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Coastal bathing water quality and climate change – A new information and simulation system for new challenges

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ABSTRACT

Human pathogenic micro-organisms in coastal waters receive increasing attention. Climate change with its multiple effects on micro-organisms is one major reason. Changing survival rates, sources and new invasive species are a challenge for bathing water quality management. We present a new online bathing water information system. It includes an alerting system, software to supports communication between authorities, local municipalities and the public as well as simulation tools, based on a 3D-flow and particle tracking model. In scenario simulations with focus on enterococci and *Escherichia coli* bacteria we show the potential impact of climate change on bathing water quality and the potential relevance as a decision support system in the large, shallow Szczecin lagoon. Szczecin lagoon in the Baltic at the German/Polish border is a pollution hot-spot and frequent bathing prohibitions hamper tourism development.

Because of climate change, the risk of river floods is supposed to increase in future. Higher discharge causes an increased transport velocity in the river flow. At the same time, run-off from city surfaces and agricultural land along the river can cause increased *E. coli* concentrations in all surface waters. As a consequence *E. coli* and especially Enterococci are transported far into the lagoon and high concentrations can cause bathing water quality problems even on distant beaches. Especially heavy lasting rain in the river basin together with local rain events are a serious threat for bathing water quality in the lagoon and will very likely require a closing of beaches for swimming. Similar to other coastal waters, a wide range of other potentially human pathogenic micro-organisms might create a threat for the lagoon in future.

1. Introduction

The effects of climate change on waterborne and vector-borne diseases are intensively studied and have high relevance for public health (e.g. Epstein, 2002; Patz et al., 2005; Lafferty, 2009). Examples are ongoing discussions of climate change effects on the infection risk of dengue fever (Hales et al. 2002), malaria (Paaijmans et al., 2009) and cholera (Lipp et al., 2002). Increasing temperatures due to climate change can have multiple effects on vectors and diseases (Gubler et al., 2001; Hunter, 2003), will alter the survival conditions for several human-pathogenic microorganisms, and allows the invasion of new vectors and diseases. Especially human pathogenic microorganisms in coastal waters and their relation to climate change receive increasing attention (Roijackers and Lürling, 2007). Improved monitoring and analytical methods draw attention to unknown and invasive organisms and raised awareness of existing risks. Examples along the southern Baltic coast are recently observed high concentrations of native vibrions (*Vibrio vulnificus*), which caused lethal infections in the coastal Baltic Sea and are today considered as a major threat for summer seaside resorts in Germany (Böer et al., 2010). Another example of a new challenge is *Escherichia coli* O157:H7, an *E. coli* strain that can produce toxins and can cause gastroenteritis, urinary tract infections and neonatal meningitis (e.g. Mudgett et al., 1998; Paunio et al., 1999). Many other, potentially more problematic microorganisms, might create problems in our coastal waters (Roijackers and Lürling, 2007). Even if bathing water meets the microbiological standards of the European Bathing Water Directive (2006/7/EC), many potential pathogenic organisms could be present (WHO, 2009). Furthermore, many of these microorganisms

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will benefit from climate change and might cause increasing problems in future. Against this background, new simulation, management and decision support tools for bathing water quality are required.

We present a new on-line bathing water quality information system. The system has been developed within the project GENESIS as a general European approach to support regional authorities. It combines a model and simulation tool with an alerting and improved communication system. The model tool consists of a three-dimensional flow model (GETM) together with a Lagrangian particle tracking routine (GITM). Here, we exemplary apply our model tool and prove its suitability as well as its potential and practical relevance. Spatially, we focus on the Szczecin lagoon at the German/Polish border (southern Baltic coast). The Lagoon is affected by the Odra river and sewage water of Szczecin city and is a pollution hot-spot region. Insufficient bathing water quality causes beach closures and hampers tourism development. In several scenario-simulations we give an overview how climate change might affect the survival of various human-pathogenic organisms in this region and assess how the spatial contamination risk in the lagoon will alter in future and show the benefit of the bathing water quality information system. In these scenarios we focus on the indicators of the European Bathing Water Directive (2006/7/EC), namely enterococci and *E. coli* bacteria.

