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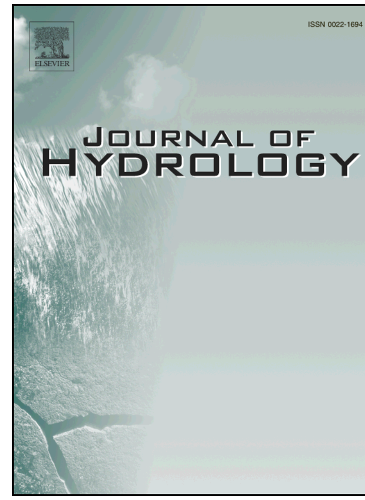

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Hydrodynamic modelling of recreational water quality using *Escherichia coli* as an indicator of microbial contamination

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Abstract

Microbial contamination of recreational beaches is often at its worst after heavy rainfall events due to storm floods that carry fecal matter and other pollutants from the watershed. Similarly, overflows of untreated sewage from combined sewerage systems may discharge directly into coastal water or via rivers and streams. In order to understand the effect of rainfall events, wind-directions and tides on the recreational water quality, GEMSS, an integrated 3D hydrodynamic model was applied to assess the spreading of *Escherichia coli (E. coli*) at the Sandvika beaches, located in the Oslo fjord. The model was also used to theoretically investigate the effect of discharges from septic tanks from boats on the water quality at local beaches. The model make use of microbial decay rate as the main input representing the survival of microbial pathogens in the ocean, which vary widely depending on the type of pathogen and environmental stress. The predicted beach water quality was validated against observed data after a heavy rainfall event using Nash-Sutcliffe coefficient (E) and the overall result indicated that the model performed quite well and the simulation was in - good agreement with the observed *E. coli* concentrations for all beaches. The result of this study indicated that: 1) the bathing water quality was poor according to the EU bathing water directive up to two days after the heavy rainfall event depending on the location of the beach site. 2) The discharge from a boat at 300-meter distance

to the beaches slightly increased the *E. coli* levels at the beaches. 3) The spreading of microbial pathogens from its source to the different beaches depended on the wind speed and the wind direction.

Key words: *Escherichia coli*; faecal contamination; water quality modelling; GEMSS model; recreational water.

1. Introduction

Surface runoff after heavy rainfall potentially transports a large number of faecal matter and microbial pathogens to the coastal ocean and poses public health concerns for beach-users (Ahn et al., 2005; Noble et al., 2003). The sources of microbiological pollution of coastal waters varies from place to place (Colford Jr et al., 2007). The major pathways of faecal contamination of coastal environments are sewage discharges including partially treated sewage, combined sewer overflows, storm water discharges, sewage network failures, polluted river discharges, possible run-off from agricultural activities and specific discharges that could come from ships, wild birds, bathers, and sediments (Clark et al., 1989; Vikas and Dwarakish, 2015). Several studies have shown that coastal bathing waters located near river estuaries are often highly contaminated after rainfall events, due to high discharges from the river (Billen and Garnier, 1997; Ludwig et al., 2009; Tilburg et al., 2015). An increasing concern about the bathing water quality at coastal beaches has inspired to the application of hydrodynamic models as a tool to understand the processes that affect the spreading of microbial contaminants in the coastal water, and to predict the effect of changing conditions (Davies et al., 2009; Rodriguez et al., 2004). Significant variation of the spatial and temporal spreading of microbial contaminants at recreational beaches requires frequent in-situ monitoring, which is difficult in terms of operation and costly (Enns et al., 2012; Kinzelman et al., 2006). Hydrodynamic modelling has the potential to overcome such problems if the modelling have reasonable spatial and temporal resolution, and combined with supplementary information from monitoring at a time interval (Bruni et al., 2015; Holt et al., 2005).

A hydrodynamic model is a comprehensive approach to mimic water dynamic processes generated by a number of different drivers. The base of the model concept is the numerical solution for the governing equations of conservation of momentum and mass, which is the set of equations that describe the motion of fluids (Liu et al., 2007). Coastal hydrodynamic modelling are applied at several localities to understand different ecological problems by using a range of model configurations and forcing (Ferrarin and Umgiesser, 2005; Fossati and Piedra-Cueva, 2013; Gao et al., 2015; Henderson et al., 2001; Zacharias and Gianni, 2008). The models utilize a wide range of meteorological data, river inflow and tidal signals. Hydrodynamic modeling, including *E. coli* or specific microbial pathogens, as a constituent and microbial decay rate as a model parameter, is a useful tool to describe the temporal and spatial variability of microbial concentrations, even below the detection limits of analytical methods. Furthermore, hydrodynamic modeling is useful to explore the effect of different scenarios and situations in order to support management decisions. A number of publications about hydrodynamic water quality modelling have focused on nutrients in relation to eutrophication and sediment transportation (Kock Rasmussen et al., 2009; Park et al., 2005; Tkalich et al., 2002; Tufford and McKellar, 1999). Some studies include microbial water quality modelling using faecal coliform and *E. coli* as a constituents (Bougeard et al., 2010; Sokolova et al., 2014).

