The consequences of the Odra flood (summer 1997) for the Odra lagoon and the beaches of Usedom: What can be expected under extreme conditions?

Christiane Fenske¹, Helmut Westphal³, Alexander Bachor⁴, Elke Breitenbach², Wladyslaw Buchholz⁵, Wolf-Dieter Jülich⁶, Peter Hensel⁶

¹ Zoological Institute, University of Greifswald, Greifswald, Germany
² Geological Institute, University of Greifswald, F.-L.-Jahnstraße 17a, D-17487 Greifswald, Germany
³ Energiewerke Nord GmbH, Postfach 1125, D-17507 Lubmin, Germany
⁴ State Agency of Environment, Nature & Geology Mecklenburg-Vorpommern, Goldberger Straße 12, D-18273 Güstrow, Germany
⁵ Maritime Research Institute Szczecin, Monte Casino 18a, PL-70467 Szczecin, Poland
⁶ Landeshygieneinstitut Mecklenburg-Vorpommern, Außenstelle Greifswald, Lange Reihe 2, D-17489 Greifswald, Germany

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Abstract

The exceptional flood of the river Odra in July/August 1997 caused severe damage, especially on the Polish side of the Odra valley. An additional 5 km³ of water were discharged during the flood. This represents about a third of the normal annual Odra discharge of 17 km³.

Large agricultural and industrial areas were submerged, as well as towns and villages. However, as regards the Odra lagoon and the beaches of the Isle of Usedom, the substances transported, such as nutrients and pollutants, did not cause much damage, due to strong dilution. Hygienic investigations (human pathogenic bacteria and viruses) showed that the water had bathing quality during the whole flood.

Key words: Odra flood – Odra lagoon – nutrients – heavy metals – pesticides – bacteria – viruses – suspended matter

Introduction

The Odra lagoon (= Szczecin Lagoon) acts as a link between the river Odra and the Baltic Sea. It has been investigated with regard to its genesis, hydrographical conditions, sediments, heavy metal concentrations, suspended matter, nutrients, primary production, and macrozoobenthos (Lampe 1998a, Leipe et al. 1998).

In summer 1997, investigations concerning bacteria and viruses have been intensified. Besides the regular bi-weekly monitoring, samples for hygienic investigations were taken daily during the Odra flood at bathing places on the beaches. Moreover, daily measurements of nutrients, chlorophyll-a, phaeophytine, and primary production were carried out in order to evaluate the effect of the extraordinary event.

Floods of the river Odra have occurred before (Gocke 1988, von Berg 1997), usually after a typical meteorological situation developing in late June, therefore named “St. John’s flood” (Rosenthal et al. 1998).
However, the 1997 flood was by far the strongest since the commencement of the records (Oppermann 1997).

Two main reasons caused the flood:

1) high precipitation of up to 400 l/m² in the source area of the river in the mountains between Poland and the Czech Republic (Siegel et al. 1998); this amounted to 6 km³ in the catchment area from July 3rd to 9th and another 4 km³ from July 17th to 21st (Rosenthal et al. 1998); strong winds from NE (6–7°B) hindered the outflow of the water into the Baltic (Lysiak-Pastuszak et al. 1998);

2) anthropogenic factors such as melioration, lack of inundation areas, deforestation and the consequent erosion. After the heavy rainfall, the level of the Odra rose quickly within a few days in July 97.

A marked outflow from the Odra Lagoon into the Baltic started on 20 July 1997, due to a change in water level. The floodwater from the Odra started to fill the Grosses Haff (Zalew Wielki) on 23 July 1997, maximum inflow occurred on 7 August 1997. The water of Grosses Haff was replaced by water from the river after about 5 days. The Kleines Haff, on the contrary, was later affected and not to the same extent. The floodwater reached the western end of the lagoon around 13 August 1997 (HELCOM 1998a). Maximum current velocities of up to 3000 m³/s were measured, compared to average discharges of 540 m³/s.

Measured and modelled water transport in the Odra lagoon for the period of July/August 1997 are presented by Rosenthal et al. (1998) and Müller-Navarro et al. (1999).

Daily observations of Sea Surface Temperature (SST) images (derived from data of the Advanced Very High Resolution Radiometer (AVHRR) working on NOAA weather satellites) showed the warm and low-salinity plume of the floodwater intruding into the Pomeranian Bay, north of the Swina (Siegel et al. 1998). WIFS (Wide Field Sensor) images even revealed the distribution of suspended matter and showed again that most of the water flowed directly through the eastern part of the lagoon into the Baltic Sea, without previous horizontal mixing with water from the western part. A simulation of the spatial behaviour of the Odra plume in the lagoon and the Baltic Sea (Pomeranian Bight) was also carried out by Scherniewski et al. (in press).

