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Natural Hazards
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Sciences
Discussions

Evaluating health hazard of bathing waters affected by combined sewer overflows

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Abstract. Combined Sewer Overflows (CSO) affect bathing water quality of receiving water bodies by bacterial contamination. The aim of this is study is to assess the health hazard of bathing waters affected by CSOs. This is useful for bathing water managers, for risk assessment purposes and for further impact and economical assessments. Contaminant hazard was evaluated based on two novel indicators proposed in this study: the mean duration of insufficient bathing water quality (1) over a period of time (i.e. several years) and (2) after single CSO/rain events. Particularly, a novel correlation between the duration of sea water contamination and the event rainfall volume was developed. Contaminant hazard was assessed through a state-of-the-art coupled urban drainage and sea water quality model that was developed, calibrated and validated based on local observations. Furthermore, hazard assessment was based on a novel statistical analysis of continuous simulations over a 9 year period using the coupled model. Finally, a validation of the estimated hazard is also shown. The health hazard was evaluated for the case study of Badalona (Spain) even though the methodology presented can be considered generally applicable to other urban areas and related receiving bathing water bodies.

1 Introduction

Bathing water quality is regulated by the Bathing Water Directive (2006/7/EC) (BWD) and the corresponding transposition law within each EU nations. For instance, in Spain it is the Real Decreto REAL DECRETO 1341/2007. The BWD sets the guidelines for the bathing water monitoring and classification, the management and the provision of information to the public. Short term pollution events (having usual durations of less than 72 hours) like the ones caused by Combined Sewer Overflows (CSOs) lead to insufficient bathing water quality and require additional monitoring/sampling of bathing waters. Model simulations can be used to predict the contaminant plume spatial and temporal evolution in bathing water bodies, however such tools are not widespread (Andersen et al. 2013). In case of moderate and heavy rains, CSOs discharge high concentrations and loads of the bacteria *E. Coli* and *Enterococci Intestinalis* (coming from waste and stormwater runoff) in the receiving water bodies where concentrations can exceed the bathing water quality standards. If bathing water quality is insufficient, then local authorities should inform end-users, discourage bathing and collect water samples to monitor bacterial contamination. Generally, safe bathing can be re-established after a collected water sample have shown acceptable bathing water quality.

In the field of risk management, and considering a social based risk approach, the risk can be assessed through the combination of the hazard likelihood and the vulnerability of the system referring to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events (BINGO_D4.1, 2016). In this framework, risk can be defined as the combination between hazard and vulnerability (including exposure, sensitivity and recovering capacity) according to literature (Turner et al., 2003; Velasco et al., 2018). Donovan et al. (2008) and Viau et al. (2011) evaluated the risk of gastrointestinal disease associated with exposure of people to pathogens like E.Coli and Enterococci. In the former study, hazard was assessed by statistical analysis of observed bacterial concentrations during 6 days in a year that was considered as representative whereas in the latter one it was estimated by simple assumptions. Andersen et al. (2013) presented a coupled urban drainage and sea water quality model to quantify microbial risk during a swimming competition where lots of gastrointestinal illnesses occurred due to the presence of CSO in sea water. O'Flaherty et al. (2019) evaluated human exposure to antibiotic resistant-Escherichia coli through recreational water.

Several water quality models of receiving water bodies were developed to simulate spatial and temporal variations of bacterial concentrations originating from CSOs and other sources. These water quality models also include hydrodynamic models most of the times. Scroccaro et al. (2010) developed a 3D sea water quality model to simulate bacterial concentrations originating from waste water treatment plant discharges. Jalliffier-Verne et al. (2016) and Passerat et al. (2011) developed river water quality models. Liu and Huang (2012) developed a 2D model of an estuary exposed to tides. Sokolova et al. (2013) and Thupaki et al. (2010) presented hydrodynamic 3D models of lakes to simulate E. Coli based on contaminant discharges estimated from observations at the affluent rivers and/or sewers. Also, coupled urban drainage and water quality models of receiving water bodies were developed to simulate spatial and temporal variations of bacterial concentrations for bathing water quality affected CSOs (Andersen et al., 2013; Marchis et al., 2013).

None of the studies presented above provided a methodology to evaluate health hazard of bathing waters affected by CSOs that is the main aim of this study. Health hazard was evaluated based on two novel indicators proposed: the mean duration of insufficient bathing water quality (1) over a period of time (i.e. several years) and (2) after single CSO/rain events. Particularly, a novel correlation between the duration of sea water contamination and the event rainfall volume is presented. This is useful for bathing water managers, for risk assessment purposes and for further impact and economical assessments. For example, the presented correlation can be useful to water managers and regulators to predict how long a rainfall event is going to affect the bathing water quality and when could be the optimal time to collect bathing water samples. Also, to estimate direct and indirect economic impacts of CSOs on coastal economies as was done in BINGO (2019). Health hazard was quantified through a coupled urban drainage and sea water quality model that was developed, calibrated and validated based on local observations. Furthermore, a novel statistical analysis of continuous simulations over a 9 year period using the coupled model is presented.

Finally, a validation of the estimated hazard is also shown. The health hazard of bathing waters affected by CSOs was evaluated for the case study of Badalona (Spain).

2 Materials and Methods

2.1 The case study

Figure 1 shows the case study area of Badalona (Spain). Badalona, the fourth city of the Catalonia region, is part of the metropolitan area of Barcelona with an extension of 21 km^2, 215 000 inhabitants and it is highly urbanized. It has approximately 5 km of bathing sandy beaches facing the Mediterranean Sea. Several CSO points discharge combined sewers along the beaches. Generally, rainfall events larger than few mm cause CSOs and during the bathing season bathing is usually forbidden during at least the 24 hours following a CSO events.

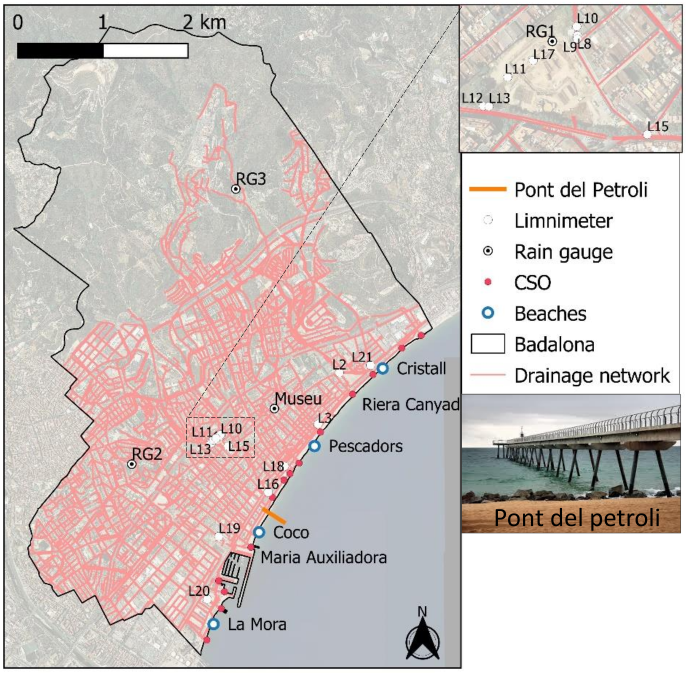

Figure 1. Plan view of Badalona together with the drainage network, the name of some of the beaches, the CSO points, the rain gauges, the limnimeters and the pedestrian bridge Pont del Petroli. Background image from © Google Maps.