The effects of heavy rainfalls on the microbial water quality at coastal beaches are of particular concern in the Oslo fjord where the storm water from urban areas and farmland catchments directly discharge into the fjord. Moreover, overflow from the combined sewer system and pumping stations during and after rainfall event discharge significant amount of untreated sewage water in to the fjord. This study was designed to characterize the temporal and spatial variations of faecal indicator bacteria (*E. coli*) after rainfall events at the recreational beaches adjacent to the Sandvika urban settlement receiving discharges from river Sandvikselva and overflows from the local combined sewer system. The GEMSS hydrodynamic model was set up and applied at the Sandvika recreational coastline in order to visualize the impacts of different scenarios and discharges after rainfall events. The overall objective of this study was to understanding the influence of different processes (rainfall, discharge from boats, and wind directions) on the microbial concentrations at the recreational beaches, and to demonstrate the importance of hydrodynamic modelling as a tool to identify the risk of contamination of recreational beaches in order to prioritize mitigation measures.

Study area

The study area is located in Bærum municipality, south of Sandvika, Norway. A number of bathing areas, river and streams inflow, and urban settlement along the coastline characterize the study area. During the summer time, a significant number of bathers who perform different recreational activities like boating, swimming and various sports frequently visits the beaches.

For this study, six beach-sites were included. Kadettangen main beach and Kadettangen to north, which is the largest and most crowded beach during summer, are connected to Kalvøya Island with a bridge. The island has bays with sand beaches with swimming facilities. These are Kalvøya small, Kalvøya big, and Kalvøya nudist beach. Høvikodden beach is a sandy beach on the mainland east of Kalvøya nudist beach (Figure 1). The main source of pollution in the area is river Sandvikselva, in particular - after rainfall events when combined sewer overflows (CSOs) discharge into the river. In addition, two CSOs discharge directly to the fjord. The catchment area of river Sandvikselva include boreal forest (83 %), which is the upper parts of the catchment, and the lower parts are dominated with farmland (6.5 %) and urban settlement (10.5 %) (Nizzetto et al., 2016).

2. GEMSS hydrodynamic model

The complexity of physical processes governing the transport and fate of an introduced constituent, such as bacteria, in the ocean circulation system suggests the use of advanced hydrodynamic models (Ji, 2017). For this study, the GEMSS model was used to explore the hydrodynamic and related microbial water quality along the Sandvika coastlines. GEMSS is an integrated system of 3D hydrodynamic and transport models embedded in a geographic information and environmental data system (GIS), grid generator and editor, control file generator, 2-D and 3-D post processing viewers, and meteorological and flow data processor to support 3-D modeling. The model is able to simulate horizontal and vertical distributions of water velocities and temperature, salinity, water surface elevations, and water quality in rivers, lakes, reservoir, estuaries, and coastal water bodies at different spatio-temporal resolution (ENTRIX et al., 2001; Kolluru et al., 2014). The model has been applied in different regions for various water quality problems (Dargahi and Setegn, 2011; Goetchius and Salmun, 2002; Na and Park, 2006; Wu et al., 2001).

The GEMSS model uses GLLVHT (Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport) that computes time-varying velocities, water surface elevations, and water quality constituent concentrations in different water bodies (ERM, 2006). The hydrodynamic and transport relationships used in GLLVHT was developed from the horizontal momentum balance, continuity, constituent transport and the equation of state (Edinger and Buchak, 1980). The details of the model can be found in the technical documentation of GEMSS (ERM, 2006) and also a detailed description of the model and its application can be found in the per reviewed publications (Dargahi and Cvetkovic, 2011; ENTRIX et al., 2001; Kolluru et al., 2014).

3. Boundary conditions and model application

The horizontal and vertical model domains were defined from the shorelines and the bathymetry data. The Inner Oslofjord (Figure 2) was divided in calculation cells. Horizontally the cells were of variable size. The vertical layers were 1 m thick down to 20 m below surface and thereafter 10 m thick. The horizontal resolution was more detailed in the Sandvika area that was of special interest in this research. In this area, the average horizontal grid size was around 100 m x 100 m. For each cell, the results were calculated forward in time with steps of some minutes.

The input data for the hydrodynamic model calibration and simulation were obtained from the Norwegian meteorological institute (eKlima), the Norwegian marine data centre, Bærum municipality and direct observation. The data set included flow data (river discharge and combined sewer overflow (CSO)), forced meteorological data (air temperature, dew point temperature, seawater temperature, cloud cover, pressure, wind speed, and wind direction), and water quality parameters (temperature, salinity, and *E. coli*) (Table 1). Some small streams flow into the Sandvika beach but only Sandviksilva River that have significant discharge and two small CSOs discharging directly to the fjord were included in the model as point source inflow. *E. coli* concentrations and corresponding water flows monitored in the river and CSOs were used as an input to the model. For the two small CSOs, the registered time of overflow were used as input to the model, assuming that 50% of the sewage was discharged in this period.