During the flood, the content of suspended matter in the western part was much higher than that in the eastern part, thus indicating biological activity and particle formation in comparably stagnant water, whereas the eastern part was characterized by very strong discharges. The outflow was so intense that most of the microscopic algae in the Pomeranian Bay originated from the Odra lagoon and were not formed autochthonously. Markers such as chlorophyll-a or fucoxanthin (marker pigment for diatoms) showed conservative mixing patterns (Humborg et al. 1998), thereby proving the dominance of the outflow against biological activity in the Baltic Sea. An exception was found with zeaxanthin, which is included in high amounts in pico-cyanobacteria that make up a large part of pelagic autotrophic biomass during the summer in the open Baltic. Zeaxanthin showed non-conservative mixing patterns because only minor amounts of this pigment could be built up in cyanobacteria in the river due to the lack of light. It is likely that most of the zeaxanthin originated from the standing stock of pico-cyanobacteria in the Baltic (Humborg et al. 1998).

Investigation area

The Szczecin Lagoon (= Oderhaff or Odra lagoon, Fig. 1) has a size of 687 km² and a volume of approx. 2.6 km³. It represents a natural reception pool for water from the rivers Odra (= Oder), Peene, Zarow and Uecker. The largest water supply comes from the river Odra (approx. 17 km³/a), compared to 0.76 km³/a from the Peene, 0.19 km³/a from the Uecker, and 0.11 km³/a from the Zarow (Lampe 1993).

The western part (277 km²) is German (Kleines Haff); the larger eastern part (410 km²) is Polish (Grosses Haff or Zalew Wielki).

Average salinity in the lagoon lies between 1 and 3 PSU (practical salinity unit), with extreme values of 0.2 and 6.4 PSU. The slope of the Odra lagoon bottom (from the mouth of the river Odra to the Baltic Sea (approx. 40 km) is 22.7 cm (Herr, quoted after Brandt 1894/96) and there are only three narrow outlets, therefore the flow velocity of the water masses is slowed down, before they enter the Baltic through the three straits (Swina, Peenestrom, Dziwna). On average, 70% of the overall water exchange takes place through the Swina and Piastowski channel, whereas the Peenestrom and the Dziwna contribute approx. 20% and 10% respectively. These relations stayed the same, even during the flood (Rosenthal et al. 1998). Only in September 97 did the ratio between the different branches vary more strongly due to changing weather conditions.

Some of the imported substances, mainly heavy metals, can sediment in the lagoon. Former statements characterizing the inner coastal waters as important filter and buffer zones had to be modified: long-term investigations showed that the coastal lagoons in this area hold back only 2–5% of the nutrients imported, and 15% of the metals (Lampe 1998b).

Usually the Szczecin Lagoon is well mixed due to its average depth of only 3.8 m. A high nutrient content causes a strong development of phytoplankton, which in turn is responsible for the high turbidity (Secchi depth of only 50–60 cm in summer).
Water movements (currents and convection) are mainly influenced by wind.

The Pomeranian Bay is characterized by sandy shallow bottoms (0–20m) and a salinity of 6–8‰ near the coast (Powilleit et al. 1995; for a review on transport and modification processes between the lagoon and the Pomeranian bay see von Bodungen et al. 1995). The beaches on the Isle of Usedom at the southern edge of
the bay are intensively used by tourists. Water quality is monitored bi-weekly and has been very good so far, with only very few exceptions when the hygienic limiting value was exceeded locally.

Methods

Besides the monitoring carried out by the State Agency for Environment, Nature, and Geology Mecklenburg-Vorpommern (LUNG), several parameters were measured continuously by the GKSS research centre (sea level, wave height, current direction and current velocity, wind direction and speed, air and water temperature, turbidity and salinity). Additionally, a special measurement programme was carried out at the time of the flood (July–September 1997) in the Odra Lagoon and the adjoining Pomeranian Bight of the Baltic Sea.

The following parameters were measured:

Meteorological and hydrological parameters: wind direction and speed, water and air temperature, current direction and velocity, salinity, oxygen saturation, turbidity

Biological parameters: bacteria (Rheinheimer 1981), chlorophyll-a and phaeophytine (Rohde and Nehring 1979, Gocke 1988), primary production (radio carbon method after Gocke 1988), viruses (Julich et al. in press); sampling for hygienic investigations was bi-weekly (bacteria) or daily (viruses).

