First of all, the authors thank the Editor and the reviewers for their constructive and valuable feedbacks.

Please find the authors' replies to the comments of the Editor written in blue.

EDITOR

Comments to the Author:

The research work is impressive and useful. The presentation of the work needs improvement to make the knowledge accessible and citeable. The reviews were helpful and it looks like the authors made many improvements. However, from the authors' response to the reviewers' comments, it is often impossible to see what changes you made. You need to indicate in your response how you changed it. You can copy-paste your corrections from the manuscript in the response or you can indicate the line numbers of the corrections and add a manuscript with track changes. I have a few additional comments that need to be addressed.

GENERAL COMMENTS

(1) Add a section in the Methods Section that explains the calibration, validation and model application (model parameters, objective functions, events). Specify the time interval of the data used for RMSE. Remove methods from the Results Section.

The calibration and validation section of both the urban drainage and the sea water quality model was moved into the methodology part. Also, model parameters, objective functions, time interval of the data used for RMSE were specified. (From line 230 to 386 of the revised manuscript with changes marked)

(2) Describe the selection of model input data (e.g., use of data from Figure 3 and Literature, e.g., l.224-238) in a section in the Methods.

The calibration and validation sections that included the description of both fixed and calibrated parameters were moved to the methodology section along with different clarifications requested by the specific comments provided by the reviewers. (From line 230 to 258 and lines 310 to 317 of the revised manuscript with changes marked)

(3) Deliverables of the BINGO project are grey literature. Try to limit references to grey literature as much as possible. Add Supplementary information instead, as also requested by RC1 (GC2).

We removed some BINGO references and added several graphs to the manuscript (4 graphs were added to Figure 7). Nevertheless, there are many calibration and validation graphs both from the urban drainage and the sea water quality model. We like to leave all the remaining graphs as referenced the 2 public deliverables of BINGO (we have specified the URL to the public pdf): D3.3 and D4.1.

(4) Put reference to the BINGO project in the acknowledgements, not in the scientific manuscript.

We removed the general BINGO reference and add the project URL in the acknowledgements.

(5) I would strongly suggest to add you data sets in ZENODO and add a reference to these data sets (you will be the author).

Due to the confidentiality of the data shared among the local project stakeholders of Badalona, the authors prefer to avoid the publication of the dataset on ZENODO. Notwithstanding, other authors can contact us and, in agree with other project local stakeholders, we will try to provide specific data needed for specific scientific purposes.

SPECIFIC COMMENTS

l.88-93: Specify when the sensors and samplers were installed and operational.

Done

l.99: potential oxygen reduction - please explain how this is measured.

In order to avoid confusion we have removed this indicator as it was not used in this study.

l.122-123: The model simulates rainfall-runoff processes, domestic and other types of sewage water produced …

Specify that only the rainfall-runoff processes are used for this application.

Actually all the processes were included into the simulation of urban water quantity. We clarified this point. (line 259 of the revised manuscripts with changes marked)

l.175-176: Don’t repeat the table in the text, either use a table or use text. (See also RC1, SC10).

Ok. We left the table and removed the 2 lines of text.

l.180: simulating

Ok.

l.213-217: Manual calibration also belongs in the Methods. Specify what is calibrated (which parameters are changed) and why would this not affect the results. You want to make sure that it “did not affect” instead of “would not affect”.

Ok.

I am looking forward to receiving an improved response to the comments of the reviewers and to the above comments!

REVIEWER 1

General comments (GC)

This manuscript reports on a how a modelling study was used to obtain a relation between the duration of seawater pollution events and rainfall volume. Two models were used: an urban drainage model to simulate combined sewer overflows (CSOs) and a hydrodynamic model to simulate the spread of pollution in the nearshore area. This work contributes to the existing body of literature on the impact of CSOs on the water quality. In my opinion, the scientific significance and scientific quality are good, while the presentation of the manuscript can be improved.

GC1

Consider restructuring the manuscript to improve clarity and flow – see the proposed outline below. The suggestion is to report the calibration and validation of each of the two models directly next to the description of the modelling set-up, to make it easier for the reader to follow.

Proposed outline:

1 Introduction

2 Methods

2.1 Study area

2.2 Hazard assessment (the hazard levels were defined; the coupled model was used to obtain the data for hazard assessment)

2.3 Urban drainage model

2.3.1 Model set-up of the urban drainage model (Model type and software; Input data: types of data and sources of these data, assumptions)

2.3.2 Calibration and validation of the urban drainage model (Data used for calibration and validation (what periods and why); Calibrated parameters (which and why, selected values); Calibration and validation results, e.g. graphs, RMSE, etc.)

2.4 Hydrodynamic model

2.4.1 Model set-up of the hydrodynamic model (Model type and software; Input data: types of data and sources of these data, assumptions)

2.4.2 Calibration and validation of the hydrodynamic model (Data used for calibration and validation (what periods and why); Calibrated parameters (which and why, selected values); Calibration and validation results, e.g. graphs, RMSE, etc.)

3 Results and Discussion

3.1 Hazard assessment

3.2 Validation of hazard assessment

3.3 Applicability of the suggested approach (here, the limitations and advantages of the modelling approaches and of the hazard assessment approach can be discussed, also in the context of existing literature)

4 Conclusions

Reviewer 1 proposes a restructuring of the manuscript in order to improve clarity and flow, whereas Reviewer 2 finds the paper "well organized and well structured".

In order to improve clarity and flow we have significantly improved the old Section 2.3 and changed the title of the old section 2.2 following the reviewer's suggestions relative also to the Specific Comments SC4, SC6 and SC8.

We moved the calibration and validation sections to the methodology as requested. The second suggestion of Reviewer 1 is to remove the data section 2.3 (a section dedicated to all the data used in the whole study) and describe the data separately in each section ('urban drainage model calibration and validation', 'sea water quality model calibration and validation' and 'Validation of the hazard assessment'). We believe it is better to keep the data section separately in order to avoid many repetitions that would occur. This is because the same data are often used in different sections: for instance some of the data used in the section 'sea water quality model calibration and validation' are the same data used in the section 'Validation of the hazard assessment'. The data section was improved by adding several lines guiding the reader to improve readability.

GC2

Consider revising which tables and figures are necessary to include in the manuscript, which can be placed as supplementary material, and which can be omitted. The quality of the figures can be improved to make them clearer and more informative.

Figures 7 and 8 were merged into one figure and 3 more graphs were added. Figure 10 was modified in order to make it clearer. Figure 3 was corrected. 2 out of 4 graphs were removed from Figure 11. We did not consider adding supplementary material as all the additional figure can be found in the public deliverables of the BINGO project.

GC3

Consider more clearly stating which data and which periods/events were used for calibration and validation of the different models and methods, with motivation why. Consider showing more (all?) graphs for visual comparison of the modelled and observed data, either in the main text (if appropriate) or as supplementary material.

We have added some sentences stating which data and which periods/events were used for calibration and validation of the different models and methods (Line 231-240 of the revised manuscript with changes marked). Also, we have added more graphs for visual comparison of the modelled and observed data. (Figure 7 of the revised manuscript with changes marked)

GC4

Consider including a (more detailed) discussion of the applicability and limitations of the used modelling approaches and of the developed hazard assessment approach, also in the context of other studies.

We consider that the applicability and limitations of the used modeling approaches were already sufficiently discussed throughout the paper also with comparison to other studies. We have not added more details as suggested by the reviewer.

Specific comments (SC)

SC1

Title: I would suggest mentioning in the title that the modelling approach was used. Also, I would recommend against using the word "health" in the title, because health or infection risks are beyond the scope of the paper, the paper is about E. coli levels representing the fecal pollution of the water.

We agree with the reviewer and we have modified the title.

SC2

Line 52-53: "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" I would suggest reformulating this statement. There are examples in the literature combining bathing water quality modelling with quantitative microbial risk assessment, i.e. to evaluate health hazards.

We have improved this sentence and part of the following ones. (Lines 57-68 of the revised manuscript with changes marked)

SC3

Consider explaining what BINGO is (very briefly).

We have added a line at the end of the abstract.

SC4

Line 90 and onward: Automatic samplers – how often/how many times/when were they used? Why is it relevant to this study? See also my suggestion to restructure the presentation of the data used in the study (GC1).