The water level difference, mainly due to tides, at the southern open boundary was about 1 m. Moreover, Oslo and Bærum municipality were regularly monitored water flow and faecal indicator bacteria in the rivers around Oslofjord and the data were utilized for this modelling. For this study, *E. coli* were monitored in the Sandvika beaches during and after the precipitation (Table 2), and both discharges and *E. coli* concentrations in the Sandviksilva river and CSOs were used as an input for this model.

4. Model simulation

First, the model was validated by comparing observed *E. coli* concentration against modelled values. Afterwards, simulation were conducted for three conditions: 1) after rainfall event, 2) boat discharge scenario, 3) wind direction scenarios. Microbial contamination of the recreational beaches was studied during and after rainfall events during the summer 2014. We used two scenarios to separately assess the impact of boat sewage discharge and wind directions on the recreational beaches water quality. The boat discharge scenario was if a single boat with 200-litre toilet tank discharge its sewage at 300 meters from the nearest beach (assuming *E.coli* concentration is 3 x 10^{7} MPN/100 ml, equivalent to one day-production of *E. coli* from four persons) (Al Baz et al., 2008). The wind direction scenario was developed by adjusting the wind input data set, which was carried out by tuning all winds into one direction using the average wind speed for all.

5. Water quality modelling results

5.1. Model validation

Model calibration in this hydrodynamic modelling is the processes of finding a set of optimal variables to yield the best agreement between the predicted and observed variable of interest. The model was calibrated by making minor adjustments to the boundary conditions and by adjusting the Chezy friction coefficient. Comparisons of the observed and computed salinity level was made to evaluate the performance of the calibration processes. A good agreement observed between observed and computed values of salinity during the period of calibration. This confirms that the model calculates the overall water movements in the fjord in a realistic way (Tjomsland et al., 2014).

To ensure that the simulated spatio-temporal spreading of *E. coli* at the beach sites was realistic, the model results was validated by comparing the simulated *E. coli* concentrations with monitored data for four consecutive days after the rainfall event at all beach sites. Model validation was based on the statistical comparison of daily observations of *E. coli* and the corresponding model simulation results summarized for all beaches and shown in Table 3. The value of Nash-Sutcliffe coefficient, which ranges from -∞ to one, was 0.36 and the relative volume of error was 8.4 %, which was less than 10% suggesting reasonable close agreement between observed and simulated *E. coli* concentration. The error for minimum value was much higher compared with the maximum value.

Simulation of the spreading of *E. coli* after the rainfall event

The two main sources of faecal contamination of the Sandvika beaches that were considered in this work were the river Sandvikselva and a CSOs discharging close to Høvikodden beach. In addition, swan droppings at each beach site were included, while other potential minor sources were ignored. The simulations showed that the impact of swan faeces was negligible due to the dilution effect. To be able to model the local impact of swan faces a much denser grid than 100x100 meter is required. Analysis of water samples showed a significant impact of swan faeces on the local water quality.

The survival of *E. coli* after it is discharged into coastal water depends on many abiotic and biotic factors like sunlight, temperature, salinity, competitive bacteria, viruses, predators etc.

(Rozen and Belkin, 2001; Stewart et al., 2008). To illustrate how the different decay rates may affect the simulated concentration at the beaches, *E. coli* was given two different decay coefficients (k = 0.7 and k = 0.1, representing half-life time of 1 day and 1 week) representing the sensitive and resistance organisms. The spreading of *E. coli* from the sources into the beach areas were simulated for the consecutive three days after the rainfall event and the daily average *E. coli* concentration were plotted for each decay rate coefficient as shown in Figure 3. According to the simulation results, the daily average *E. coli* concentration one day after the rainfall event was much higher than the second and the third days at all beaches and the magnitude difference was highest in the case of Kalvøya small beach followed by Kalvøya big and Kadettangen beaches. In addition, the impact of the microbial decay rate coefficient on the daily average *E. coli* concentration was substantial. If we take Kadettangen and Kalvøya small beaches as an example, the change in half-life time from 1 day to 1 week resulted in an increase in daily average *E. coli* concentration by 38.6 %, 95.0 %, and 146.7 % at Kadettangen beach and 17.3 %, 44.9 %, and 61.1 % at Kalvøya small beach for the first, the second, and the third days respectively.

The simulation results of the spreading of *E. coli* at the beach sites in graphics form for the top 1 meter depth are shown in Figure 4. As we can see from the figure, the first three hours after the heavy rainfall event the *E. coli* dispersion was limited only to the surrounding area of river Sandvikselva and the river mouth. However, 24 hours after the rainfall event that caused increased discharges of *E. coli* via the river, the affected coastal area was increased and then the concentration was gradually reduced until the end of the third day.