2.2 Definitions

Figure 2 shows the definition of a total rain event duration and a sea water pollution event. Two different sea water pollution events are shown for an easier clarification of the definition adopted in this study. The figure shows 3 different rain events, each of them causing CSOs to the sea and 2 different sea water pollution events. The sea water pollution events are defined to occur when bacterial concentrations exceed the selected thresholds. A sea water pollution event can last up to a couple of days and can be generated by different rain/CSO events. Therefore, the definition of a total rain event duration is considered practical for this study considering also the different time scales of the different events involved. A similar definition was introduced in other urban water quality studies analyzing the performance of urban drainage structures such as detention ponds and basins on receiving water bodies (Sharma et al., 2016).

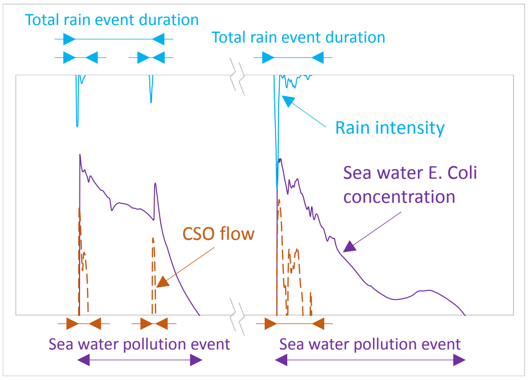

Figure 2. Definition of total rain event duration and sea water pollution event.

2.3 The data

This section provides an overview of the data available at the case study. Figure 1 shows the location of the 4 rain gauges (tipping buckets of 0.1 mm capacity) and 14 water level sensors that are operating since 2011.

Other sensors were also installed in BINGO at the two CSOs points of Maria Auxiliadora and Riera Canyadó (see Figure 1): a radar level and a temperature sensor upstream, and a temperature sensor and a turbidity sensor downstream each of the two weirs. When a CSO occurs, both temperature sensors indicate approximately the same value and the water level sensors are activated, so it is possible to detect the duration of the overflow and the frequency of occurrence of this type of events. Also, two automatic 12 bottle samplers were installed to measure turbidity, dissolved oxygen demand, suspended solids, Enterococci and E. Coli at the two CSO structures.

Sea water quality data were measured by the laboratory technicians of the municipality of Badalona during 5 different field campaigns that consisted in taking sea water samples after (sometimes also during) CSO events. Sea water samples were taken at 3 different points (1-close to the shoreline, 2-in the middle of the pedestrian bridge and 3-at the most offshore point) along the pedestrian bridge 'Pont del Petroli' (Figure 1). The samples were taken once a day (normally between 9AM and 2PM) for the few days following CSO events until bacterial concentrations would recover to small values. The data measured were: E. Coli and Enterococci Intestinalis concentrations, salinity, turbidity, suspended solids and potential oxygen reduction. Sea water quality data are also available from the continuous water quality sampling campaigns that are mandatory in order to classify the water quality at the different bathing locations. For instance, during the last years, more than 400 water samples were collected (and analyzed) at each of the 4 beaches shown in Figure 1 with a sampling frequency of approximately once every couple of weeks. All the water quality indicators were obtained from laboratory analysis of the collected samples.

Figure 3 shows both the E. Coli concentration and the CSO water level measured at the two monitored CSO points during the only two events registered: the 30-5-2017 that had 3-4 mm of rain in 3 hours and the 24-3-2017 that had 55-67 mm in 12 hours. The water level sensors are located after the weirs and the measured water levels are available only during a CSO. Instead, the E. Coli is measured inside the CSO chamber and concentration start to be measured before the beginning of the CSO. Figure 3a show 4 E. Coli measurements that coincide with the CSO measurements and Figure 3b only 2. These observations are between 5.7·10^5 and 1.0·10^6 CFU/100 ml (Colony Forming Units). Figure 3c shows 3 E. Coli measurements between 8.2·10^4 and 2.3·10^5 CFU/100 ml during the first 40 minutes of the 12 hours long CSO. Analysis of such observation was not done due to the sparse data.

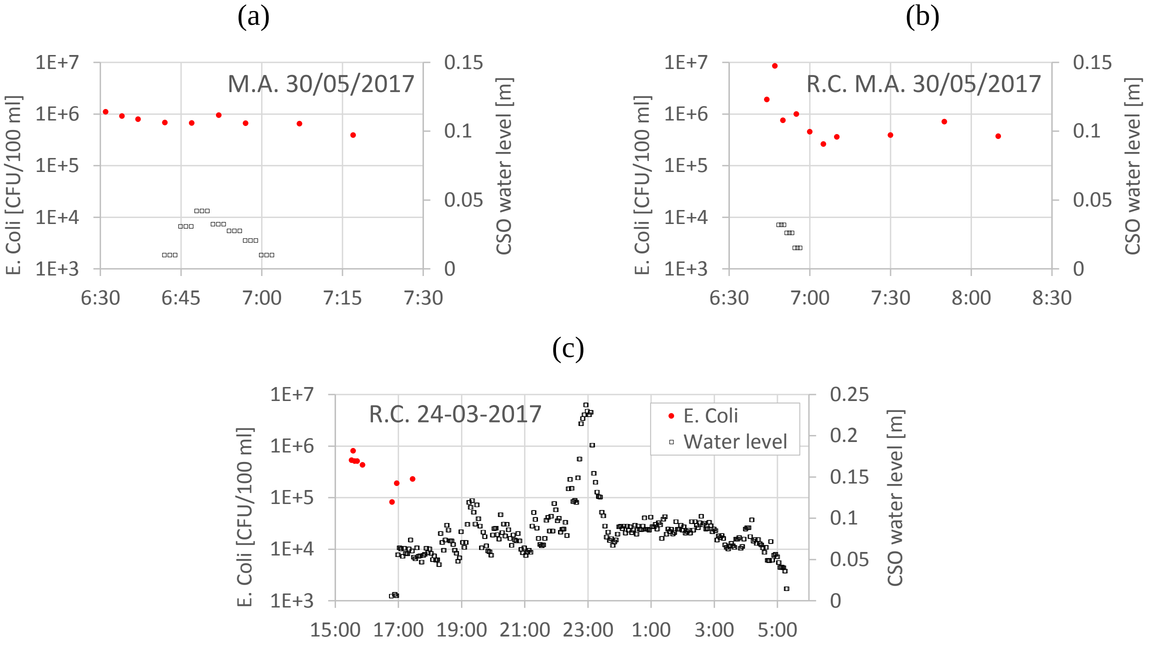

Figure 3. E. Coli concentration and CSO water level measured at the two CSO structures of Riera Canyado (R.C.) and Maria Auxiliadora (M.A.).

2.4 The model

A coupled urban drainage and sea water quality model was developed, calibrated and validated based on local observations. The urban drainage model is used to simulate CSO hydrographs at all the CSO points of Badalona. These hydrographs are used as inputs to the sea water quality model to simulate near-shore water quality. The two models are coupled in a sequential way, this means that first the urban drainage and then the sea water quality model are executed. This is acceptable as the physical processes occurring in the sea do not affect CSO hydrographs in Badalona.

2.4.1 The urban drainage model

The urban drainage model aims at simulating CSO hydrographs at the more than 10 CSO structures of Badalona that will then be used as inputs to the sea water quality model. The model simulates rainfall-runoff processes, domestic and other types of sewage water produced and hydrodynamics in the drainage network over the whole area of Badalona.