We added some lines in order to clarify these points. (Lines 105-111 of the revised manuscript with changes marked)

SC5

Line 97: Consider specifying how long the pedestrian bridge is – here or where appropriate.

Ok. (Line 140 of the revised manuscript with changes marked)

SC6

Section 2.3: The data – It could be better to mention the different types or data where relevant instead, for example, in the sections about the urban drainage model, in the section on hydrodynamic model, in the section of hazard assessment. See also GC1.

We believe that a unique section including all the data would be clearer. Nevertheless, we have improved the readability of the data section also following the suggestions of SC4.

SC7

Line 105-110: The description of what is shown in Figure 3 is unclear, consider revising. For example, it is written that there are 4 measurements in Figure 3a while there are 2 measurements in Figure 3b – unclear how this is meant, there are many points in these figures. Also, Figure 3b indicates two locations (R.C. M.A.). Consider improving the text and Figure 3.

We clarified the text and corrected the figure. (Lines 122-134 of the revised manuscript with changes marked)

SC8

Section 2.4.1: Consider clearly stating which model was used to simulate the urban drainage processes. It is mentioned that the original model (using which software?) was integrated into InfoWorks (consider explaining what InfoWorks is – it is not very clear from the provided website). Then it is stated that runoff-rainfall was simulated using SWMM. What model was used for simulating the flow in the sewers? Also, see comment GC1.

We clarified these points. (Lines 161-168 of the revised manuscript with changes marked)

SC9

Line 185: Figure 1 indicated that there are several rain gauges in the city of Badalona. On line 185 it is mentioned that the rain data were used from the city of Barcelona – why? Consider motivating why local data were not used. The same is relevant for the wind data.

We explained this. (Lines 397-400 of the revised manuscript with changes marked)

SC10

Table 1 is unnecessary, since this hazard classification is explained in the text.

We prefer to keep this table as part of the manuscript as it shows the hazard criteria that are a main input for the methodology.

SC11

Table 2: specify the unit for the return period.

Ok.

SC12

Section 3.1: How were the calibration and validation events selected? Were data from other overflow events available? Why were the SCOs in 2017 not included in the calibration/validation procedure? See also GC3.

We clarified this and improved the description of the section. (Lines 231-239 of the revised manuscript with changes marked)

SC13

Section 3.1: Which parameters were calibrated?

We clarified this. (Lines 249-256 of the revised manuscript with changes marked)

SC14

Line 220: Why were these periods selected for calibration/validation? Were there data available for more events? Could it be more relevant to look at more periods during the bathing season? See also GC3.

We clarified this and added a line at the end of the Section. (Lines 310-311 and 384-386 of the revised manuscript with changes marked)

SC15

Figure 6 can be placed in supporting information.

We prefer to keep this figure as part of the manuscript as it shows the temporal variation of one of the most influential and calibrated model parameters.

SC16

Figures 7 and 8: Consider showing the graphs for all three calibration/validation events. The results for E. coli (three graphs) and salinity (three graphs) could be combined into one figure with six graphs in total. This would provide more information on how the E. coli concentrations and salinity change during overflow events.

Figures 7 and 8 were merged into one figure of six graphs as recommended by the reviewer.

SC17

Table 4 is unnecessary since it presents only four values – it would be better to present these values in the text.

We prefer to keep the table in the manuscript as we consider that it helps readability.

SC18

Consider improving Figure 10 to make it more easily readable.

We modified Figure 10.

SC19

Figure 12 can be placed in supporting information instead.

We prefer to keep this figure as part of the manuscript as it is a visual example that helps the reader understanding the procedure adopted.

SC20

Line 317 “The validation of the mean duration of high hazard per bathing season was not done due to lack of observed data.” Are not data available on how many days the beaches were closed during each bathing season?

We clarified this. (Lines 443-447 of the revised manuscript with changes marked)

SC21

Line 330 It is not very clear what is meant here about the percentiles – consider rephrasing.

We clarified this. (Lines 435 of the revised manuscript with changes marked)

SC22

In general, I think it would be good to include a table that summarises which events (periods of time) and types of data were used for calibration and validation of the models and approaches: sewer model, hydrodynamic model, hazard assessment. I think this should be explained where relevant in the text (in separate sections where the models are described), but a summarising table can be provided as supporting material.

A summary table was not introduced as it is was not considered to be relevant since the text was improved and all the suggested details related to the calibration and validation processes are now present in the text.

SC23

In general, in the figures, make sure that it is clear whether the figure shows observed (measured data) or modelling results (see e.g. Figure 11).

The caption of Figure 11 was modified.

SC24

Section 3.3.1 and conclusions: Was the purpose of developing this approach to predict the duration of water pollution events based on the rainfall volume? What are the practical implications of this work? Can this method be used by water managers? Any other reflections about the significance of the findings?

These questions were already addressed in the text. Further reflections about the significance of the findings were not added.

SC25

Figure 13: How were the events for validation of this approach selected? Were there more data available? Currently, measurements/estimations for three years are presented, with some of the measurements being outside of the bathing season. See also GC3.

We added some lines in the data section in order to clarify this.

SC26

Conclusions – first line: I think it is better not to call this “health” hazard, because the health and health risks (measured in e.g. probability of infection or DALYs) were not calculated – beyond the scope of this study. See also SC1.

We like to keep “health hazard” as also the Bathing Water DIRECTIVE 2006/7/EC treats the bathing water quality as a hazard for human health.

SC27

Conclusions: “A novel correlation between the duration of sea water contamination and the event rainfall volume was presented.” Consider discussing (in the appropriate section of the text) whether there are other studies attempting to do something similar – correlate precipitation, impact of CSOs with bathing water quality.

To our knowledge there were no other studies attempting something similar.

Technical corrections

E. coli and Enterococcus intestinalis: small letter for the species name, Italics for Latin. The way E. coli is written needs to be corrected everywhere in the manuscript, including figures.

Text and figures were corrected.

My impression is that “wastewater” is most often written as one word.

Wastewater was modified throughout the manuscript.

“Pollution” and “contamination” seem to be used interchangeably in the manuscript. Consider if it would be better to use one term only, if no difference is meant.

Ok. We used pollution which seems to be more appropriate for our case according to the following definitions:
http://www.fao.org/3/x5624e/x5624e04.htm#1.1%20contamination%20or%20pollution.

REVIEWER 2

The manuscript titled "Evaluating health hazard of bathing waters affected by combined sewer overflows" introduces the use of new health hazard indicators for bathing water, correlating the rainfall volume with the duration of the bathing water contamination.
These indicators are applied in a real world application. For this reason, the authors coupled an urban drainage model using the Infoworks software with a sea water quality model using the MOHID software. The manuscript is well-written, well organized, well structured and is scientifically consistent. The authors provided all the required information and assumptions and did not hide the "weak" approximations. Their method is practical (and still consistent) and can be applied directly to other case studies. I suggest to be published after some minor revisions.

My remarks:
1) In Table 2 there is the variable T in the brackets and I suppose is the return period calculated using the available IDF curves and rainfall duration. Regarding the rainfall intensity, I am a little bit surprised to see such small values (from less than year to 6 years). The authors shall double check these values.

We clarified how the return period was calculated and checked all and corrected some of the values. (Table 2 of the revised manuscript with changes marked)

2) Which is the way for calibrating the urban drainage model? The authors automatized Infoworks and used an optimization algorithm and if yes, which is the algorithm.

We clarified this. (Line 231 of the revised manuscript with changes marked)

3) Which is the objective function for the calibration of the urban drainage model? The sum of the RMSEs?

We clarified this. (Line 231 of the revised manuscript with changes marked)

4) The authors obtained a rather small value for the Manning coefficient at impervious areas (0.013 s/mˆ1.3). Although these areas are mad from asphalt or concrete and are characterized by small roughness, however in real world there are several obstacles in surface, increasing the roughness. Did the authors use constraints for keeping a physical meaning at the variables which were calibrated, or the parameters are considered as black-box parameters?

We added some lines comparing literature values of the Manning coefficient with the ones obtained in our calibration. (Line 249-256 of the revised manuscript with changes marked)

5) Except of the mentioned parameters at the urban drainage model which were calibrated, what did the authors with the rest, such as parameters for the hydraulic structure of the CSO? These are the parameters which were manually calibrated?

