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Effects of a 20 year rain event: a quantitative microbial risk assessment of a case of contaminated bathing water in Copenhagen, Denmark

S. T. Andersen, A. C. Erichsen, O. Mark and H.-J. Albrechtsen

ABSTRACT

Quantitative microbial risk assessments (QMRAs) often lack data on water quality leading to great uncertainty in the QMRA because of the many assumptions. The quantity of waste water contamination was estimated and included in a QMRA on an extreme rain event leading to combined sewer overflow (CSO) to bathing water where an ironman competition later took place. Two dynamic models, (1) a drainage model and (2) a 3D hydrodynamic model, estimated the dilution of waste water from source to recipient. The drainage model estimated that 2.6% of waste water was left in the system before CSO and the hydrodynamic model estimated that 4.8% of the recipient bathing water came from the CSO, so on average there was 0.13% of waste water in the bathing water during the ironman competition. The total estimated incidence rate from a conservative estimate of the pathogenic load of five reference pathogens was 42%, comparable to 55% in an epidemiological study of the case. The combination of applying dynamic models and exposure data led to an improved QMRA that included an estimate of the dilution factor. This approach has not been described previously.

Key words | combined sewer overflow, dilution factor, extreme rain event, hydrodynamic modelling of bathing water quality, hydrodynamic modelling of sewers, quantitative microbial risk assessment

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INTRODUCTION

Contamination of bathing water by combined sewer overflows (CSOs) from extreme rain events is problematic, causing several outbreaks among people taking part in recreation (Curriero *et al.* 2001; Ahern *et al.* 2005). The risk of such events can be assessed by quantitative microbial risk assessment (QMRA) (Donovan *et al.* 2008; Veldhuis *et al.* 2010; Viau *et al.* 2011). QMRA is a well-recognised tool to estimate the risk of disease but often relies on many assumptions, especially regarding water quality and hydrological conditions due to insufficient quantitative data. Further epidemiological data are typically lacking, thus preventing validation of the QMRA.

To apply QMRA to CSO-contaminated bathing waters much information is required: on concentration of pathogens, exposure of the swimmers to the pathogens, and dose-response relations for each pathogen. However, the quality of the source water will vary with time and environmental conditions and following dilution in the receiving waters. Hence, estimation of the exposure concentration is a difficult part of QMRA, especially when sampling and analysing are impossible, and estimating the health risk from a CSO is a challenge.

The concentrations of pathogens in sewage, exemplified by the bacteria *Campylobacter jejuni* and the parasites *Giardia* and *Cryptosporidium*, vary between studies (Payment *et al.* 2001; Pusch *et al.* 2005; Ottoson *et al.* 2006; Rechenburg & Kistemann 2009), and are influenced by catchment type, seasonality and sanitary conditions.

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Furthermore, the time of contamination, type of recipient and decay of the pathogens from the time of contamination until exposure are central variables often estimated or excluded from the risk assessments due to inaccessibility of data. Finally, dilution by rain and recipient water has to be estimated when quantitative data are missing. It has become possible to generate estimates by a combination of hydraulic and hydrodynamic models, exemplified by the dynamic bathing water models established in the harbour of Copenhagen in 2002 (Mark & Erichsen 2007) and in Barcelona in 2008 (Gutiérrez *et al.* 2010). However, very few such models exist and this kind of application is very rare.

An extreme rain event, a 20 year event in August 2010 in Copenhagen, Denmark, led to CSO into bathing water where an international ironman competition was held shortly afterwards and where the resulting outbreak was studied epidemiologically (Harder *et al.* 2010).

The aim of the current study was to advance the quality of the QMRA by better estimates of the water quality by applying dynamic hydraulic models to provide information on the dilution of waste water from the drainage system to the recipient bathing water, and subsequently to evaluate the results of the QMRA by comparing the results to an epidemiological study of the ironman competition.