Geochemical parameters: concentrations of nutrients: dissolved inorganic nitrogen = DIN, dissolved inorganic phosphate = DIP (Rohde and Nehring 1979, Autorenkollektiv 1982), dissolved silicate, heavy metals, hydrocarbons, pesticides (methods described in Gewässergütebericht Mecklenburg-Vorpommern (GGB-MV) 1996/97).

Seston analysis: total particulate carbon (TPC), particulate organic carbon (POC) and particulate inorganic carbon (PIC) were measured using a C/S-Analyser METALYT CS (firm ELTRA). The procedure is described in Fenske et al. (1998).

The stations for the measurements were located as follows (Fig. 1 and BSH 1999):

Kleines Haff:
- Tonne H3 53° 49.50’N 14° 03.30’E
- centre 53° 49.50’N 14° 06.00’E
- German-Polish border 53° 48.50’N 14° 14.10’E
- near Kamminke (Kam) 53° 51.60’N 14° 12.30’E
- Ueckerminde (Ueck) 53° 45.40’N 14° 05.10’E
- near Mönkebude (Moe) 53° 49.50’N 14° 00.60’E
- Karnin 53° 50.40’N 13° 51.50’E

Grosses Haff/Zalew Wielki:
- Karsibor (Kars) 53° 52.00’N 14° 16.80’E
- Tor 1 53° 48.50’N 14° 20.55’E
- Tor 2 53° 45.70’N 14° 24.30’E
- Tor 3 53° 42.90’N 14° 28.20’E
- Tor 4 53° 39.95’N 14° 32.00’E
- Odra mouth 53° 39.80’N 14° 32.20’E
- Tonne MeW 53° 46.40’N 14° 29.10’E

The water samples for the hygienic investigations were taken from piers in the sea resorts of the island of Usedom at 19 stations along the coastline of 36 km. A further 8 stations are situated in the Achterwasser and the Peenestrom, i.e. the inner coastal waters. One station was the central Kleines Haff (Tonne H3). For the evaluation of health risks only the stations fairly close to the Odra water were included: those were no. 724–727 and 729–730 at the beaches of Usedom close to the Swina mouth, and stations no. 707, 709, and 714 at the Peenestrom (Fig. 1). It was assumed that if no critical concentrations of potentially harmful bacteria and viruses were detected close to where the Odra water flows into the Baltic, then beaches farther away should not be endangered.

Results

Nutrients

Comparing the amounts of nitrate, orthophosphate, total nitrogen, and silicate transported into the Pomeranian Bay from June to August 1995 and 1997, the effect of the Odra flood can clearly be seen (Fig. 2). In 1997 loads were up to 7.8 times higher (silicate), nitrate occurred in 4.7 fold amounts compared to 1995, and the load of orthophosphate and total-N more than doubled.

The high amounts of nutrients are likely to come from agricultural areas that were involuntarily flooded and released manure and/or fertilizers. Moreover, 56 water treatment plants in Poland closed temporarily during the flood because they no longer could handle the water masses, thereby allowing all the discharge to flow downstream untreated.

However, at the Piastowski channel, the main outlet of the lagoon, inflows of water from the Baltic sea were measured again in mid September and found to be carrying about 2.5 t/d of DIN and 6t/d of DIP (Fig. 3). On 18/9/97 the current direction changed during the day so that after an inflow a strong outflow was recorded, exporting about twice the load that had been imported before (−1.45 versus +3.44 t DIN, and −3.79 versus +7.97 t DIP). Undoubtedly, large amounts of nutrients were transported into the Baltic, but as regards concentrations, these were not extraordinarily high due to the strong dilution. For orthophosphate (= dissolved inorganic phosphorus, DIP), similar concentrations were measured in both parts of the lagoon. Usually the Grosses Haff has a much smaller DIP concentration in summer than the Kleines Haff. During the flood, DIP concentrations in the Kleines Haff were only half the average level of 6–8 µmol/l (Fig. 4) whereas concentrations of 5 µmol/l in the central part of the Grosses Haff represent a six-fold increase as compared to 1996 (0.8 µmol/l). However, this increase disappeared after the flood: at the end of September concentrations of
about 2.5 \( \mu \text{mol/l} \) were measured in the central part of the Grosses Haff, compared to 4.45 \( \mu \text{mol/l} \) in 1996.