2. Study site and methods

2.1. Szczecin coastal region

The Odra (German: Oder) coastal region, with the large Szczecin lagoon, is located at the German and Polish border in the southern Baltic. The lagoon covers an area of 687 km^2 and has an average depth of 3.8 m. Tourism is the major source of income in the coastal region. According to the Central Statistics Office in Poland the municipalities counted the following numbers of tourist overnight stays in 2006: Goleniów (3 018), Stepnica (207), Dziwnów (87 371), Kamień Pomorski (4 914), Międzyzdroje (110 165), Wolin (8 524), Nowe Warpno (7 637), Police (7 784), Świnoujście (111 614) and Szczecin (352 415). Major beaches in the Polish part of the lagoon are Stepnica, Trzebież, Czarnocin, Lake Nowowarpieńskie and Wolin. The municipalities differ considerably in terms of population and income. The municipalities with the highest income are the tourism resorts located on the Baltic Sea coast. Municipalities around the lagoon have an income below the national average mainly from farming, light industry and commerce. However, tourism is still growing and of increasing importance. Especially the fast development of marinas in the lagoon with about 2 400 mooring spaces is one indicator (10 marinas on the Polish side with altogether about 600 mooring spaces as well as 14 marinas in the German part of the lagoon) (Steingrube et al., 2004). The regional plan by the Marshal of Zachodniopomorskie Voivodship suggests the creation of a West Pomeranian Sailing Route covering the lagoon and the Baltic. It includes new sport boat harbours and the modernization of existing ones. For a further development of tourism around the lagoon a good water quality is imperative.

During recent years, the Oder/Odra estuary faced many problems with microorganisms. A *Salmonella* pollution event in the seaside resort Miedzyzdroje caused a beach closing for more than 4 weeks during high-season in August 2008. High concentrations of *V. vulnificus* were frequently found in Karlshagen, Island of Usedom and in Lubmin, Greifswald Bodden. In 2009, the maximum was above 1 million germs per litre in Lubmin. In 2003, 2010 bathers died after a vibrion infection and in 2006, three people fell ill but and were saved only by fast application of antibiotics (LAGUS pers. com). However, most common are problems due to high concentrations of coliform, *E. coli* and *Enterococci* bacteria. In the past, coliform bacteria often caused a closing of beaches according to EU Bathing Water Quality Directive (76/160/EEC), e.g. in Stepnica (from 08.08.2006 for 25 days; from 19.07.2006 for 15 days), in Trzebież (from 01.08.2006 for 42 days; from 20.07.2007 for 42 days; from 24.07.2008 for an unknown period) and in Czarnocin (from 27.07.2006 for 50 days; from 10.07.2007 for 35 days and from 01.08. 2008 for an unknown number of days). Data on bathing water quality in Poland are publicly provided by the Chief Sanitary Inspectorate. Data on local bathing water quality are also available on the websites of public health services.

Insufficiently treated sewage water is the most important reason for microbial problems and caused serious water quality problems in the lagoon during the last decades. Today the situation is improving because 288 million Euros have recently been invested in sewage treatment plants around the city of Szczecin, which is the major centre and located at the Odra river, north of the lagoon. However, the other municipalities sharing the Polish coastal region play a role, as well. The total population (Central Statistics Office data for 2006) and the percentage of it connected to a sewer system differs between the municipalities: Goleniów (33 289, 76%), Stepnica (4,770, 66%), Dziwnów (4,127, 95%), Kamień Pomorski (14 664, 59%), Międzyzdroje (6,449, 90%), Wolin (12 475, 43%), Nowe Warpno (1,605, 61%), Police (41 099, 80%), Świnoujście (40 688, 93%) and Szczecin (401 437, 89%). In 2006, 65% of the sewage was treated biologically/chemically while 27% of Szczecin's effluents were still treated mechanically and 8% of the water even went untreated (Council of Ministers Republic of Poland, 2008).

In 2010 the amendment of the Polish Water Law was published. It defines objectives, instruments, procedures, institutional actors of the water administration, implemented the new EU Bathing Water Quality Directive (2006/7/EC) and modified some responsibilities. Today, bathing sites are managed on a local level by administrators or the communities and the Sanitary Inspection takes care of bathing water monitoring and the compliance of water quality with Directive (2006/7/EC). In the following we focus on *E. coli* and *Enterococci* bacteria because they are the new indicators in this Directive and in 2011 replace coliform bacteria in the monitoring programme. One of the crucial element in the new EU Bathing Water Directive are bathing water profiles. Their aim is to provide the public and authorities with information about physical, geographical and hydrological characteristics of a bathing places as well as possible pollution sources impacting bathing water quality.

2.2. The model system

In this study we apply the General Estuarine Transport Model (GETM, Burchard and Bolding (2002); Burchard (2009). This 3D-flow model allows reliable and spatially high resolved flow and transport simulations in shallow systems with a complex bathymetry and coastline. It was successfully applied and validated in recent studies (see e.g. Burchard et al., 2005; Lettmann et al., 2009; Hofmeister et al., 2011; Gräwe and Burchard, 2011). The model allows coastal areas to be flooded and to fall dry at low water levels. Wave dynamics is not taken into account. Basis for the flow calculation is a curvilinear grid that reflects the coastline and the bathymetry of the estuary. The horizontal spatial grid resolution varies between 15 m in the southern Odra mouth (our focus region) and 200 m in the Pomeranian Bight. The vertical water column is always subdivided into 10 layers with a similar thickness (sigma levels). The whole area covered by the model-grid (domain) contains 800 *1300*10 (x,y,z) grid points (see Fig. 1).

