclear weapons production, and it poses a significant challenge in terms of management and safety due to its high risk to humans and the environment. Besides their radioactivity, these wastes can serve as reservoirs for radioactive heavy metals (plutonium and uranium) and non-radioactive heavy metals, such as lead, mercury, cadmium, and antimony [180]. These wastes are mostly stored in specific facilities, such as high-level waste repositories, with containment and security measures designed to prevent the release of radioactive materials and heavy metals [377]. However, climate change presents a new set of challenges for radioactive waste management, and research projects are ongoing [147].

The risk of climate change for radioactive waste repositories has been highlighted in the context of the Paris Agreement on Climate Change, especially concerning areas with a legacy of nuclear testing, such as the Marshall Islands which will be flooded by sea-level rise [135, 158]. Rising temperatures and extreme weather patterns can trigger unusual weather events, such as floods and storms, endangering the integrity of radioactive waste management facilities and nuclear power plants [3, 301].

For instance, floods have been documented in uranium mines [253], underscoring the vulnerability of radioactive waste storage facilities to extreme weather events [154]. The International Atomic Energy Agency (IAEA) has identified climate change as a significant risk factor concerning uranium mine wastes [141]. The concern lies in the need to isolate the waste from water in the environment, be it in the form of rain, streams, rivers, land flooding, springs, or groundwater [142, 329], necessary during the thousands of years in which the wastes will remain radioactive [143].

Climate change has also led to a reevaluation of traditional design parameters, as extreme weather events can exceed the capabilities of radioactive waste management facilities and pose a significant risk of releasing radioactive materials and heavy metals [3, 144].

Furthermore, certain rivers have been contaminated in the past by the release of radioisotopes, which can worsen with extreme weather events [140]. Sediment contamination in rivers, such as the Techa River, Russia, can present environmental and public health risks as heavy metals and radioactive materials can mobilise and spread in the aquatic environment [142, 297].

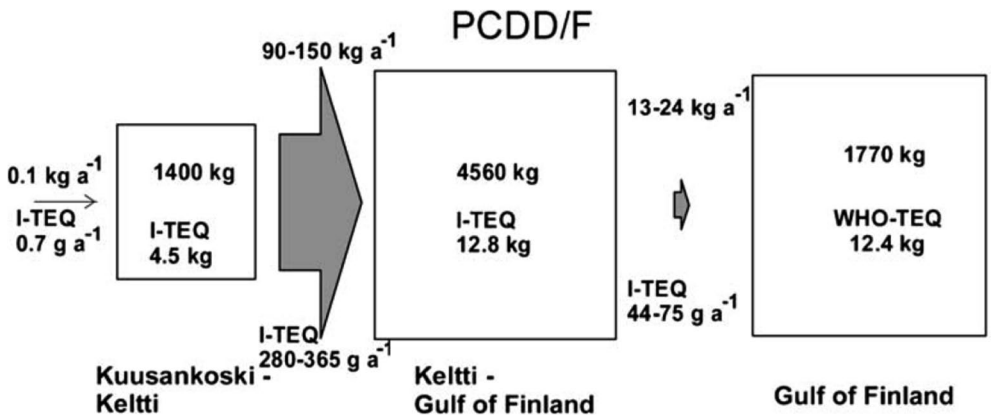


**Fig. 3** Schematic diagram showing the burden of PCDD/PCDF in different Kymijoki River regions and annual transport between the pools and to the Gulf of Finland in 2001. The size of the arrows is proportional to the quantity [344]

In summary, radioactive wastes not only represent a radiological threat but also a source of potentially hazardous heavy metals. Climate change adds an additional layer of risk by increasing the likelihood of extreme weather events that could jeopardise the safety of radioactive waste management facilities and the integrity of the repositories. Long-term management of these wastes requires careful consideration of the challenges posed by climate change and the need to effectively isolate the wastes for thousands of years.

#### *3.2.4 Contaminated flood plains and coastal sediments*

In the last decade, it has been revealed that many floodplain soils are highly contaminated with heavy metals, including Cd, Cu, Pb, and Zn (e.g., [164, 223, 251, 282, 342]). These metals originate from various human activities such as mining, industry and agriculture, which release them into the environment. Once released, they can be transported by watercourses and deposited in floodplains during flood events [42, 251]. Over time, these sediments can accumulate a significant load of heavy metals. These contaminants have the ability to bind to soil and sediment particles in floodplains through adsorption processes, allowing them to remain in the area even after floodwaters have receded [42, 369].

Additionally, Ciszewski and Grygar [42] pointed out that contamination in floodplains, especially the most severe contaminations, is primarily caused by the accumulation of large volumes of contaminated sludge, given as "pulses of contamination," following failures of mining tailings dams (see above) or the mobilisation of sludge caused by extreme precipitation events [42].

Climate change is altering flood patterns and precipitation regimes in many regions, which can have significant consequences for the dynamics of heavy metals in contaminated floodplains as well as transferring contamination from land to sediments in lakes and coastal areas. In some cases, such as the former use of mercury in the chloralkali process as well as in the pulp and paper industry, the direct release of heavy metals into shallow coastal recipients has resulted in large areas of fibre banks and fibre-rich sediments [214]. Transformation and release of Hg may be enhanced by various sediment perturbation processes directly linked to climate change, e.g., increased wave heights caused by extreme weather (winds) as well as increased dissolved organic matter (DOM) release from flooding (Land–Sea interaction). It is shown that these processes clearly increase the formation of methyl-Hg, which thus also enhances the risk scenario of Hg cycling in coastal areas [389]. Hence, an increase in the frequency and intensity of floods and extreme weather events can result in the greater mobilisation of stored heavy metals in floodplains due to soil erosion and sediment re-activation increasing the risk of releasing these contaminants into surrounding terrestrial and marine ecosystems [42, 236].

#### *3.2.5 Increased release from melting glaciers and permafrost*

Increased melting of glaciers and permafrost driven by climate change also contributes to the release of heavy metals, POPs, and other PBTs [24, 176, 229, 314]. Whilst the release of POPs from glaciers seems a minor reservoir compared to POPs in landfills and soils, projections suggest that mercury emissions to the atmosphere from permafrost regions are likely to significantly grow as a result of climate change: Under a high greenhouse gas (GHG) emissions scenario, mercury emissions from permafrost alone could reach a peak of $1.9 \pm 1.1$ Gg Hg year$^{-1}$ in 2200, which is similar to current global atmospheric emissions [314].

### 3.3 POPs and PBT contamination of soil and sediments and mobilisation by flooding

Sediments and soils are important reservoirs for POPs and other PBTs [93, 212, 241], and the flood risks are a key issue for the modern river basin management approach in high-income countries. For some rivers in Europe and the US, decades of assessment and remediation are known, which are shortly described in this paragraph for selected rivers. On the other hand, low- and middle-income countries, have partly established large production facilities where POPs and other PBTs have been used and released since 20 years or more, resulting in pollution of rivers and sediments [37, 64, 122, 387]. Larger remediation activities are scarce [122] and these countries will likely need assessment and remediation activities in the future.

#### *3.3.1 Historic release of POP/PBTs into rivers and contamination of sediments*

Industrial activities, and thus associated contaminated sites, are often located on rivers and coasts due to their needs for process and cooling water as well as effluent discharges [127, 233]. Some factories had released large amounts of POPs pollutants, such as PCB, PCDD/PCDF, HCB, HCHs, and PFOS directly into rivers [93, 127, 150, 166, 220, 344, 351]. These POPs contaminated sediments and flood plains of entire river systems for tens to hundreds of km with long-term remediation challenges [93, 339, 340, 344, 366, 367]. These sediments, along with the pollutants, are increasingly mobilised by extreme weather events and related flooding [51, 186, 264, 368, 375].

*River Kymijoki, South-Eastern Finland* [344]. A chlorophenol-based wood preservative, known as Ky-5, was manufactured in the upper reaches of the river between 1940 and 1984 causing severe pollution of river sediments with PCDD/PCDF. The total volume of contaminated sediments was estimated to reach 5,000,000 $m^3$, and hot spots with extremely high toxic equivalency (TEQ) concentrations (1,060 ng I-TEQ $g-1$ d.w.) were located immediately downstream from the pollution source (approximately 90,000 $m^3$). Sediment contamination was accompanied by changes in benthic assemblages, but direct effects were masked by many factors. The annual PCDD/PCDF flux to the Gulf of Finland, the Baltic, was estimated to vary from 13 to 24 kg/year (44–75 g/year I-TEQ) and the total load to the Gulf as 1770 kg or 12.4 kg WHO-TEQ (Fig. 3). With no remediation, 25–50% of the PCDD/PCDF deposited in the immediate sedimentary basins would have been transported downstream within 30 years, according to the estimation. Removing and/or capping these sites (36,000 $m^3$, 40% of contaminated sediments) between the source and Keltti would have had significantly reduced the PCDD/PCDF transport downstream. The highest transport percentages indicate circumstances of increased high flows (probability of one occurrence within 100–500 years based on data from 30 years of monitoring) because of climate change [344].