5.2. The vertical distribution of *E. coli* concentration at the beaches

The stratification of the *E. coli* concentration is complicated by its temporal and spatial variations within and among the beaches water column. In order to simplify the presentation of the simulation result, the vertical distribution of the *E. coli* concentration at a specific time (15:00 the day after the rainfall event) at two beaches is shown as an example in Figure 5. As shown in the plot the situation was quite different at the two beaches. *E. coli* stratification had a two-layer structure in the case of Høvikodden, surface layer (0-3.5 m depth) and the bottom layer (3.5-7.5 m depth). The bottom layer *E.coli* concentration was increased from 64 MPN/100 ml at 3.5 m to 950 MPN/100 ml at 7.5 m depth while the surface layer varied from 64 MPN/100 ml at 3.5 m to 150 MPN/100 ml at the surface. The highest *E. coli* concentration at the bottom layer was caused by the CSOs discharging to the deep water around the Høvikodden. In the case of Kadettangen beach, the depth is relatively shallow and the *E. coli* concentration decreased with depth, from 495 MPN/100 ml at the surface to 425 MPN/100 ml at 1.5 m depth.

5.3. Scenario with discharge from a septic tank from a boat

In the Inner Oslo fjord, there are several thousand private boats/yachts. As the number of boats and beach users increases through time, the pressure on the water quality along the coastal beaches increase and need proper protection measures.

The spreading of *E. coli* from the discharge of boat sewage was simulated in order to investigate its impact on the recreational water quality of the beaches under different situations. The distance between the discharging point and the beaches, 300 meters, as the minimum required distance from the mainland, according to the regulation of boat sewage discharge in the Oslo fjord. The simulation result showed that the discharge of 200-liter sewage with 3 x 10^7 *E. coli* per 100 ml will most probably affect the nearby beaches by relatively low levels of *E. coli* (20-24 MPN/100 ml) (Figure 6). In this study, the realistic simulation of *E. coli* concentration from the boat discharge scenario could severely limited by the constraints on coarse spatial resolution, therefore, relatively smaller resolution, the effect of different volume of discharge from different distance and directions could be investigated in the future study.

5.4. Scenarios with different wind directions

The key factors for the spreading of pollutants in the coastal environments are wind and current and the influence of wind on the spreading of microbial pollutants because of ocean circulation was an important aspect of this hydrodynamics study. In this regard, the spreading of *E. coli* from its source was investigated using different wind directions scenarios. In these simulations, the four scenarios were N-, S-, E-, W-winds, representing wind blowing to north, south, east and west respectively. Simulation using the actual observation was denoted by natural simulation. In Figure 7 a relative magnitude of simulated *E. coli* concentration associated with the scenarios with different wind directions, are presented. Different wind directions was shown to have various impacts on the spreading of *E. coli* in the study area and as we can see from the Figure 7, wind blowing to west affected Kadettangen beach more than Høvikodden and Kalvøya nudist beach. Whereas wind that were blowing to south, in the same direction as the pollution source flow, was the predominant wind direction that affected all the beaches sites. These simulations demonstrated that the effect of wind direction depended on the location of the beaches relative to the main pollution source, and in this case, the river Sandvikselva was the main source of pollution.

6. Conclusion

For beaches exposed to short-term pollution during/after heavy rainfall events, it is useful to know the main factors affecting the water quality, to make decisions about whether to warn against swimming or not, and eventually for how many days. To study this the three-dimensional GEMSS hydrodynamic model was set up for the Inner Oslofjord and successfully applied to simulate the spatial and temporal spreading of *E. coli* after a heavy rainfall event in the Sandvika area. The model was used to demonstrate the impact of different wind directions on the spreading of *E. coli*, as well as for investigating the effect of a discharge from a septic tank on a boat.

The results of the simulations lead to the following conclusions: 1) the risk of microbial contamination was high after one day of heavy rainfall as compared with the second and third days and the level of risk was highest at Kalvøya small beach due to the position of the beach, which is located close to the river inlet. 2) The risk of microbial contamination of the local beaches from a boat, emptying the septic tank at 300 meter distance from the beaches could substantial although minor increase in *E. coli* was resulted in the simulation. However, the simulation could severely limited by the constraints on coarse spatial resolution, therefore, relatively smaller resolution, the effect of different volume of discharge from different distance and directions recommended in the future study. 3) The spreading of microbial contaminants from its source highly depended on wind speed and direction, and the degree of pollution depends on the location of the beach relative to the source of pollution. 4) Hydrodynamic modelling offers a useful tool to understand the spatial-temporal spreading of microbial pathogens at recreational beaches in order to prioritize mitigation measures for the beach management strategies.