To compute 2D variables like (e.g. sea surface elevation), a time step of 0.4 s is used. To compute the 3D variables (temperature, salt and flow) a time step of 480 s is chosen. The output fields are stored on an hourly basis. GETM was forced with 2D and 3D fields along the open boundaries at the Pomeranian Bight. The forcing includes sea surface elevation and depth averaged currents in combination with Flather boundary conditions (Flather, 1976). The 2D fields have a temporal resolution of 1 h. The boundary information is taken from Baltic Sea model with a 600 m resolution.

The freshwater river discharge of the Peene and Uecker rivers are constant values of 20.6 m^3s^{-1} and 9.5 m^3s^{-1} (summer median) for all simulations, since they are negligible. The Odra river discharge dominates processes in the lagoon and differs between the scenarios. Time series of water gauges and sea surface temperature were provided by the Federal Maritime and Hydrographic Agency for all German stations and are used to validate the model. All Polish data, including water quality measurements, have been provided by the Institute for Meteorology and Water Management Krakow. The model validation and detailed information about the set-up is given in Schippmann et al. (2013).

The General Individuals Tracking Model (GITM, Nagai et al., 2003; van der Molen et al., 2007), a Lagrangian particle-tracking tool is used to simulate transport and behaviour of microorganisms. It assumes that the organisms are floating passively with currents and allows the tracing of single particles. The GITM 3D offline particle tracking model solves the equation of motion of individual particles and describes particle movement depending on advection and turbulence. The horizontal and vertical diffusion of every particle are simulated with the random walk method of Hunter et al. (1993). It uses temporally and spatially varying vertical diffusion coefficients calculated by the hydrodynamic model and a constant horizontal diffusion of $K_h = 1\ m^2\ s^{-1}$, which has been estimated with drifter experiments in the Szczecin Lagoon (Schernewski et al., 2012). In all simulations the model calculation time step is 10 s and the output is stored every 30 min. In our simulations, the exponential mortality (die-off) rate (Chick, 1908) is the only property of *E. coli* and *Enterococci* bacteria and differs between the scenarios. The emission locations are the east branch of the river, off the city center of Szczecin, and the west branch of the Odra river, south of the Dabie lake. In all *E. coli* simulations we assume that $2*10^5$ bacteria are represented by one particle. In scenario 0, for example, altogether 2 500 particles were emitted in the simulation once per day.

2.3. The bathing water quality information system

The project GENESIS provided web portal software and a set of distributed secured web services, including interfaces and adaptable web service clients that can be employed at the web portal. Typical services include data access services, catalogues services, viewing services, geo-information processing services, alert services as well as a workflow management component. To implement GETM and GITM in the GENESIS Internet portal, the toolbox, the viewing and geo-information services (Geoserver) had to be installed on our local server. It allowed to run our model system online in to the GENESIS system and to visualize the results. Space and calculation speed limitations do not allow in-situ flow simulations. Therefore pre-simulated steady state flow fields are stored and provided for online-users on our server. The connection of our model with the GENESIS system works via a 'workflow' WPS service in the toolbox. It is defined as a bash shell script which calls the necessary input files from the IOW server and runs GITM (a Fortran executable), runs a Python script to post-process the model results and converts this output via a Perl script into a gml output for visualising the particle movement. Both, input and output are defined by the service provider in the DescribeProcess.xml. It is imported into the toolbox when creating the WPS service. If end-users are calling the service on the portal, it is executed at our local toolbox. The graphical visualisation was done using the GeoServer on the local server by adding new layers from GIS shape files.

3. Results and discussion

3.1. The bathing water quality information system

Objective of the large-scale integrating project European FP7-project GENESIS (GENeric European Sustainable Information Space for Environment), with its 29 partner institutes, was to provide an up-to-date technical framework that enables the development of customized regional and thematic information systems all over Europe. It provided generic services, portal components, information models, an application toolkit and the related documentation. All elements took into account international standards (e.g. W3C, CEN, ISO, OGC, OASIS) and global harmonization initiatives (e.g. GEOSS, INSPIRE). For the Oder/Odra estuary, a bathing water quality information system has been developed within the GENESIS framework. The work was carried out in cooperation with major end-users, especially the Sanitary Inspectorate in Szczecin and local administrations. The system is linked to the general Coastal Information System Odra Estuary and provides information for the public, e.g. relevant geographical background data and bathing water quality data. However, the main purpose is to provide a supporting tool for authorities. It includes a) a prototype of an alerting system, based on in-situ sensor measurements, which informs the Sanitary Inspectorate about microbiological hazards; b) a bulletin software which supports communication between authorities, local municipalities and the public and c) simulation tools. A typical application case of the system would be the following:

The suspended solid sensor serves as indictor for pollution and is located in the river north of the city. The city and the river upstream are the main potential sources of pollution. If the sensor reports that the concentration threshold is exceeded, a message is sent via the information system to the Sanitary Inspectorate. The Sanitary Inspectorate enters the information system and gets an overview about the observed suspended solids concentration including thresholds as well as up-to-date weather information (e.g. temperature, wind speed and direction). This data allows the application of the online simulation tool to get an impression at what time the pollution will reach a certain place (e.g. town, beach or harbour) and how it spreads in the river and in the lagoon. If the likely pollutant (e.g. *E. coli*, *Enterococci*, viruses) is known, a more realistic simulation is possible. It can take into account e.g. the die-off rates and the decay of problematic organisms and the potential pollutant concentrations at certain places can be estimated. If the authority comes to the conclusion that a risk exists, the simulation results allow to organize an optimized monitoring and to inform local actors when and where to take what kind of water sample. After the laboratory analysis, the data is stored and those locations where water quality thresholds are exceeded automatically receive an alert email.

On a regular and event-driven basis, bathing water quality data and other relevant information are distributed via newsletter to a broader public. The preparation and distribution are supported by a software tool. Our brief phone survey among several end-users showed that improved information about water quality aspects is appreciated. The newsletter structure and content where positively evaluated by users and above 25% planned to further disseminate it. The system is still a prototype and not all functionality is fully in place yet. Among the benefits of such a system are a) a fast and systematic reaction in case of pollution events, b) a spatially and temporal optimized monitoring, c) accelerated alerting and communication with subsequent reduced heath risk for the local population and tourists, d) an improved awareness, knowledge and transparency about water quality issues, and e) the support of beach profile development and evaluation according to Directive (2006/7/EC). The development of the system or of parts is pushed forward by IMGW PIB (Institute of Meteorology and Water Management-National Research Institute). The web portal www.baltyk.pogodynka.pl can serve as an example. The system is still not able to serve as a reliable early-warning system for pollution entering with the river. The permanently recording sensor for particulate matter in the river does not sufficiently indicate microbial pollution.

The online simulation tool in the Internet information system is a simplified version of the described GETM flow and GITM particle tracking model. It allows end-users to carry out simple but flexible and fast simulations e.g. after accidental release of microorganisms in the coastal area or after the observation of high concentrations at beaches. In a first step the end-user enters the wind situation (direction and speed). The information system contains pre-simulated and stored, steady state flow simulations for altogether 16 wind situations (combinations of direction and speed). The system uses the one that reflects the users demand best. In the second step the user chooses the number, type and properties of particles (e.g. *E. coli* are defined by a specific die-off rate) defines the location of the emission and the simulation period. The propagation of the particles with time is displayed and the final result can be visualized in different ways (Fig. 2). The information system provides additional tools to control and display the simulation process and its result. It is suitable for scenario-simulations and can serve as a decision support system. In the following, we carry out scenario analysis on the potential impact of climate change on bating water quality, to show the potential relevance of these simulation tools. For this analysis we do not use the simplified online-tool in the information system but the more flexible original simulation models GETM and GITM.

3.2. Climate change and microorganisms: the scenarios

Climatic changes during the 20th century and future climate change projections for the Baltic Sea region are summarized in von Storch and Omstedt (2008). Between 1871 and 2004 mean annual temperatures in the southern Baltic increased by 0.07 °C per decade. Precipitation slightly increased, as well, but the spatial pattern and seasonal varies. In the southern Baltic the trends indicate less rain in summer and more rain in winter. In future, the number of heavy precipitation events shall increase. The projected future warming in the Baltic is higher compared to the world-wide average. An increase in summer temperatures by 3–5 °C until 2 100 is likely. Projected changes in precipitation bear many uncertainties but trends towards drier summers and rainy winters are likely to go on. In the southern Baltic the total precipitation might slightly decrease or change not. However, a decreasing (increasing) riverine discharge during summer (winter) (Graham et al., 2007) and an increased temporal variability of river discharge are likely. Heavy local rain events and river floods seem to have a higher likelihood in future.

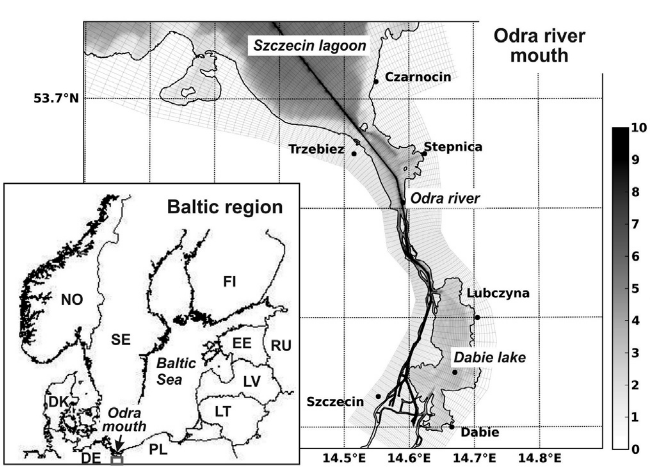

Fig. 1. The Oder/Odra river mouth at the German/Polish border (southern Baltic) and the model domain.