*Passaic River, US* [335, 339]. The Passaic River sediment Superfund site dates back at least to 1984, when the USEPA listed the former Diamond Alkali manufacturing plant site on the banks of the Passaic on the National Priorities List due to high levels of PCDD/PCDF. The plant, located about 3.5 miles (5.6 km) upriver from the Passaic's confluence with Newark Bay, had manufactured 2,4,5-trichlorophenoxyacetic acid/Agent Orange (estimated release of 2,3,7,8-TCDD: ~ 8 kg), DDT, and other pesticides and herbicides for about 20 years until closure in 1969 [26, 337]. The 5 million tonnes of sediments of the Lower Passaic contained ~ 29 kg TEQ [104]. For 30 years the remediation of the Passaic River megasite did not progress much with over 300 public- and private-sector parties involved. In 2014, the EPA issued the Focussed Feasibility Study that recommended bank-to-bank dredging and capping of the lower 8.3 miles (13.4 km) of the river. By the EPA's estimate, this would require removal of 3.3 million $m^3$ of contaminated sediments, at a cost of $1.73 billion [334]. Occidental Chemical Corporation is currently doing the engineering work needed to design complex remediation work in the lower 8.3 miles. EPA anticipates that engineering work will be completed soon. Once it is completed, it will take approximately 6–8 years to perform the cleanup [339].

Potential impacts from climate change have been assessed, and the performance of the remedy is currently not at risk due to the expected effects of climate change in the region and near the hot spot properties [337]. The floodwall, constructed to an elevation of 4.6 m above mean sea level, was designed to protect the site from a 100-year flood. Two examples of extreme storm events in recent history are Hurricane Irene 08/2011 and Superstorm Sandy in 10/2012. The Passaic River did not breach the floodwall during either storm, preventing both flooding of and damage to the site [337].

*Hudson River, US.* 322 km of the total 507 km of Hudson River stretch are defined as Superfund site [340]. During a 30-year period ending in 1977, when EPA banned the production of PCBs, it is estimated that around 600 tonnes of PCBs were discharged into the Hudson River from two General Electric (GE) capacitator manufacturing plants located in Fort Edward and Hudson Falls (State of New York) [340]. These PCBs contaminated sediments and, over time, also locations along the shoreline in the floodplain [340]. Since 1976, high PCB levels in fish have led New York State to close various recreational and commercial fisheries. In 1984, 200 miles

(322 km of the river were placed on EPA's National Priority List of the country's most contaminated waste sites. The dredging of PCB-contaminated river bottom sediment began in 2009 and was completed in 2015, approximately 2.1 million cubic metres of PCB-contaminated sediment was removed from the river bottom and 7.6% of the river bottom received "capping" [339]. GE informed that it has spent $1.6 billion on the cleanup, the EPA puts the total at roughly $2 billion [196]. Under a September 2022 legal agreement with EPA, GE will investigate the Lower River portion of the Hudson River PCBs Superfund site to determine next steps for addressing contamination and monitoring studies in 2023 and 2024 [340].

Upper River Rhine; Germany [259]. In 1975, a first study of fish for chlorinated aromatic hydrocarbons indicated values of up to 150 mg HCB/kg fat in the Upper River Rhine. Subsequently, the wastewater discharges of an organochlorine company in Rheinfelden at Rhine-km 148.3 had been identified as the main source of this HCB pollution. Since the 1960s, this company operated a plant for the production of pentachlorophenol (PCP) and its sodium salt (PCP-Na). According to the first wastewater inventory in the year 1981, the emission into the Rhine was in the order of 10 kg HCB/day. Finally, the production of PCP-Na had been stopped in 1985 and that of PCP in 1986. As an alternative business for the closed PCP/PCP-Na production capacity, the company significantly increased the production of chlorosilanes; here, during hydrochlorination of silicon at high temperatures, HCB is unintentionally formed to a relevant extent (in kg scale) [321]. Until 1993, the company continued to discharge untreated rinsing and cleaning water; however, even when from 1994 onwards, the discharged HCB load to the Rhine was low, the sediment samples still indicated high contamination. In 2003, just before a risk study for the Port of Rotterdam [131] was started, HCB concentrations in suspended matter up to 400 µg/kg have been determined in the Upper Rhine. In a report of the European Water Framework Directive, the river section from the border to Switzerland up to the last barrage near Iffezheim was considered as "endangered" with regard to the chemical quality of the water due to the contamination of sediments with HCB [9].

The Iffezheim barrage became the starting point for a serious conflict with the Port of Rotterdam, when the annual 130,000 $m^3$ HCB-contaminated material, that needed to be dredged at this site, could not further be disposed in nearby containment facilities. The Waterway and Shipping Administration (WSA) followed the economic management objective and looked for the least expensive solution at this site. Whilst, according to the discussion at that time, the German decision to "relocate" the material—that means "flushing" into the flowing Rhine River downwards—would comply with national regulations, the Port of Rotterdam voiced its fears that this procedure may lead to an exceedance of the HCB concentrations in the port [8], which would forbid the disposal of sediment at sea (threshold values of a "Chemical Toxicity Test" (CTT); see Sect. 2.3.4). The relocation at sea was seen as the least expensive option for the Rotterdam port authorities [56]. On April 27, 2005, a group of Dutch NGOs initiated a formal complaint to the European Commission concerning failure to comply with community law, e.g., non-deterioration principle [130, 190]. During the following years, the Iffezheim case was a central theme in science and policy of the River Rhine basin [145, 231, 280]. Finally, in the biannual campaigns of 2010–2011, an average volume of 230,000 $m^3$ at costs of 7 million Euros was dredged and transported to the Netherlands for deposition [168]. For the HCB and PCB contaminations in Rhine sediments, a Sediment Management Plan was adopted in 2009 and continues to be implemented [146].

Spittelwasser tributaries to River Elbe, Germany [93]. In the Bitterfeld region, Germany, the historical production of magnesium and other light metals using elemental chlorine from the 1930s to 1945 in three facilities have released a large amounts of PCDD/PCDF into the tributary of the Elbe River [150]. The total load has not been inventoried but a similar magnesium production using elemental chlorine has released an estimated amount of 50 to 100 kg TEQ into the Norwegian Fjords [170]. Highly loaded PCDD/PCDF sediment and soil reservoirs remained in the 1990s in the Spittelwasser. The sediments in the Spittelwasser area had a PCDD/PCDF contamination with peaks of 140,000 ng I-TEQ/kg and organotin concentrations up to 1050 mg/kg. The sediment reservoir was attributed in the 1990s primarily to a still water area of approximately 800 m length in the Spittelwasser creek sediment with a thickness of up to about 2 m [93]. A rough calculation showed that the main contamination—5,000 $m^3$ sludge from the largest and most heavily loaded Spittelwasser pond with estimated average of 20,000 ng PCDD/PCDF-TEQ/kg—had the potential for contaminating 5 million cubic metres sediment of the Elbe to a concentration of 20 ng TEQ/kg (safe sediment value) [69, 93, 132].

#### 3.3.2 *Inventory of sediment reservoirs: best practise with special reference to persistent pollutants and sediment stability*

A key for appropriate decisions in the sediment management of a river (or other waters) is a sediment and pollutant inventory and the knowledge of hot spots and the respective volumes [344]. At the end of the first Water Framework Directive (WFD) cycle, the Background

Document "Pollutants" of the Elbe River Basin Management Plan (RBC [244]) called it a "success", when some information from the Tauw Report [150] suggested that the summer flood of 2002 could have eroded the most critical PCDD/PCDF hot spots from the Spittelwasser river bed. In their expertise, Jacobs et al. [150] calculated a new integrated mass load (down to 0.3 m sediment depth) for PCDD/PCDF of 0.61 kg TEQ for the central Spittelwasser area between Jeßnitz (south-east) and Raguhn (north), documenting that still a large PCDD/PCDF reservoir is present with associated risk for mobilisation by flooding.

A prioritisation scheme of the RBC Elbe and IKSE Sediment Management Concept [243] for measures on contaminated sediments is based on threshold values of substances which are explicitly regulated with respect to the protection of human health, e.g., As, Cd, Hg, Pb, HCHs, HCB, benzo(a)pyrene (PAH), and PCDD/PCDF. An initial classification follows the specific criterion "the higher the ranking of the region of origin (here for either "contaminated sites" or "sediment"; for the Bode, Saale or Elbe River) or source type (side structures, lock reservoirs, sedimentation zone, and groyne fields), respectively, the more urgent is the recommendation" [93]. In the assessment of the sediment and pollutant budgets within the Elbe catchment area, a special emphasis was given to the aspect of potential remobilisation during flood events. Two methodological approaches, which have been intensively studied in the coordinated research programme SEDYMO [370], were the "SETEG flume" [173] and the Benthic-Water-Column-Simulator [124]. The former was used amongst others at the Saale River [213, 373] [also presenting an overview on these techniques]) for sediment cores sampled by G.E.O.S. [105], the latter, called Gust method [123] was applied on sediments from side structures along the Elbe River [128, 129], downstream from the Mulde and Saale confluents. The sediment budgets, stabilities, and pollutant characteristics of the major source areas in the rivers Saale and Elbe were studied from 2011 to 2015 by different teams [93] giving an insight into the mobilisation risks be flooding:

*Saale and tributaries:* In the navigable section of the Saale river approx. 190,000 tonnes of fine-grained sediments are deposited, of which approx. 75% are classified as remobilisable: in the Bode River, 37,000 tonnes of fine-grained sediment were found (e.g., weir Stassfurt), of which 75% are classified as "remobilisable". The highest concentrations of PCDD/PCDF—2220 ng and 6650 ng I-TEQ/kg—were found in deeper layers of core sediments downstream from Stassfurt, where one of the production sites for light metals using elemental chlorine was located (see above).