The model was originally developed in 2012 for the Drainage Management Plan (DMP) of Badalona. As part of this study, the model was imported into InfoWorks (www.innovyze.com), updated to include the new pipes and one detention tank of approximately 30000 m^3 that were constructed during the last years and calibrated and validated with new data. Figure 1 shows the modeled drainage network. Overall, the model includes approximately 368 km of pipes, 11338 manholes, 11954 sub-catchments, 62 weirs, 4 sluice gates and 1 detention tank.

The sewer flows were simulated by the full 1D Saint-Venant equations. Rainfall-runoff processes were simulated with the SWMM model (included in InfoWorks) that routes flow using a single non-linear reservoir with a routing coefficient that is a function of surface roughness, surface area, terrain slope and catchment width. Initial losses are generally small for both impervious urban areas and green areas ($\leq$ 1 mm) and continuous losses for green areas are simulated using the Horton model. The area of Badalona area was divided into 11954 computational sub-catchments of different areas. The sub-catchments were obtained by GIS analysis of the digital terrain model (2 m x 2 m resolution) and have areas in the range of 0.01-1 hectares in the urban areas and 1-100 hectares in the upstream rural areas. Each sub-catchment includes the GIS derived information of impervious area and pervious areas that are used to apply either the impervious or the pervious rainfall-runoff model. Impervious areas have not continuous hydrological losses meaning that all the net rainfall (after initial losses) contributes to stormwater runoff.

2.4.2 The sea water quality model

The sea water quality model aims at simulating near shore (within few hundred meters from the shore line) bacterial concentrations in the Badalona sea water during and after CSO events. The water quality model was developed for the area of Barcelona (Gutiérrez et al., 2010) and it is operating since 2007 for real time simulations of bathing water quality of the Barcelona beaches. This model was updated, calibrated and validated for Badalona as part of this study.

The sea water quality model was developed using the software MOHID by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST). The model simulates both the hydrodynamics of the sea in the coastal region and the contaminant transport resulting from CSOs.

Simulation of near shore water quality and hydrodynamics during and after CSOs requires spatial discretization scales in the order of tens of meters whereas other coastal hydrodynamic processes can occur at much larger scales. Therefore, 3 model domains are used to simulate hydrodynamic processes from the large regional scale to the local near shore scale of Badalona. Figure 4 shows the three model levels. Level 3 represents city scale processes, O(10km) and is nested into Level 2 that represent sub-regional scale, O(50km), and it is further nested into Level 1, regional scale, O(200km). The 3 levels continuously interact with each other during simulations. Level 1 covers an area of approximately 20,000 km^2 with 6500 squared cells of approximately 1x1 km^2. At this domain, the hydrodynamic processes of astronomic tides and wind induced waves and currents are simulated in 2D mode (barotropic). Level 2 covers an area of approximately 1000 km^2 with 54000 rectangular cells of sides from 500 m to 200 m (finer cells close to the shore line). Level 3 covers an area of approximately 50 km^2 with 117528 rectangular cells of sides from 200 m to 40 m (finer cells close to the shore line). The vertical discretization of Level 2 and 3 was defined with a Sigma approach with thinner cells close to the sea surface and thicker ones close to the sea bed. The percentages used to define the thickness of each of the 8 vertical layers as a function of the water depth were: 0.458, 0.227, 0.134, 0.079, 0.047, 0.028, 0.017 and 0.01 (the thinnest layer at the sea surface is 1% of the water depth at that location). At Level 2 and Level 3 domains the processes of currents and waves; density, temperature and salinity variations; near shore currents generated by CSOs and river discharges; advection and dispersion of E.Coli from CSOs are simulated in baroclinic mode with a 3D mesh.

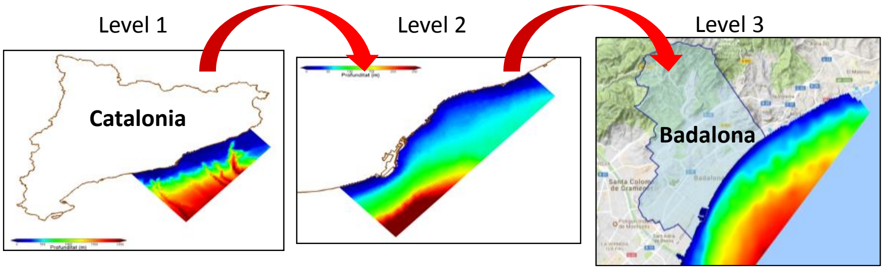

Figure 4. The 3 model domains of the sea water quality model. The colors represent the bathymetry (blue=shallow and red=deep). Background image from © Google Maps.

CSOs are simulated in the sea water model as both water discharges and concentration inputs. Water discharge time series at the CSO points are obtained from the urban drainage model and the input concentrations used for CSO discharges were assumed to be fixed (further details are given in the results section).

The hydrodynamic model solves the primitive continuity and momentum equations for the surface elevation and 3D velocity field for incompressible flows, in orthogonal horizontal coordinates and generic vertical coordinates, assuming hydrostatic equilibrium and Boussinesq approximations (http://wiki.mohid.com). The selected turbulence model was the Smagorinsky model with default values. Wave height and period was computed as function of wind speed, according to ADIOS model formulations (NOAA, 1994).

2.5 Hazard assessment

Table 1 shows the hazard criteria applied. Hazard is considered low if E. Coli concentrations are smaller than 250 CFU/100ml; medium if concentrations are between 250 and 500 CFU /100ml and is high above 500 CFU /100ml. The selected approach is similar to the one proposed in the BWD and the REAL DECRETO 1341/2007 to classify bathing water quality. High hazard (E. Coli > 500 CFU /100ml) is here considered as insufficient bathing water quality.

Hazard is quantified based on two novel indicators proposed that were computed for every beach of Badalona by continuously simulate 9 consecutive bathing seasons (here assumed to be from 1st of June to 1st of September) from 2006 to 2014 using the coupled (urban drainage – sea water quality) model:

- the duration of insufficient bathing water quality over a bathing season.
- the duration of insufficient bathing water quality after rain/CSO events. Particularly, the duration of insufficient bathing water quality is presented as a function of the event rainfall volume.

Both wind data and rainfall data between 2006 and 2014 (9 years) were obtained from the station of Fabra located in the neighbor city of Barcelona.

Hazard maps were also analyzed. However, together with the project stakeholders, they were not considered to be an interesting output because of the time and spatial variation of hazard during each different contamination event. Finally, a validation of the hazard assessment is shown for the duration of insufficient bathing water quality after rain/CSO events.

Table 1. Hazard criteria based on E. Coli concentration in sea water

Hazard criteria	E. Coli concentration [CFU/ 100 ml]
Low	<250
Medium	250<x<500
High	>500

3 Results

3.1 Calibration and validation of the urban drainage model

Table 2 shows the 3 events used for calibration and the one for validation. Also the different rainfall intensities, volumes and return periods evaluated based on local rainfall Intensity-Duration-Frequency curves are shown for each event. It is noted that the selected calibration events have generally high intensities and volumes compared to the majority of the events that can cause CSOs (as mentioned above events larger than few mm usually cause CSOs in Badalona). Rain data from the rain gauges were applied in the model using Thiessen Polygons.