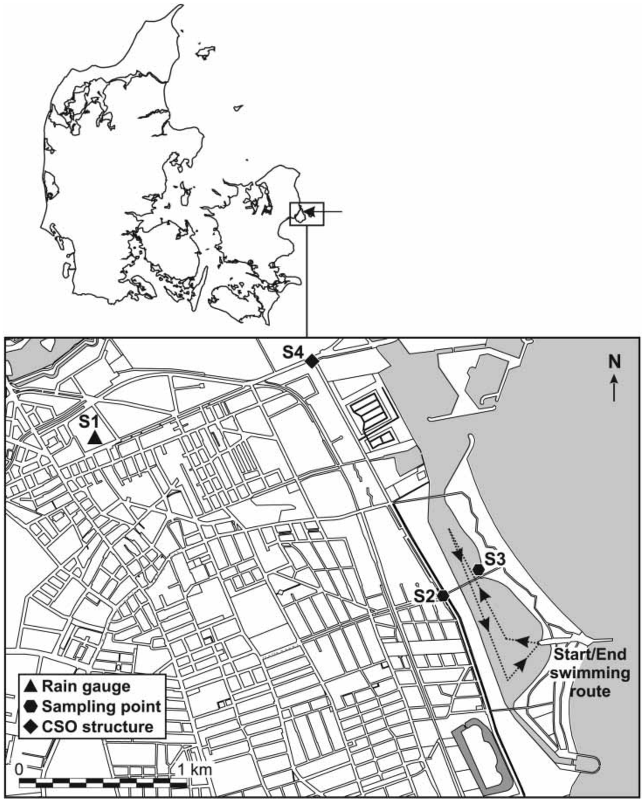

Figure 1 | The catchment investigated with sampling locations for water quality analysis. A rain gauge (S1) and a CSO structure (S2) are located to the north. Sampling point for the sewer system (S3) and bathing water station 375 (S4) are shown. The swimming route, with start and end points of the ironman competition, is shown by arrows.

METHODS AND MATERIALS

Study site

A recreational area including a lagoon with bathing water in the catchment of Kloevermarken is located in Copenhagen, Denmark (Miljoeforvaltningen 2008). The lagoon hosted the swimming part of an ironman competition in 2010; the swimming route is shown in Figure 1. A combined sewer outlet is located 1 km north of the bathing area. However, overflow did not occur during the period 2007–2010, as shown by the online registration system. The combined sewer outlet has a maximum discharge capacity of 6.9 m^3/s and receives waste water from the catchment of Kloevermarken where residential and industrial structures and a hospital are located. A local rain gauge, operated by the Danish Meteorological Institute (DMI) is sited 1 km northwest of the bathing area.

The ironman competition

The ironman competition is one of the most challenging triathlons. The contest consists of open water swimming (3.8 km), cycling (180 km) and running (42.2 km). On 15 August 2010, an ironman triathlon took place in Copenhagen, Denmark, starting at 07:00 hours (Figure 2), and 1312 competitors (1,164 male, 148 female) completed the whole distance (KMD, Challenge Copenhagen, results 2010), with average swim times of 76 min (range 46 to 166 min). The ironman competition was repeated one year later on 14 August 2011 (Figure 2), when 1365 competitors (1,196 male, 169 female) completed the whole distance (KMD, Challenge Copenhagen, results 2011).

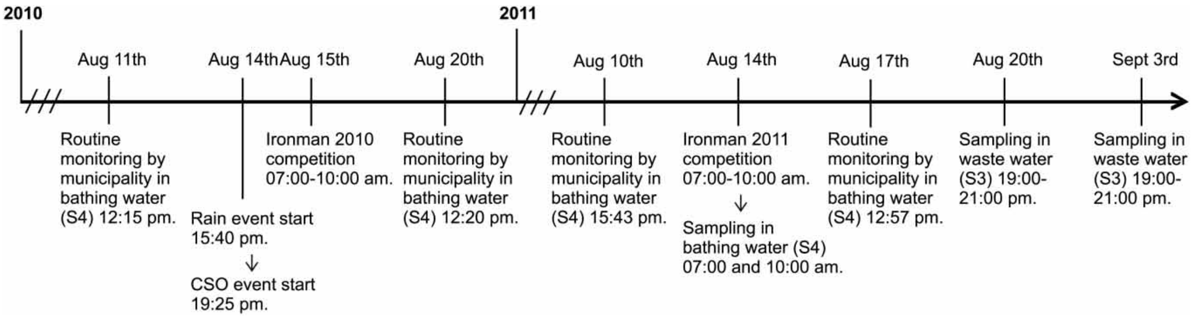

Figure 2 | Timeline showing date and time of the rain and CSO event, the ironman competitions of 2010 and 2011, routine monitoring by the municipality in bathing water (location S4) and sampling in waste water (location S3).