Nitrate in the Kleines Haff reached concentrations of 26 \( \mu \text{mol/l} \) during the flood (Fig. 4), compared to a maximum of over 100 \( \mu \text{mol/l} \) that had been measured in the years before.

Total dissolved inorganic nitrogen (nitrite, nitrate and ammonium) in the Grosses Haff ranged between 6 and 31 \( \mu \text{mol/l} \) during the time of the investigation (22/7–25/9/97). An even higher range (5–55 \( \mu \text{mol/l} \)) was measured at the mouth of the river Odra (before entering the lagoon).

Compared with our data from 1996 and data from other authors (Vietinghoff et al. 1995, GGB-MV 1996/97), the concentrations of DIN during the Odra flood in 1997 were not extraordinarily high. In the central part of the Grosses Haff concentrations of 35 \( \mu \text{mol/l} \) DIN were found in June/July 1996 and 26.4 \( \mu \text{mol/l} \) in September 1996 (Fenske et al. 1998).

The input of DIN was positively correlated to the amount of river water transported.

Considering the river discharge, the Odra transported a load of 6–65t/d DIN into the Grosses Haff.

Silicate concentrations (max. 213 \( \mu \text{mol/l} \) in the Kleines Haff) were much higher than in other years. This is probably due to the fact that phytoplankton populations, especially diatoms, did not have enough time to keep pace with the amount of nutrients supplied. However, silicate is a naturally occurring mineral and even higher amounts do not cause harm.

Although the Kleines Haff and Grosses Haff are connected by a broad stretch of water, they do not always show the same reactions. Concentrations of different substances varied between these two different parts of the lagoon, probably because a large part of the water flows directly from the Odra via the Grosses Haff into the Baltic, without efficient mixing with the water from the Kleines Haff. The currents between the Kleines and the Grosses Haff do not follow a clear pattern. Synchronous measurements along the German-Polish border showed that at different points water either flows east-westwards, west-eastwards, south-northwards or does not move at all. Near the bottom there are also north-southwards currents. The latter are of particular importance because they transport saline water from the Baltic into the lagoon.

For further details about nutrient concentrations and other parameters measured during the Odra flood in both parts of the lagoon see Fenske et al. (1998).

Chlorophyll-a, phaeophytine, and primary production

With one exception (4/8/97: 198 \( \mu \text{g/l} \)) chlorophyll-a contents were not higher during the flood than usual. Concentrations of 40–90 \( \mu \text{g/l} \) were measured in the Grosses Haff and 30–110 \( \mu \text{g/l} \) in the Kleines Haff. Both values correspond to our average concentrations observed over several years as well as to the data acquired in the projects GOAP (Westphal and Lenk 1998) and PIONEER (Fig. 5). A large steady phytoplankton population could not develop, presumably because the current velocity and the water discharge were too high.

Larger differences in chlorophyll-a contents within a few days can be explained by concentration of algae at the surface of the water. The algae population was mainly composed of coccal cyanobacteria and coccal Chlorophycea (Hübel, pers. comm.).

As expected, the results for Secchi depth and chlorophyll-a content were reciprocal. In comparison with other inner coastal waters, the Odra lagoon contains enormous amounts of algae, even in “normal” years. The Greifswald Bodden, which is comparable in size and volume (510 km², 2.960 km³) but has a
stronger exchange with the Baltic Sea, has an average chlorophyll-a content that is only one fifth of the value for the Odra lagoon (10 µg/l compared to 50 µg/l; Westphal and Lenk 1998)

Phaeophytine, indicating the amount of inactive chlorophyll, was measured in relatively high amounts (max. 22 µg/l) in the central part of the lagoon during the main wave of the Odra flood (Fig. 5). At the Odra mouth near Trzebiez there were always increased concentrations of phaeophytine. This means that a great part of the algae was damaged. In other years no phaeophytine was detected during summer.

Concentrations of chlorophyll-a during the flood were normal for the time of the year, indicating no extraordinarily high primary production. Comparing summer '97 with spring '98 and autumn '98, the results for primary production lie in the same range (Fig. 6).

In the Grosses Haff an average primary production of 280 mg C/m² × h (range 100–680 mg C/m² × h) was determined (radio carbon method, simulated in situ). The average primary production in the Kleines Haff was 250 mg C/m² × h (ranging between 23 and 840 mg C/m² × h) during the course of the year 1997.