Table 2. Events used for calibration and validation of the urban drainage model

Date event	**P (mm)** Cumulative rainfall	**I_{20Min} (mm/h)** maximum 20 minutes rainfall intensity (return period)	**I_{5Min} (mm/h)** maximum 5 minutes rainfall intensity (return period)	**Event used for**
22 August 2014	25.5	42.6 (T=0.4)	74.4 (T=0.6)	Calibration
28 July 2014	46.5	56.4 (T=0.8)	91.2 (T=0.8)	Calibration
03 October 2015	34.1	81 (T=2.1)	122.4 (T=1.1)	Calibration
14 September 2016	21.7	64.5 (T=1.1)	142.8 (T=6.1)	Validation

The Horton parameters were: an initial infiltration capacity of 20 mm/h, a final one of 7 mm/h, a capacity decrease exponent of 0.043 h^{-1} and a capacity increase exponent 0.108 h^{-1}. The initial loss was calculated as *Value/slope*$^{0.5}$, where *Value* was set to 0.000071 and 0.00028 m for impervious and pervious surfaces respectively and slope was the average slope of the sub-catchment calculated with GIS. The Manning's roughness coefficient of surface impervious areas was set to 0.013 and the one of pipes was set to 0.012.

Figure 5 shows two examples of simulated and observed water levels at two different locations during 2 different rain events. Table 3 shows the computed Root Mean Square Error (RMSE) and Absolute Maximum Error (AME) (Bennett et al., 2013) for the calibration and validation events. The magnitude of the errors are similar to the ones reported in other urban drainage models (Russo et al., 2015). Overall, the model simulates the observed water levels in the sewer network in an acceptable way.

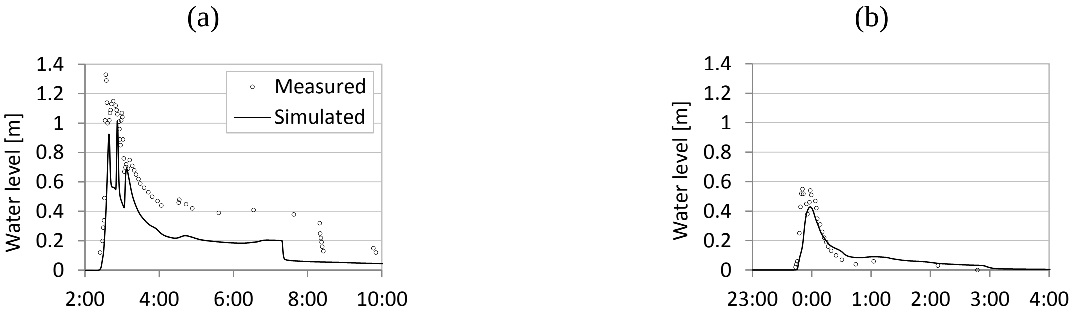

Figure 5. Example of simulated and measured water levels in the sewer pipes at the location BA15 during the rain event of the 03-10-2015 (a) and at BA2 the 14-09-2016.

Table 3. Root Mean Square Error (RMSE) and Absolute Maximum Error (AME) for the calibration and validation events.

	Calibration						Validation	
	22 August 2014		28 July 2014		3 October 2015		14 September 2016	
Water level sensor	RMSE [m]	AME [m]	RMSE [m]	AME [m]	RMSE [m]	AME [m]	RMSE [m]	AME [m]
L2	0.066	0.062	0.065	0.028	0.200	0.215	0.181	0.102
L4	0.045	0.033	0.049	0.218	0.150	1.422	0.057	0.022
L8	0.008	0.075	0.005	0.032	0.011	0.055	0.021	0.027
L9	0.157	0.666	0.000	0.322	0.006	0.733	0.001	0.321
L10	0.103	0.725	0.098	0.501	0.087	0.472	0.101	0.128
L11	0.212	0.627	0.222	1.150	0.495	2.390	0.244	1.333
L12	0.123	0.019	0.167	0.340	0.295	0.790	0.189	0.169
L13	0.094	0.315	0.094	0.565	0.713	0.907	0.238	0.631
L15	0.236	1.036	0.195	0.656	0.322	0.315	0.183	0.791
L16	0.264	0.537	0.032	2.065	0.850	1.828	0.147	0.357
L19	0.131	0.214	0.099	0.617	0.209	0.686	-	-
L20	0.346	0.387	0.148	0.190	0.333	0.059	0.096	0.159
L21	0.056	0.290	0.082	0.222	0.099	0.190	0.181	0.300

Finally, after the calibration and validation, a further manual adjustment of the simulated CSO flows was performed using measurements of CSO water levels during three different CSO events from 2017 (67 mm the 24/03, 22 mm the 27/04 and 4.2

mm the 30/05) at the two monitored CSO structures. The simulated height of these 2 weirs was manually calibrated so that the simulated CSO water levels would better fit (visual judgment) the observed ones. It was verified that this manual calibration would not affect the errors provided in Table 3.

3.2 Calibration and validation of the sea water quality model

There different events were used: two for calibration (one in January 2018 and one in September 2016) and one for validation (October 2016). Three events may sound as a limited number for calibration and validation. This was because of the long computational time of the coupled model and because of the data required for bathing water quality models are generally sparse and limited to some events. Similar models in the literature were also based on few events for calibration and validation: Marchis et al. (2013) and Passerat et al. (2011) used a single event and Andersen et al. (2013) used 2 events.

Calibration was based on a trial and error approach trying to both optimize the visual fitting between observed and simulated values and to minimize the computed errors. Both E. Coli concentrations and salinity were used in the calibration process. The 2 calibration parameters (wind drag coefficient and E. Coli decay rate) were selected after a sensitivity analysis (BINGO_D3.3, 2019). A fixed E.Coli concentration of $1 \cdot 10^6$ CFU/100 ml was used as input for the CSO hydrographs. This is a significant influential parameter and such choice was justified after both literature review and by the available observed data that were shown in Figure 3. Different approaches were presented in the literature: Andersen et al., (2013) simulated CSO dilution using a drainage model with a fixed E. Coli concentration for waste water based on literature review and assuming clean stormwater runoff. Marchis et al. (2013) used 5 events with river discharge and E. Coli measurements to calibrate both water quantity and quality from the modelled sub catchment. Jalliffier-Verne et al., (2016) estimated the CSO concentrations based on a fixed discharge per person multiplied by the number of people connected to the sewer network. Passerat et al., (2011) observed E. Coli concentrations of $1.5 \cdot 10^6$ CFU/100 ml for a CSO where 89% of the discharge were estimated to be from stormwater runoff. McCarthy et al. (2008) analyzed 56 wet rainfall events between 3.2 and 25 mm at 4 different catchments to estimate uncertainty and event mean concentrations of E. Coli. Wind data for these events were obtained from Puertos del Estado (www.puertos.es). Particularly, a model reproduced observed wind over a selected cell (approximately 10 km long) that covered the area of Badalona and such wind speed was uniformly applied to the sea water quality model.

