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# Risk assessment of virus infections in the Oder estuary (southern Baltic) on the basis of spatial transport and virus decay simulations

Gerald Schernewski[1], Wolf-Dieter Jülich[2]

[1] Baltic Sea Research Institute Warnemünde, Rostock-Warnemünde, Germany
[2] Institute of Pharmacy, University of Greifswald, Germany

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## Abstract

The large Oder (Szczecin) Lagoon (687 km$^2$) at the German-Polish border, close to the Baltic Sea, suffers from severe eutrophication and water quality problems due to high discharge of water, nutrients and pollutants by the river Oder. Sewage treatment around the lagoon has been very much improved during the last years, but large amounts of sewage still enter the Oder river. Human pathogenic viruses generally can be expected in all surface waters that are affected by municipal sewage. There is an increasing awareness that predisposed persons can be infected by a few infective units or even a single active virus. Another new aspect is, that at least polioviruses attached to suspended particles can be infective for weeks and therefore be transported over long distances. Therefore, the highest risk of virus inputs arise from the large amounts of untreated sewage of the city of Szczecin (Poland), which are released into the river Oder and transported to the lagoon and the Baltic Sea.

Summer tourism is the most important economical factor in this coastal region and further growth is expected. Human pathogenic viruses might be a serious problem for bathing water quality and sustainable summer tourism. The potential hazard of virus infections along beaches and shores of the Oder lagoon and adjacent parts of the Baltic Sea is evaluated on the basis of model simulations and laboratory results. We used two scenarios for the Oder Lagoon considering free viruses and viruses attached to suspended particle matter. The spatial impact of the average virus release in the city of Szczecin during summer (bathing period) was simulated with a hydrodynamic and particle tracking model.

Simulations suggest that due to fast inactivation, free viruses in the water represent a risk only in the river and near the river mouth. On the other hand, viruses attached to suspended matter can affect large areas of the eastern, Polish part of the lagoon (Grosses Haff). At the same time the accumulation of viruses on suspended particulate matter increases the likelihood of an infection after incorporation of such a particle. There is no evidence, that there is a risk of virus infections in the western part of the lagoon (Kleines Haff) or along the outer Baltic Sea coast.

**Key words:** Szczecin Lagoon – coastal zone – sewage – bathing water quality – hydrodynamic model – virus

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**Corresponding author:** Dr. Gerald Schernewski, Baltic Sea Research Institute Warnemünde, Seestraße 15, D-18119 Rostock-Warnemünde, Germany, phone: +49 381 5 197 207, fax: +49 381 5 197 207, E-mail: Gerald.Schernewski@io-warnemuende.de

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## Introduction

The Oder Estuary at the border between Germany and Poland is an attractive, ecologically valuable landscape with high tourist potential. The large Oder (Szczecin) Lagoon (687 km$^2$) is separated from the Baltic Sea by the islands of Usedom and Wolin. At the Baltic Sea coast of Usedom and Wolin bathing and summer tourism has a long tradition and is the most important economic factor. The tourist industry along the inner coasts of the Oder Lagoon is less developed, but considerable efforts were undertaken to catch up (Regionales Raumordnungsprogramm, 1998). Examples are towns like Ueckermünde or Mönkebude with extended beaches, marinas and various water sport activities.

At the same time, the river Oder drains about 17 km$^3$ water per year as well as large amounts of nutrients and pollutants into the lagoon and further into the Baltic Sea. The result is eutrophication with intensive algae blooms and the danger of hygienic water quality problems. Especially infective viruses are a largely unknown potential hazard for water sports, swimming and bathing in the lagoon and along the outer Baltic coast.

Viruses can be expected in all waters that are affected by municipal sewage water, but usually virus concentrations in natural surface waters are low due to dilution. According to Dumke and Feuerpfeil (1997) and Lopes-Pila and Szewzyk (1998) less than 50 or 10–50 viruses, respectively, are the threshold for an infection of predisposed persons. Some authors assume that a threshold is not useful at because even lowest virus concentrations can be a problem all (Gerba and Haas, 1988; Ward and Akin, 1984; Ward et al., 1986). Infections and subsequent swimming prohibitions may seriously damage the reputation, public acceptance and economic development of resorts.