More than 1000 *Elbe River side structures* (harbours, cut-off meanders, bays, blind channels; approx. 50 $km^2$) comprise a total sediment discharge potential of 20–100 million tonnes, 80% located in the Elbe River section downstream from km 300.

*Elbe River groyne fields:* The Inland Elbe River exhibits 6600 groyne fields, which play a role as interim storage for the fine-sediment transport, estimated for 1.3 million tonnes along the Elbe; more than 80% of the muddy, relatively easily remobilisable material is located downstream of Elbe-km 350.

Elbe River floodplain sediments: Compared with the suspended sediment load in the lower Elbe River (Station Hitzacker), the sediment retention in the flood plain is approx. 6.5% at small floods, 24% at middle floods, and up to 27% at high floods; this corresponds to nearly 500,000 tonnes during the extreme flood in 2006. Floodplain characteristics influencing sediment and pollutant retention are vegetation patterns, inundation frequencies, and morphological features.

*The Bitterfeld Mulde reservoir lake as sediment and pollutant sink* [385]*, an important pollutant tributary to Elbe & North Sea*: Due to their origin in the Ore Mountains, the rivers Freiberger and Zwickauer Mulde are the major Elbe-wide sources of heavy metals and arsenic [119]. Since 1975, the united Mulde river has flown through the abandoned open-cast lignite mining pits at Muldenstein near Bitterfeld. Ever since the resulting Mulde river reservoir has built a sediment and pollutant deposit with supra-regional impact on the quality in the lower Elbe stretch extending to the port of Hamburg area and the North Sea. No major practical actions have been undertaken so far with the problems associated with historically contaminated sediments in the inland Elbe River basin, neither in the context of the recent inventories towards the end of the first WFD phase (Section "Regulatory action on contaminated sediments") nor in the 20 years after the fall of the Iron Curtain in Central Europe [93]. Since 1993, the Port of Hamburg has spent ~ 400 million € for the construction and operation of the METHA (Mechanical Treatment of Harbour Sludge) plant to separate grain size of 300,000 $m^3$ p.a. Elbe sediment and deposit the worse contaminated fine fraction on land. On the other hand, the plan of the District Office Bitterfeld to cleanup the Spittelwasser PCDD/PCDF hot spots—20,000 $m^3$, excavation, sand separation, and incineration of fine fraction, estimate 10–15 million €—was not executed. However, the feasibility study [93] is still relevant for similar sites of mobile historically contaminated sediments; with the more recent technical developments, e.g., for new hydraulic devices, the loss of contaminated sediments during extraction could be minimised. Given the present retention capacity, the legacy

Bitterfeld sediment reservoir will continue to serve as an important pollutant trap for at least another 770 years [161]. This example shows that no-action removing contaminated sediment near a pollutant source multiplies the costs to be paid for cleanup downstream.

#### 3.3.3 Remediation measures on sediment reservoirs

Removal and land deposition of contaminated sediments is an efficient measure that could be applied to several of the identified hot spots to reduce particular contaminant inputs into the River Elbe [93]. Claus et al. [44] argued that for a wide acceptance and best economic efficiency, such sanitation measures should be taken in combination with other goals, such as the improvement of the hydromorphological conditions or the river continuity for fish. In the lower part of the Saale River, the major part (85–90%) of the material transport takes place via the weirs. Since periodic dredging for navigation is required in the sluice canals anyway, the management regime of more sluices could be adapted to reach higher fine-sediment yields that could be dredged and deposited on land [44]. Dredging of sluices and dams can be applied to many rivers where sluices and dams are present. Dredged contaminated sediments need an environmentally sound management (ESM) and disposal, they cannot, e.g., be disposed to land with access of cattle which has resulted in the past in PCDD/PCDF and PCB-contaminated meat [366]. Instead, such sediments need to be safely disposed to landfills or thermally treated, e.g., in cement kilns [41, 55]; in the latter case, chlorine and/or mercury content might restrict the co-incineration [353].

Since the turn of the century and mainly pushed by the USEPA Superfund programme [90], sediment cleanup activities have moved to in situ technologies such as sediment capping, a form of in situ containment, and monitored natural recovery (MNR), where natural processes are used to mitigate the transfer of particle-bound contaminants into the water phase and/or biota [222]. Application of a combined sub-aquatic depot and active capping technology can, e.g., be considered for side structures, such as small yachting harbours [93].

The concept of natural attenuation/intrinsic remediation relies on natural processes rather than traditional engineered procedures. Stabilising factors, so-called "diagenetic" or "ageing" effects, which alongside chemical processes directly involving contaminants include enhanced mechanical consolidation of soil and sediment components by compaction, loss of water and mineral precipitation in pore spaces, may result in a quite significant reduction of the reactivity of solid matrices [89].

In situ sequestering of contaminants has successfully been treated on groundwater contamination, but these technologies—when applied to sediment remediation—are generally placed into or onto the sediment surface layer, into a sand cap, or within a geotextile mat [333]. In particular, in situ amendment of activated carbon (AC) to contaminated sediments effectively reduces organic contaminant bioavailability and has provided a new direction in contaminated sediment management. [110]. Porewater concentration reductions of 70–99% have been reported for sediments with PCBs, polycyclic aromatic hydrocarbons (PAH), PCDD/PCDF, inorganic Hg, and MeHg at environmentally relevant concentrations [114]. An overview on performance and cost evaluation of different techniques is presented by Patmont et al. [227].

#### 3.3.4 Pollution of river deltas and risk for open sea and related management challenges

The polluted sediments of industrially impacted rivers reaching river delta represent a particular challenge for management. This is well documented for rivers such as the Rhine River at Rotterdam [118, 375] or the Elbe River in Hamburg [265].

In the Port of Rotterdam, decisions on those management options for the 20 million m3 that are annually dredged in the harbours and channels are based on a system for assessing the acceptability of dredged material for dispersal in saline waters, the "Chemical Toxicity Test" (CTT), in which chemical target values are supplemented by biological effect considerations and the potential environmental risk of the contaminants present [260, 284].

The prioritisation of sites in catchments with regard to the risk they pose for downstream areas should apply a three-step approach [131]. The risk assessment for the harbour sediments due to POPs and other PBTs that could derive from the identified "areas of concern" requires a) estimating of resuspension, b) transport probabilities, and c) determination of transported quantities. The final assessment of "areas of risk" had to take into account the impact of event-related increased discharge levels.

In the case of contaminated sediments in Port of Rotterdam, an indication of the potential of an "area of concern" to lead to an exceedance of the local threshold value (CTT value) to be resuspended and transported downstream is derived from taking into account dilution by suspended matter (SM) originating mainly from the tributaries: XA = X * SMKB/SMA.

(where "XA" is the concentration at location "A" which would be needed for the respective CTT value at Rotterdam to be exceeded; "X" is the CTT value for the respective substance; "SMKB" is the suspended matter load at Kleve-Bimmen (close to Dutch/German border); "SMA " is the suspended matter load at location "A").

Evidence of risk for the Port of Rotterdam was only found for five areas [130]. Of these, two regions were classified as areas presenting a "high risk with high certainty" under certain levels of water discharges:

- The Ruhr was assessed to represent a risk at increased water discharges. High concentrations of polycyclic aromatic hydrocarbons (PAH) but also of the other substances that are of concern in that river, especially cadmium, are likely to be resuspended and transported downstream under those circumstances.
- The barrages in the Upper Rhine were the only sites in this study that may already present a risk during average annual flood events, at which increased concentrations of hexachlorobenzene (HCB) have been measured in suspended matter at Iffezheim (the history of HCB pollution in the Upper Rhine and the influences on the Port of Rotterdam; see Sect. "Historic release of POP/PBTs into rivers and contamination of sediments").

#### 3.3.5 Transfer of POP/PBT contaminated sediments and impact to flood plains

During floods, sediments are partly transferred from the river beds to the floodplain soil. Deposition of sediments from flooding can reach significant quantities, which for some river systems had/has positive implications with respect to fertility of the land [224] but can also negatively impact the fertility by sand deposition [328]. Each year, a major portion of about 2.5 billion tonnes of sediments carried by major river systems is deposited on crop fields [224] and areas where cattle are grazing [366]. POPs and PBTs are transferred to flood plains together with sediments and can contaminate these areas. Elevated levels of PBDEs in floodplains downstream textile industries have shown elevated levels in soil living biota, i.e., earthworms [266]. For some river flood plains, the contamination with PCDD/PCDF and PCBs with associated exposure of grazing cattle and related human exposure have been documented [177, 302, 364, 366, 367] (see below).