We clarified this. (Line 266-272 of the revised manuscript with changes marked)

6) Regarding the sea water quality calibration the authors might provide a magnitude of the computational time (hours, days?) in order to support their decision for manual calibration. Besides they could provide some additional references about the use of Machine Learning in such cases, when a highly computationally demanding software requires calibration.

Finally, taking into account the nature of the observations (some points vs. a dynamic time-series), the process followed by the authors is more a plausible check than a proper calibration and they should discuss about that.

We added the computational time required. We did not add references about machine learning as we consider it beyond the scope of the paper. Finally, we have specified that sparse data and few events are commonly used for calibration and validation of similar studies (Some literature studies were also provided). (Line 309-317 of the revised manuscript with changes marked)

7) The authors classified the rainfall volume to bins (e.g. Fig 11) but the range between 8-10 mm is not appearing. Is there a reason for that?

The manuscript already includes an explanation for the selected rainfall ranges. We further clarified this in the manuscript. (Line 426-437 of the revised manuscript with changes marked)

8) Can the authors support bibliographically their decision to assume that the evolution of E. Coli concentration is done with this linear way or it is an assumption for practical reasons (this does not reduce the importance of their work).

We assume that the reviewer is talking about the E. Coli degradation rate. The manuscript already include some lines discussing the selected E. Coli degradation rates and comparison with literature (section “Calibration and validation of the sea water quality model”). (Line 338-350 of the revised manuscript with changes marked)

~~Evaluating health~~Modelling of E. coli distribution for hazard assessment of bathing waters affected by combined sewer overflows

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Keywords: modelling, CSO, urban drainage, water quality, *E.* ~~Coli~~*coli*, Bathing Water Directive, hazard and risk assessment

Abstract. Combined Sewer Overflows (CSO) affect bathing water quality of receiving water bodies by bacterial ~~contamination.~~pollution. 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~~Pollutant 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~~pollution and the event rainfall volume was developed. ~~Contaminant~~Pollutant 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. The case study presented is part of the EU funded H2020 project BINGO (Bringing Innovation to Ongoing water management—a better future under climate change).

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~~pollutant 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*~~intestinal enterococci (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.~~pollution. 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).~~(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~~*coli* based on ~~contaminant~~pollutant 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 that combined simulated *E. coli* concentration with hazard criteria 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~~pollution 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~~the BINGO project. *E. coli* concentration in the receiving water body were simulated by a coupled urban drainage and sea water quality model that was developed, calibrated and validated based on local observations. Health hazard was then quantified through the coupling of simulated *E. coli* concentrations and hazard criteria that were defined based on the BWD specifications. 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~~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.

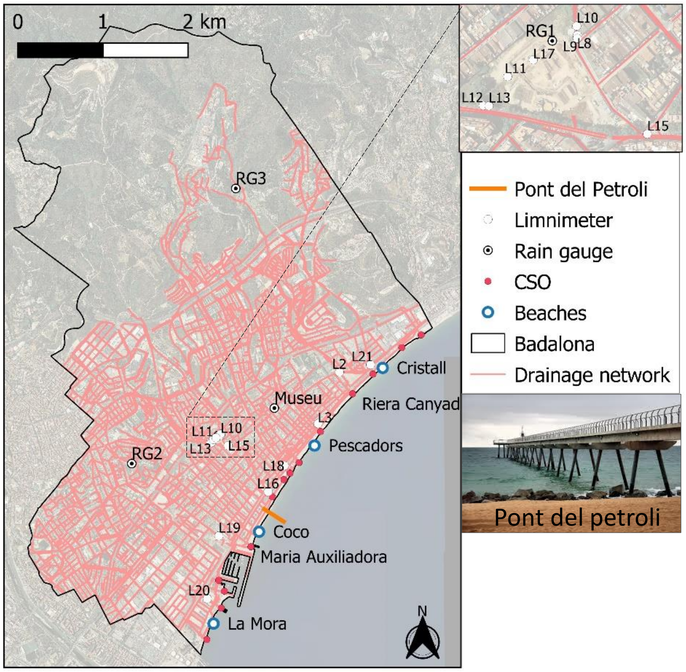


Figure 1~~1~~. Plan view of Badalona together with the drainage network, the name of some of the beaches, the CSO points, the rain gauges, the limnimeters and the pedestrian bridge Pont del Petroli. Background image from © Google Maps.

~~2.2 Definitions~~

2.2 Definition of sea water pollution events

Figure 2~~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).

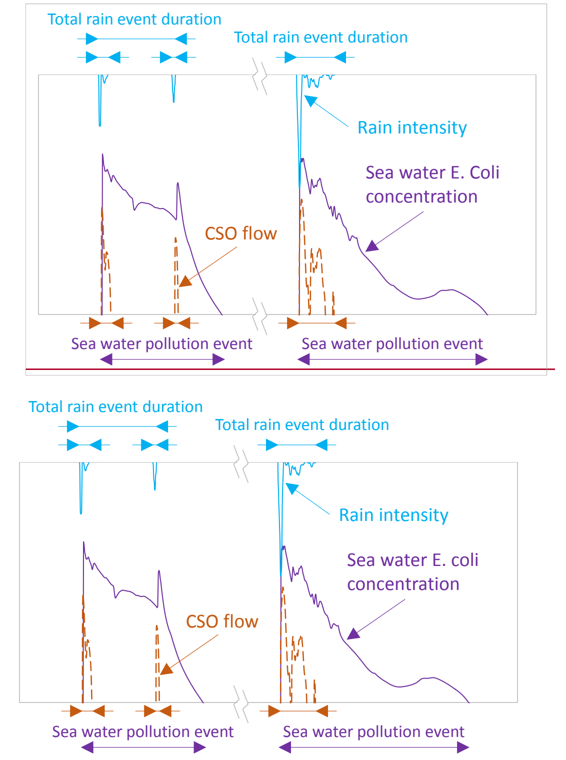


Figure 2~~2~~. Definition of total rain event duration and sea water pollution event.

2.3 The data

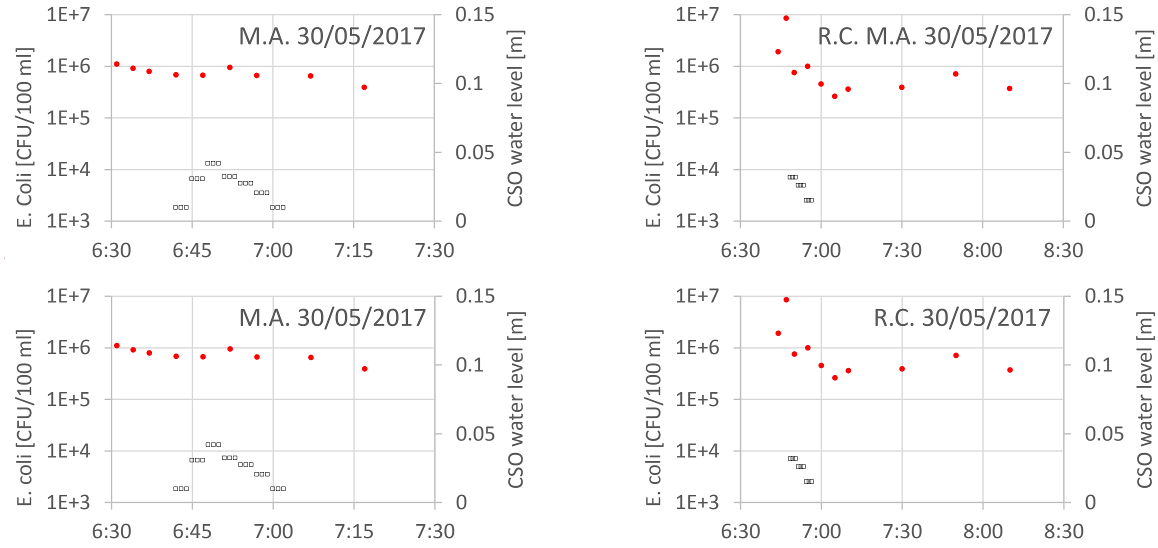
This section provides an overview of the data ~~available~~collected at the case study. Figure 1~~Figure 1~~ shows the location of the 4 rain gauges ~~(tipping buckets of 0.1 mm capacity)~~ and 14 water level sensors that are operating since 2011. These data were relevant for the calibration of the urban drainage model (Section 3.1). The rain gauges RG1, RG2 and RG3 were installed and operational from 2014 providing the time of each tipping of the 0.1 mm buckets 'capacity. The rain gauge of the Museu was installed and operational from 2002 and open access daily rainfall data are available.