Up to now, no generally accepted indicator systems for viruses are available. Therefore our knowledge about the potential hazard due to viruses in the Oder Lagoon and along the beaches is limited. Especially the large city of Szczecin (Stettin) and its high release of untreated municipal sewage into the river Oder is problematic. Our goal was to assess the potential impact of this release on the Oder Lagoon and its shores and beaches as well as for the outer Baltic Sea coast. For this purpose we assumed an average virus release from the city of Szczecin and applied two scenarios: a) free viruses in the water and b) viruses attached to suspended matter. The second scenario can be regarded as the worst case because all viruses are assumed to be attached to suspended matter. A hydrodynamic flow and drift model was applied for typical average summer river discharge and wind conditions. Our goal was to obtain highly resolved information about the spatial virus behaviour and transport in the lagoon.

## Materials and methods

The city of Szczecin with a population of about 420,000 inhabitants is located at the river Oder, 21 km upstream of the Oder (Szczecin) Lagoon. Detailed data about sewage treatment in Szczecin is available from Wallbaum and Rudolph (2000) and Boczar and Szaniawski (1993). At the present state about 47.4 million m$^3$ waste water accrue per year. 38 % are mechanically treated in one of the seven sewage treatment plants and additional 5 % receive a biological or chemical treatment. 67 % of all waste water is directly discharged into the river Oder through one of the up to 70 known pipes, ditches and small tributaries.

To analyse the hazard of virus infections along the shores and beaches of the Oder Lagoon we assumed a virus concentration of $10^7$/m$^3$ sewage water. This means that the sewage water released into the Oder near Szczecin contained an enteric virus number (of varying virus composition) of $10^{11}$ to $10^{12}$ (infective units). This is equal to about 100 infected persons (0.02 % of the population of Szczecin), which usually excrete about $10^4$ to $10^{10}$ viruses per g excrement. The assumption holds for an average situation. During an epidemic a much higher virus release can be expected.

Altogether about 130 virus types are known to cause water-borne infections (Dumke and Feuerpfeil, 1997). For inactivation measurements polio-1 viruses were chosen, which are known to be very stable in natural waters. Tests of virus inactivation were conducted in ultra-filtrated river and lagoon water at different temperatures as well as with suspended particle matter of typical Oder characteristics. Additional data of virus inactivation times were derived from different sources: suspended particle matter, defined layered clay minerals, green algae and cyanobacteria as well as fungi. A linear regression was applied to the logarithmic profile of the virus concentrations to calculate the time ($T_{90}$-value) needed for a decrease of the virus concentration by 90 %.

The transport and spatial dispersion of viruses in the river and the lagoon is affected by two time-dependent parameters: the Oder water discharge and the prevailing wind conditions. Between 1981 and 1990 the water discharge of the river Oder showed a typical annual course with average minimum values of 388 m$^3$/s in October and a maximum of 761 m$^3$/s in May (Fal et al., 1997). From July to September the average discharge varied between 401 m$^3$/s and 427 m$^3$/s. Due to this small variation a constant discharge of 415 m$^3$/s was applied for virus transport and dilution during summer. The simulations always started at the broadening of the Roztoka Odrzanska, about 21 km north of Szczecin (Fig. 2). Considering an average Oder cross section of 2500 m$^2$, the water and particle transport with the river downstream to this location took about 35 hours.

Up to $10^{12}$ viruses per m$^3$ enter the river with sewage from Szczecin. After complete mixing with river water the virus concentration decreased to about $10^4$ infective units/m$^3$ river water due to dilution. To evaluate the hazard of virus in-