Fluctuations in the carbon assimilation on different days were caused by the differing light intensity (PAR).

Combining our results with other measurements not presented here, we assume a primary production of 500 g C/m² × a.

Heavy metals

Overall concentrations of the trace metals such as zinc, copper, nickel, lead, and cadmium have been measured routinely in unfiltered water samples in the central area of the Kleines Haff (station “centre”) since 1992. During the period of the Odra flood, measurements were also done at the other six stations of the Kleines Haff.

The zinc, copper and nickel concentrations were lower in July and August 97 than during the first half of the year. All three elements showed similar changes, e.g. a relatively distinct decrease on July 8 and an increase on August 11. By this date the Odra flood had reached the central part of the Kleines Haff. However, the mid August concentrations of zinc, copper, and nickel were about 50 % lower than at the beginning of the year.
In contrast to this, concentrations of lead, cadmium, and mercury increased during the flood, thus indicating higher inputs from the Odra water. Usually, high concentrations of heavy metals occur in winter or spring in times of high discharge (GGB-MV 1996/97). In 1997, the situation was reversed: high concentrations were detected in summer, during the flood.

On July 31, the highest concentrations of lead (3.3 µg/l) since the beginning of measurements (1992) were registered in the central part of the Kleines Haff. On the other hand, the Odra water reached this part of the Szczecin Lagoon only on August 11. Therefore the main input of lead into the Szczecin Lagoon must have taken place before the flood reached its peak (Röpke et al. 1998). This result is supported by direct measurements in the Odra river carried out by the State Agency of Environment Brandenburg (Landesumweltamt Brandenburg 1998).

Results for cadmium are similar to those for lead (Fig. 7). 98 and 92 ng/l were measured on July 31 and August 4 respectively. This value is 5 times higher than the detection limit. However, cadmium concentrations even above 100 ng/l had already been registered earlier in the Kleines Haff.

In general, mercury is hard to detect in water. Signals above the analytical detection limit are very rare. During the Odra flood this was the case. On one single day (August 11), an extraordinarily high concentration of mercury (210 ng/l) was registered in the central part of the Kleines Haff. Two days later we also found mercury concentrations between 76 and 88 ng/l (significantly above the detection limit) at three stations in the eastern part of the Kleines Haff.

The increase of heavy metals could have been caused by contaminated sediment transported from upstream riverbanks and by effluents from flooded industrial areas. Contamination can be expected to originate from mining and smelting operations at industrial centres between Katowice and Glogow (Müller 1998).

Organic contaminants

During the special investigation concerning effects of the 1997 Odra flood in the Szczecin Lagoon several organic contaminants were analysed for the first time at

![Graph of nutrient concentrations](image)
two stations in the Kleines Haff. Out of 26 pesticides, four (atrazine, simazine, desethylatrazine and 2,4 dichlorphenoxy-acetic acid) appeared in concentrations above the analytical detection limit.

Atrazine, which it has been forbidden to use in Germany since 1992, was detected during the flood in the eastern part of the Kleines Haff. Concentrations increased from 28/7 to 4/8/97 from 0.11 µg/l to 0.19 µg/l and decreased after 15/8/97 (Fig. 8). Concentrations in the central part of the Kleines Haff were lower: 0.02–0.11 µg/l. Higher values close to the German-Polish border indicate that the pesticide arrived with the Odra water. In most of the rivers of Mecklenburg-Vorpommern, including the rivers Uecker and Zarow, atrazine was not detected at all in 1997. Only in the river Elbe concentrations were above 0.10 µg/l measured (GGB-MV 1996/97). In 1998, atrazine was detected again in the Szczecin Lagoon (Fig. 8) but in much lower concentrations (max. 0.04 µg/l). Due to its long life time of 28 years, atrazine and its metabolites desethylatrazine and desisopropylatrazine are still in the ground water following their widespread use as a herbicide in maize fields.

Desethylatrazine was found in concentrations up to 0.06 µg/l on 4/8 and 6/8/97 in the eastern part of the Kleines Haff. Traces of simazine near the detection limit (0.02 µg/l) were measured only at the border station. 2,4 dichlorphenoxy-acetic acid was found in concentrations between 0.05 and 0.09 µg/l in the eastern part of the Kleines Haff throughout the whole period of the special investigation. At the central station in the Kleines Haff it was detected later and in lower concentrations. The amounts of herbicides detected in the water were below the guideline values of the WHO for drinking water.