The calibrated wind drag coefficient was 0.0008. Generally, the higher the coefficient, the higher the sea water velocities and consequent contaminant advection and dispersion. The model MOHID allows either a user defined fixed value that is suggested to be 0.0015 or the use of the function of Large and Pond, (1981) to compute the wind drag coefficient as a function of the wind speed. The calibrated value is within the proposed ranges of Large and Pond, (1981) and Sokolova et al., (2013) used 0.001255. Figure 6 shows the calibrated E. Coli decay rate expressed as T90, defined as the time at which 90% of the bacterial population is no longer detectable, meaning a one-log reduction of the number of pathogens. T90 could be computed as a function of water temperature, salinity and solar radiation (Canteras et al., 1995; Sokolova et al., 2013). However, such formulations was tested and would produce excessive decay rates for this case study and therefore the decay rate was assumed to have a fixed daily pattern that was calibrated. The calibrated decay rate (Figure 6) shows night T90 values of 4 days (equivalent to k=0.576 day^{-1}=0.024 h^{-1}) and peak daily values of 1.33 days (equivalent to k=1.73 day^{-1}=0.072 h^{-1}). Marchis et al. (2013) and Scroccaro et al. (2010) used fixed day and night T90 values of 1 and 2 days for sea water. For river and lake waters (that are supposed to have slower decay rates compared to salty sea water) Jalliffier-Verne et al. (2016) used fixed day and night decay rates of 0.011 h^{-1} and 0.037 h^{-1} and Passerat et al. (2011) 0.045 h^{-1}. In this case the same fixed decay rates were applied to calibration events during both winter and summer periods even though winter decay rates are likely to be slower due to lower water temperature and solar radiation.

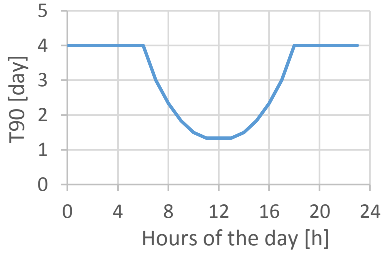

Figure 6. Calibrated E. Coli decay rate.

Figure 7 shows two visual examples of the simulated versus the observed E. Coli concentrations at the near-shore sampling point at the Pont del Petroli. Upper and lower bounds of the simulated concentrations are also shown and were obtained by running the model using both 10^7 and 10^5 CFU/100ml as fixed E. Coli concentration input at the CSO points (the continuous black line uses 10^6 CFU/100ml). Despite the sparse data, the model seems to be able to reproduce the observed concentrations with an order of magnitude precision. Figure 8 shows a visual example of the simulated versus the observed salinity concentrations at the near-shore sampling point at the Pont del Petroli. It is noted that during rainfall events the near shore sea water salinity falls significantly due to the discharge of not salty CSO water into the sea of Badalona. The sea water salinity recovers to typical sea water concentrations (37.5-38 ‰) within some hours, faster than the time it takes for E. Coli to recover below 500 CFU/100 ml (Figure 8 and Figure 7a). Due to the daily resolution of observed data, observed peaks of E. Coli and salinity were poorly detected.

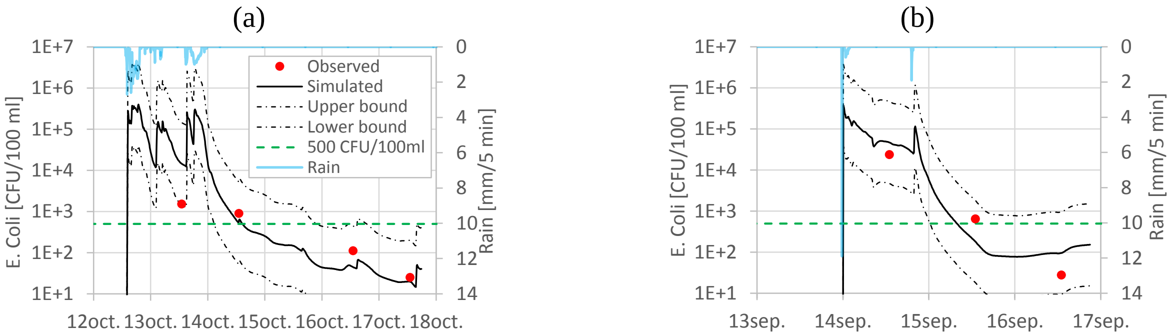

Figure 7. Examples showing the near-shore simulated and observed concentrations for the validation event (a) and a calibration one (b).

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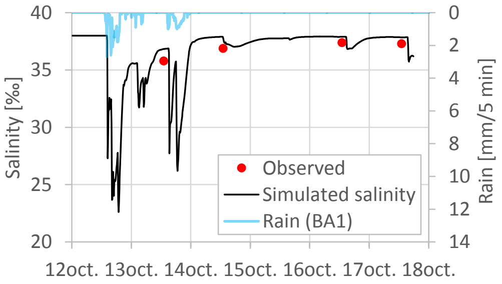

Figure 8. Examples showing the near-shore simulated and observed salinity for the validation event.

Figure 9 shows scatter plots of simulated and observed E. Coli concentrations (a) and salinity (b). The simulated E. Coli concentrations are shown to reproduce the observed ones with an order of magnitude accuracy. Order of magnitude E. Coli concentration accuracy is considered acceptable (Pongmala et al., 2015), particularly when simulating concentrations in receiving water bodies where models can be assessed at the order of magnitude level (Dorner et al., 2006). Salinity also seem to somehow follow the 1:1 line of simulated versus observed concentrations even though the majority of the observed values fall within 36 and 38 ‰ that might be a small range compared to the simulated values that can get down to less than 25 ‰ due to CSOs (Figure 8).

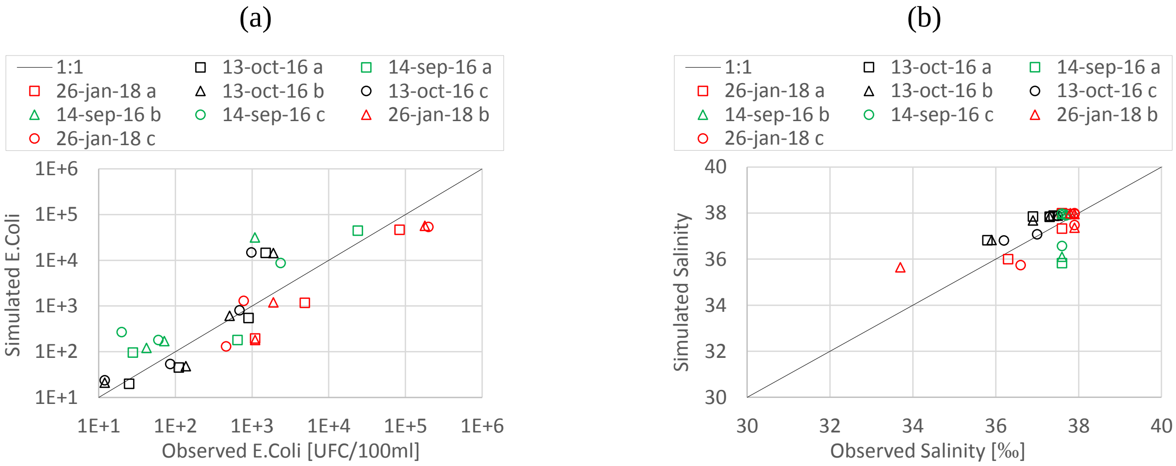

Figure 9. Scatter plots of simulated and observed E. Coli concentrations (a) and salinity (b).