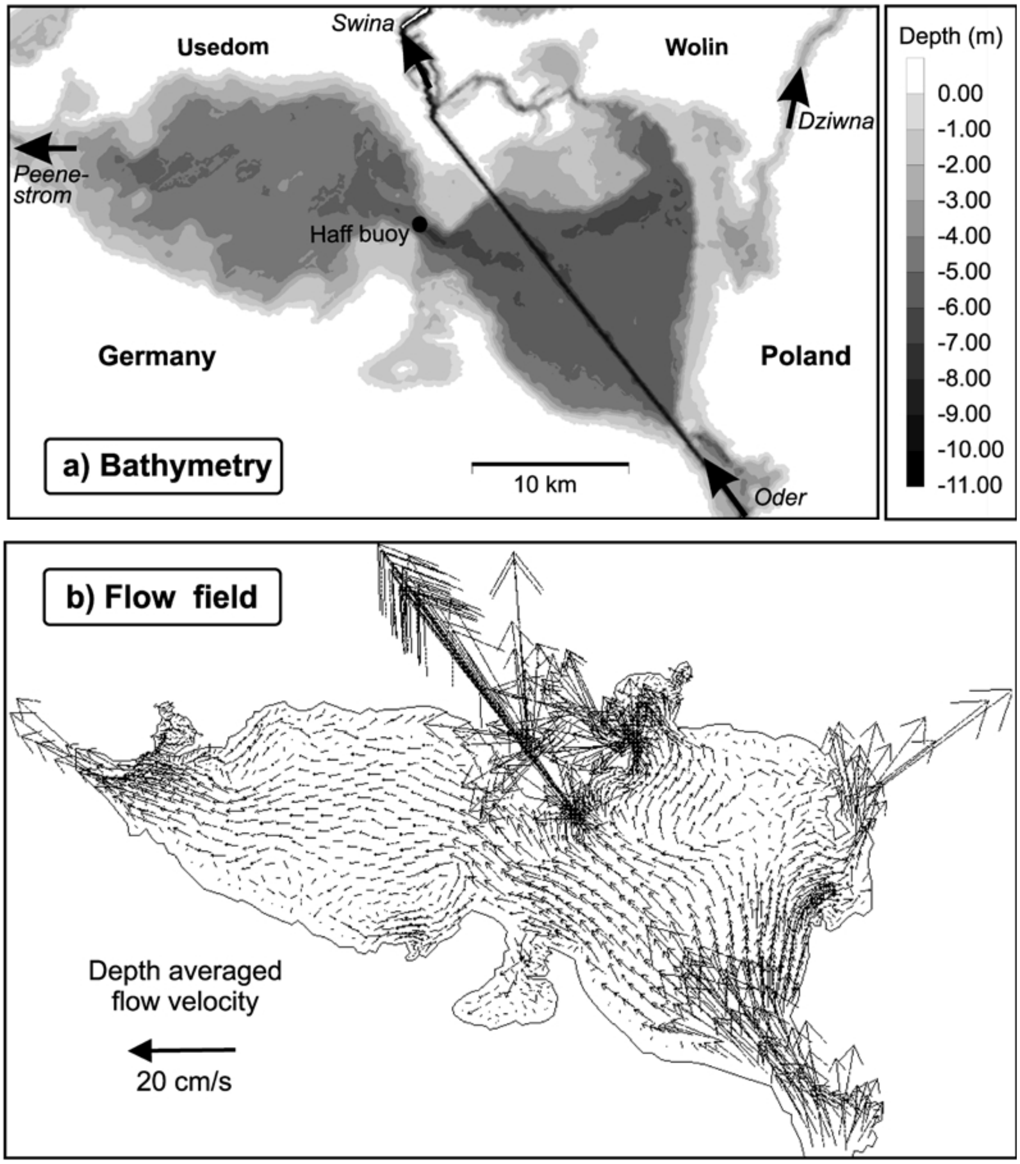

**Fig. 1.** a) Bathymetric map of the Oder (Szczecin) Lagoon at the German/Polish border. (The discharge by the Oder as well as the outlets Peene Strom, Swina Strait and Dziwna are indicated by bold arrows). b) Depth-averaged flow field in the lagoon under typical summer conditions with an averaged wind from south-west of 1.3 m/s and 415 $m^3/s$ Oder river discharge. This flow field was used in all transport simulations.

fections in the lagoon two different scenarios were used in our simulations. We assumed that previous laboratory experiments with polio-1 viruses can be transferred to natural conditions:

a) It was assumed that the viruses are freely distributed in the water. Laboratory experiments at a water temperature of 20° yielded a $T_{90}$-value of 1.5 days (Table 1) or a total inactivation time of 6 days. During transport to the lagoon the virus concentration decreased to $10^3$ viruses/$m^3$. This value was used as a starting concentration for the simulations.

b) Viruses entirely linked to suspended matter have a $T_{90}$-value of 14 days (Table 1) and become inactivated after 57 days. Due to sedimentation the load of suspended matter from the Oder mouth into the Baltic Sea is reduced by 90 %. The sedimentation loss in the lagoon itself was negligible compared to the decay rate and was not taken into consideration. The same is true for the inactivation rate during river transport, which was not considered. Starting condition was a virus concentration of $10^4/m^3$. It was assumed that 10 viruses are linked to one particle, yielding a particle number of $10^3/m^3$.