Water temperatures have a direct effect on survival rates of microorganisms. Decay rates strongly differ between different bacteria and usually show a fast initial decay, followed by a slower decay. According to Easton et al. (2005), the initial die-off rate for e.g. *E. coli* (Enterococci) at 23 °C is 0.503/day (0.359/day) and at 9 °C is 0.351/day (0.164/day). High temperatures reduce the survival of both bacteria in waters. However, it is well known that other parameters may play an equal role (e.g. Rhodes and Kator, 1988). Floodwaters in rivers, following heavy rainfall and run-off, are a major source of microorganisms and a threat for coastal bathing water quality (Hunter, 2003; Velduis et al., 2010). At a beach after a rainfall, Scopel et al. (2006) observed 100-fold increased *E. coli* numbers with concentrations up to 4 500 CFU/100 ml. The following scenario simulations use *E. coli* and *Enterococci* as exemplary microorganisms and show potential consequences of climate change on bathing water quality in summer in the Szczecin lagoon. We assume the following scenarios:

Scenario 0 'average conditions': The total number of *E. coli* bacteria in treated discharge of sewage treatment plants is usually between 10^3–10^4 cfu per 100 ml (e.g. The central sewage treatment plant Zdroje has a sewage water discharge of 18 000 m^3 per day. Common background concentrations of 10 *E. coli* per 100 ml (pers. com. IMGW) are assumed in the river. Based on long-term discharge data for the Odra river (time series of 1912–2003) the summer average summerly river discharge is 414 $m^3 s^{-1}$. Altogether the total daily *E. coli* emission is 5^*10^{12}. We assume a mortality rate of 0.019 h^{-1} (T90 = 54.1 h) for *E. coli* (Easton et al., 2005).

Scenario 1 'river flood': Heavy rain events in the river basin with subsequent increased river discharge and increased *E. coli* concentrations in the river because of wash off from land surfaces in the catchment. A discharge of 2 100 $m^3 s^{-1}$ is assumed. During the Odra flood in summer 1997 the summer maximum discharge was 2 600 $m^3 s^{-1}$. The mortality is similar to the previous scenario. Then total daily *E. coli* emissions of 2^*10^{13} are more than four times higher compared to scenario 0.

Scenario 2 'local heavy rain': Heavy local rains around the lagoon cause increased diffuse emissions from municipal sewage treatment plants, small point discharges (brooks, drainage pipes) and diffuse run-off from agricultural land. According to the observations of Scopel et al. (2006), it is assumed that 1.5^*10^{13} *E. coli* bacteria per day are emitted equally along the entire Odra river mouth coast. Additionally the emission of Szenario 0 is taken into account, so that we end up with the same total emission like in szenario 1. The mortality for *E. coli* is similar to the previous scenarios.

Scenario 3 'warming': Climate change causes a summerly water temperature increase of 3 °C with negative effects on bacteria survival. Mortality rates of = 0.019 h^{-1} (T90 = 54.1 h) for *E. coli* and 0.014 h^{-1} (T90 = 71.6 h) for *Enterococci* are derived from experiments of Easton et al. (2005). For a warmer climate (23 °C) die-off rates of 0.021 h^{-1} (T90 = 47.7 h) for *E. coli* and 0.015 h^{-1} (T90 = 66.9 h) for *Enterococci* are used according to Easton et al. (2005). Because of lacking information about potentially realistic