A strong input of hydrocarbons from mineral oil proved the influx of contaminated Odra water at the beginning of August 1997. This may have been heating oil from flooded houses. After a short peak with a duration of a few days, hydrocarbons were no longer detectable.

Suspended matter
Not only as a carrier for heavy metals but also for bacteria and viruses, suspended matter (SPM) plays an important role in the ecosystem. Most of the potentially harmful substances occur absorbed by or adsorbed to
particles. Usually the amount of SPM is highly correlated to the wind velocity (Pearson correlation factor for the time period 18/7–11/8/97 in the Kleines Haff: $R = 0.76$). During the flood, however, this correlation was not so strong. The maximum concentration of SPM was 45 mg/l (Fig. 9).

Concurrently with the arrival of the flood wave in the Kleines Haff a decrease of the SPM content was detected, starting on 7/8/97. This was probably due to the dilution of SPM. A minimum of 15 mg/l was measured on 14/8/97 (Fig. 9).

At the same time, contents of particulate organic carbon (POC) and total particulate carbon (TPC) increased slightly. Wind is always able to cause resuspension of the sediment, thereby increasing the amount of SPM (20/7 and 28/7/99).

However, the changes in the SPM content of the water in the Odra lagoon during the flood were within the usual annual variations.

**Microbiological investigations**

Regular bacteriological investigations (daily, later 2–3 times per week) during the Odra flood showed no harmful situations. Results were similar to those from previous years. An impairment of the water quality could not be detected, neither at bathing places of the Achterwasser nor at the Baltic beaches of the isle of Usedom. All bathing places had a good water quality. The few occasions when the EU-guideline limit was exceeded occurred as rarely as in the years before or after the flood (Fig. 10). Faecal *Streptococcus* species were never detected. Eighty-eight isolated bacteria strains were investigated for their resistance against antibiotics. Each of them was sensitive, i.e. there were no hints of the existence of multiresistant species of bacteria.

Investigation of Enterovirus, cultivated from ultrafiltered 10-l water samples in of FL (fibroblast-like) cells, showed that the particular conditions of the Odra flood hindered the occurrence of Enterovirus. Comparing the virus contents of the Odra and the water at the beaches of Usedom in June/July and August 97, there were fewer infectious units in the water during the flood (Fig. 11). Two factors are considered as important: 1) strong dilution by the water masses 2) inactivation during the transport, e.g. by UV radiation (Jülich et al. in press). Moreover, there might have been virus-inhibiting substances such as acrylic acids or polyphenoles produced by the phytoplankton (Burger 1995), thus preventing the development of viruses that could have been a danger for human health. Harmful substances such as pesticides or heavy metals also have a destroying effect on viruses.

![Figure 6](image_url)  
**Fig. 6.** Chlorophyll-a concentrations and primary production in the Zalew Wielki (Grosses Haff). Comparing summer 97 with spring 98 and autumn 98, the results lie in the same range, i.e. there was no marked effect of the flood.
Discussion

The Odra lagoon, situated at the end of the polluted river Odra, is predestined by nature to become eutrophic. The Odra is a major source of pollution of the Baltic Sea (HELCOM 1998b). A large part of the load (e.g. heavy metals) is imported with suspended particulate matter (SPM) and accumulates in the sediments of the lagoon. Especially zinc is found in very high concentrations in the SPM of the Odra estuary (1997: 1200 mg/kg, 1998: 937 mg/kg). Increased concentrations were also detected for cadmium which is known

![Graph showing heavy metal concentrations and salinity in the Szczecin Lagoon (station "centre")]
to be very toxic for organisms (1997: 3.7 mg/kg, 1998: 4.3 mg/kg) (Eidam et al. 2000). The joint project GOAP (Greifswald Bodden and Odra Estuary Exchange Processes, 1993–1997) showed that the sediments of the estuary were so polluted with nutrients and heavy metals that the vast majority of these substances freshly arriving with the Odra water were transported into the Baltic without much transformation or storage in the estuary (Lampe 1998 a, b, 1999). Because of the sediments’ pollution, it was not clear what the additional very high input of the Odra summer flood in 1997 would bring about.

A flood wave adds to the usual disturbance of the sediment, thereby increasing the concentration of suspended matter and remobilising heavy metals. However, the flood sediments along the whole river Odra were also able to absorb contaminants, due to their specific composition, especially their contents of organic matter and clay minerals (Damke et al. 1999).