Wind is an important force that controls transport in the lagoon. During the years 1989 and 1998 the predominant wind direction was west to south-west in Northern Germany (47 %) and linked to the highest average wind speeds. East wind caused a second maximum in the relative annual frequency (13 %). In summer (July–September) the dominant wind direction differed from year to year and between the

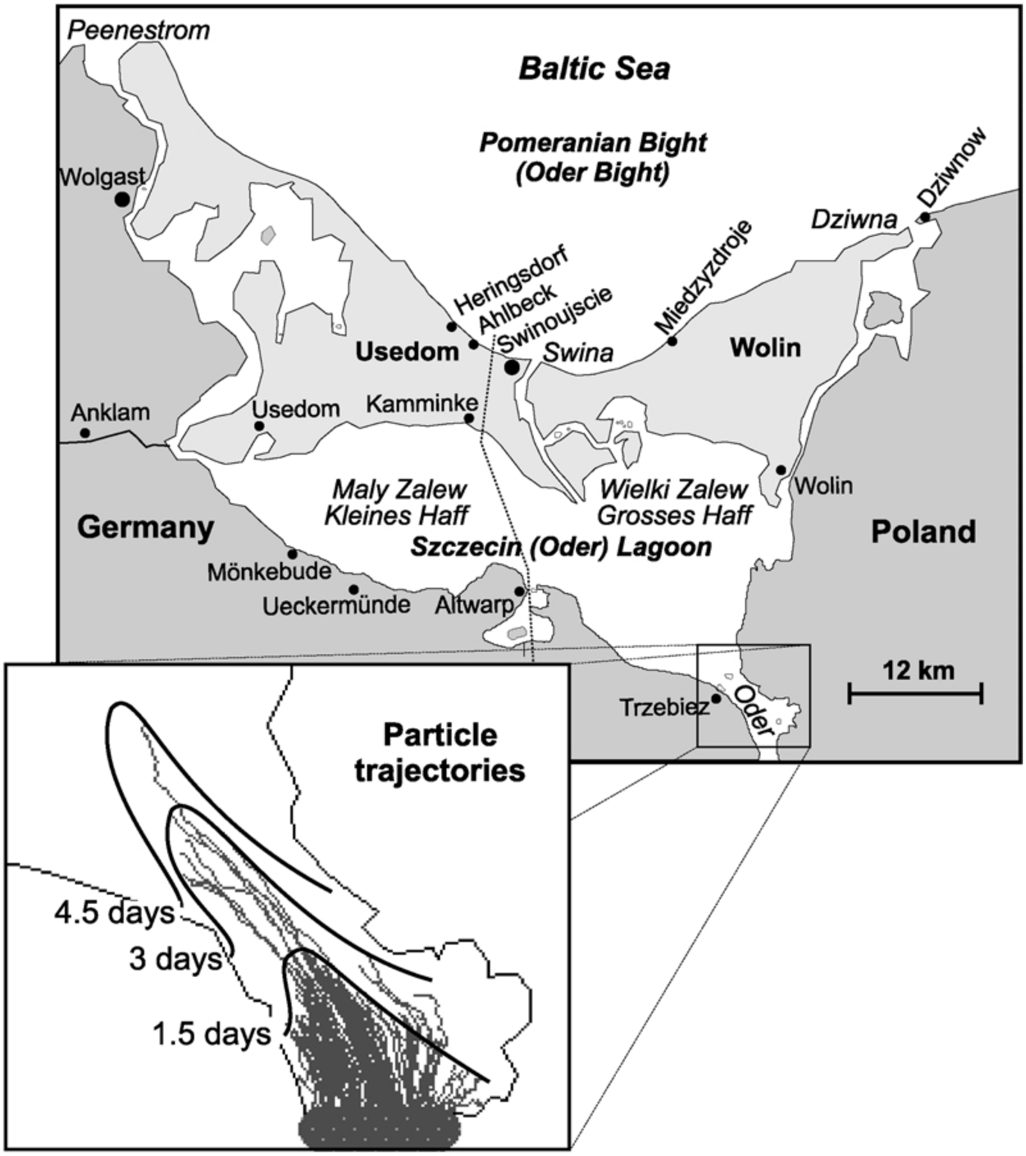

**Fig. 2.** Geographical information about the Oder coastal zone and virus transport simulations. Source for the human pathogenic viruses is poorly treated sewage of the city of Szczecin (Poland). The sewage is released into the river Oder 21 km upstream. The particle drifts indicate transport and decay of free infective viruses in the Oder Lagoon. The concentration in the Oder mouth was assumed to be $10^3$ viruses/m$^3$. After 1.5 days a concentration of $10^2$ viruses/m$^3$ remained and after 4.5 days it decreased to 1 virus/m$^3$. An infection risk can be excluded after 4.5 days.

single months (Hörmann & Schernewski subm. ). Altogether an average wind vector indicating wind from SW with a speed of 1.3 m/s is the typical driving force for the flow model during summer and was applied in our model.

