Early warning of bathing water quality – an operational water forecast service

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ABSTRACT

Faecal pollution of recreational water is a worldwide problem posing risk to human health. Therefore regional and district councils in New Zealand monitor the hygienic water quality at 350 coastal recreational sites every summer. Samples are typically collected once per week to test for the concentration of the indicator bacteria enterococci. These test results show that recreational waters are not always safe. In addition management is retrospective as the results of the testing are not available until after human exposure to the hazard. To overcome the latter problem operational modelling of the water quality today and in the coming days is now applied at several recreational sites in Denmark and Sweden. This Bathing Water Forecast supports the daily management of the sites and provides the authorities with a tool for timely warning of bathers when human health is at risk. Results are published on the internet, smartphones, Facebook and by direct emailing. Important inputs are actual data on loading and meteorological forecasts. The core of the system – a combined hydrodynamic and water quality model – is also a strong tool for assessment of cost-effective investments to reduce the risk of pollution, i.e. to improve sewer systems. This presentation will describe the Danish Bathing Water Forecast and discuss experiences.

KEYWORDS

Early warning, water forecast, recreational waters, bathing waters, water quality, hygienic water quality, operational modelling, E. coli, enterococci, indicator bacteria

1 INTRODUCTION

Clean beaches and bathing water are valuable assets to the users enjoying aquatic recreational areas and to the tourism industry profiting on the attracting effects of nice beaches and safe waters. Much is therefore done to protect our beaches and their water quality. Pollution with faecal microorganisms does however still pose a serious health risk to bathers and other users (Prüss 1998, WHO 1999, Pond 2005). Amongst the faecal organisms are pathogenic species (including bacteria and vira) which may cause a wide range of diseases, including ear, nose, and throat problems, gastroenteritis, and respiratory illness (Pond 2005).

The faecal organisms can enter the recreational waters directly or indirectly via upstream waterways and their catchment areas by discharge of human sewage, storm water runoff, waste from mammals and birds, and agricultural runoff. In most areas the major threat to bather's health is short term pollution caused by sewage outfall in connection with heavy rainfall. Other sources such as large bird population must however also be taken into consideration for certain areas (Wither et al. 2005). As indicators of pollution with pathogenic microorganisms, the organisms coliform bacteria, *E. coli*, and Enterococci are traditionally used (one or a mix of these organisms).

Worldwide, regulation requires that the quality of marine and freshwater recreational waters is checked to detect pollution with pathogenic organisms. In New Zealand regional and district councils monitor the hygienic water quality at 350 coastal recreational sites every summer (ANOM 2011). Samples are typically collected once per week to test for the concentration of the indicator bacteria enterococci. The purpose of the monitoring is to inform the users on the quality of the waters and to assist water managers in identifying needs for measures to protect bathers and sewage water operators in planning mitigation measures.

When considering the protection of the bathers, the present monitoring strategy has shortfalls as it only provides snapshots at fixed spots in space and time. The measurements may give an overview of the general status of recreational waters – dependent on the intensity of the monitoring (e.g. how often; how many places). However, they are not feasible as a basis for early warnings advising the bathers if it is safe to go to the beach today and the following days. The pollution will most probably be long gone before the manager becomes aware of the event, and warnings can be posted to the bathers. It may also be that a measurement immediately after a rain fall indicates that the water is safe because hydrographical processes have caused a delay in the polluted water reaching the beach area. The snapshot strategy does not take hydrographical and weather conditions (having marked influence on decay rate) into account and does not provide forecasts of the water quality. Hence, the traditional water quality monitoring provides information on the average quality but does not provide any indications of the quality on the actual day and the likely duration of an unsafe pollution incident.

To overcome these shortfalls, a Bathing Water Forecast System (BWF system) has been developed. The rationale behind the BWF is to provide the manager and the users of recreational beach areas with a continuous evaluation of today's bathing water quality as well as the consequences for the quality in the coming days (Erichsen and Rasch 2001). It is an innovative on-line predictive tool that facilitates timely and useable information to the beach visitors. The water managers gets an efficient tool to follow the developments in water quality and get a solid basis for determining the need for action both on a short term and long term scale.