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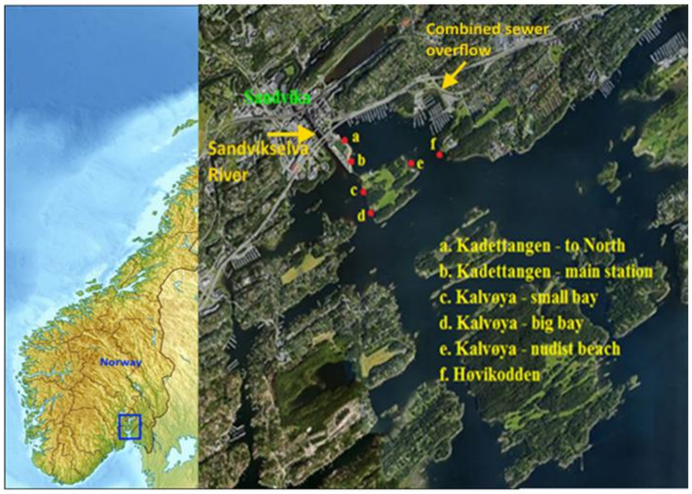
Combined sewer overflow
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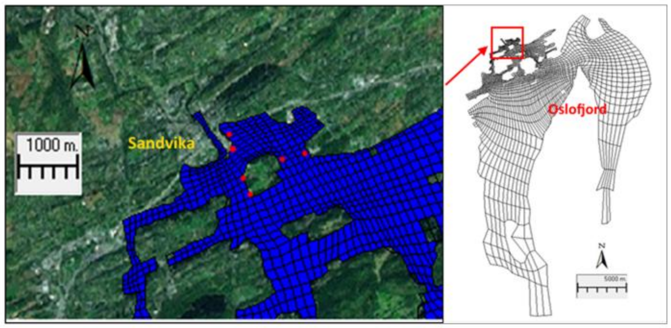
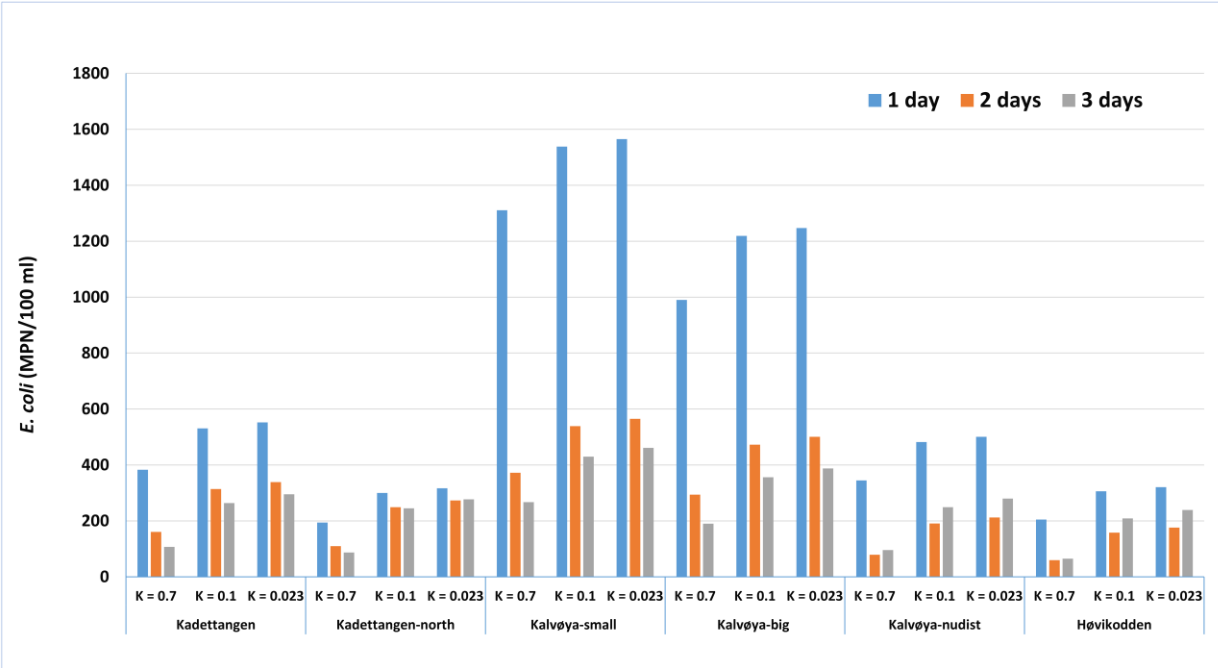