In the last decade, it has also been revealed that many floodplain soils are highly contaminated with heavy metals, such as Cd, Hg, and Pb, from the transfer of sediments (e.g., [99, 194, 230, 245, 249, 250, 270, 352].

#### 3.3.6 Ongoing releases from land to rivers/surface waters and related sediments

There are POPs for which there are exemptions for further production and use and which are released to rivers and sediments such as PFOA or SCCPs [185, 188, 355]. Also, unintentional POPs, including PCDD/PCDF, PCB, and HCB, are still released from industries to rivers [166, 383, 384].

Continuous PCBs inflow from former mining to tributaries of the Rhine River has been documented [59, 60, 366, 367, 371] as well as PCB releases from landfills to rivers [383, 384]. It is estimated that in West Germany up to 12,000 tonnes of PCB might have been released from hydraulic fluids into mines during the1950s to 1990s [366, 367]. The fate of these PCBs is uncertain in particular when considering that the pumping of groundwater in the mines has been reduced with the consequence that these mines will be flooded. Also, the removal of PCB paints from bridges, dams, and ships has resulted in water contamination [157, 367, 152]. In this respect, it is interesting that recent studies on Orca and Dolphins in European water have found PCB levels at alarming high levels which were associated with a reduction of reproduction and risk of extinction and lead to a call for better management of PCB legacies [57, 155, 286]. The ongoing inflow of PCBs from ongoing sources and PCB-contaminated sediments and other large reservoirs might present a reason for non-declining PCB levels in marine mammals around European coasts.

Furthermore, contaminated soils containing POPs and other PBTs are transferred by soil erosion facilitated by high precipitation to rivers and lakes converting to contaminated sediments and contaminating fish and other aquatic food. A well-documented example is the long-term release of PCDD/PCDF from Japanese rice soils originating from pesticide use in the 1970s to 1980s and subsequent contamination of Tokyo Bay sediments and lake sediments [199, 200]. Similarly, Sundqvist et al. [288] reported on ongoing release of PCDD/PCDF from Swedish former sawmill and wood treatment sites to the Bothnian Sea in the Baltic. These sites have been contaminated by 5–50 kg TEQ [289] and the fingerprint analysis demonstrated that the source composition of PCDD/PCDF in historic PCP-preservatives used at saw mill sites was found in the upper core of sediment samples in the Baltic [288]. Later, the source-related fingerprint of PCDD/PCDF from sawmills has also been reported in recent off-shore sediment, indicating an ongoing transport of PCDD/PCDF from land to coast and further out to off-shore areas of the Bothnian Sea [10, 11].

Also, POPs contaminated flood plains can redistribute POPs deposited in the past back to the river system. This has been documented for the Elbe River containing a large PCDD/PCDF reservoir in the floodplains [116].

Increased precipitation and associated soil erosion and flooding events can significantly increase the release of POPs associated with soils to surface waters.

#### *3.3.7 Regulatory action on contaminated sediments*

During the implementation of the European Water Framework Directive (WFD), it became clear that the original legislative system has to be complemented by further central "directives". Three of them addressed the aspect "pollutants" and these with special reference to historically contaminated sediments [93]:

(1) The Directive 2013/39/EC from August 24, 2013 reacts on the "actual legal situation" at Environmental Quality Standards (EQS) for priority hazardous substances. With the PCDD/PCDFF, a substance group is involved, which has not been regulated so far, but may provide the widest consequences.
(2) Downstream from pollutant sources, possibly until the coastal waters and the North Sea, environmental objectives can only be achieved if the pollutant loads existing in the upstream catchment are reduced or eliminated (Marine Strategy Framework Directive 2008/56/EC (MSFD of June 2008).
(3) The Directive 2007/60/EC of October 2007 on the assessment and management of flood risks increasingly deals with the specific challenges from particle-associated priority pollutants, such as PCDD/PCDF.

These three directives are highly interconnected, with direct implications for the chances of achieving the "good chemical status" of surface waters. It has been stated that it is imperative to closely coordinate measures in context of the Floods Directive, the MSFD and the WFD to be able to reach the individual goals of each of the legislations [133, 206].

### 3.4 Assessing the risk of POPs/PBTs reservoirs for food and drinking water safety

A particular concern of sediment transfer to floodplains is the related transfer of POPs, heavy metals and other PBTs to soils of the flood plains and food and feed safety. Some river floodplain systems have been contaminated with PCDD/PCDF or PCBs with associated exposure of grazing cattle and related human exposure [163, 366, 367]. Reservoirs of POPs in soil, sediments and other reservoirs have a long-term impact on food contamination in particular to free-range livestock [27, 85, 162, 232, 256, 296, 361, 366].

Mobilisation by flooding but also by construction measures, including sediment dredging, are mechanisms for increasing POP/PBT releases with potential relevance for feed and food [237, 361, 366, 375, 384]. These releases of contaminants into sediments result in contamination of the aquatic food chain by exposure and subsequent bioaccumulation of POPs and other PBTs in fish and other aquatic foods [11, 14, 106, 256, 361, 384]. Furthermore, it has been revealed that highly persistent sediment-bound contaminants such as PCDD/PCDF and PCBs are transferred to flood plains and can contaminate grazing livestock via feed and related soil uptake [162, 177, 262, 366]. Therefore, for several hundred kilometres, the use of ElbeRiver floodplains for grazing cattle is difficult and only possible with a strict management regime (see below). Similarly, floodplains of the Rhine River are contaminated in the Netherlands and have resulted in PCDD/PCDF contamination of cattle [137]. Another example is the northern Baltic Sea which has, during the last decades, slowly recovered from high contamination levels of POPs (PCDD/PCDF and PCBs) in fish

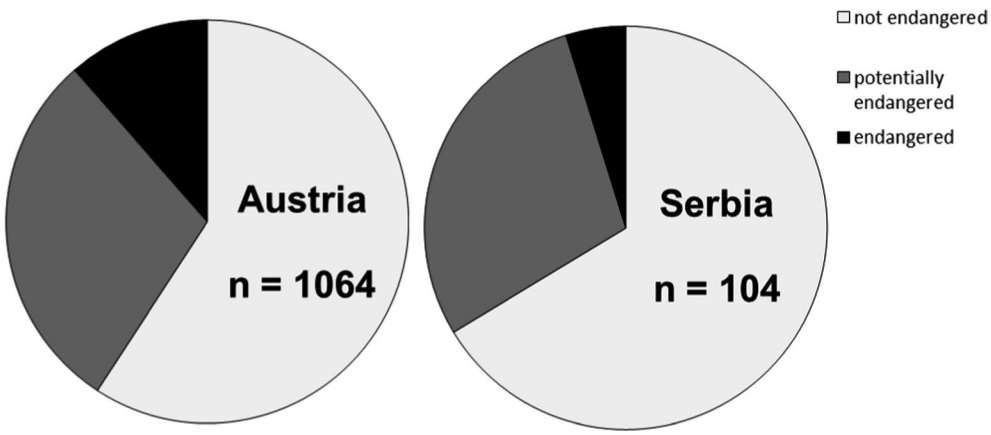


**Fig. 4** Proportion of landfills potentially endangered (i.e., in or in direct vicinity to flood risk zones) or endangered (i.e., located in flood risk zones) by flooding out of landfills with a waste volume above 25,000 $m^3$ in Austria [183] and Serbia [219]

[203]. However, brownification (DOM increase) of surface waters is observed in the boreal forest areas having a large number of rivers entering the Baltic Sea. The degree of release and mobilisation of POPs from background atmospheric deposits in the boreal landscape and not the least from secondary sources of POPs, often located at coastal industrial sites in soil and sediments, is determined by the release of DOM [11, 21, 159]. Thus, climate change-induced DOM mobilisation (and high precipitation) might reverse the declining trends of PCDD/PCDF and PCBs in Baltic fish. The full magnitude of these processes is not fully understood presently.

Also, heavy metals contaminating floodplains and release from tailings can impact food and feed. A notable example comes from Sudbury, Canada, where floods in areas adjacent to mining activities, such as the disaster at the Mount Polley open-pit copper and gold mine, released heavy metals like nickel, copper, and cadmium, affecting both soils and local water sources [136]. This raised concerns about the safety of locally grown food. Another impactful case was the cyanide spill at the Baia Mare gold mine in Romania in 2000 associated with extreme weather events (See the section "Mine tailings and related dams"), resulting in significant fish mortality in Hungary and Yugoslavia [252]. These examples underscore the urgent need to assess and control heavy metals in floodplains and tailings effectively to preserve food and water safety in communities exposed to these risks.