The BWF system presented is developed by DHI in Denmark and it has been in operation since 2002 as a service under DHIs Water Forecast service (DHI Water Forecast 2011a). The first client, and still a user of the service today, was the Danish capital Copenhagen (Erichsen et al. 2003). Since then the coverage by the BWF has been expanded to include beaches in 11 Danish and 3 Swedish municipalities. The Danish and Swedish forecasts are disseminated on two websites, one for Denmark and one for Sweden (DHI 2011b).

The core of the BWF system is hydrodynamic-ecological models (2D or 3D) which simulate the physical conditions and growth and death of the indicator bacteria E. coli and Enterococci in real-time (today) and gives forecasts for 3-4 days. The models are MIKE by DHI tools. Currently the possibility to use other model tools is being investigated. The models are executed in operational mode and the results are disseminated through websites, emails, smartphone APPs designed to fulfil the needs of the users; manager or public. Thus, on one hand the BWF system ensures that managers and bathers are warned when the water is unsafe to swim in, and on the other hand guarantees that warnings on health risks are posted for as short periods as possible.

In addition to the operational mode, the system provides a tool for evidence based fully spatial and temporal prediction of water quality in an area of interest with the potential to reduce or focus the scope of expensive and time consuming field sampling programs. Once a BWF system has been established the component models can also be utilise by councils for scenario-modelling providing a quantitative assessments of the impact of pollution sources and thus for identifying the effectiveness of mitigation measures and needed capital investments. Thereby managers and decision makers are ensured a trustworthy basis for identification of the most cost-effective measures to reduce contamination.

This paper describes the BWF system, the architecture/infrastructure, operation and dissemination of results. Furthermore, an example of offline use of the model tool is given.

2 THE BWF OF THE CAPITAL CITY COPENHAGEN

The BWF for the Danish capital Copenhagen (Erichsen et al. 2003) has been an integrated part of a targeted investment with the purpose to open the harbour for swimming after more than 50 years of bathing prohibition. The Copenhagen EPA decided to introduce an early warning system because they considered it crucial to protect the public from health threats from pathogenic bacteria and because they found that traditional monitoring does not provide sufficient information on today's quality and it does not give predictions for the coming days. In the first version only the harbour area was covered as the main purpose was to provide prognoses for a number of new bathing facilities in the harbour. Later the BWF has been extended to include the city's coastal beach areas.

As is the case for bathing water quality in many places around the world, the most important source of bacterial pollution of Copenhagen harbour is combined sewer overflow (CSO). During a bathing water season (May-August) Copenhagen has in average 3-5 incidences of CSOs. The CSOs occur in connection with heavy rain and thunderstorms. As part of the pollution originates from upstream municipalities, the BWF model setup for Copenhagen recreational waters comprises both an operational 3D receiving water model (MIKE 3) and an operational 1D river model (MIME 11) transporting the upstream source inputs to the harbour area.

3 THE BATHING WATER FORECAST (BWF) CONCEPT

At the frontend the BWF presents as a single system. At the backend and from a technical perspective the system consist of a number of elements including deterministic models adapted to different recipients and of various dissemination schemes based on a common skeleton being tailor-made to specific receivers. Regarding models, the Danish BWF comprise today of 3 model set-ups and the Swedish one model set-up. The extent of each model is determined by the operational execution time: a 24 hour forecast must be executed within one hour.

3.1 THE INFRASTRUCTURE AND DATA FLOW

The elements of the BWF and the overall data flows are shown in Figure 1.