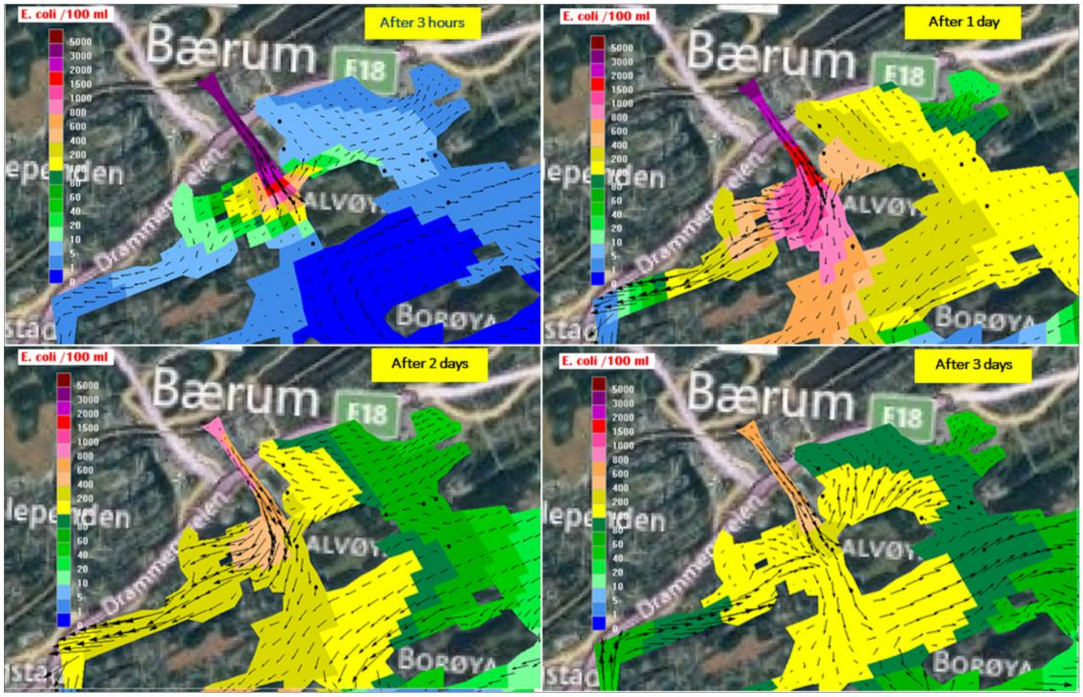
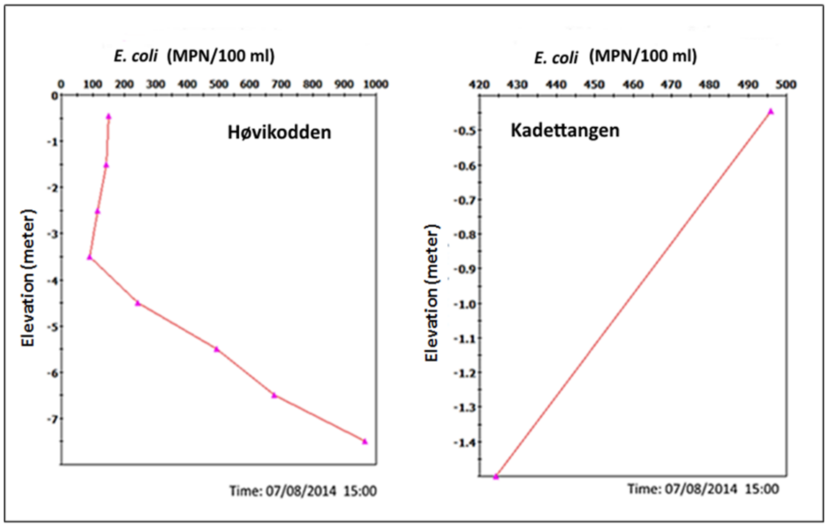
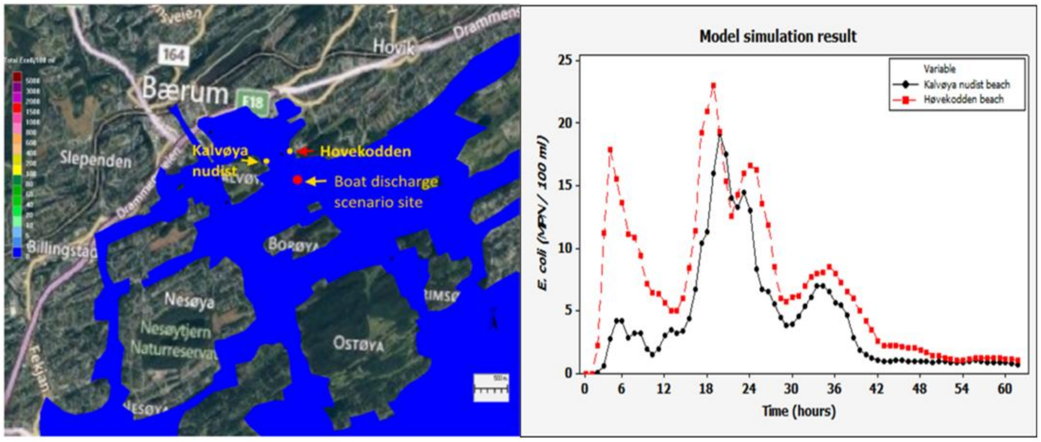
f
Norway
a. Kadettangen - to North
b. Kadettangen - main station
c. Kalvøya - small bay
d. Kalvøya - big bay
e. Kalvøya - nudist beach
f. Høvikodden