Table 4 shows the model performance parameters for the calibration and validation events. Log (base 10) Transformed Root Mean Square Error (LTRMSE), Mean Square Log (with base 10) Error (MSLE) and Pearson Product moment correlation (PPMC) were used for E. Coli and Root Mean Square Error (RMSE) for salinity (Bennett et al., 2013; Hauduc et al., 2015). Few studies reported model performance errors for E. Coli concentrations in receiving water bodies. Thupaki et al. (2010) obtained a LTRMSE of 0.41 and Liu et al. (2006) in the range of 0.705-0.835. Chen et al. (2019) obtained RMSE error values for salinity simulations of an estuary in the range of 0.13-3.01.

Table 4. Model performance parameters.

Calibration and validation events	E. Coli concentration	MSLE	0.44
		LTRMSE	0.66
		Pearson correlation coefficient	0.83
	Salinity concentration	RMSE [‰]	0.73

3.3 Hazard assessment

Figure 10 shows the average number of days with high hazard at the different beaches of Badalona and for the 9 consecutive bathing seasons from 2006 t0 2014. The annual average number of days (the thick black line) with high hazard is in between 0 and 9 days per bathing season every year with an overall mean of 3-4 days per bathing season (the black dashed line). The results show a high variability that is highly related to the number and volume of rainfall events occurring during the different bathing seasons. The variability among the different beaches during the same bathing season is smaller compared to the variability due to different years.

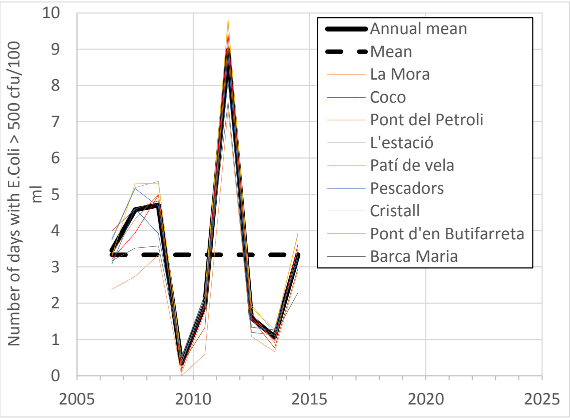

Figure 10. Simulated number of days per bathing season with high hazard (E. Coli concentrations > 500 CFU/100ml).

Successively, the duration of every single sea water pollution event (defined in Figure 2) was correlated to the total rainfall volume that fell during the same sea water pollution event (the total rain event duration of Figure 2) and the results are shown in Figure 11 (top figures). Figure 11 shows the results at two beaches (Coco and Pescadors), even though all beaches were analyzed. Overall, the results show that the higher the rainfall volume, the longer the time period the beach is exposed to E.Coli concentrations above threshold; however, above 15-25 mm of rain volume the increasing tendency seems to vanish; also, only rainfalls above few mm can cause sea water E. Coli concentrations > 500 CFU/100ml. The large spreading of the correlation plots is mainly due to the different total rain event duration and the magnitude of marine currents. Overall, longer rain events produce longer CSOs and therefore longer sea water pollution events. Similarly, stronger winds and rougher sea produce shorter sea water pollution events.

The bottom graphs of Figure 11 are a rearrangement of the top ones and show the probability distribution of sea water pollution events as a function of the rainfall volume. The discretization of the rainfall volume (x-axes) into 4 ranges was chosen in order to obtain both a reasonable number of events simulated in each range and volume ranges that are considered reasonable for local applications. This statistical approach was the best one among several attempts of correlation between sea water pollution duration and rain intensities of different duration (30, 60, 120, etc. minutes rainfall).

The bottom graphs of Figure 11 provide one of the two main indicators proposed in this study: the duration of high hazard (insufficient bathing water quality) as a function of the event rainfall volume. For instance an event of 10 mm rainfall is estimated to produce a median of 0.5 days of high hazard. The percentiles provided include an estimation of inter event uncertainty obtained by continuous simulations using the deterministic coupled model. Other uncertainties like the ones associated to selected and calibrated parameters were not addressed.

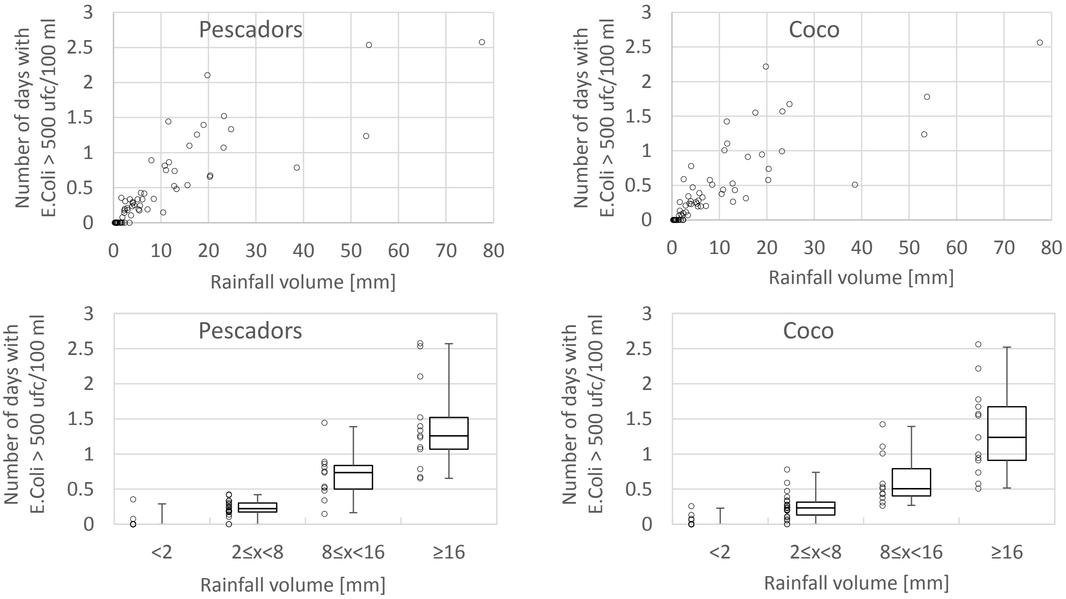

Figure 11. Correlation between the number of days with sea water E.Coli concentrations above 500 CFU/100ml and the rainfall volume at two different beaches (Pescadors and Coco). The wisker boxes show 1st, 25th, 50th, 75th and 99th percentiles.

3.3.1 Validation of the hazard assessment

A validation was performed only for the indicator of high hazard as a function of the event rainfall. The validation of the mean duration of high hazard per bathing season was not done due to lack of observed data.

Figure 12 shows an example of how the duration of a sea water pollution event was graphically obtained based on rainfall data and observed E. Coli concentrations. The sea water pollution event is assumed to start when the accumulated rainfall exceeds 1 mm. An analysis of the simulation results showed that a sea water pollution event can start up to an hour later compared to the proposed beginning point. This depends on how far from the CSO is the control point and also on the CSO events can start with a delay compared to the rainfall. The sea water pollution event is supposed to end when the simple linear interpolation (the red dashed line of Figure 12) between measured concentrations crosses the selected threshold of 500 CFU/100 ml. The total rainfall associated to the sea water pollution event is the average total volume (from the available rain gauges) that fell during the pollution event.

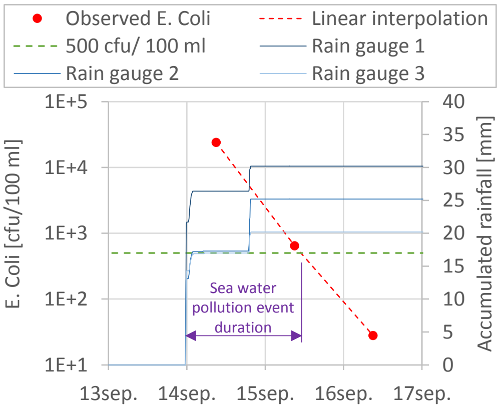

Figure 12. Example of how the duration of a sea water pollution event was graphically obtained.