The Oder Lagoon is extensive, (687 km$^2$) but with an average depth of 3.8 m shallow (Mohrholz, 1998; Mohrholz and Lass, 1998). Due to its shallowness only some central areas show a temporary vertical stratification and allowe the application of a two-dimensional, finite element, flow model FEMFLOW2D. The Model is described in detail by Podsetchine and Schernewski (1999). Detailed information about bathymetry (Fig. 1a) was supplied by K. Buckmann, Greifswald.

According to Mohrholz and Lass (1998) the discharge of the lagoon into the Baltic Sea via three outlets varies depending on prevailing wind directions. In the simulations the proportion was adapted to the average wind situation and kept constant with time (17 % Peene Strom, 14 % Dziwna Strait, 69 % Swina Strait). Intrusion of sea water was neglected. The models were run on a PC workstation under Windows NT 4.0 operating system. For model validation and applications see Schernewski et al. (2000a; b). The virus transport was calculated with a particle tracking module. The passive particles' movement was simulated on the basis of the pre-calculated flow field (Fig. 1b). The decay of viruses was simulated by repetitive applications with logarithmic reduced particle numbers and increased simulation times.

## Results

Under average summer conditions with a river discharge of 415 $m^3/s$ and weak wind from SW the depth averaged flow velocities in central parts of the lagoon are weak and hardly exceeded 5 cm/s. Most of the entering Oder water crossed the lagoon along the deep shipping channel (Fig. 1a) passing the Swina Strait, where current speeds above 50 cm/s occurred (Fig. 1b), and reached the Baltic Sea after 28 days. Smaller portions of the Oder water turned east and were released through the Dziwna or crossed central parts of the Kleines Haff and entered the Peene Strom. Some special features of the flow field were several large eddies in the north-eastern part of the Grosses Haff as well as along the north and south coast of the Kleines Haff.

Fig. 2 gives an overview of the geographical situation and shows the simulation results of the first scenario. Table 1 shows all $T_{90}$-values. One and a half and 14 days were simulated.

The large number of thin lines in Fig. 2 indicates the drift of every particle (virus) and how far they advanced into the lagoon. After 1.5 days the number of particles decreased to 100, which means that the concentration of active viruses declined by 90 % to 100 viruses/$m^3$ or 1 virus/10 litre water. After 4.5 days even the last particle, which was transported about 10 km into the lagoon vanished. The bold line after 4.5 days (6 days after release in Szczecin) indicates water with a remaining infective virus concentration of 1/$m^3$. Assuming a homogeneous virus distribution, the likelihood to detect a virus in 10 litres of water after 4.5 days of transport in the lagoon is only 0.01 %. EU regulations for bathing water (76/160/EWG) are met, when 95 % of all samples show no viruses in 10 litre water. The water along and behind the 4.5 day transport line is in compliance with the EU-guideline. The drift calculations are well in agreement with measurements. In 1997 a maximum of $10^2$ infective units per $m^3$ was observed near Police (12 km north of Szczecin). Near the Haff buoy at the German/Polish border and the entrance to the Kleines Haff (Fig. 1) an average of 10 infective units per $m^3$ was found once in 1997 and during 1998 and 1999 no viruses were detected. The applied standard method detects the number of free viruses in 10 l sample water. The values for 1997 were averaged and converted into number of viruses/$m^3$.

**Table 1.** Average inactivation times for polio-1 viruses in different water samples and after absorption or attachment to various materials. (Adrian, Cuypers, Jülich, Lindequist in prep.)

| Sample | Time needed for a virus concentration decrease by 90 % ($T_{90}$-value) | | |
|---|---|---|---|
| | 4 °C | 12 °C | 20 °C |
| Filtrated river water (Oder) | 3.7 d | 3.22 d | 1.46 d |
| Filtrated lagoon water (Swina) | 4.3 d | 2.85 d | 1.94 d |
| Suspended matter (Oder) | | | 14.1 d |
| Bentonit | | | 14.9 d |
| Clay | | | 32.3 d |
| Kaolinit | | | 22.2 d |
| Unicellular Chlorophyceae | | | 10.5 d |
| Microcystis aeruginosa | | | 9.7 d |
| Marine fungi (*Asteromyces cruciatus / Dendryphiella salina*) | | | 27.9 d |