Other sensors were also installed in 2015 (as part of the H2020 BINGO project) at the two CSOs points of Maria Auxiliadora and Riera Canyadó (see Figure 1~~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. These water level data were used for calibration of the simulated CSO hydrographs (obtained by the urban drainage model) at the two observed CSO points (Section 3.1). Also, two automatic 12 bottle samplers were installed to measure CSO turbidity, dissolved oxygen demand, suspended solids~~,~~ and Enterococci and *E.* ~~Coli~~*coli* concentrations at the two CSO structures. The measured *E. coli* concentration at CSOs were used for the estimation of CSO concentrations used as inputs for the sea water quality model (Section 3.2). Turbidity, dissolved oxygen demand, suspended solids and Enterococci concentrations were used for other purposes (see H2020 BINGO and LIFE EFFIDRAIN projects) out of the scope of this paper.

~~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~~Figure 3~~ shows both the *E.* ~~Coli~~*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. During the latter event only data from one (Maria Auxiliadora) of the two monitored CSO structures were available. The water level sensors are located after the weirs and ~~the~~they measured the CSO water levels~~ are available only during a CSO.~~. Instead, the bottle samplers for *E.* ~~Coli is measured~~*coli* concentration measurements were located inside the CSO chamber~~ and concentration start to be measured~~. Generally, bottle sampling started (the first bottles were filled) before the ~~beginning of the CSO.~~onset of CSOs. During the CSO event of the 30-5-2017, bottle sampling continued also after the end of the CSO. Instead, in the event of the 24-3-2017 bottle sampling only covered the first approximately 40 minutes of the CSO event. The automatic bottle sampling frequency was set every 3 minutes for the first bottles up to 30 minutes for the last ones. Figure 3~~Figure 3~~a show 4 *E.* ~~Coli measurements that coincide with the CSO~~ *coli* measurements during the CSO (CSO is identified by CSO water levels larger than zero) and Figure 3~~Figure 3~~b only 2. These observations are between $5.7\cdot10^{5}$ and $1.0\cdot10^{6}$ CFU/100 ml (Colony Forming Units). Figure 3~~Figure 3~~c shows 3 *E.* ~~Coli~~*coli* measurements between $8.2\cdot10^{4}$ and $2.3\cdot10^{5}$ CFU/100 ml during the first 40 minutes of the 12 hours long CSO. ~~Analysis~~Further analysis of such observation was not done due to the sparse data.

(a) (b)



(c)

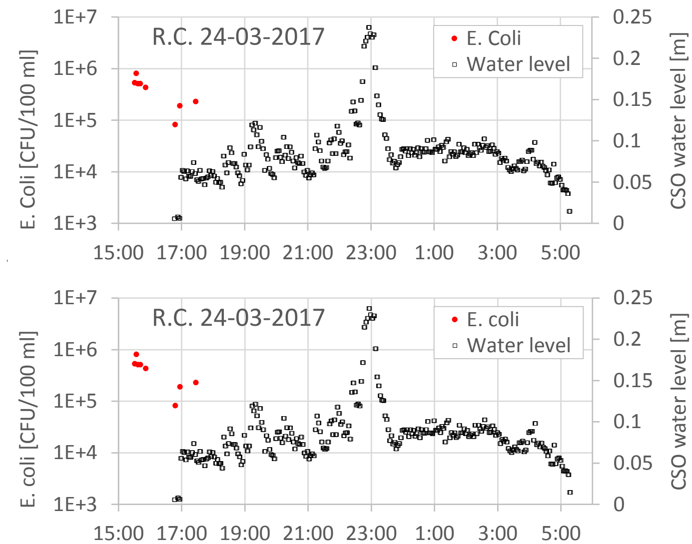


Figure 33. *E.* ~~Coli~~*coli* concentration and CSO water level measured at the two CSO structures of Riera Canyado (R.C.) and Maria Auxiliadora (M.A.).

Sea water quality data were measured by the laboratory technicians of the municipality of Badalona during 5 different field campaigns (in the period 2016- 2018) that consisted in taking sea water samples after (sometimes also during) CSO events. Sea water samples were manually 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 approximately 200 m long pedestrian bridge 'Pont del Petroli' (Figure 1~~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 intestinal enterococci concentrations, salinity, turbidity and suspended solids. 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~~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. Observed sea water *E. coli* and salinity concentrations were used for calibration and validation of the sea water quality model (Section 3.2) and *E. coli* concentrations also for the validation of the hazard assessment (Section 3.3.1). Sea water turbidity, suspended solids and potential oxygen reduction data were not used in this study.

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~~industrial sewage water ~~produced~~fluxes and hydrodynamics in the drainage network over the whole area of Badalona.

The model was originally developed in ~~2012~~MIKE URBAN (www.mikepoweredbydhi.com) for the 2012 Drainage Management Plan (DMP) of Badalona. As part of this study, the model was imported into InfoWorks ICM 8.5 (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~~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~~for each sub-catchment 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 (≤ 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.

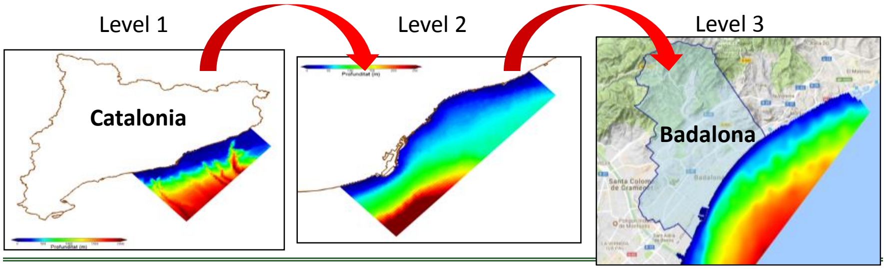


Figure 4. The 3 model domains of the sea water quality model. The colors represent the bathymetry (blue=shallow and red=deep). Background image from © Google Maps.

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

The urban drainage model was calibrated using a trial and error approach with the objective of minimizing the sum of all the Root Mean Square Errors (RMSE) calculated for each of the observation points. The RMSE was calculated for the duration of each simulated event, usually an hour before the beginning of the rainfall and some hours after the end. Table 1~~Table 2~~ shows the 3 events ~~used~~selected 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). These events were considered ideal for calibration and validation because of both the significant observed water level variations in the drainage pipes and the overall quality and quantity of the collected rainfall and water level data. Rain data from the rain gauges were applied in the model using Thiessen Polygons.

Table 1~~2~~. Events used for calibration and validation of the urban drainage model

Date event	**P (mm)** Cumulative rainfall RG1, RG2, RG3	**I_{20Min} (mm/h)** maximum 20 minutes rainfall intensity (T= return period)	**I_{5Min} (mm/h)** maximum 5 minutes rainfall intensity (T= return period)	**Event used for**
22 August 2014	~~25.5~~18.6, 17.4, 26.0	42.6 (T=0.4 y)	74.4 (T=0.6 y)	Calibration
28-29 July 2014	46.5, 36.0, 2.8	56.4 (T=0.~~8~~7 y)	91.2 (T=0.8 y)	Calibration
03 October 2015	33.4, 34.1, 26.0	81 (T=2.~~1~~3 y)	122.4 (T=1.1 y)	Calibration
13-14 September 2016	~~21.7~~30.2, 25.2, 20.2	64.5 (T=1.1 y)	142.8 (T=~~6.~~1.3 y)	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)~~The calibrated 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 not calibrated and it 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 calibrated Manning's roughness coefficient of surface impervious areas was set to 0.013 and the one of pipes was set to 0.012. The calibrated Manning's roughness coefficients are in the lowest parts of the ranges proposed in similar urban drainage studies (Fraga et al., 2017; Locatelli et al., 2017; Russo et al., 2015) and more general hidrologic studies (Dingman, 2015; Henriksen et al., 2003).

Figure 4~~Figure 5~~ shows two examples of simulated and observed water levels at two different locations during 2 different rain events. All the other graphs can be found in (BINGO D3.3, 2019). Table 2~~Table 3~~ shows the computed 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.