Figure 13a shows the comparison between the simulated and observed high hazard duration. 8 events were used for the comparison. Overall, the majority of the observed durations fall within the 1st and 99th percentiles. However, there are some outliers. The 2 outliers at the Mora beach are likely because this beach is close to the mouth of the Besos River that might not be properly represented in the model. Also, there are several model uncertainties that were not simulated (for example, input parameters and calibration uncertainties). Further, it seems that the observed values are in the higher range of the simulated percentiles, this can be because all the CSO events that caused little sea water pollution could not be measured by the available sampling resolutions (approximately a sample per day). Overall, this can be considered as a preliminary visual validation.

For risk assessment purposes in BINGO (2019), together with the project stakeholders, it was decided to adjust/calibrate the proposed percentiles duration in order to obtain a deterministic maximum durations of high hazard that is shown in Figure 13b. For this purpose, several steps were applied: the observed sea water pollution duration derived from Enterococci Intestinalis observations was compared to the simulated E. Coli percentiles durations of Figure 13a; all the beaches were merged into a unique representative value of pollution duration obtained from the worst 99.9 percentile among all the beaches; finally, a further safety factor of 5% was applied so that all the outliers would be accommodated within the newly developed bars representing a practical deterministic value of maximum sea water pollution duration as a function of 4 different rainfall ranges.

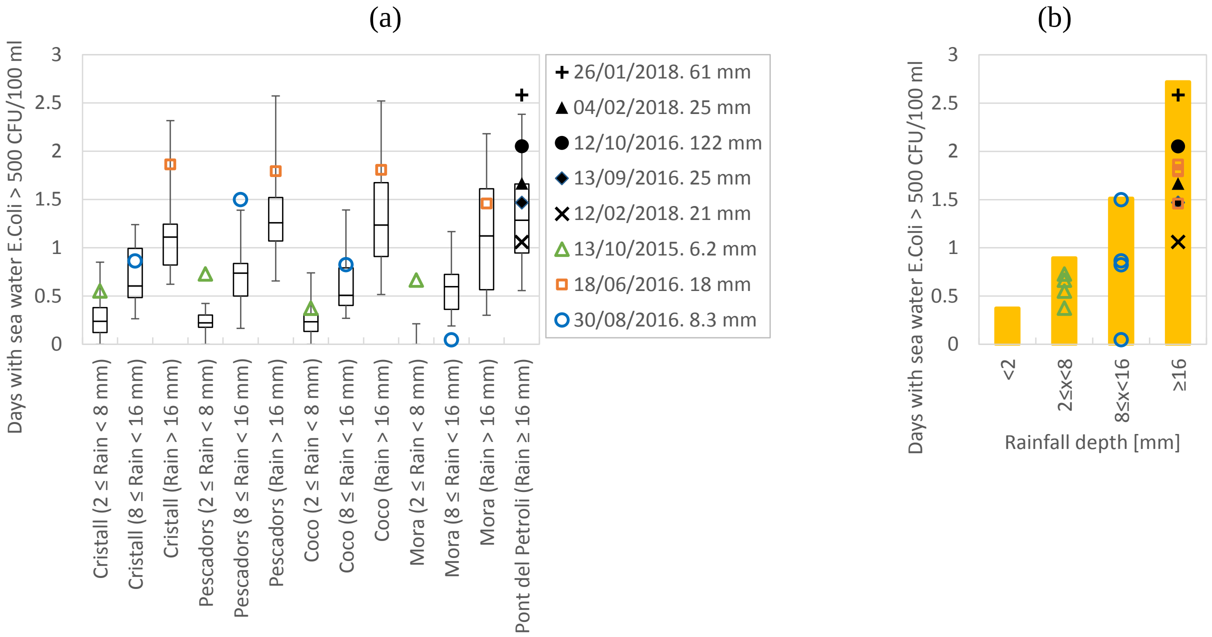

Figure 13. (a) Comparison between the estimated and the observed duration of high hazard (sea water E. Coli > 500 CFU/100ml). The wisker boxes show 1st, 25th, 50th, 75th and 99th percentiles of the duration of sea water contamination. (b) Maximum sea water pollution duration (orange bars) as a function of 4 different rainfall ranges.

4 Conclusions

This study quantified the health hazard of bathing waters affected by CSOs based on two novel indicators: the mean duration of insufficient bathing water quality (1) per bathing season and (2) after single CSO/rain events. Overall, a great uncertainty is associated to the evaluated contaminant hazard, mainly due to the variability of water quality variables, rainfall patterns and sea water currents. A novel correlation between the duration of sea water contamination and the event rainfall volume was presented. Also, a state-of-the-art coupled urban drainage and sea water quality model was developed, calibrated and validated based on local observations. Furthermore, hazard assessment was based on a statistical analysis of the continuous simulations simulation results of 9 consecutive bathing seasons using the coupled model. Finally, a validation of the estimated hazard was also shown.

The contaminant hazard of bathing waters affected by CSOs was assessed for the case study of Badalona (Spain) even though the methodology presented can be considered generally applicable to other urban areas and related receiving bathing water bodies. The results of this study were useful for risk assessment and to analyze direct, indirect, tangible and intangible impacts related to CSO and consequent pollution of sea water (BINGO, 2019). Also, the correlation presented to predict the duration of insufficient bathing water quality as function of the observed rainfall volume can be useful to bathing water managers.

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Competing interests

The authors declare that they have no conflict of interest.

Code/Data availability

Model files and data are not provided.

Author contribution

Beniamino Russo and Montse Martinez coordinated the research project. Luca Locatelli, Beniamino Russo and Montse Martinez managed the data collection. Luca Locatelli and Beniamino Russo developed the conceptual model and Luca Locatelli did the code and performed the simulations. Luca Locatelli prepared the manuscript with contributions from all co-authors.

References

Andersen, S. T., Erichsen, A. C., Mark, O. and Albrechtsen, H. J.: Effects of a 20 year rain event: A quantitative microbial risk assessment of a case of contaminated bathing water in Copenhagen, Denmark, J. Water Health, 11(4), 636–646, doi:10.2166/wh.2013.210, 2013.

Bennett, N. D., Croke, B. F. W., Guariso, G., Guillaume, J. H. A., Hamilton, S. H., Jakeman, A. J., Marsili-Libelli, S., Newham, L. T. H., Norton, J. P., Perrin, C., Pierce, S. A., Robson, B., Seppelt, R., Voinov, A. A., Fath, B. D. and Andreassian, V.: Characterising performance of environmental models, Environ. Model. Softw., 40, 1–20, doi:10.1016/j.envsoft.2012.09.011, 2013.

BINGO_D3.3: Calibrated water resources models for past conditions, H2020 BINGO. Bringing Innov. to onGOing water Manag. – a better Futur. under Clim. Chang. Grant Agreem. n° 641739 [online] Available from: http://www.projectbingo.eu/content/deliverables, 2019.

BINGO_D4.1: Context for risk assessment at the six research sites, including criteria to be used in risk assessment, H2020 BINGO. Bringing Innov. to onGOing water Manag. – a better Futur. under Clim. Chang. Grant Agreem. n° 641739 [online] Available from: http://www.projectbingo.eu/downloads/BINGO_Deliverable4.1.pdf, 2016.