The contents of heavy metals in the river water and in the SPM as well as in the sediments developed irregularly, because of the successive flooding of differently contaminated sedimentary sources and polluted regions (Lehmann et al. 1999, Damke et al. 1999). However, the median concentrations of suspended particulate matter did not exceed the values of older samples taken during mean discharge conditions between 1989 and 1995, and correspond to those of the river Elbe in 1990. The heavy-metal load of the Odra strongly decreased from 1988 to 1997 (Zn by 85%) (Niemirycz 1999). But still the Odra is categorized as “very highly contaminated” with regard to Zn (Eidam et al. current investigation). The accumulation of heavy metals in sediments and SPM of the Odra lagoon usually shows maximum values at the points close to the Polish border, confirming that the input comes from the river Odra. Concentrations of heavy metals in fine-grained sediments (<20 µm) of the Kleines Haff are up to three times higher than the concentrations in the Greifswald Bodden (GGB-MV 1996/97). Target values for Cr, Cu, Hg, Ni, Pb, Zn, and Cd in SPM were by far exceeded in the Kleines Haff both in the flood year 1997 and in 1998 (Eidam et al. 2000).

During the flood (5 weeks) approximately ⅓ of the usual annual particular load of Cu, Pb and Zn was...
transported (Müller and Wessels 1999). For the total loads of dissolved trace elements temporary increases at Hohenwutzen ranged from 4-fold (Cr) and 5-fold (Pb) to 16-fold (Zn) and 17-fold (Cd), comparing conditions before (10 July) and during the flood 1997 (Lehmann et al. 1999).

Investigating the sediments of the Odra river basin in November 1997, Müller and Wessels (1999) found maximum concentrations for Cu and Pb not in the Odra lagoon but in the downstream part of the river. This illustrates the retention potential of the sediment and explains why the consequences for the lagoon were milder than assumed.

The strong outflow of the flood’s water masses swept the heavy metals into the Baltic, where they were taken up by macrozoobenthic animals. Since 1994 mussels (*Mytilus edulis*) in coastal waters of Mecklenburg-Vorpommern have been investigated for their content of heavy metals and organic contaminants. Investigations of *Mytilus edulis* on the Odra bank (in the Pomeranian Bay) showed that the contents of lead, cadmium, chromium and arsenic after the flood were about twice as high as in the years 1994–96 (GGB M-V 1996/97). For the recruitment of mussels (*Mytilus edulis* in the Baltic, *Dreissena polymorpha* in the Odra lagoon) the level of SPM might also play an important role. Ruth (1998) found in laboratory experiments that the growth of *Mytilus* larvae from the North Sea was inhibited by sediment concentrations in the water >0.5g/l. As mortality rates of mussels are inversely proportional to their size, growth in the first year of life is a crucial factor. Although the water in the Odra lagoon is often very turbid, especially in summer, the concentration of SPM during the flood was lower than usual, and the threshold value of 0.5g SPM/l was never reached.

Thus, in the lagoon it is not the concentration of SPM itself but the heavy-metal contamination of SPM that is likely to have affected the mussels. In the fraction <20 µm, the metal content (Zn, Pb, Cu, Cd, Co, Ni, Cr, Mn, Fe) was significantly higher than in the whole sediment (Helios Rybicka and Strzebonska

![Fig. 9.](image-url)
1999), probably due to the higher surface/volume ratio of small particles. Zebra mussels (Dreissena polymorpha), however, prefer smaller particles (15–40 µm) and are therefore exposed to higher concentrations than that of the total SPM. Moreover, the composition of SPM is likely to have changed during the flood to higher amounts of fine-grained and more strongly polluted particles (Lehmann et al. 1999). One mussel may filter up to 2.4 l of water per day in order to obtain food (Claudi and Mackie 1994). In this process, more than 100 mg of more or less polluted SPM might be taken up per day. A long-term survey would be necessary to assess the flood impact on the population.

Not only heavy metals occurred in higher amounts, but also phosphorus and nitrogen. Müller (1997) and Müller and Wessels (1999) found for the lower Odra (near Schwedt) that during the flood these nutrients in SPM occurred in amounts 2 and 5 times as high respectively as compared to 1996. This large increase was also measured in the Pomeranian Bight (Fig. 2), comparing the nutrient load in 1995 and 1997. However, the actual concentrations were not extraordinarily high.