At the same time, human reliance on water resources and food (including fish) supply will increase with growing population [341]. On the other hand, global food security has decreased in recent years due to the COVID-19 pandemic and the war in Ukraine, with high domestic food price inflation in low-, middle-, and high-income countries [376]. The current and potential future impact of POP/PBT deposits and contaminated sites is another threat to food and drinking water safety.

Depending on the water solubility of a contaminant, also drinking water can become impacted. For example, groundwater pollution around PFOS/PFOA and other PFAS deposits contaminated also the drinking water, and several hundred million people have been affected with related human contamination [7, 188, 220, 346]. Also, for chlorinated POPs with lower molecular weight and water solubility in mg/L range (e.g., HCH and HCBD) (Table 1), drinking water can become contaminated from reservoirs [43, 96, 100, 315, 320]. This was demonstrated for a Swiss city where for decades, HCBD was in the drinking water before the drinking water works upgraded the cleaning steps [96]. Also, HCH has contaminated the drinking water of an Italian city where the deposits on a former HCH production site contaminated superficial aquifers and engendered fears of pollution of the deep aquifers whence the town draws its drinking water [100]. The more water-soluble chlorinated organics like tetrachloroethene (150 mg/L) and vinyl chloride (1100 mg/L)—present often at high levels in landfills of organochlorine POPs productions—are even more mobile and can spread either via surface or groundwater [17, 115, 118, 285, 378]. Whilst increase of precipitation might dilute pollutants in some areas, they will then be further spread, impacting more water resources. Furthermore, large PFAS, HCH, or HCBD deposits from production sites can contain thousands of tonnes of POPs at the sites [220, 228, 348, 351, 362] and, therefore, increased percolation or flooding of such sites will eventually increase the pollution footprint to tens or hundreds of $km^2$ [220, 348, 378].

### 3.5 Inventories of POP/PBT reservoirs contaminated and endangered by flooding

For an overview of the current pollutant reservoir, inventories of critical pollutants such as POPs and other PBTs need to be established. The risk for future contamination, such as the risk of flooding and related possible migration and pollution of the environment and related risk of feed and food contamination need to be assessed. The development of National Implementation Plans (NIPs) for the Stockholm Convention on POPs and the Initial Assessments for the Minamata Convention (MIAs) on mercury could be global entry points to initiate such inventory work also in low- and middle-income countries with elaboration of activities included in the National Implementation Plans.

#### *3.5.1 Inventories of landfills endangered by fluvial and coastal flooding*

First national inventories of municipal waste landfills endangered by fluvial flooding have been established for Austria [183] and Serbia [219]. Increased leaching and (partial) erosion of old municipal solid waste landfills during flood events have been observed in Austria [6] and is probably the case in many countries where landfills or dump sites have been located on marginal land close to rivers [54] as, e.g., documented for yearly flushing of plastic from flooded landfills in Bosnia [66].

In the case of Austria, the database to evaluate flood risk exposure of landfills is rather elaborate and includes waste management reports about controlled landfills (formal permission), an extensive database of old landfills (mainly operated before 1989), and nation-wide flood risk zonation data. In the case of Serbia, the evaluation is based on more easily collectable data with no nation-wide dataset about flood risk zones being present. Consequently, a more sophisticated approach to evaluate flood risk exposure of landfills is used for Austria than for Serbia. In Austria, landfills endangered by flooding

are identified from a sample of 1064 landfills (sites with volume > 25,000 $m^3$) by checking the landfill location against the dataset on flood risk zones with a statistical discharge return period threshold of 200 years [183]. In the case of Serbia, a two-step procedure was used to identify (potentially) endangered sites based on landfill volume and its distance from the nearest river, in the first step, and a visual inspection method using aerial photographs, in the second step. The first step is used to identify potentially endangered landfills (> 25,000 $m^3$) and the second step serves as a basis to prioritise critical landfills (potential effect of landfill flooding on downstream subjects) amongst the sites potentially endangered by flooding [219].

The results of the flood risk evaluation study in Austria and the screening study in Serbia are shown in Fig. 4. It is apparent that the Austrian study is based on a larger sample of landfills (1064 sites) than the Serbian study (104 sites). This is probably due to the more complete coverage of existing landfills in the Austrian database [278]. For Serbia, there is a dominance of small- and middle-sized landfills (97% of all known landfills), which were not well registered [219]. Nevertheless, the results in terms of the share of sites potentially endangered by flooding (located in or close to flood risk zones) are similar (around 30% in both cases). In case of Austria, only 5% of these landfills have technical flood protection measures in place. The fraction of landfills regarded as endangered by flooding (located in a flood risk zone) is around 11% in case of Austriaand around 5% in case of Serbia. However, it should be noted that for Serbiathe evaluation also includes considerations with respect to the potential damage caused by contaminated flood water downstream of the site (secondary risks of flooding). In the Austrian study, the evaluation of secondary risks is done for selected case studies, which focus on the pollution potential of the main contaminants leached from municipal solid waste (MSW). Due to the focus on deposited MSW and related emission levels, the finding that these emissions are not outstanding compared to other sources (e.g., wastewater treatment plants) during a flood event, is not to be transferred to landfills containing hazardous and chemical wastes with completely different substance inventories.

For England, a comprehensive analysis of historic solid waste landfill sites vulnerable to coastal flooding and erosion at a national level has been developed considering also sea-level rise [28]. Coastal landfills were defined as those within an area with 0.5% annual probability of tidal flooding, ignoring the presence of flood defences. In total, over 1200 landfills in low-lying coastal areas were detected. Without intervention, 79, 122, and 144 historic English coastal landfills are expected to start to erode and release waste into coastal waters in the short-term (by 2025), medium-term (by 2055), and long-term scale (by 2105), respectively, accelerating with respect to the anticipated effects of climate change [28]. It needs to be stressed that the flooding with marine waters substantially modifies the landfill hydrochemistry and can solubilise significant metal load [28, 88].

Furthermore, the inventory of all landfills in England found that 2636 (13.4%) historic landfills are within 25 m of the centre of a statutory main river, and 667 (3.4%) are within 25 m of the centre of a priority river (or

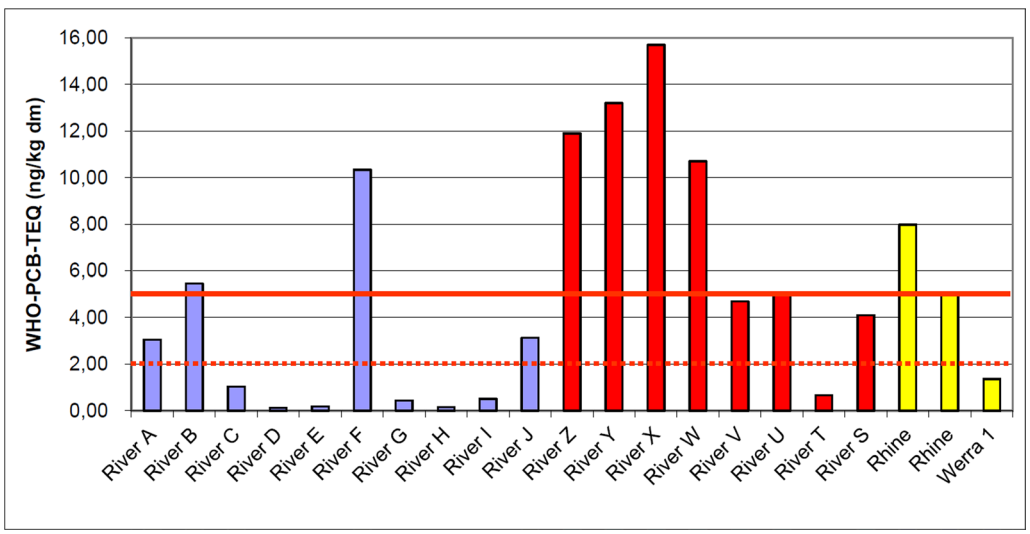


**Fig. 5** Dioxin-like (dl-) PCB levels in soils of flood plains of rivers from three German federal states (federal states marked in different colours) and related risk levels for cow meat production (5 ng PCB-TEQ/kg) [364, 367]

headwater) habitat. At least 6451 (32.7%) of England's historic landfills are in areas with soils that freely drain to inland surface waters or with naturally wet soils that drain to inland surface waters, and only 97 of these are recorded as having leachate controls in place. Flood Zone 3 (land with a 1% or greater chance of flooding each year from rivers and with a 0.5% or greater chance of flooding each year from the sea, respectively) contains 4767 (24%) of England's historic landfills; the vast majority of these (83%) are not currently protected by flood defences. The majority (79%) of these landfills in Flood Zone 3 are in fluvial flood zones, suggesting fluvial flooding of historic landfills may pose a greater risk than coastal flooding. Within areas that are recorded as having been flooded in the past, there are 2096 (10.6%) historic landfills [29].

Apart from England, a screening analysis for several other European countries (France, Germany) and Florida confirmed that thousands of coastal landfills are potentially concerned by sea-level rise, with documentation that some of them already released waste into the environment [211].