BINGO: Bringing INnovation to onGOing water management – a better future under climate change, H2020. Grant Agreem. n° 641739 [online] Available from: http://www.projectbingo.eu/, 2019.

Canteras, J. C., Juanes, J. A., Pérez, L. and Koev, K. N.: Modelling the coliforms inactivation rates in the Cantabrian Sea (Bay of Biscay) from in situ and laboratory determinations of t90, Water Sci. Technol., 32(2), 37–44, doi:10.1016/0273-1223(95)00567-7, 1995.

Chen, J., Liu, Y., Gitau, M. W., Engel, B. A., Flanagan, D. C. and Harbor, J. M.: Evaluation of the effectiveness of green infrastructure on hydrology and water quality in a combined sewer overflow community, Sci. Total Environ., 665, 69–79, doi:10.1016/j.scitotenv.2019.01.416, 2019.

Donovan, E., Unice, K., Roberts, J. D., Harris, M. and Finley, B.: Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River, Appl. Environ. Microbiol., 74(4), 994–1003, doi:10.1128/AEM.00601-07, 2008.

Dorner, S. M., Anderson, W. B., Slawson, R. M., Kouwen, N. and Huck, P. M.: Hydrologic modeling of pathogen fate and transport, Environ. Sci. Technol., 40(15), 4746–4753, doi:10.1021/es060426z, 2006.

Gutiérrez, E., Malgrat, P., Suñer, D. and Otheguy, P.: Real Time Management of Bathing Water Quality in Barcelona, Conf. Pap. NOVATECH., 1–10, 2010.

Hauduc, H., Neumann, M. B., Muschalla, D., Gamerith, V., Gillot, S. and Vanrolleghem, P. A.: Efficiency criteria for environmental model quality assessment: Areview and its application to wastewater treatment, Environ. Model. Softw., 68(3), 196–204, doi:10.1016/j.envsoft.2015.02.004, 2015.

Jalliffier-Verne, I., Heniche, M., Madoux-Humery, A. S., Galarneau, M., Servais, P., Prévost, M. and Dorner, S.: Cumulative effects of fecal contamination from combined sewer overflows: Management for source water protection, J. Environ. Manage., 174, 62–70, doi:10.1016/j.jenvman.2016.03.002, 2016.

Large, W. G. and Pond, S.: Open Ocean Momentum Flux Measurements in Moderate to Strong Winds, J. Phys. Oceanogr., 11(3), 324–336, doi:10.1175/1520-0485(1981)011<0324:OOMFMI>2.0.CO;2, 1981.

Liu, L., Phanikumar, M. S., Molloy, S. L., Whitman, R. L., Shively, D. A., Nevers, M. B., Schwab, D. J. and Rose, J. B.: Modeling the transport and inactivation of E. coli and enterococci in the near-shore region of Lake Michigan, Environ. Sci. Technol., 40(16), 5022–5028, doi:10.1021/es060438k, 2006.

Liu, W. C. and Huang, W. C.: Modeling the transport and distribution of fecal coliform in a tidal estuary, Sci. Total Environ., 431, 1–8, doi:10.1016/j.scitotenv.2012.05.016, 2012.

Marchis, M. De, Freni, G. and Napoli, E.: Modelling of E. coli distribution in coastal areas subjected to combined sewer overflows, Water Sci. Technol., 68(5), 1123–1136, doi:10.2166/wst.2013.353, 2013.

McCarthy, D. T., Deletic, A., Mitchell, V. G., Fletcher, T. D. and Diaper, C.: Uncertainties in stormwater E. coli levels, Water Res., 42(6–7), 1812–1824, doi:10.1016/j.watres.2007.11.009, 2008.

NOAA: ADIOSTM (Automated Data Inquiry for Oil Spills) user's manual. Seattle: Hazardous Materials Response and Assessment Division, NOAA., 1994.

O'Flaherty, E., Solimini, A., Pantanella, F. and Cummins, E.: The potential human exposure to antibiotic resistant-Escherichia coli through recreational water, Sci. Total Environ., 650, 786–795, doi:10.1016/j.scitotenv.2018.09.018, 2019.

Passerat, J., Ouattara, N. K., Mouchel, J. M., Vincent Rocher and Servais, P.: Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River, Water Res., 45(2), 893–903, doi:10.1016/j.watres.2010.09.024, 2011.

Pongmala, K., Autixier, L., Madoux-Humery, A. S., Fuamba, M., Galarneau, M., Sauvé, S., Prévost, M. and Dorner, S.: Modelling total suspended solids, E. coli and carbamazepine, a tracer of wastewater contamination from combined sewer overflows, J. Hydrol., 531, 830–839, doi:10.1016/j.jhydrol.2015.10.042, 2015.

Russo, B., Sunyer, D., Velasco, M. and Djordjević, S.: Analysis of extreme flooding events through a calibrated 1D/2D coupled model: the case of Barcelona (Spain), J. Hydroinformatics, 17(3), 473, doi:10.2166/hydro.2014.063, 2015.

Scroccaro, I., Ostoich, M., Umgiesser, G., De Pascalis, F., Colugnati, L., Mattassi, G., Vazzoler, M. and Cuomo, M.: Submarine wastewater discharges: Dispersion modelling in the Northern Adriatic Sea, Environ. Sci. Pollut. Res., 17(4), 844–855, doi:10.1007/s11356-009-0273-7, 2010.

Sharma, A. K., Vezzaro, L., Birch, H., Arnbjerg-Nielsen, K. and Mikkelsen, P. S.: Effect of climate change on stormwater runoff characteristics and treatment efficiencies of stormwater retention ponds: a case study from Denmark using TSS and Cu as indicator pollutants, Springerplus, 5(1), doi:10.1186/s40064-016-3103-7, 2016.

Sokolova, E., Pettersson, T. J. R., Bergstedt, O. and Hermansson, M.: Hydrodynamic modelling of the microbial water quality in a drinking water source as input for risk reduction management, J. Hydrol., 497, 15–23, doi:10.1016/j.jhydrol.2013.05.044, 2013.

Thupaki, P., Phanikumar, M. S., Beletsky, D., Schwab, D. J., Nevers, M. B. and Whitman, R. L.: Budget analysis of Escherichia coli at a Southern Lake Michigan Beach., Environ. Sci. Technol., 44(3), 1010–1016, doi:10.1021/es902232a, 2010.

Turner, B. L., Kasperson, R. E., Matsone, P. A., McCarthy, J. J., Corell, R. W., Christensene, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A. and Schiller, A.: A framework for vulnerability analysis in sustainability science, Proc. Natl. Acad. Sci. U. S. A., 100(14), 8074–8079, doi:10.1073/pnas.1231335100, 2003.

Velasco, M., Russo, B., Cabello, Termes, M., Sunyer, D. and Malgrat, P.: Assessment of the effectiveness of structural and nonstructural measures to cope with global change impacts in Barcelona, J. Flood Risk Manag., 11, S55–S68, doi:10.1111/jfr3.12247, 2018.

Viau, E. J., Lee, D. and Boehm, A. B.: Swimmer risk of gastrointestinal illness from exposure to tropical coastal waters impacted by terrestrial dry-weather runoff, Environ. Sci. Technol., 45(17), 7158–7165, doi:10.1021/es200984b, 2011.