The situation for the second scenario with viruses completely linked to suspended matter is presented in Fig. 3 and Fig. 4. Starting condition is a virus concentration of $10^4/m^2$ attached to 1000 particles. Fig. 3 shows the spatial distribution and decrease after 14, 21, 28 and

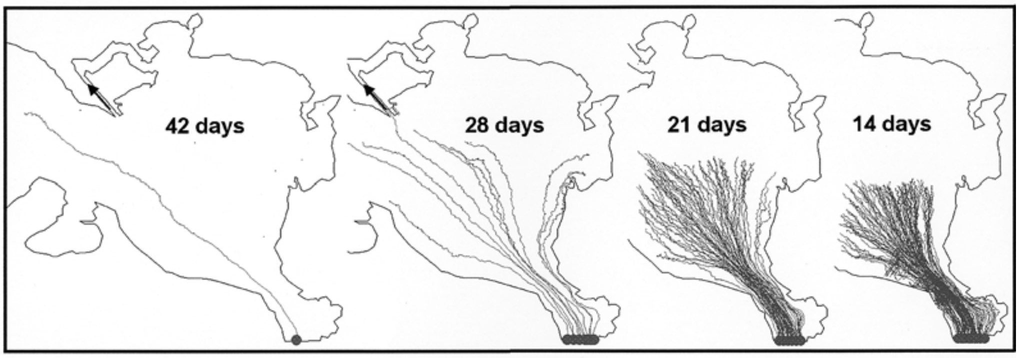

**Fig. 3.** Particle drifts indicating transport and decay of infective viruses attached to natural suspended particle matter in the Oder Lagoon under typical summer conditions. The starting concentration was $10^4$ viruses/$m^3$ at the river mouth. In the simulation $10^3$ particles with ten attached viruses each were assumed. After 14 days a concentration of $10^2$ particles ($10^3$ viruses/$m^3$) remained and after 42 days the number decreased to 1 particle (10 active virus/$m^3$). An infection risk can be excluded after 56 days.

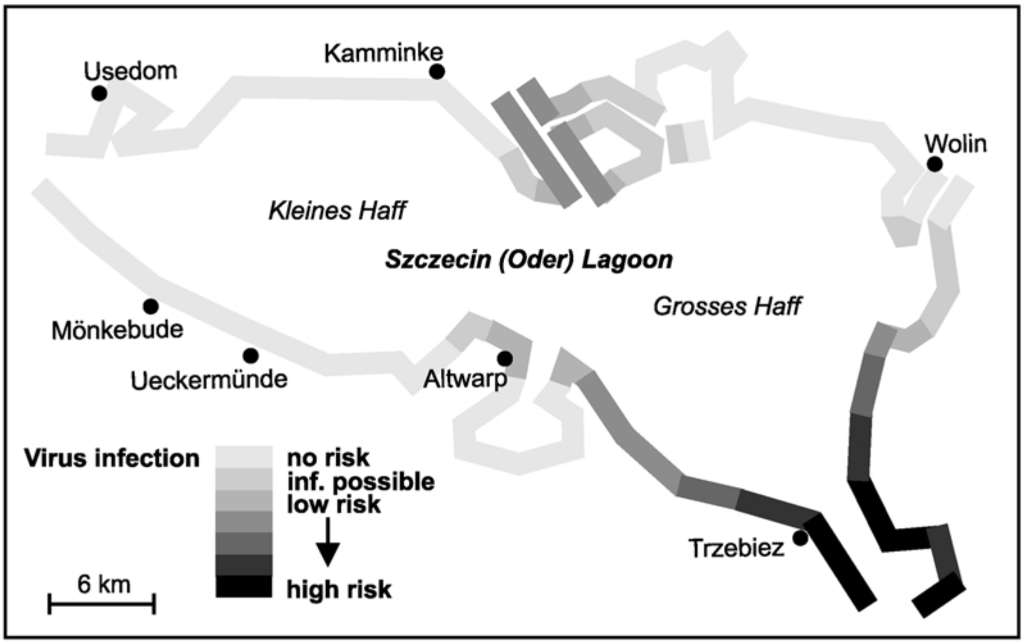

**Fig. 4.** Evaluation of the risk of a virus infection in the Oder Lagoon during typical summer conditions on the basis of simulations in Fig. 3 and additional particle tracking simulations. The areas where an infection is regarded as possible, takes into account that under certain meteorological conditions, extreme river discharges or an increased release of viruses due to epidemic situations a realistic risk of infection can occur. Concerning uncertainties and limitations of these results we refer to the discussion.