1000 m.
Sandvika
Oslofjord
5000 m


1800
1600
1400
1200
1000
800
600
400
200
0
E. coli (MPN/100 ml)
1 day
2 days
3 days
K = 0.7
K = 0.1
K = 0.023
Kadettangen
Kadettangen-north
Kalvøya-small
Kalvøya-big
Kalvøya-nudist
Høvikodden


E. coli /100 ml
After 3 hours
After 1 day
After 2 days
After 3 days
Bærum
E18
ALVØY
BORØYA
5000
3000
2000
1500
1000
800
600
400
200
80
60
40
20
10
5
1
0


E. coli (MPN/100 ml)
0 100 200 300 400 500 600 700 800 900 1000
0 -1 -2 -3 -4 -5 -6 -7
Elevation (meter)
Høvikodden
Time: 07/08/2014 15:00
E. coli (MPN/100 ml)
420 430 440 450 460 470 480 490 500
-0.5 -0.6 -0.7 -0.8 -0.9 -1.0 -1.1 -1.2 -1.3 -1.4
Elevation (meter)
Kadettangen
Time: 07/08/2014 15:00


Kalvøya nudist
Høvekodden
Boat discharge scenario site
Bærum
Slependen
Billingstad
Nesøya
Nesøytjern Naturreservat
Borøya
Østøya
Høvik
Model simulation result
Variable
Kalvøya nudist beach
Høvekodden beach
E. coli (MPN / 100 ml)
Time (hours)

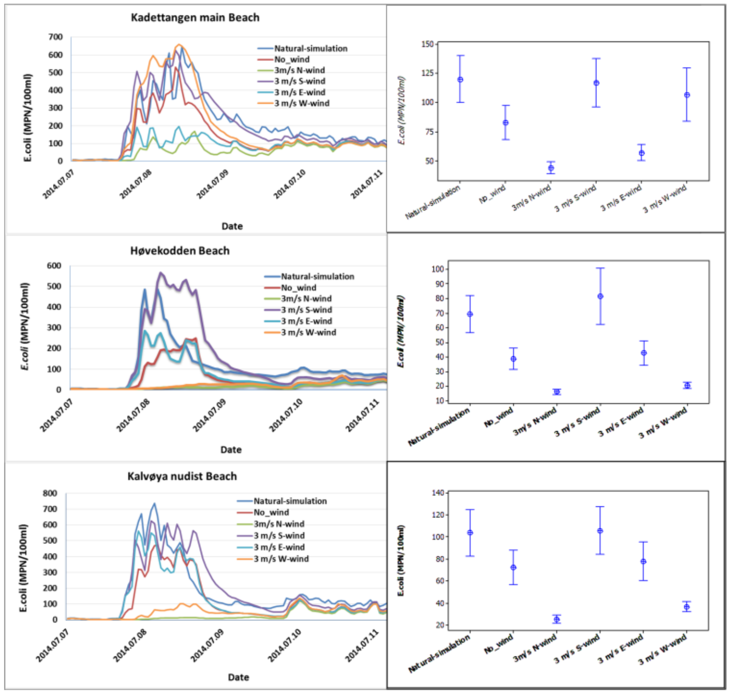

Kadettangen main Beach
E.coli (MPN/100ml)
Natural-simulation
No_wind
3m/s N-wind
3 m/s S-wind
3 m/s E-wind
3 m/s W-wind
Date
Høvekodden Beach
Kalvøya nudist Beach

Figure captions

Figure 1. The map of the study area and the position of the beaches (Source: http://www.maps-of-europe.net/maps-of-norway/ and google map)

Figure 2. Oslofjord shoreline, model grid of the study area and the position of the six beach sites (red dots).

Figure 3. Simulated daily average *E.coli* concentration after the rainfall event for three-consecutive days using decay rate coefficient of k = 0.7 and K=0.1 per day, representing half-life time of 1 day and 1 week respectively.