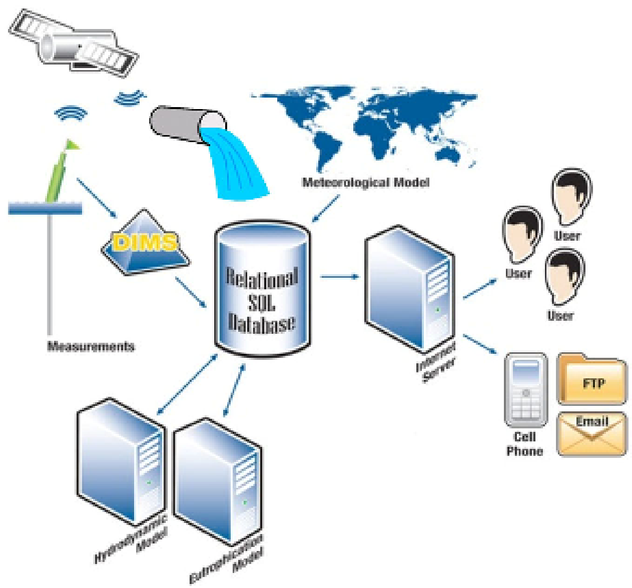

Figure 1: The infrastructure and data flow of the Danish Bathing Water Forecast system

Hydrodynamic boundary conditions are delivered online by the WaterForecast - an operational service by DHI providing daily updated data on current speed and direction, wave periods, heights and directions, salinity and temperature (Erichsen and Rasch 2001). Meteorological boundary conditions are acquired online from a Weather Forecast supplier. Data on sources to bacterial pollution is delivered online by the companies responsible for sewage and storm water discharge influencing the recreational water. The bathing water forecast data is obtained by operationally running coupled hydrodynamic-ecological models. Finally dissemination schemes process relevant data to provide tailor-made information to bathers and managers on various media such as the internet (web sites, RSS feeds, etc.), via emails and also smart phone APPs.

3.2 ACQUISITION OF SOURCE DATA

When addressing bathing water quality it is essential to obtain data describing sources of pollution. These sources can be numerous and experiences from almost 10 years of operational bathing water modelling suggests that implementing a forecast system is a useful part of the process with regard to defining and understanding the source data. Much knowledge is usually learnt during the set-up process making it possible to improve the forecasting. On the other hand experience also shows that even with fewer but high quality data a reliable forecast can be produced.

For the recreational waters covered the existing BWF system different methods are applied to quantify the sources dependent which type of sources are considered and how the sources are monitored. The most common methods range from direct measurements of flow or calculation of flow from water level measurement in the sewer system, to urban modelling (e.g. using MIKE Urban) and/or other means of catchment/river modelling. The Copenhagen BWF and the Swedish BWF components illustrate two different types of set-up; partly due to differences in important sources and partly determined by the difference in the availability of direct monitoring of sources. In Denmark pollution almost solely originates from combined sewer outfalls (CSO) in connection to heavy rain or thunder storms. Whereas in Sweden most problems regarding bathing water quality relates to diffuse loadings and pollution from separate sewer systems. Regarding measurements, Copenhagen sewer system is comprehensively monitored while monitoring is less wide spread in the Swedish areas. For the Copenhagen BWF set-up flow measurements are therefore the key instrument to provide source data. The Swedish BWF set-up follows the same approach as Copenhagen in some locations but in addition - due to shortfalls in direct monitoring - a number of empiric and/or dynamic run-off models relying on rainfall measurements are used to drive the system.

The concentrations of indicator bacteria in the source waters are fixed; i.e. do not vary with time. The values are based on monitoring programs conducted to estimate the mean concentrations or in some cases are informed by data in the literature and experiences from the first years of running the BWF for a certain area.

3.3 THE MIKE MODELLING TOOLS – RECIPIENT MODELLING

The core of the BWF is the MIKE by DHI modelling tools (2D, 3D). These comprise of free surface, stretched sigma coordinate, flexible mesh, finite volume hydrodynamic solver models (MIKE 3 and MIKE 21) combined with a dynamically coupled open differential equation solver model (MIKE ECOLab). The dynamic coupling makes it possible to define the ecosystem to the degree of complexity required and still be able to utilise the transport and dispersal of material and substances in a highly accurate manner. ECO Lab thus provides the basis for accurate spatial and temporal predictions of any aquatic ecosystem response - regardless of the size and structure. The ecological model ECO Lab of the BWF simulates growth and death of the indicator bacteria E. coli and enterococci based on key forcing factors such as irradiance, temperature, salinity and current delivered by the hydrodynamic MIKE 3 model. In the Danish and Swedish BWF systems 3D model are applied as in these waters it is paramount to describe the spreading and transport of the contamination in both horizontal and vertical dimensions due to persistent stratification and minimal influence of tides. The model system is running in high resolution (flexible mesh) covering the recreational waters, see Figure 2.