42 days. After 14 days 100 particles are left. After 28 days the number of remaining particles has decreased to 10. Accelerated transport in the deep shipping channel across the lagoon allowed particles to pass the Grosses Haff and the Swina Strait and to enter the Baltic Sea after 28 days. It took another 14 days until the last remaining particle had entered the Kleines Haff. The hazard of a virus infection along the coast of the lagoon is summarised in Fig. 4. No risk of an infection is attributed to areas which cannot be reached by particles within 56 days under these assumed summer conditions. The whole Kleines Haff as well as north-eastern parts of the Grosses Haff have no infection risk, which means the concentration is far below one suspended particle per $m^3$. Larger coastal areas of the Polish Grosses Haff have a potential risk of virus infections.

## Discussion

In pure water under laboratory conditions viruses are able to survive for a long time (Dumke and Burger, 1995). Despite their resistance a variety of inactivation and elimination mechanisms reduce the virus load in natural surface waters efficiently. The respective composition of water constituents plays a major role for inactivation rates and limits the extrapolation of results to other rivers and surface water with different conditions. In the river Oder especially the high amount of suspended particle matter plays an important quantitative role as a carrier for viruses. With a $T_{90}$-value of 1.5 days viruses freely scattered in the water have a much higher elimination rate than those linked to suspended particle matter ($T_{90}$-value 14 days). 90 % of free viruses are already inactivated during river transport and after another 4.5 days in the lagoon the concentration decreased to 1 infective virus/$m^3$. This means that after 10 km in the lagoon there is practically no infection risk. Free viruses are no hazard for the beaches of the lagoon. This is true even for a much higher virus release, due to an epidemic in Szczecin, higher river discharge and unfavourable weather conditions.

Weekly data collection in several locations between 1997 and 1999 support the model simulations. Only in very few cases a virus contamination in the lagoon was detected and never exceeded 10 infective units per $m^3$. EU regulations for bathing water are met, when 95 % of all samples show no viruses. In the lagoon this was always the case and corresponded to the simulation results. It became obvious, that several conditions influenced the detection of viruses. High values measured sporadically were always linked to lower temperatures at the beginning of the bathing season.

The situation is different when viruses are attached to suspended particle matter. Due to the slower decay rate, at about 40 % of the total coastline of the lagoon an infection is potentially possible. A high infection risk is limited to a small area of several kilometres close to the river mouth, where active virus concentrations exceed $10^3$ viruses/m$^3$ in this scenario. Viruses released at Szczecin can enter the Baltic Sea after about 4 weeks. The dilution in the Baltic Sea reduces the concentration by several orders of magnitude. Even under unfavourable east wind conditions a hazard by viruses from Szczecin for the well known seaside resorts Ahlbeck, Heringsdorf or Bansin along the Baltic coast of Usedom can be excluded.

One has to be aware that the results presented in Fig. 3 are a simplification and contain several uncertainties. All viruses are assumed to be attached to suspended matter and all types of viruses are expected to behave like polioviruses in the laboratory experiment.

The average concentration of enteric viruses in biologically treated sewage is about $10^4$/m$^3$ (Hahn et al., 1991; Lopes-Pila and Szewzyk, 1998; Schulze, 1996). A much higher virus load can be expected in older sewage plants and untreated water (Hugues et al. 1997). On this background our assumption of $10^7$ viruses per m$^3$ untreated sewage can be regarded as realistic, but the amount may differ by one or two orders of magnitude, eg. due to an epidemic. The impact of this uncertainty on the possible spatial distribution in the lagoon is limited due to the rapid logarithmic decay of viruses and generally does not question the presented results.

Another uncertainty arises from flow and transport simulations. One has to keep in mind that the simulations are based on depth-averaged flow velocities and constant wind from south-west as well as constant discharge. This average long-term flow field under typical average wind conditions in summer hardly can be supported by direct flow measurements, but the comparison of the flow field during the Oder flood fits to remote sensing data as well as to measurements and 3D-flow model simulations (Rosenthal et al. 1998). In the Grosses Haff the flow field is very much affected by river discharge, whereas wind plays only a minor role. Therefore other prevailing wind directions do not alter the presented flow pattern near the Oder mouth and in the southern part of the Grosses Haff very much. Altogether the shown flow field as well as the virus transport and its spatial pattern is a generalisation but can be regarded as reliable.