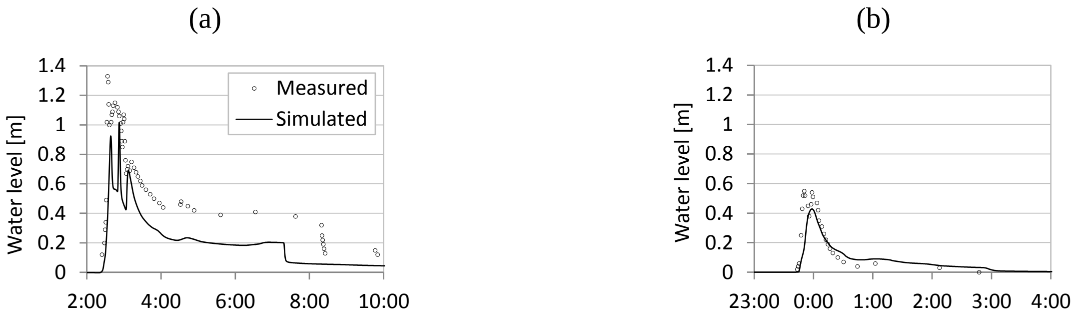


Figure 4~~5~~. Example of simulated and measured water levels in the sewer pipes at the location BA15 during the rain event of the 03-10-2015 (a) and at BA2 the 14-09-2016~~.~~ (b).

Table 23. 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 at the two monitored CSO structures 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 and CSO structure geometry (weir crest level and width) of the two monitored CSO structures. The simulated heightcrest level of these 2 weirs was manually calibratedadjusted by few cm so that the simulated CSO water levels would better fit (visual judgment) the observed ones. It was verified that this manual calibration wouldfurther model adjustment did not affect the errors provided in Table 2Table 3. The crest level and width values of all the other CSO structures were obtained from the database of the network that came from the DMP of Badalona of 2012.

3.2 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 pollutant 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 5Figure 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.

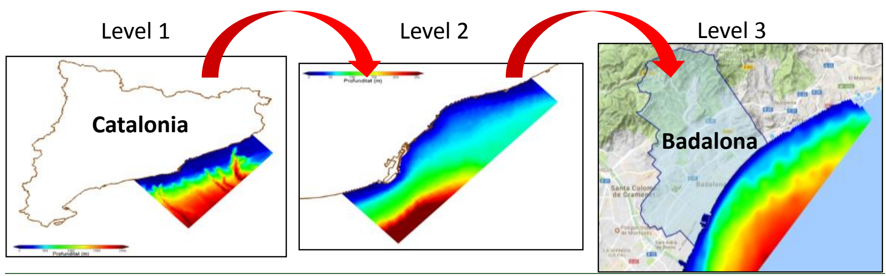


Figure 54. The 3 model domains of the sea water quality model. The colors represent the bathymetry (blue=shallow and red=deep). Background image from © Google Maps.

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).

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). These events were selected because they were the ones with the largest number of sea water *E. coli* and salinity measurements mainly due to both the relatively high observed *E. coli* concentrations and their slow recovering pollutographs. 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 sparse data and 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. The computational time of the sea water quality model was in the order of 2 hours per each simulated day using an Intel(R) Core(TM) i5-6200U CPU @ 2.3 GHz processor.

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*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).(BINGO D3.3, 2019). A fixed E.Coli concentration of $1\cdot10^6$ 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 3Figure 3. Different approaches were presented in the literature: Andersen et al., (2013) simulated CSO dilution using a drainage model with a fixed *E.* Coli*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*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*coli* concentrations of $1.5\cdot10^6$ 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*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 contaminantpollutant 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 6Figure 6 shows the calibrated *E.* Coli*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 6Figure 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.

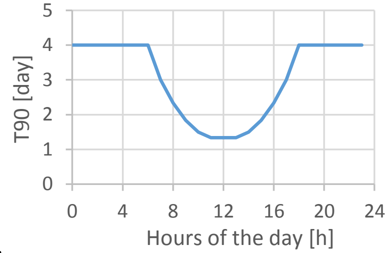


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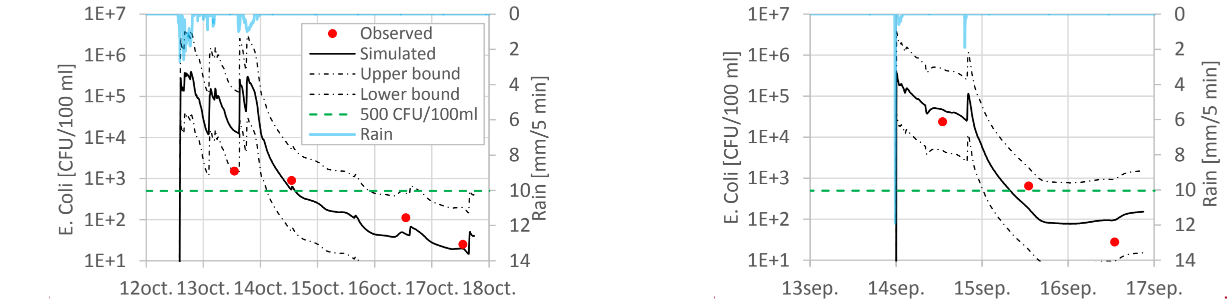
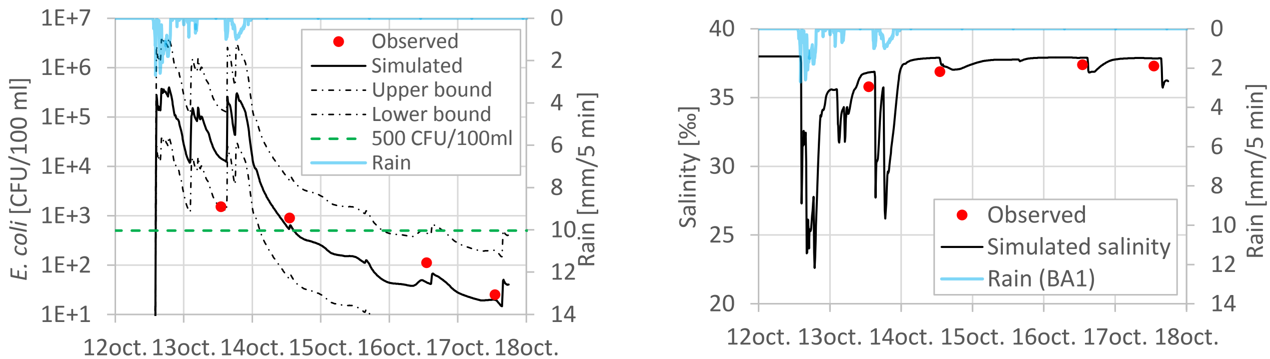
Figure 6~~6~~. Calibrated *E.* ~~Coli~~*coli* decay rate.

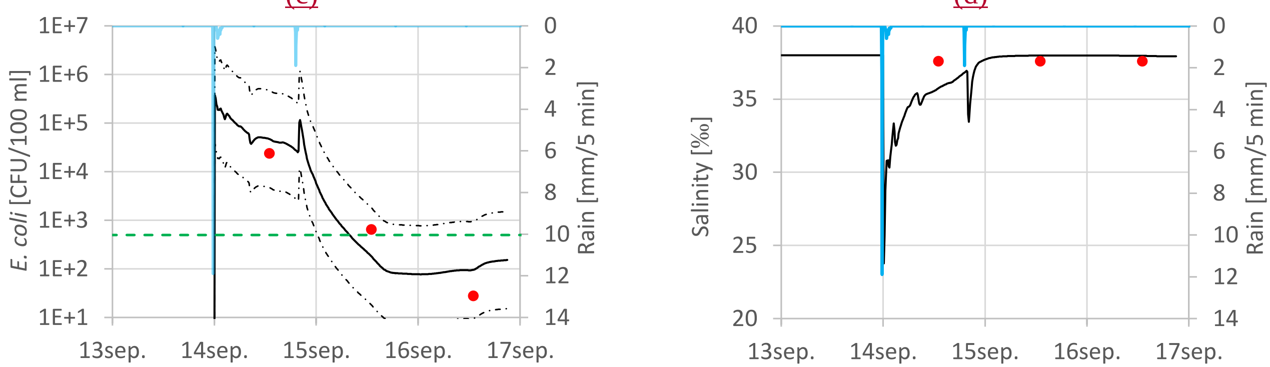
Figure 7~~Figure 7~~ ~~shows two visual examples of~~a, c and e show the simulated versus the observed *E.* ~~Coli~~*coli* concentrations for the calibration and validation events at the near-shore sampling point at the Pont del Petroli. Upper and lower bounds of the simulated concentrations are also shown and were obtained by running the model using both 10^7 and 10^5 CFU/~~100ml~~100 ml as fixed *E.* ~~Coli~~*coli* concentration input at the CSO points (the continuous black line uses 10^6 CFU/~~100ml~~100 ml). 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~~**Figure 7**~~Figure 7~~b, d and f show 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~~*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~~*coli* and salinity were poorly detected.