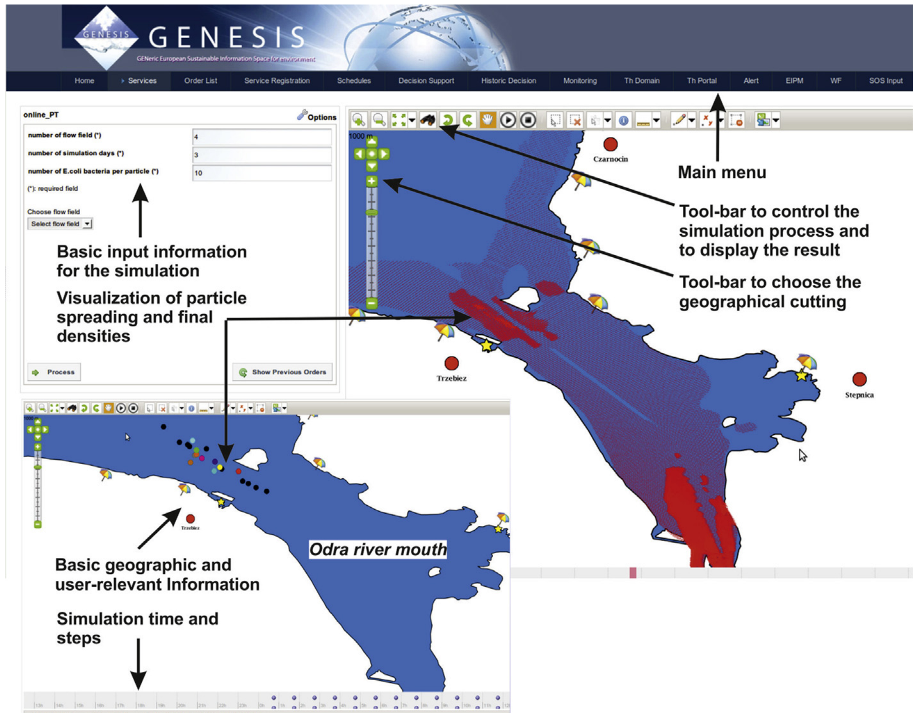

Fig. 2. The internet surface of the GENESIS bathing water quality information system for the Oder/Szczecin lagoon.

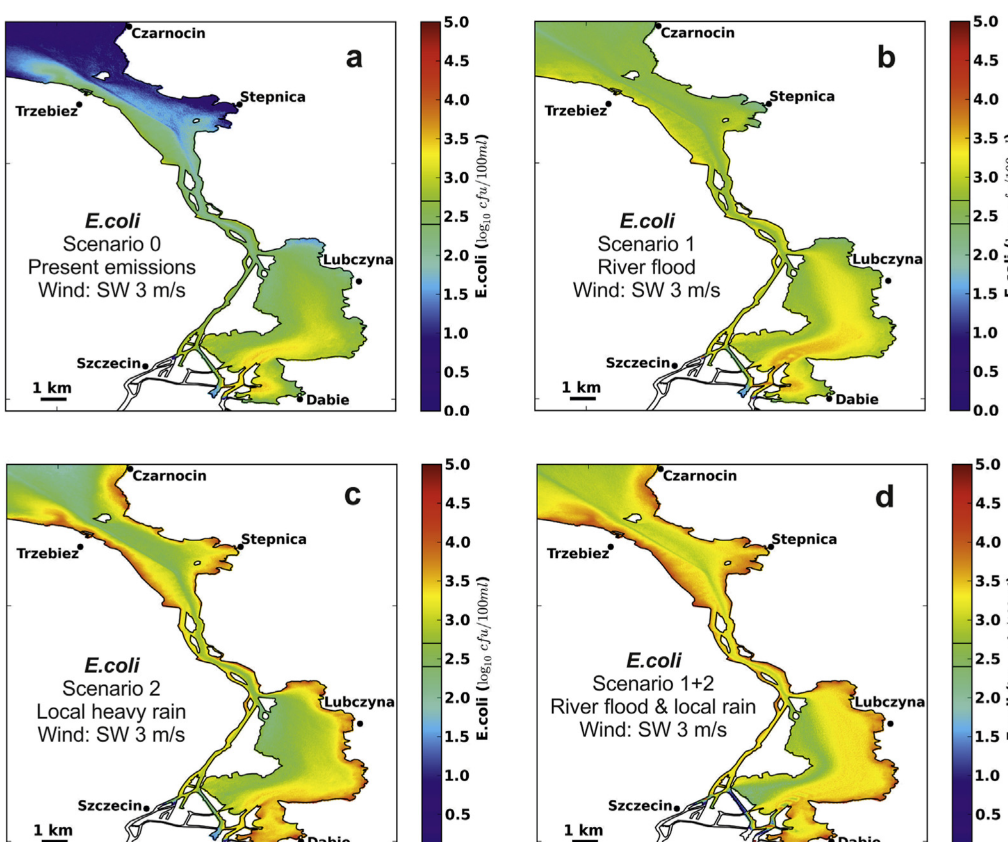

Fig. 3. Transport and die-off of *Escherichia coli* bacteria (*E. coli*). The present average *E. coli* emission situation (a) comparedc to the likely effects of climate change, namely heavy river floods (b) and heavy local rain events (c) as well as w combination of both (d). Details about the scenarios are given in the text.

emissions of *Enterococci*, the results are presented in simulation particle numbers and are not re-calculated into *Enterococci* densities.

3.3. Model simulations

In the present situation *E. coli* transport with the Odra river and emissions in Szczecin cause high concentrations at beaches in lake Dabie, with a high likelihood that bathing water quality thresholds are exceeded (Fig. 3a). This is confirmed by data and lead to a permanent closing of beaches near to the city of Szczecin. Scenario 0 results for the beach in Dabie (observed compared to model simulation) can be regarded as a model validation and confirms that the assumptions and transport pattern are realistic. More detailed validations are shown in Schernewski et al. (2011) and Schippmann et al. (2013). The high *E. coli* die-off rates in natural surface water cause a fast reduction of the concentrations in the river during transport. The beaches of Stepnica, about 26 km north of Szczecin, are hardly affected any more. Fig. 4 provides an overview about the *E. coli* concentrations for different scenarios at the different beaches.