The simulation of the transport with suspended matter is also a simplification: a fixed number of viruses attached to a particle and the decay of the complete particles are assumed. This would be correct if sedimentation would be the main reason for the decay rates. Nevertheless the concentrations derived from these simulations are correct. The final points of the particle drifts outline a region where a certain virus concentration occurs, no matter how homogenous the viruses are dispersed.

The scenarios were calculated on the basis of $T_{90}$-values at 20 °C. At lower temperatures viruses remain infective for a longer time and the scenarios would be worse. Higher virus concentrations are a hazard only during summer, when a lot of water activities take place and therefore lower water temperatures characteristic for other seasons are negligible. Comparing $T_{90}$-values at 20 °C (Table 1) shows that the slowest decay takes place when viruses are linked to clay or clay minerals. It is still unknown to what extent viruses are attached to clay in natural surface water, to what extent they remain infective after sedimentation and resuspension processes. Linked to clay, viruses generally can be transported far into the Kleines Haff and more detailed studies are necessary to evaluate their behaviour and hazard.

As mentioned before, a threshold of 10 to 50 viruses or even less can be regarded as minimum infective dose (Dumke and Feuerpfeil, 1997; Gerba and Haas, 1988; Lopes-Pila and Szewzyk, 1998; Teunis et al., 1996; Ward and Akin, 1984; Ward et al., 1986). Schiff et al. (1980) examined the minimal infective dose of enteric viruses in drinking water. One hundred healthy adults obtained different doses of the low pathogenic Echo-virus 12 with drinking water. A number of 17 plaque forming units was obtained as a minimal infective dose. The probability of an infections depends on the number of infective viruses (N) and a virus specific term (r). r comprises the likelihood to remain infective in the organism, to reach the target cell and to infect it.

$$P = 1 - e^{(-Nr)} \qquad (1)$$

In the case that only a small number of viruses was swallowed the following approximation holds:

$$P = N\,r \qquad (2)$$

Usually it is assumed that 10 ml to 100 ml water are incorporated during bathing (Johl et al. 1995). Supposing a homogeneous distribution, like the EU guideline does, the uptake of viruses is proportional to water uptake. Viruses linked to suspended particle matter cause an inhomogeneous distribution. In this case a higher number of viruses can be incorporated even when the average virus concentration per m$^3$ water is low and a possible threshold value for an infection can easily be exceeded. Not much is known about the behaviour of viruses attached to particles. In the worst case even the number of viruses attached to one particle might be sufficient to cause an infection after incorporation by predisposed persons.

It is not easy to link a virus infection to insufficient bathing water quality. From our calculated virus concentrations an infection probability between 0.01 and

0.001 arises. The resistance of a person determines whether a disease emerges or not. Under these circumstances virus induced diseases remain singularities and a direct relation to the virus source is hard to find. Even several similar cases, caused by high virus concentrations in the water can hardly be attributed to this source because viruses are not determined in the routine bathing water quality monitoring. Due to the incubation time and the fast decay of viruses in natural systems a water quality analyses afterwards is very often useless.

Nevertheless, examples in the References clearly reflect the hazard of virus infections. Adamzyk et al. (1970) reported an echovirus type 30 epidemic affecting 249 people. The medical history suggested municipal swimming pools and lakes as likely sources. In a bath in Dresden coxsackievirus type 3 was found several times. At the same time, this virus type was isolated from 26 patients which were fallen ill with meningitis or enzephalitis (Liebscher, 1970). According to Heinrich et al. (1978) it is very likely that coxsackieviruses in the Baltic Sea caused a meningitis epidemic. In this example unfavourable meteorological conditions promoted high virus concentrations near a bath.

However, virus infections in the Kleines Haff caused by a release in Szczecin always will be individual cases. It is very unlikely that the beaches of Mönkebude, Ueckermünde or at the inner coast of Usedom can be affected and endangered by viruses from Szczecin at any time. Near the Oder mouth or further in the Grosses Haff swimming and bathing can be negatively affected by infections (Fig. 4). Here swimming cannot be recommended. This underlines that improved virus elimination in sewage treatment is still necessary.

The fast virus decay suggests that smaller pollutants like cities along the coast of the lagoon might be of higher importance than a heavy but more distant pollutant like the city of Szczecin. During the last decade new sewage treatment plants on the German side of the lagoon improved the released sewage water quality and decreased the risk of high virus release into the Kleines Haff. Recently new sewage plants with high capacity were established on the Polish side in Swinoujscie and Miedzyzdroje, too. Altogether, the adjacent towns nowadays have to be regarded as less important sources for viruses. Despite this, a local virus release never can be excluded.

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