(a) (b)


E. Coli [CFU/100 ml]
Rain [mm/5 min]
Observed
Simulated
Upper bound
Lower bound
500 CFU/100ml
Rain
12oct. 13oct. 14oct. 15oct. 16oct. 17oct. 18oct.
13sep. 14sep. 15sep. 16sep. 17sep.


E. coli [CFU/100 ml]
Rain [mm/5 min]
Observed
Simulated
Upper bound
Lower bound
500 CFU/100ml
Rain
Salinity [‰]
Observed
Simulated salinity
Rain (BA1)
12oct. 13oct. 14oct. 15oct. 16oct. 17oct. 18oct.

(c) (d)


E. coli [CFU/100 ml]
Rain [mm/5 min]
Salinity [‰]
13sep. 14sep. 15sep. 16sep. 17sep.

(e) (f)

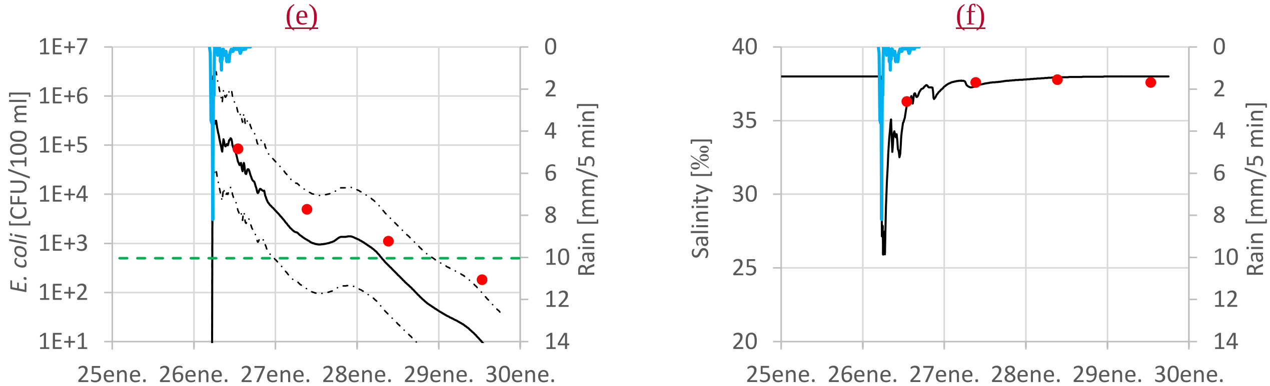

E. coli [CFU/100 ml]
Rain [mm/5 min]
Salinity [‰]
25ene. 26ene. 27ene. 28ene. 29ene. 30ene.

Figure 77. **Examples showing the nearNear**-shore simulated and observed ***E. coli*** concentrations **for the validation event** (a), c and **a calibration one (b).**

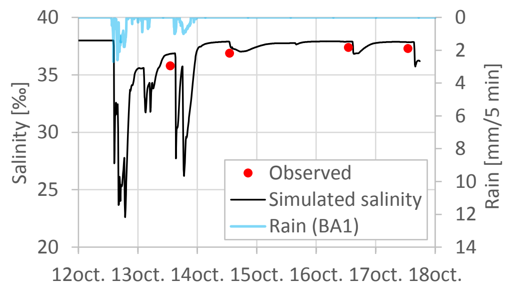


Figure 8. Examples showing the near-shore simulatede) and observed salinity (b, d and f) for the calibration and validation eventevents.

Figure 8Figure 98 shows scatter plots of simulated and observed *E.* Coli*coli* concentrations (a) and salinity (b). The simulated *E.* Coli*coli* concentrations are shown to reproduce the observed ones with an order of magnitude accuracy. Order of magnitude *E.* Coli*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 7**Figure 7b, d and f).

(a) (b)

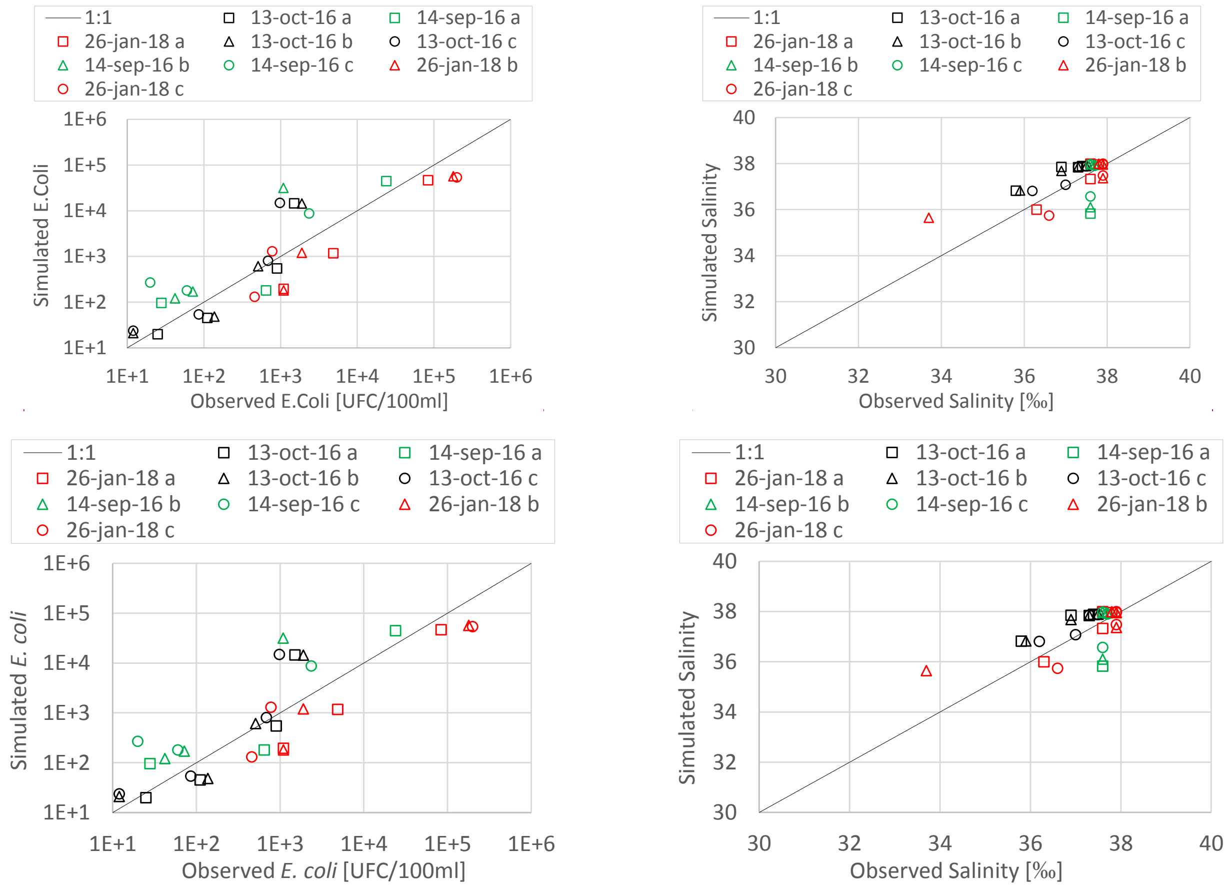


Figure 898. Scatter plots of simulated and observed *E. Colicoli* concentrations (a) and salinity (b).

Table 3Table 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. Colicoli* and Root Mean Square Error (RMSE) for salinity (Bennett et al., 2013; Hauduc et al., 2015). Few studies reported model performance errors for *E. Colicoli* 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 34. Model performance parameters.

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

~~**3.3 Hazard assessment**~~

~~Figure 10~~It is noted that the 3 events used for calibration and validation of the sea water quality model are from September, October and January. It could be relevant to look at more events during the bathing season that is the focus period of the hazard assessment.