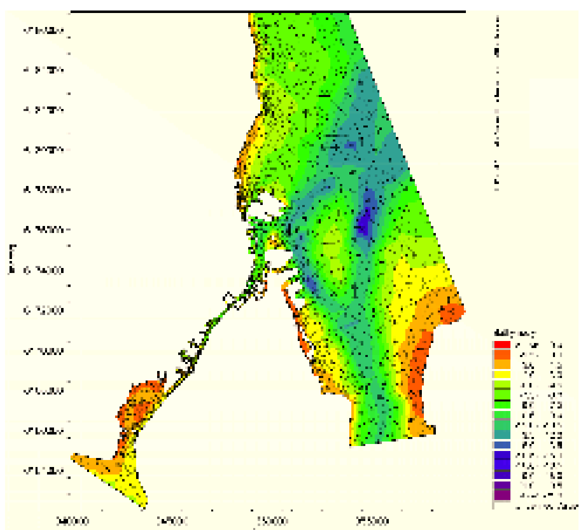

Figure 2: Example of the high resolution bathymetry and mesh used in the modelling of bathing water quality. The area shown is the model area covering recreational sites of the Danish capital Copenhagen.

4 SYSTEM OPERATION

DHI's existing downstream services are operated as part of the 'Water Forecast – a service by DHI'. All Water Forecast (WF) services run on Standard Workstation PCs (Quadcore processor) with Windows 7 operating. Data are retrieved via the File Transfer Protocol (FTP), either by fetching the data at a remote FTP site or by a data provider placing the data on DHI's FTP server. The data is either in a predefined ASCII format or in GRIB/NetCDF files. All retrieved time series data are stored in the DHI Dynamic Integrated Monitoring System (DIMS) database. All input and output data are finally stored in DHIs MySql database system. The most important data placed on DHI’s FTP server is MET data from STORM and EO data from GRAS. Important data fetched from external FTP’s are e.g. monitoring data from the Danish monitoring programme. All models operated by the Water Forecast are Mike by DHI (Mike 3, Mike 21, Mike3 FM, Mike 21 FM, ECO Lab). Model executions are done by scripts written mainly in WBScript. Web presentation and system monitoring running based on ASP.NET.

If the polluting conditions are ‘dry’ the models are executed two times per day when new meteorological forecasts are received. If the polluting conditions are ‘wet’, the model execution starts as soon as ’new’ pollution is registered in the system and re-runs continue until the situation is back to normal. New pollution data is registered by the system when, for example, a flow measurement indicates increased water flow, rain measurements indicate potential pollution, etc.

At DHI an operational forecaster is monitoring and controlling the execution and publication of the BWF 24/7. For this purpose an operator system monitoring system has been developed.

5 DISSEMINATION TO MANAGERS AND USERS

The frontend of the BWF comprise internet websites as well smartphone APPs, Facebook and direct emailing.

5.1 PUBLIC WEBSITES

Presently the results of the execution of the BWF at DHI are disseminated on two websites: one for the Danish recreational waters and one for the Swedish (DHI 2011b); see Danish example in Figure 3.