In light of the rather large fraction of (MSW) landfills potentially endangered by flooding in Austria and Serbia (cf. Figure), studies explicitly looking at deposits of chemical and industrial wastes and at the emission behaviour of POPs with their tendency to migrate and then bio-accumulate would be highly relevant. It has been demonstrated for Austria and Serbia that inventories can be built based on different datasets as a part of a screening analysis to further investigate and prioritise landfills with high secondary risks in case of flooding. However, in addition to the lack of inventories of landfills containing problematic wastes and endangered by flooding, there is also little knowledge about the emission behaviour of landfills under flooded conditions. Current data do not allow for realistic estimates of substance mobilisation rates from the waste under such conditions. Therefore, in addition to national flood risk inventories for landfills (ideally including considerations about the effects of climate change), efforts to investigate mobilisation processes for problematic substances contained in the deposited waste during and after the flood event are needed to assess environmental risks associated with flooded landfills.

When developing inventories of landfills, sites with specific hazardous reservoirs need to be earmarked and treated as a priority. The pollutant reservoirs of problematic landfills should be established as detailed as possible.

#### 3.5.2 Inventories and further activities for mine tailings

The failure of Tailings Management Facilities (TMF) leads to severe disasters worldwide (see the section "Mine tailings and related dams"). The United Nations Economic Commission for Europe (UNECE) thus developed the "Safety Guidelines and Good Practises for Tailings Management Facilities" (UNECE, [326]) promoting inventory, assessment and good practise of TMF.

Recently, an Internet portal with a global inventory for mine tailings has been compiled, which brings together the disclosures that mining companies have made about their tailings storage facilities with the aim to give communities, investors, regulators, and the media unprecedented access to information about mine waste [323]. Information on flooding risks could be included in this inventory for promoting risk assessment and mitigation for these large PBT reservoirs.

#### 3.5.3 Inventories of contaminated sediments and soils including floodplains

The reservoirs of POPs and PBTs in contaminated sites (soils and other affected materials) or contaminated rivers, considering sediments and flood plains, are needed to better understand and eventually control pollution risks. Also, the risks of feed and floods and related releases should be included in inventory developments [366]. One example of combining inventories of climate change effects and contaminated areas can be found in Sweden. Here, the two governmental agencies, The Swedish Civil Contingencies Agency (MSB) and Swedish Geotechnical Institute (SGI), got the mission in 2019 to identify all areas at risk of landslides, erosion, and flooding from the perspective of climate change effects [269]. The Swedish Environmental Protection Agency (SEPA) has combined this information with the inventories of contaminated areas (in total approx. 86,000 sites, of which 1200 in highest risk class I and 8500 in second highest risk class II). The combined information showed that more than 3700 contaminated sites have very high risk or high risk for human health and environment as being in areas with risk of climate-induced landslides, erosion, and/or flooding [290]. Significant efforts are needed to increase the pace of climate adaptation and ensure sufficiently prevention measures.

*3.5.3.1 Inventory of POPs and other PBTs in river sediments* For a few rivers, a POPs inventory has been established, in particular for those where larger remediation activities with detailed monitoring are conducted, such as Kymijoki River or the Passaik River inventories for the respective major POP pollutant (see the section "Historic release of POP/PBTs into rivers and contamination of sediments"). For the Kymijoki River, in addition to the inventory, also the substance flow and prediction for PCDD/PCDF (Fig. 3) and mercury have been conducted [344]. Based on such inventories and predictions, risk assessment, cost–benefit assessments, and remedia-

tion priorities could be developed for river sediments to enable further sediment management.

*3.5.3.2 Inventory of POPs and other PBTs in flood plains* One baseline information for the risk of feed and food contamination by floods is the current level of pollution of the flood plains of the individual rivers and river segments. Flood plains are often fertile, and, in some countries, even the most fertile land and therefore abundantly used for agriculture. Some industrial countries have started to make inventories in this respect.

Macklin et al. [193] compiled global data on the locations of active and inactive metal mines and tailings dams which hold mine waste. Using hydrologic models, they assessed river system contamination from mines and failed tailings dams and determined the floodplains, people, and livestock that could be affected. According to their estimate, over 23 million people live on the ~ 164,000 square kilometres of floodplains affected by mining [193].

In the UK, floodplains of rivers have at least partly been assessed for PCDD/PCDF and PCBs [177].

A systematic assessment of the contamination of flood plains has only been done for selected POPs for a few rivers, e.g., in Germany (Fig. 5; [116, 303, 364, 367]). Some German Federal States monitored PCB levels in the flood plains for major rivers and detected levels for some river flood plains, which resulted in risk for meat production (Fig. 5, [364, 366, 367]).

Such assessments should be conducted at least for all rivers with industrial or mine tailing impacts and related flood plains. In such an assessment, a particular focus should be on the exposure of livestock. An assessment of PCDD/PCDFs and PCBs in the feed for livestock and management measures like cutting the height of the grass has been conducted for the Elbe River [162, 366].

Floods can also damage drinking water wells and lead to aquifer and well contamination. Floodwater can contaminate well water with chemicals, livestock waste, human sewage, and other contaminants that can lead to illness when used for drinking, bathing, and other hygiene activities [330]. In particular, dug wells, bored wells, and other wells less than 15 m deep are more likely to be contaminated [330]. For PFAS, the impact of water pollution caused by increased precipitation has resulted in increased pollution in some areas due to mobilisation, whilst also a decrease in other areas has been reported due to dilution [215].

### 3.5.4 Inventories of POP/PBT reservoirs in the technosphere in the face of Natech accidents

Technological accidents triggered by a natural hazard or disaster which result in consequences involving hazardous substances (e.g., fire, explosion, and toxic release) are commonly referred to as Natural and Technological (Natech) accidents [72]. If industrial sites are located in naturally hazard-prone areas, technological accidents can be triggered by Natech events and may modify as well as increase the impact and overall damage in surrounding areas [102]. Climate change can alter the intensity, frequency, and local distribution of hazard sources like heavy rainfall, flooding, or winter storms. The International Panel on Climate Change (IPCC) already highlighted in 2012 that these risks need to be managed [148]. Operators of installations in which large quantities of hazardous substances are present and the authorities responsible for them must therefore adapt their risk management.

In recent years, Natech events have received significant attention, and reviews from the last three decades have been published [38, 52, 275, 172, 246], European Commission 2023). The European Joint Research Centre has developed an eNatech Database which aims to inventorize Natech accidents (European Commission 2023). The aim of this database is to systematically collect information on Natech accidents that occurred worldwide and allow the searching and analysis of accident reports for lessons-learning purposes. Floodings are amongst the most frequent natural hazards that trigger accidents in chemical infrastructures or oil and gas pipelines that result in the release of hazardous materials/chemicals, fires, and explosions [233]. Several thousand PBTs are used in industries and productions [257, 283, 357] and need to be considered in release risk assessment. Since industries often require water as raw material, for cooling, and as a transport system for raw materials or products, a lot of establishments, according to the Seveso III Directive (European [77]) and installations containing substances hazardous to water are located close to rivers. Floods and other natural disasters can trigger technological accidents and damage [171, 233]. Natech accidents at these facilities can pose a significant risk for the release of hazardous substances, so inventories of chemicals used and measures to avoid the release of PBTs in the case of Natech events are needed. The European Commission's Joint Research Centre has recognised the risk associated with Natech accidents and is doing systematic research into Natech accidents and their underlying dynamics [171]. An assessment by the German Environmental Agency also indicates that natural disasters have the potential to trigger the release of hazardous chemicals and other hazardous materials. Therefore, it was concluded that natural disasters should be considered as separate accident-triggering events in the planning, design, and operating stages of industrial facilities that process or store hazardous substances [83]. The German study

identified gaps in flood risk management at industrial sites and installations even for a well-regulated industrial country, and recommendations on policy, regulations, standards, and safety management were made for improvements [83]. Since the intensity of flooding and other effects triggered by climate change is increasing, the IPCC has included Natech in a report on "Managing the risk of extreme events and disasters to advance climate change adoption" [148].

Furthermore, the Natech accident at the Fukushima Daiichi nuclear power plant revealed the risk of large volumes of radioactivity being released from nuclear power plant flooding [205, 358, 372].

## 4 Recommendations to minimise risks from POPs/PBTs reservoirs considering climate change

### 4.1 Systematic development of inventories of POPs/PBT reservoirs

POPs/PBT reservoir inventories are not or only rudimentarily developed, and there are no comprehensive estimates of which reservoir types (landfills, contaminated sites, contaminated sediments, contaminated soils, or technosphere) contain the largest POPs/PBTs quantities and what the release risks are. Due to the lack of this information, it is unknown which of the reservoirs presents the largest risk for future releases, environmental pollution, and exposure. To evaluate risks to human health and ecosystems due to exposure to POPs/PBT reservoirs as well as releases resulting from floods and storm surges, inventories of POPs and PBTs reservoirs need to be established in a first step to plan and execute additional necessary actions. This should include inventories of contaminated industrial areas, landfills, and dump sites as well as sediments and contaminated soils. In this inventory process, the locations of reservoirs should be comprehensively mapped and matched with future scenarios of floods and releases, to predict the potential spread of pollutants.