2.5 Hazard assessment

Table 4~~Table 1~~ shows the hazard criteria applied. 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/100 ml) 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 simulating 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 (approximately 10 km away from Badalona) located in the neighbor city of Barcelona. Data from Fabra were used as 9 years of continuous high resolution data were not available from Badalona.

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 pollution event. Finally, a validation of the hazard assessment is shown for the duration of insufficient bathing water quality after rain/CSO events.

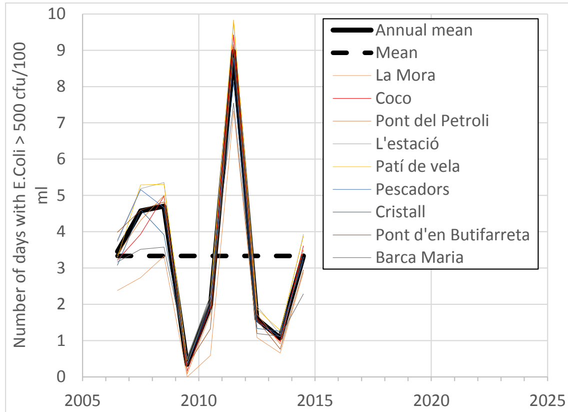
Table 4~~1~~. Hazard criteria based on *E. coli* concentration in sea water

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

3 Results

3.1 Hazard assessment

Figure 9~~Figure 9~~ 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.



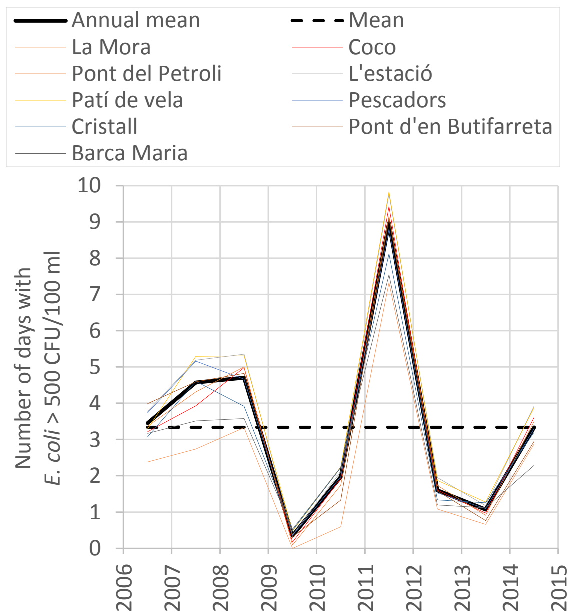
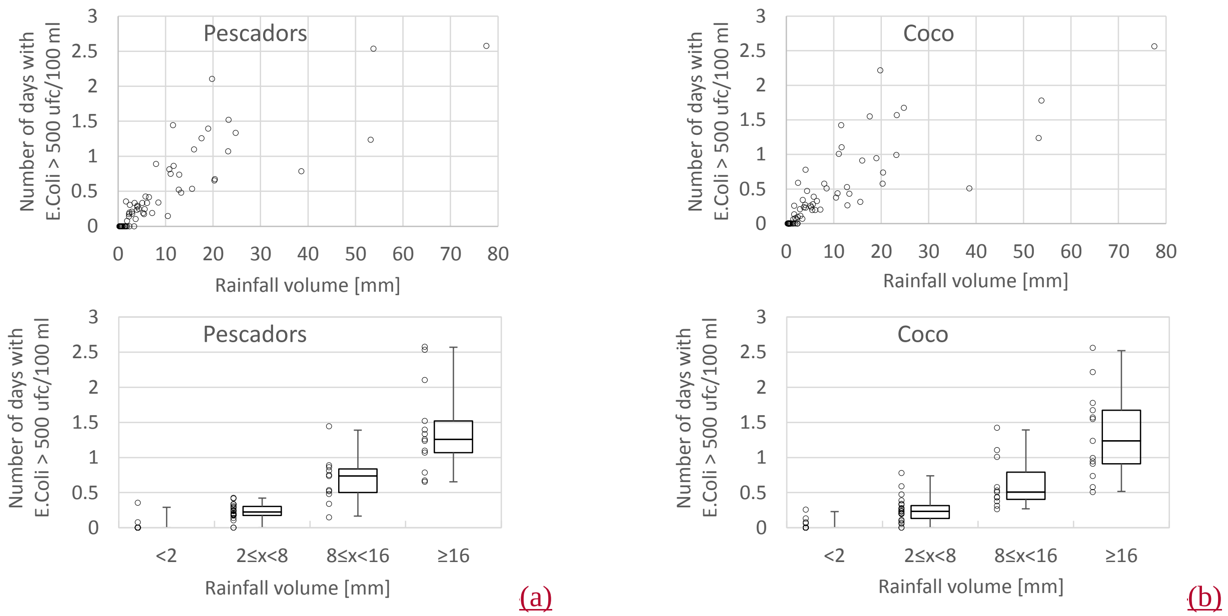


Figure 9~~10~~9. Simulated number of days per bathing season with high hazard (*E.* ~~Coli~~*coli* concentrations > 500 CFU/~~100ml).~~100 ml) at all the different beaches of Badalona.

Successively, the duration of every single sea water pollution event (defined in Figure 2~~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~~Figure 2~~) and the results are shown in Figure 10~~Figure 1110 (top figures).~~a. Figure 10~~Figure 1110~~a shows an example of the results ~~at two beaches (~~from the Coco ~~and Pescadors),~~beach, even though all beaches were analyzed and all the graphs can be found in the delivery D4.4 of the BINDO project. 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~~*coli* concentrations > 500 CFU/~~100ml~~100 ml. 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 10~~Figure 11~~~~10~~ ~~are~~b is a rearrangement of ~~the top ones~~Figure 10~~Figure 10~~a and ~~show~~shows 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~~that considered the total rainfall volume was considered 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 10~~Figure 11~~10 ~~provide~~b provides 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~~12 mm rainfall (that would fall in the bin of 8≤x<16 mm of Figure 10~~Figure 10~~b) is estimated to produce a median of 0.5 days of high hazard~~.~~ at the Coco beach. The percentiles provided with the wisker boxes 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.



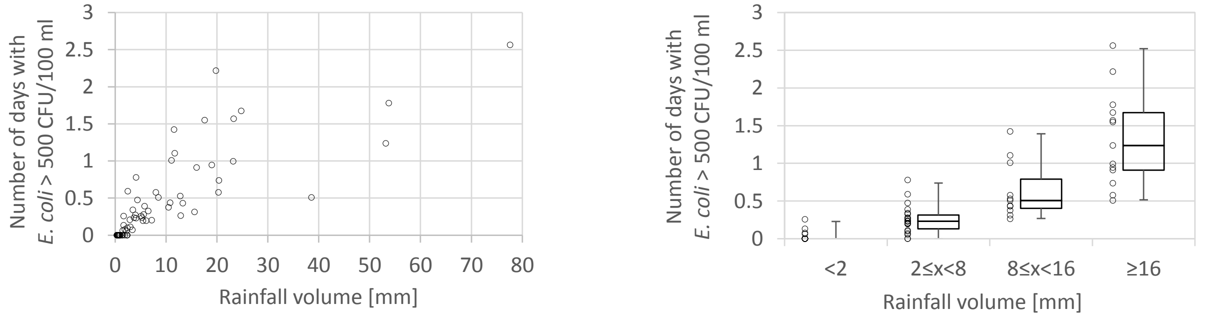
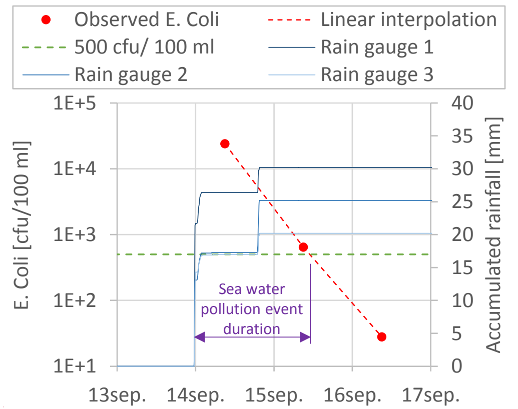


Figure 10~~11~~~~10~~. (a) Correlation between the simulated number of days with sea water *E.*~~Coli~~ *coli* concentrations above 500 CFU/~~100ml~~100 ml at the Coco beach and the rainfall volume~~ at two~~. (b) The rainfall volume is categorized into 4 different ~~beaches (Pescadors and Coco).~~ranges. The wisker boxes show 1st, 25th, 50th, 75th and 99th percentiles.