The risk of river floods is supposed to increase in future. Higher discharge causes an increased transport velocity in the river flow. At the same time run-off from city surfaces and agricultural land along the river can cause increased *E. coli* concentrations in all surface waters. As a consequence *E. coli* are transported far into the lagoon and high concentrations can cause a bathing water quality problems even on distant beaches, like Czarnocin or Trebiez (Fig. 3b). The entire lower river is accompanied by meadows, wetlands and fens, which are separated by reed belts from the river mouth. Ditches and drainage pipes ensure a fast de-watering and enable cattle farming. Cattle farming favour the accumulation and survival of *E. coli* bacteria on surfaces and in soils. Agricultural run-off water after heavy rains contains high concentrations of faecal bacteria. In case of the land around the lagoon, this pollution enters the river without much time delay and die-off. The pollution enters through diffuse and small point sources and can cause near shore bathing water quality problems along the entire coastline (Fig. 3c). Heavy lasting rain in the river basin together with local rain events are a serious threat for bathing water quality in the lagoon and will very likely require a closing of beaches for swimming. This scenario has an increased likelihood in future due to climate change. These events are hard to predict and usually short-termed. Even if the management possibilities are only limited, these events require a fast reaction. The functionality of our bathing water quality information system should be very useful for such cases.

The potential transport distance of human-pathogenic organisms depends on flow velocity and die-off or inactivation rates. In

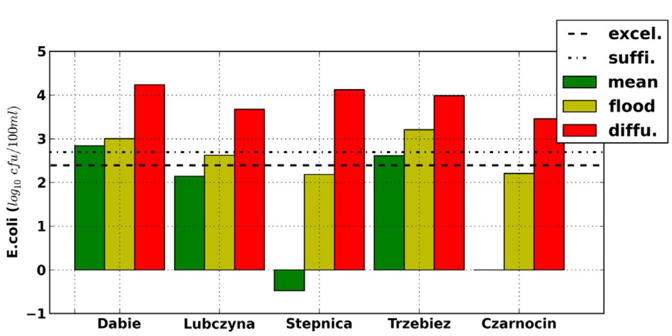

Fig. 4. *E. coli* concentrations at beaches in the Szczecin lagoon (Odra river mouth). The results are based on model simulations assuming scenario 0 (mean present summer situation), scenario 1 (Odra river flood) and scenario 2 (diffuse emission after local rain). The horizontat line indicates the thresholds for excellent and sufficient bathing water quality.

case of *E. coli* and *Enterococci* higher water temperatures have a negative effect on survival in natural waters. Fig. 5 shows the transport and survival of *E. coli* in a future climate. Compared to the present situation (Fig. 3a) the effect of the slightly higher die-off rate is hardly visible. Increasing temperatures may have a slightly positive effect on water quality, but many other parameters influence the survival in natural waters. Effects due to temperature changes can very likely be neglected. The same is also true for *Enterococci* (Fig. 5c, d). Compared to *E. coli*, *Enterococci* have a lower die-off rate, survive longer in natural waters and are transported much further into the lagoon. Other human-pathogenic bacteria might even survive much longer and affect large parts of the lagoon. The potentially problematic bacteria *E. coli O157:H7* undergoes a faster decay compared to *E. coli* (Easton et al., 2005) and has slightly reduced spatial spread in the river mouth. The completion of additional state-of-art sewage treatment plants and the on-going renovation of the entire sewage treatment system of Szczecin (European Commission, 2000) is an important step towards improved bathing water quality.

3.4. Bathing water quality problems and climate change

Enterococci and *E. coli* are indicator organisms for faecal pollution and serve as examples. A wide range of other organisms might create a threat for the lagoon in future. Giessen et al. (2004), Pond (2005), and Roijackers and Lürling (2007) provide an overview of most important organisms (bacteria, algae, protozoa and viruses) that are a serious health risk for bathers and estimate how climate change will change the risk of infection in the Netherlands. Out of 21organisms 14 are supposed to have at least a slightly increased infection risk in future. Among those are e.g. the bacteria *Legionella pneumophila* (Legionnaires' disease), *Leptospira icterohaemorrhagiae* (Weil's disease), *Mycobacterium avium* (lung damage), *Vibrio cholerae* (diarrhoea), *V. vulnificus* (letal necrotising wound, gastrenteritis) or the viruses human adenovirus (upper respiratory tract), coxsackievirus and echovirus (gastro-enteritis) as well as hepatitis A and E (jaundice). According to Chan et al. (1999), and Roijackers and Lürling (2007) 4 out of 5 vector-borne pathogens transmitted by waterborne organisms have at least slightly increased infection risk due to climate change in future, namely *Plasmodium* spp. (malaria), dengue virus (dengue fever), Trematodes (schistosomiasis) and West-Nile virus (West-Nile fever). Beside climate change, migration, tourism and trade (e.g. ballast water) are important for spreading pathogens and increasing infection risks. Climate change will cause more favourable conditions for several tropical and subtropical pathogens or their vectors. Malaria and denge e.g. are favoured by increasing temperatures and rainfall. The denge vector, the mosquito *Aedes aegypti* has already reached Italy, Belgium and the Netherlands with imported bamboo shoots from China (Reinhold 2007 in Roijackers and Lürling, 2007). The conditions in Germany and Poland do not differ much from the situation in the Netherlands. Therefore the Odra mouth region is facing similar risks and challenges.