Also, it is essential to develop inventories and control measures for POPs, PBTs, and other chemicals of concern present in the technosphere. This becomes particularly important in industries located in floodplains and flood-prone areas as well as in connection with risks associated with extreme climatic events (Natech). In this context, it is important to conduct a detailed assessment of the inventory of chemicals used or stored in these industries. Additionally, it is crucial to analyse their related safety and protection against flood events, which must comply with regulations established by appropriate legislation. A range of control measures has been developed, mainly in high-income countries, for contaminated floodplains and for potentially affected industries and storages could be considered and further implemented.

These inventories can contribute to climate information and early warning systems (CIEWS) [178, 319] and can contribute to disaster risk reduction. The inventories can also contribute to the impact-based people-centred Multi-Hazard Early Warning Systems (MHEWS) supporting well-informed science-based decision-making and support two pillars for implementation of MHEWS: (1) Risk Knowledge and Management and partly to (2) Observations and Forecasting. Substance flow of major heavy metals, POPs and other PBTs should be developed, considering major reservoirs and the impacts of climate change, particularly mobilisation and the potential for mobilisation through flooding events. This assessment should evaluate the potential contamination of agricultural areas and its related impact on food production, as well as the contamination of drinking water reservoirs. The risk of additional contamination of groundwater and drinking water resources should also be assessed, along with risks of exposure for humans and biota.

### 4.2 Overall management and regulatory frames

For the assessment and management of reservoirs of pollutants and their mobility risk, an overall management approach and regulatory frame are needed at national, regional, and international levels. For the European Union with the adoption of the Lisbon Treaty and the reference to territorial cohesion, environmental sustainability becomes a more visible and important component of Cohesion Policy. The EU Soil Strategy for 2030 sets out a framework and concrete measures to protect and restore soils, aiming for healthy soils by 2050 with specific actions by 2030 also considering sediments. Its objective is to reduce soil pollution to levels no longer harmful to human health or ecosystems, encompassing activities such as the restoration of degraded soils and the remediation of contaminated sites. It also emphasises increased research, data collection, and soil monitoring [71]. This stronger emphasis on the environmental dimension should encourage a more explicit consideration of the territorial dimension of the environment. It recognises interregional/transnational connections related to natural resources and the environment and underscores natural boundaries/areas as suitable management units for environmental assets. Furthermore, it promotes trans-European risk management to address hazards, mitigate, and adapt to climate change through integrated trans-European and cross-border strategies for flood protection. In this frame, it is also necessary to assess the reservoirs of pollutants mobilised and transported across borders and address measures that minimise the mobilisation of pollutants and the related risk of environment and food contamination.

During the implementation process of the European Water Framework Directive (WFD), key issues in river basin management have increasingly relied on the involvement of scientific expertise at critical steps [242]. However, achieving significant improvement is anticipated to take much longer than initially expected. For instance, the 2015 Elbe River Basin Management Plan (RBC Elbe) states: "Without goal-oriented measures for the reduction of primary and secondary pollution sources, the objectives of a good chemical and ecological quality in surface waters until the end of the second WFD management period and a good environmental state according to the [EU] Marine Strategy Framework Directive (MSFD) until 2020 will be strongly endangered". This is mainly due to the effects discussed in the present work, i.e., the impacts of sediment/particle-bound contaminants exacerbated during storm events when these deposits are mobilised and, in addition, the combination of resuspended "historical" contaminated sediments with pollutants like PCDD/PCDF and PCBs which have limited capacity for proactive measures to reduce their initial entry into the aquatic environment [75, 91]. POPs become here a more prominent role in this context. For example, during the period 2016–2021, PCDD/PCDF and dl-PCBs play a major role in three WFD-related EU-Directives. These include (i) new priority substances in the list of biota-EQS (Directive 2013/39/EC) (European [78]), (ii) seeking innovative solutions in sediment remediation (i.e., respecting the influence of mechanical processes, Flood Risk Directive 2007/60/EC) (European [74]), and (iii) indicators at the land–sea interface (MSFD) [76]. A recent ruling by the Court of Justice of the European Union [50] reinforces the WFD by stating that Member States cannot authorise projects that may "cause a deterioration of the status of a surface water body" (Art. 4 (a)(i) WFD). This clarification [343] could help overcome the blocking of remedial actions by local administrations and government lobbying groups, as seen in the case of PCDD/PCDF in the Elbe basin [93] (see the section "Inventory of sediment reservoirs – best practice with special reference to persistent pollutants andsediment stability"). A first step could be, for example, overturning the decision of the German Federal States along the North Sea coast to exclude PCDD/PCDF from their list of "common transitory provisions for handling dredged materials in coastal waters". This case will demonstrate if and how already developed regulatory frameworks can function in practise and what obstacles need to be overcome. However, in many countries, there are no adequate regulations to protect sediments and control polluted sediment or prevent flood-related pollution, and further development of related regulations and policies is necessary.

Regarding deposits of POPs/PBTs in landfills located in floodplains, it is necessary to implement flood protection and, eventually, remediation measures. These measures should be considered when developing regulations for flood or climate change mitigation. The long-term effect of rising sea levels must also be taken into account when planning new disposal sites and managing landfills and other reservoirs which contain POPs and other PBTs, which may persist until 2300 and could potentially be completely submerged according to projections (see Fig. 1). Such assessments should be integrated into current projects on landfill siting. Additionally, POPs/PBT reservoirs and other hazardous waste in flood-prone areas (fluvial and coastal) with risk of release should be removed and managed in an environmentally sound manner. This may involve destruction or storage in secure areas until capacity is available for proper disposal.

For Tailings Management Facilities (TMFs), the UNECE "Safety Guidelines and Good Practises for Tailings Management Facilities" (UNECE, 2009) comprise recommendations to authorities on the necessary legal basis for permits for the safe operation of TMFs and recommendations to operators on their safety design. The UNECE requested member countries to incorporate the safety guidelines into their national regulations and technical standards and to apply them. However, this posed problems, because the Guidelines set out safety standards in general terms only. Therefore, the German UBA (Umweltbundesamt) initiated in 2013 the groundbreaking project "Improving the safety of tailings management facilities" based on the example of Ukrainian facilities. In the following years, this was continued with the financing of the Capacity development to improve safety conditions of tailings management facilities in the Danube River Basin in 2019 and 2020 by the International Commission for the Protection of the Danube River (ICPDR) [298]. In 2021, UBA organised in the Kyrgyz Republic a training with a very useful instructional video on the TMF checklist methodology to support its future application [299]. The last version of the Tailings Management Facilities (TMF) Safety Methodology [300] was endorsed by the Conference of the Parties to the UNECE Convention on the Transboundary Effects of Industrial Accidents as well as other comparable international TMF standards. The TMF Safety Methodology is a powerful tool for the process of harmonising technical standards for the entire life cycle of TMFs throughout the UNECE region and could be utilised globally. The Tailings Management Facility Safety Methodology consists of a Checklist for verifying the actual safety situation of tailings management facilities and the Tailings Management Facility Hazard and Risk Indexes (THI or TRI) for assessment of TMFs on a regional, national and international basis [300]. This

TMF methodology can only be successful if owners of the TMFs implement the measures proposed and invest sufficient funds to ensure proper maintenance works.

With the adoption of the Chemical Strategy for Sustainability Towards a Toxic-Free Environment [70], the phase-out of persistent chemicals has received more attention and will also be integrated into the next period of Cohesion Policy, whilst it also has been criticised [226, 279, 345]. This will reduce the use of POPs and other PBTs in future and related accumulation and release risks.

### 4.3 Management of flood plain areas impacted by POPs and other PBTs

Given the importance of floodplains as reservoirs of heavy metals, POPs, and other PBTs, it is crucial to implement effective management strategies in the context of climate change [169]. This includes establishing monitoring programmes, undertaking remediation and restoration when necessary, and promoting awareness of proper management of contaminated floodplains to protect these ecosystems and reduce environmental and health risks.

After recognising the threat of feed and food contamination by PCDD/PCDF, PCBs, and other PBTs in floodplains [177, 262, 263, 366], restrictions or other countermeasures have been implemented. In the case of the Elbe River, floodplains are highly contaminated with PCDD/PCDF over several hundred kilometres, leading to the subsequent transfer of contamination to the North Sea [303]. Several research projects were conducted to develop feed and livestock management in the Elbe floodplains [120, 263, 327], and related guidelines were established and published by authorities [181, 182]. For instance, the appropriate cutting height of fodder has been developed minimising PCDD/PCDF transfer to fodder via soil particles. For suckler cow husbandry, a time limit was set for the lactation period, and subsequent final fattening in the stable with clean fodder has been established. Similar assessments and management measures should be developed for other floodplains, tailored to specific pollutants and pollution levels.