3.~~3~~1.1 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. The number of days when bathing was forbidden during bathing seasons are available. However, these data cannot be compared with the simulated high hazard because bathing forbidden days are dependent on local protocols that for instance in the case of Badalona allow the reestablishment of bathing permissions only after positive bathing water quality measurements that usually take more than 24 hours to be obtained.

Figure 11~~Figure 12~~11 shows an example of how the duration of a sea water pollution event was graphically obtained based on rainfall data and observed *E.* ~~Coli~~*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 11~~Figure 12~~11) 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.



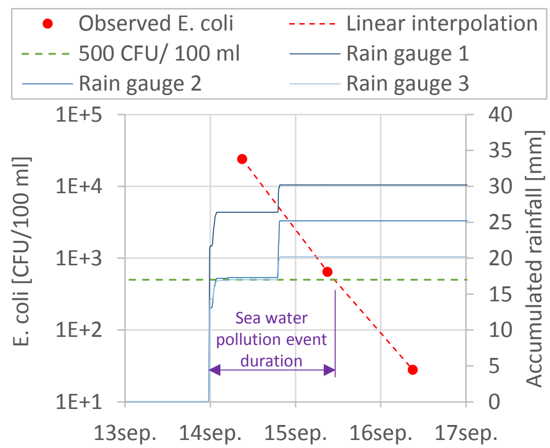
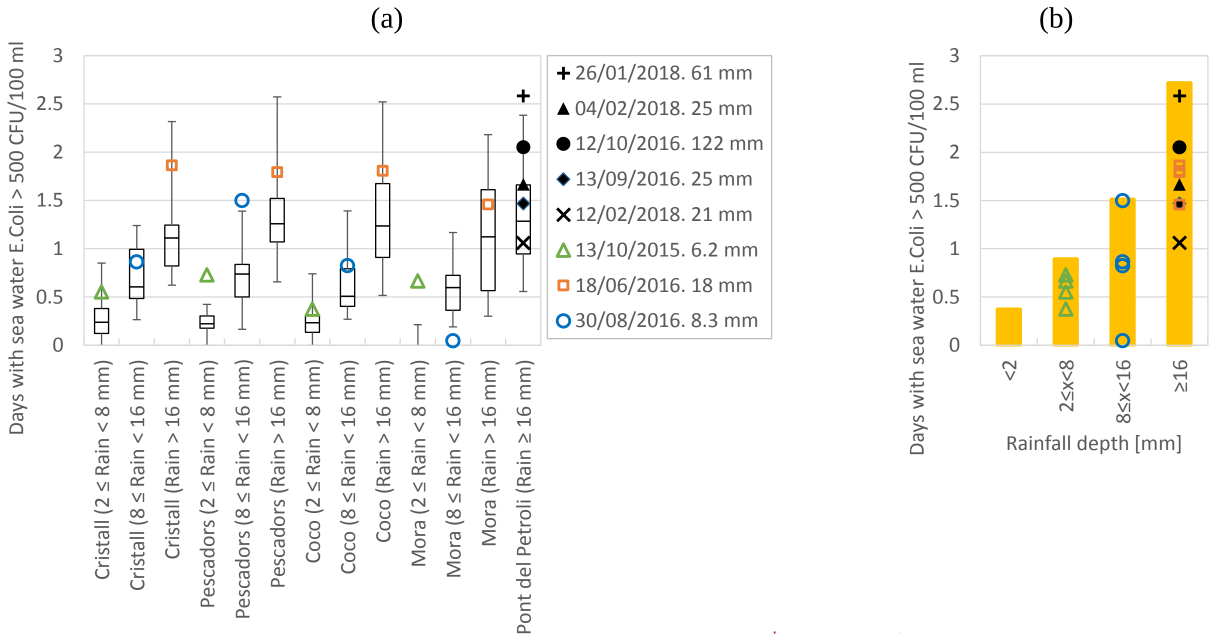


Figure 111211. Example of how the duration of a sea water pollution event was graphically obtained.

Figure 12Figure 1312a 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 simulated 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),(as part of the BINGO project), 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 12Figure 1312b. For this purpose, several steps were applied: the observed sea water pollution duration derived from Enterococci Intestinalisintestinal enterococci observations was compared to the simulated *E.* Coli*coli* percentiles durations of Figure 12~~Figure 13~~12a; 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.



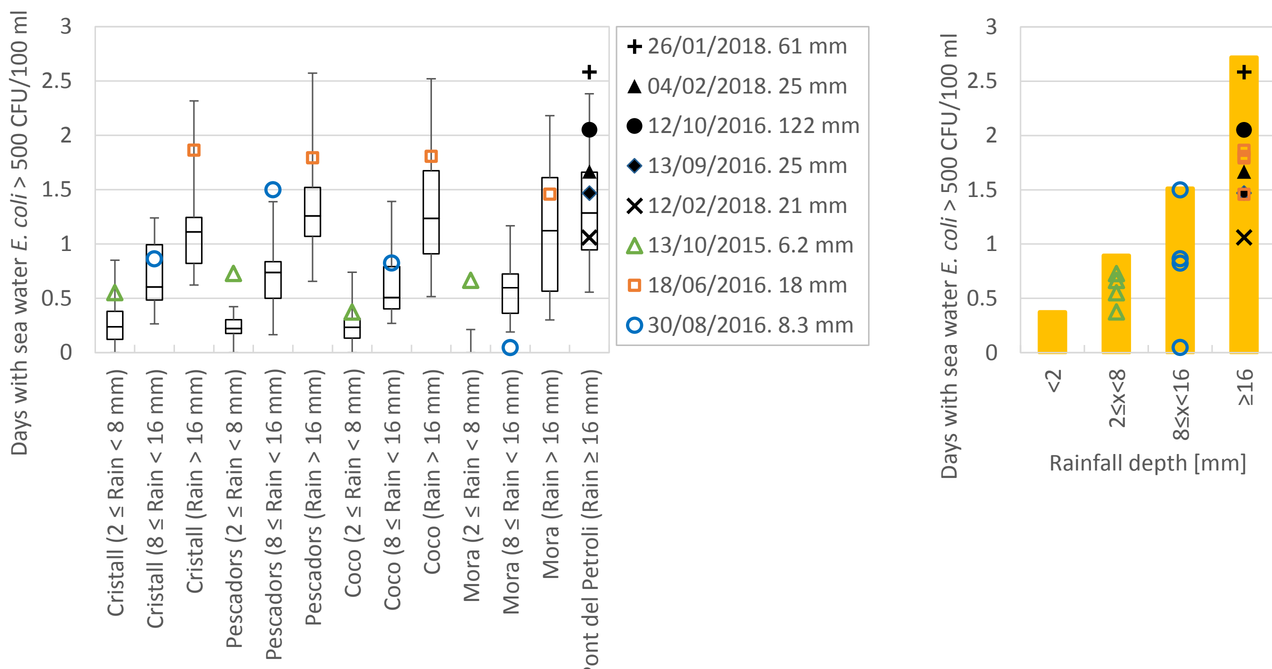


Figure 121312. (a) Comparison between the estimated and the observed duration of high hazard (sea water *E.* Coli*coli* > 500 CFU/100ml100 ml). The wisker boxes show 1^{st}, 25^{th}, 50^{th}, 75^{th} and 99^{th} percentiles of the duration of sea water contaminationpollution. (b) Maximum sea water pollution 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~~pollutant 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~~pollution 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~~pollutant 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 as inputs 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.

Acknowledgments

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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 and Luca Locatelli coordinated the research project. Alejandro Acero Oliete and, Juan Carlos Sánchez Catalán managed the data collection. Luca Locatelli, Beniamino Russo and ~~Montse~~Eduardo Martinez ~~managed the data collection. Luca Locatelli and Beniamino Russo~~ Gomariz developed the conceptual model and Luca Locatelli set-up the model, did the code and performed the simulations. Luca Locatelli prepared the manuscript with the contributions ~~from~~of all co-authors.

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