While most of the phosphorus input comes from point sources (73%), the nitrogen input is dominated by diffuse sources (59–67%) (Behrendt et al. 1999). But the actual nutrient loads are rather low as compared to the inputs. With regard to nitrogen, a flood in summer causes less trouble than in winter because the plants can use nitrate and therefore less nitrogen gets into the river and into the sea. A lot of the nutri-

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**Fig. 10.** Hygienic quality of the bathing water: Investigation of coliform bacteria showed no hazard during the flood. EU-limiting values were not exceeded in 1997 at the beaches of Usedom and only twice (= 5.1%) at the Achterwasser. These transgressions, however, did not happen during the flood.
Maximum retention of particulate matter in a polder area of the Lower Odra Valley National Park during the flood was more than 80% (Engelhardt et al. 1999). The advantage of a flood in summer is that there is more vegetation in the polders to hold back particles. In normal winter floods retention varied between 33 and 70%.

The self-purification could be further enhanced if the course of the river was developed more naturally with more areas that could be flooded in times of high discharges. One favourable side effect of more floodable areas would be that a lot of bird species such as grey herons (Ardea cinerea), common snipes (Gallinago gallinago), lapwings (Vanellus vanellus), spotted redshanks (Tringa erythropus), greenshanks (T. nebularia), wood sandpipers (T. glareola), several duck species and many others could use the habitat for resting and feeding. The Odra flood in summer '97 destroyed many nests, so that corncrake (Crex crex), spotted (Porzana porzana) and little crake (P. parva) lost their broods completely (Dittberner 1998). But the conditions afterwards with large flooded areas were ideal for many species, including migratory birds.

Gromisz et al. (1998), who investigated the composition of phytoplankton in the Pomeranian Bay during the flood, found that four potentially toxic species (Anabaena spiroides, Aphanizomenon flos-aquae, Microcystis aeruginosa, and Nodularia spumigena) occurred, but not in “bloom” quantities. The same cyanobacteria species were detected again in summer 1999 (Cuypers, pers. comm.) with lower concentrations in Ahlbeck (close to the Swina outlet into the Baltic) than at the stations further north. It can thus be assumed that even during the Odra flood the beaches of Usedom were not endangered by microalgae.

The hygienic investigations of the water along the beaches of Usedom also resulted in good quality values, therefore swimmers or bathers were not at risk, even during the flood.

However, routinely applied tests for wastewater monitoring such as tests with algae, Daphnia or photogenic bacteria proved to be not sensitive enough to show effects of the flood on aquatic organisms (Oetken 1998). It is therefore necessary to develop more sensitive biotests with reversible adverse effects (Jüllich et al. in press). Moreover, we recommend to include potentially toxic microalgae and viruses in the regular EU bathing water investigations. So far only bacteria are routinely tested.

In order to finally assess the impacts of the flood on aquatic species, it would be necessary to investigate the reproduction of sensitive species. Only the fact that they are able to reproduce properly in the habitat over several years would prove that the short-term effect of the flood does not harm the population.

Fig. 11. Comparison of the concentration of potentially harmful viruses (pathogenic for humans) in the water of the Odra lagoon and at the beaches of Usedom: During the flood lower amounts of infectious units per litre were found. This is probably due to dilution and inactivation by UV radiation, heavy metals or secondary plant metabolites.
Conclusion

With regard to the Szczecin Lagoon the flood of the river Odra had no disastrous effects. Although some substances (DIN, DIP, lead and cadmium) occurred in higher concentrations during the flood, these were only short peaks. The concentrations of most of the substances analysed did not exceed the results of the long-term investigations. However, atrazine and lead in the Kleines Haff occurred in extraordinarily high concentrations. Pb concentrations reached a new maximum (3.3 µg/l), but it could be shown that the lead had not been transported with the Odra flood. The floodwater arrived in Kleines Haff only 11 days later. Atrazine, which is thought to be carcinogenic, was even at peak concentration (0.19 µg/l) one order of magnitude below the WHO guideline value for drinking water (2 µg/l). Most of the substances imported were simply washed into the Baltic, partly due to the difference in water level caused by the specific wind situation. Extraordinarily high concentrations of nutrients or pollutants and their negative effects that might have been expected in the Szczecin Lagoon did not occur, due to the dilution by the water masses and some retention in downstream regions of the river. As regards the polluted sediments of the lagoon, the flood can even be considered as a fortunate event because a lot of it may have been exported after being stirred up by the enormous amount of water. Even during the flood there was no health risk for swimmers at any time, either in the inner coastal waters or on the beaches of the Baltic (Isle of Usedom).

References