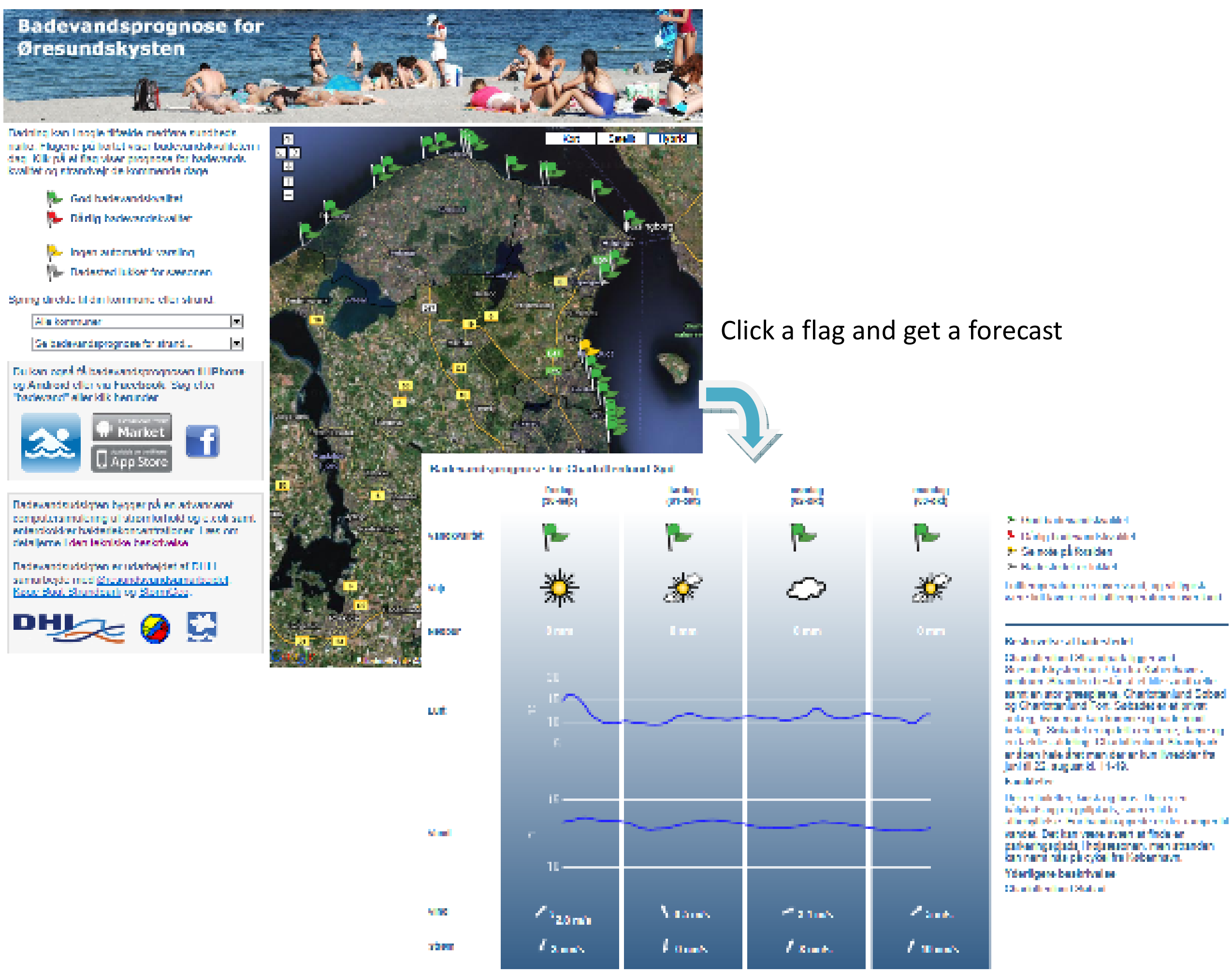

Figure 3: An example of dissemination of BWF data on the internet.

In Figure 3, the water quality is indicated by red and green flags where red indicates that EUs guideline value is exceeded and green that the concentration of indicator bacteria is below the thresholds for E. coli and enterococci. It is pre-determined which grid cells in the model (see Figure 2) are used to assess the water quality. Yellow and grey flags are reserved for special situations, e.g. when the forecast is suspended due to special events.

As appears from Figure 3 additional benefits to the website visitors are forecasts of other parameters as e.g. water temperature, tides and currents – which can be very important for safe bathing water as well - and weather forecasts.