Figure 4. The top layer simulation graphics showing the spreading of *E. coli* at different time intervals after the rainfall event (k =0.7 day^{-1})

Figure 5. Plots of simulated vertical stratification of *E. coli* concentration in the water column at Høvikodden (left) and Kadettangen (right)

Figure 6. Boat discharge site, beaches and simulated *E.coli* concentration at the beaches (k =0.7 day^{-1})

Figure 7. Predicted *E. coli* concentration at Kadettangen, Høvikodden, and Kalvøya nudist beaches, based on scenarios with different wind directions, the left plot shows the simulated time series and the right plot shows statistical summary (mean and standard deviation)

Table 1. The ranges of input data variables used for GEMSS modelling

Description	Unit	Min	Max	Remark
Meteorological data				
Air temperature	^{o}C	6.5	31.9	
Dew point temperature	^{o}C	-0.7	19.5	
Ocean water temperature	^{o}C	16.6	25.2	
Cloud cover	tenths	0.0	10.0	
Atmospheric pressure	mm of Hg	970	1016	
Wind speed	m/s	0.2	7.8	
Wind direction	degrees	0	359	
Water surface elevation	m	-0.83	0.86	
Water quality				
temperature	^{o}C	6.6	22.5	
salinity	ppt	20.1	27.6	
E. coli	MPN/100ml	5×10^{2}	3×10^{4}	River
	MPN/100ml	7.5×10^{4}	7.5×10^{4}	CSO
	MPN/100ml	1.5×10^{9}	1.5×10^{9}	Swan faeces[a]
	MPN/100ml	3×10^{7}	3×10^{7}	Boat sewage
Flow data				
River discharge	m^3/s	0.94	26.5	
Combined sewer overflow (CSO)	m^3/s	0.017	0.045	
Swan faeces	m^3/s	6.9×10^{-8}	6.9×10^{-8}	
Boat discharge	m^3/s	3.3×10^{-4}	3.3×10^{-4}	

[a] Swan faeces Assumption: 20 swans x 300 g feces each per day, 1.5×10^{7} *E.coli* /g at Kadettangen beaches

Table 2. The characteristics of the rainfall episode used for simulations

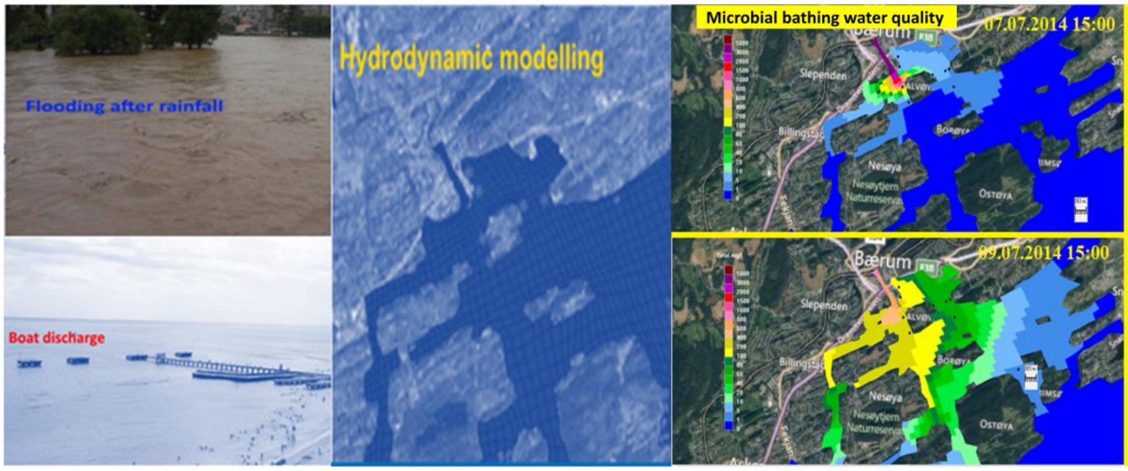
Met. Stations	Distance from Sandvika (km)	Direction from Sandvika	Rainfall episode 1 (July 7, 2014)					Days and amount of precipitation before the rainfall event	
			Time rain started	Time rain stopped	Amount of rainfall (mm)	Duration of rainfall (minute)	Average rainfall intensity (mm/hr.)	Days	Rainfall (mm)
Asker	8.26	SW	12:00	14:00	21.8	111	11.78	6	7.8
Blindern	11.66	NE	10:00	14:00	18.1	142	7.65	2	9.3
Bygdøy	8.89	NE	11:00	15:00	17.9	-	-	10	17.6

Table 3. Statistical parameters used for comparison of measured and modelled *E. coli concentrations*

E. coli	Log_{10} (MPN/100ml)				Root mean square error (RMSE)	Root volume of error (RV_E) %	Nash-Sutcliffe coefficient
	Min	Max	Mean	StDv			
Simulated	0.74	3.33	2.16	0.57	0.79	8.4	0.36
Observed	1.48	3.84	2.35	0.63			

Highlights

- GEMSS hydrodynamic model was used to predict the spreading of microbial pollutant.
- *E. coli* used as an indicator of microbial pollutant
- The model prediction was evaluated comparing with observations
- The simulation was performed for the conditions of after rainfall event, boat discharge and wind direction scenarios


Flooding after rainfall
Boat discharge
Hydrodynamic modelling
Microbial bathing water quality
07.07.2014 15:00
09.07.2014 15:00
Bærum
Slependen
Billingstad
Nesøya
Nesøytjern Naturreservat
Borøya
Østøya