4. Conclusions

A large amount of human-pathogenic microorganisms can be present in surface waters and can potentially cause a risk, even if the requirements for a good bathing water quality are fulfilled. Bathing places in a highly eutrophied lagoon, like Szczecin lagoon, that additionally receives insufficiently treated sewage water always include a higher risk of infection. Climate change, with increased likelihood of heavy rains and flooding events as well as increasing temperatures will, very likely, cause additional threats for bathing water quality. These uncertainties and challenges call

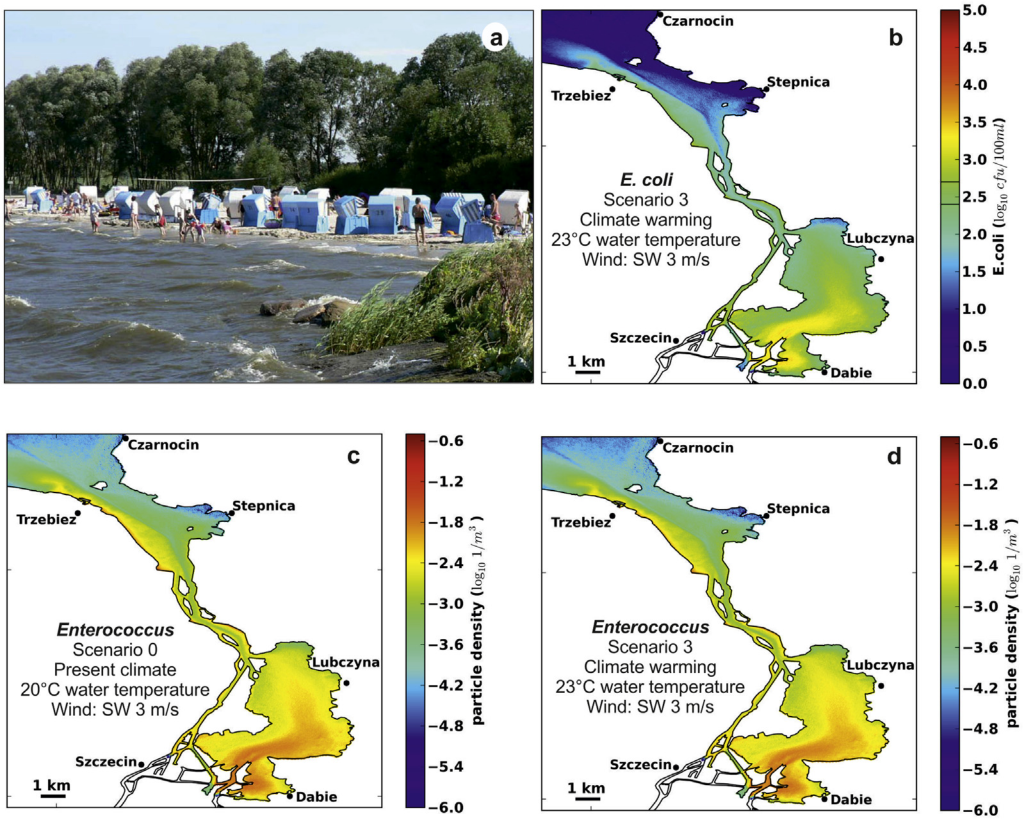

Fig. 5. Transport and die-off of *Escherichia coli* (b) and *Entercoccus* (d) bacteria in a warmer climate. The present average emission situation for *Entercoccus* is shown in (c) and for *E. coli* in Fig. 3a. (a) gives an impression of a beach at the Szczecin lagoon (Mönkebude, Germany).

for improved monitoring, management and communication as well publicly accessible and easy to handle decision support tools. Microbiological pollution usually takes place during single events that can hardly be predicted but requires a fast response. The GENESIS bathing water quality information system with its simulation tools is a prototype that serves this demand. Usually, bathing water monitoring data is available only fortnightly for selected beaches. Monitoring data does not provide sound spatio-temporal microbial concentration or pollution pattern. The model system helps to overcome this problem by visualizing spatial processes and their temporal development and enables users to take appropriate measures.

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