5.2 ALERTS VIA SMS

Data on water quality is disseminated via two types of SMS service; a public and a manager service. In one of the municipalities a public SMS service has been set up allowing the citizens to register and then receive two types of SMS messages: one early warning and one declaring that the water quality is now safe again. More common is the manager SMS service which alerts the managers of water quality when a flag has changed colour.

5.3 SMARTPHONE APPS

The bathing water quality is also published on Windows7, Android and iphone APP's.. The APP exists in three versions; one in Danish: 'Badevand', one in Swedish: 'Battvatten' and one in English 'Bathing Water'. The views of the Danish APP are shown in Figure 4.

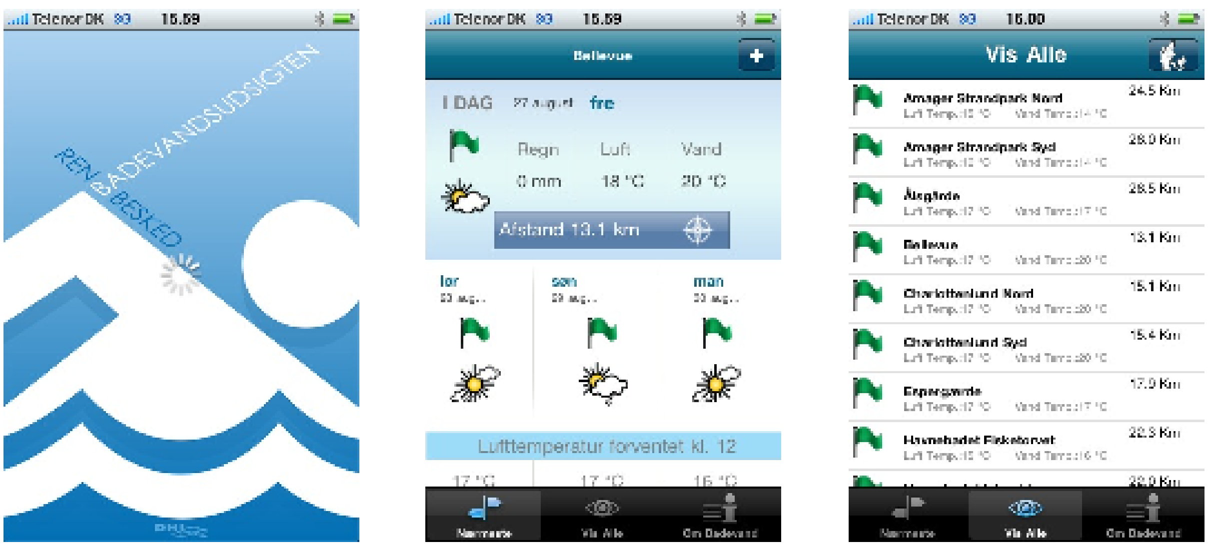

Figure 4: The Danish language APP showing bathing and weather forecasts based on the BWF system at DHI. When opening the APP the forecast for the beach closest to you is shown (view in the middle). One may also choose to see today's forecast for all beach areas (view to the right).

5.4 MANAGERS WEB

As the water manager typically requires more technical information than the public users, the BWF also provides a website for managers. On this website the managers can look at time series for the different sources and moored instrument (in case such is installed e.g. to measure currents). Some managers also request video animations showing the dispersion and transport of pollution not only close to their beach areas but in the wider region (Figure 5). Having access to this type of information gives the manager tools to access data and information on which sources are important and when and how much do they contribute to the pollution event. They are also able to do daily validation of the water forecast supplementing the checking done by the WaterForecast operational forecaster by adding more local knowledge. In some cases the managers may disagree with the BWF; then the colour of the flag can be changed manually. One of example of such case is when an animation shows near-critical concentrations of indicator bacteria very close to the recreational water. Then the manager may choose to change the flag colour to red, although the concentrations are not critical in the grids used for the automatic assessment of the quality.