Further, securing and remediation plans should be developed based on information obtained from inventories (see the section "Systematic development of inventories of POPs/PBT reservoirs") and related assessments that reveal risks. Mitigation strategies should also be formulated for pollution already occurring in river floodplains with industrial impacts, especially concerning the risk of livestock contamination and related human exposure. This interdisciplinary task will require cooperation between the Government's Environment, Agriculture and Industry Ministries, POPs/PBTs researchers, industries, geotechnical engineers, experts in contaminated sites/landfills, water management specialists, and possibly geoscientists working on climate change and floods.

For some countries like Bangladesh, which consists of approximately 80% floodplains, including agricultural and grazing lands that are regularly inundated by rivers, many of them with industrial inputs, these threats should be urgently assessed, and control measures for feed, food, and drinking water should be promoted.

Regarding heavy metals' contamination in floodplain soils, studies have explored immobilisation of different heavy metals (lead, cadmium, nickel, and zinc) using additives [271]. In these studies, amendments, such as activated carbon, different biochars, bentonite, cement kiln dust, fly ash, limestone, sugar beet factory lime, and zeolite, were tested yielding preliminary conclusions on reducing plant absorption. Whilst it is recommended to use the best practises to control and eliminate these pollutants, care must be taken to ensure that fly ash or cement kiln dust known to be often contaminated with heavy metals and other pollutants [331], do not lead to further contamination.

### 4.4 Assessment, risk management and mitigation of Natech risks

Faced with the increasing risk, a paradigm shift is proposed including the use of available specific methods and tools to accomplish a more effective control framework [205]. To estimate and mitigate Natech risks, it is crucial to conduct risk assessments for industrial facilities and establish appropriate technical countermeasures for floods and other disasters. Over the last two decades, specific risk assessments for Natech risks have been developed [52, 197, 210, 233].

Examples of good practises in Natech risk management have been compiled by a UN/OECD Project on Natech Risk Management and are available on an online platform of the German Environment Agency [108]. This includes good practises in:

- Natural Hazards Identification and Communication, Natural Hazards (Early) Warning Systems
- Consideration of Natural Hazards in Siting/Land Use Planning
- Natural Hazard Analysis and Natech Risk Analysis
- Natech Prevention: Consideration of Natural Hazards in Design and Layout
- Natech Risks in Emergency Planning, Preparedness, and Response
- Consideration of Natech Risks in Risk Communication and Natech Warning Systems

- Natech Risks in Regulations, Standards, Codes, and Guidance
- Natech Risks in Transfrontier or International Cooperation.

Within the "Natural Hazards Identification and Communication, Natural Hazards (Early) Warning Systems", the German Interactive Flood Risk Map with open access is introduced as an example of good practise [109]. Regarding case studies of best practises on Natural Hazard Analysis and Natech Risk Analysis, the "Methods for Natech Risk Assessment—RAPID-N" from the European Union is considered best practise. It is a web-based system for analysing and mapping the risk of natural hazard impacts (Natech risks) on industrial sites [160]. The system has been developed and is hosted by the European Commission Joint Research Centre (JRC) to support the systematic analysis of Natech risk including information on global Natech events [160]. Comprehensive RAPID-N user guides have been published describing the features of the system in detail and providing simple step-by-step guidance on how to use the system [111, 210].

For some countries, dedicated measures are prescribed to mitigate Natech risk from floods. For example, the German Störfall-Verordnung (Major Accident Ordinance) implements the main parts of the Seveso Directive of the European Union on controlling hazards of major accidents involving dangerous substances. Both regulations stipulate that the operator of a facility is responsible for its safety and must take all necessary measures to prevent major accidents and limit their consequences for people and the environment (Article 5 of the Seveso Directive). This must be ensured through their safety management system. Operators of lower-tier facilities, i.e., those with less hazardous substances on-site, must draft a document setting out their major accident prevention policy and ensure its proper implementation. Operators of upper-tier facilities, i.e., those with larger amounts of hazardous substances on-site, must develop a safety report and an internal emergency plan for the measures to be taken inside the facility in case of an emergency, including the flooding of endangered facilities.

The study of Misuri and Cozzani [205] highlights the main open issues and future research needs for Natech scenarios in chemical and process facilities.

### 4.5 Addressing the pollution risks and mitigation within the synergy of chemicals and climate change conventions

Climate change has important implications for the release of POPs, heavy metals, and other PBTs from contaminant reservoirs. Conventions have been established for globally addressing climate change challenges, and POPs and mercury pollution. For effectively addressing the Triple Planetary Crisis [324], coordinated implementation of Conventions and synergies of climate change conventions and chemical conventions are needed [314]. The Stockholm Convention on POPs and the Minamata Convention on mercury are both triggering global inventory and management activities for POPs for 186 and for mercury for 147 parties/countries, respectively. The inventory activities for POPs and mercury in these countries also trigger contaminated sites inventories, which—considering the synergy with the climate change convention—should be included in the assessment of the climate change risk and impacts described above. For both chemical conventions, contaminated sites guidance documents have been developed [313, 320]. The BAT/BEP guidance on POPs contaminated sites [320] include dedicated paragraphs (e.g., conceptual site model part and environmental risk assessment part) where different flooding and sea-level rise aspects of POPs contaminated sites can be considered. By this guide, countries may appropriately consider the climate change risks within the assessment of POPs contaminated sites and beyond as a step towards global action. From perspective of the climate convention, the inventories and the assessments can contribute to the CIEWS and by securing and remediation also to disaster risk reduction. Furthermore, flooding risk-informed inventories of POPs and other PBTs can contribute to the impact-based people-centred Multi-Hazard Early Warning Systems, including risk for food and drinking water. This could also be an important contribution to SDG 2 (Zero Hunger), SDG3 (Good Health and Well-Being), SDG 6 (Clean Water), and SDG 11 (Sustainable Cities and Communities).

**Abbreviations**

| | |
|---|---|
| AMAP | Arctic Monitoring and Assessment Programme |
| CIEWS | Climate information and early warning systems |
| CTT | Chemical Toxicity Test |
| dl-PCBs | Dioxin-like polychlorinated biphenyls |
| DNAPL | Dense non aqueous phase liquid |
| DOM | Dissolved organic matter |
| EQS | Environmental Quality Standards |
| FAO | Food and Agriculture Organisation of the United Nations |
| GHG | Greenhouse gas |
| HBB | Hexabromobiphenyl |
| HBCD | Hexabromocyclododecane |
| HCB | Hexachlorobenzene |
| HCBD | Hexachlorobutadiene |
| HCH | Hexachlorocyclohexane |
| IAEA | International Atomic Energy Agency |
| ICPDR | International Commission for the Protection of the Danube River |
| ICPR | International Commission for the Protection of the Rhine |
| IKSE | Internationale Kommission zum Schutz der Elbe |
| IPCC | Intergovernmental Panel on Climate Change |
| JRC | European Commission Joint Research Centre |
| MSFD | Marine Strategy Framework Directive (EU) |
| Natech | Natural Hazard Triggered Technological Accident |
| NIPs | National Implementation Plans |
| MHEWS | Multi-Hazard Early Warning Systems |

| | |
|---|---|
| MIAs | Minamata Initial Assessments |
| OCHA | Office for the Coordination of Humanitarian Affairs |
| OECD | Organisation for Economic Co-operation and Development |
| PAH | Polycyclic aromatic hydrocarbons |
| PBDEs | Polybrominated diphenyl ethers |
| PBTs | Persistent, bioaccumulative and toxic substances |
| PCBs | Polychlorinated biphenyls |
| PCDD/PCDF | Polychlorinated Dibenzo-*p*-dioxins and Polychlorinated Dibenzofurans |
| PCP | Pentachlorophenol |
| PeCBz | Pentachlorobenzene |
| PFAS | Per- and polyfluoroalkyl substances |
| PFHxS | Perfluorohexasulfonic acid |
| PFOA | Perfluorooctanoic acid |
| PFOS | Perfluorooctanesulfonic acid |
| PFOSF | Perfluoroctansulfonylfluorid |
| POPs | Persistent organic pollutants |
| QRA | Quantitative Risk Analysis |
| RBS Elbe | River Basin Community Elbe |
| SCCPs | Short Chain Chlorinated Paraffins |
| SDG | Sustainable Development Goals |
| SM | Suspended matter |
| TEQ | Toxic Equivalent |
| TMF | Tailings Management Facilities |
| UBA | Umweltbundesamt (German Federal Environment Agency) |
| UN DSA | United Nations Department of Economic and Social Affairs |
| UNECE | United Nations Economic Commission for Europe |
| UNEP | United Nations Environment Programme |
| UNISDR | United Nations International Strategy for Disaster Reduction |
| WFD | Water Framework Directive (EU) |
| WHO | World Health Organisation |

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**Author contributions**
R.W. wrote the first draft of the manuscript; L.G. contributed to the reservoirs of heavy metal part and review of other sections; U.F. contributed to sediment part and the Elbe sections; J.V. contributed to the HCH/Lindane part and comments to other sections; D.L. and M.F. contributed to the landfill and landfill-flooding part; M.T. contributed the Section on the Baltic and comments to other sections; H.H. contributed to the sediment mobilisation part and overall review. All authors reviewed the manuscript.

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