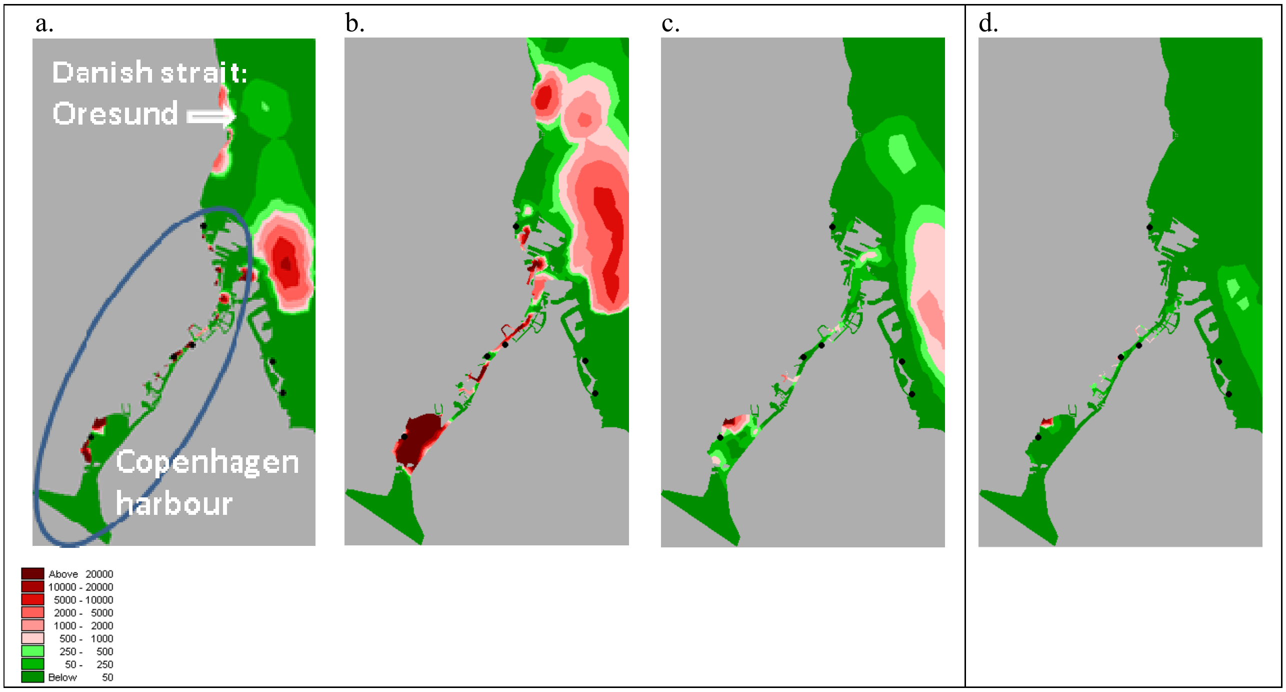

Figure 5: Time series demonstration the development in E.coli concentrations from outfalls of polluted waters on the coast north of and in central Copenhagen. The event starts at the 15/8/2011 at 1am and between the first and third picture the time difference is 8 hours. The time difference between the third and fourth picture is 24 hours. The legend gives the colour code for concentrations of E. coli (per 100 ml). Only part of the modelled area is shown.

6 VALIDATION

The BFW has been proven capable of reproducing the bacterial concentrations of the recreational water. Copenhagen city has, since the start in 2002, compared the BWF flag colour based on modelling and water sample analyses and have not observed any disagreements. In fact, they were able to warn bathers when critical pollution events occurred between water sampling. The purpose of the comparison was to ensure that the BWF was not giving false positive results i.e. indicated ok water quality at a time when the measurements showed bacteria concentrations above the threshold values. This was paramount to the city because people were sceptic about bathing in the harbour and an incidence with water related sickness would have been detrimental to the concept. For the same reason the city used very conservative thresholds for setting a red flag.

Since 2009 more systematic validations have been conducted in winter when all results from the monitoring program were available. As an example the figures for one of the Danish municipalities (Gentofte) are summarised for 2010. This municipality has 4 beaches (recreational waters) and there are 11-14 matchups per recreational water; in all there are 53 matchups. In 73% of these there is agreement between the bacterial concentrations estimated by the two approaches (taking uncertainties into consideration). Comparing instead the outcome of the assessment (i.e. if threshold values are exceeded then water quality is not satisfied and results in a red flag given by the BWF) the two approaches agree in 92% of the cases. In three of the matchups the BWF gave a false positive for *E. coli*; i.e. gave a green flag when analysis indicates it should have been red. In one of these cases, critical concentrations are observed close to the recreational water but according to the model this water mass did not reach any of the recreational water. Since there is not a similar mismatch for enterococci, an explanation may also be a failure in the analysis of the water sample. In the remaining two cases, the BWF did not receive any records on exceptional outfalls. The mismatch could also be due to missing sources as it is known that an outfall from another company further south on the coast is not yet included in the modelling and this outfall may in rare cases impact the beaches of Gentofte.

It is new in Europe to use enterococci as an official indicator organism, and it is therefore also a new facility of the BWF to prepare forecasts for this organism. For enterococci the corresponding number for false positive is two out of the 53 matchups (corresponding to the two latter E. coli cases). Contrary to E. coli, three cases of false negative are also observed; i.e. the model gave a red flag when an analysis indicated it should have been green. In all three cases, data on an extraordinary outfall was received from the water company resulting in high concentration of enterococci but not E. coli. In general there seems to be a tendency that enterococci concentration in the BWF is higher than analyses indicates and this indicates a possible need for a re-assessment of the description of the decay of enterococci in the ECO Lab model.

7 COST-EFFECTIVE INVESTMENTS

The modelling tools forming the core of the BWF system can also be used offline for assessment of investments aiming at reducing pollution from treatment plants, overflows and diffuse sources. By running scenarios different capital investments can be tested to find the most cost-effective solutions. Such application has currently been used by Copenhagen since the City decided to achieve bathing water quality in their harbour areas. Similarly the tool (including catchment modelling) is used to evaluate sources and plan investments required by upstream municipalities and to improve the bathing water quality at public beaches along the open coast.

In one Copenhagen study, the modelling tools were used to identify the relative influence of different sources to the harbour area and to single out the most important source of bacterial pollution in this part of the harbour (Erichsen & Kaas 2007). The results showed that the river Damhusaa transporting pollutant from upstream municipalities (sewage plants and storm water outfalls) was the most polluting source. The sources with outfall directly to the harbour showed the highest concentration, but the indirect upstream discharges impacted the receiving waters much longer. It was decided to prepare a plan ensuring reduction of these sources by investing detention basins, and simulation scenarios were carried out to identify the most cost-effective dimensions. The goal was to be able to accommodate a ‘one-year rainfall event’. The study emphasised the importance of taking the natural hydrographical variability in the receiving waters into account when analysing reduction scenarios. Modelling tools also enable the inherent uncertainty in input data and process description data to be assessed and provide a measure of this uncertainty in design parameters.

8 OTHER WATER FORECAST SERVICES

The DHI WaterForecast does not only prepare forecasts on bathing water quality. Based on the same principles forecasts are provided on various specific issues and to specific customers. For instance general monitoring services for Danish Waters have been in operation for many years (see example, DHI 2011c). The service is currently being improved to fulfil the requirements of the end users, which are central and local environmental authorities.

A special WaterForecast service is established for the Danish Aquaculture (DHI 2011d). The service publishes data on the hydrodynamics of the marine areas where the aquaculture is located (water temperature, salinity, current). Also environmental data is provided such as oxygen and chlorophyll. A manual HAB alert system has been operated which are now being made as automatic as possible to make the early warning more efficient.

In both the mentioned services earth observations are important (Edelvang et al. 2005). Earth observation images are shown directly using algorithms appropriate for Danish waters. The data is also use in data assimilation schemes being an integrated part of the model execution. In general an important feature of the DHI water forecasts is the application of data assimilation (Sørensen et al. 2004, 2007).

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