Dynamic modelling

Two models, (1) a drainage model (Garsdal *et al.* 1995) and (2) a 3D hydrodynamic and bacterial model, were applied to determine the degree of contamination in the bathing area at the time of the ironman competition. The drainage model was applied to estimate the quality of the CSO water by determining the dilution factor in the sewer system during and after the heavy rain event. The hydrodynamic and bacterial model was applied to estimate the quality of the recipient water by determining the dilution factor of the CSO water in the recipient water.

The drainage model covered 76 km^2 with three main catchments, and the waste water was pumped to the Lynetten treatment plant. The urban drainage model applied for this study was MIKE URBAN (Andersen *et al.* 2004) a 1D fully hydrodynamic sewer model based on an implicit finite difference scheme. The model set-up included a drainage system with approximately 5,000 nodes and drainage pipes. The diameter of the pipes was 400 mm or larger. Internal overflow pipes and weirs were all included. For the simulations of water quality, an advection-dispersion and a water quality process module was applied, including four water quality parameters (suspended solids, chemical oxygen demand, ammonium and phosphorus) together with the flow, flow velocity and water levels, which can be used to validate the modelling results with measurements.

The hydrodynamic and bacterial model used in this study is now part of the early warning system for the bathing water quality in Copenhagen (Kaas *et al.* 2011). This model comprised free surface, stretched sigma coordinate, flexible mesh, finite volume hydrodynamic solver models (MIKE 3 FM) combined with a dynamically coupled open differential equation solver model (MIKE ECO Lab). The hydrodynamic model solves the time-dependent conservation equations of mass and momentum in three dimensions, the so-called Reynolds-averaged Navier-Stokes equations. The flow field and pressure variation are computed in response to a variety of forcing functions, when provided with the bathymetry, bed resistance, wind field, hydrodynamic boundary conditions and other parameters. The hydrodynamic model is superimposed with an equation solver (ECO Lab) modelling the decay of the two indicator bacteria *Escherichia coli* and intestinal enterococci based on key forcing factors such as irradiance, temperature and salinity. The model is provided with online CSO data from surrounding municipalities (Soerensen & Andersen 2005). All times in this study are given as coordinated Universal Time (UTC).

Water sample collection and analysis

To evaluate the waste water quality of the catchment, for use in the QMRA, waste water was collected on 20 August and 3 September 2011 during dry weather conditions at sampling point S3 (Figure 1), since waste water data from 2010 were unavailable. To investigate the bathing water quality at the time of the ironman 2011 competition, when no CSO contamination took place, bathing water was collected at sampling point S4, the sampling point of the official bathing monitoring programme.

All water samples were immediately put on ice, stored in the dark and processed within 6 hours after collection. The sampling followed the standard procedure (DS/EN ISO

5667: 2007). The indicator organisms *E. coli* and enterococci spp. were quantified by Colilert-18 and Enterolert detection kits in connection with the Quantitray 2000 system (IDEXX, Westbrook, Maine, USA), according to the manufacturer's instructions.

Microbial risk assessment

A conceptual model of human health risk assessment was established to estimate the risk of swimming in CSO-contaminated bathing water. The incidence rate was investigated for a single exposure event of healthy males and females competing in the ironman competition. The primary route of exposure was assumed to be ingestion since the participants swim in whole body suits, bathing caps and flippers. Other routes were not considered. The terminal point for pathogenic exposure was therefore swimming-related gastrointestinal illness. Ingestion values of 0.60 mL/min for men and 0.44 mL/min for women was applied from Schets *et al.* (2011) and weighted in the dose estimation of the 1,164 men and 148 women who participated in the ironman competition in 2010. The average exposure time was applied to estimate the dose.

The reference pathogens selected for the risk assessment are shown in Table 1. *C. jejuni*, *Giardia lamblia* and *E. coli* (ETEC) were identified by Statens Serum Institut (SSI, Denmark) as gastroenteritis-causing organisms at the ironman 2010 competition (Harder *et al.* 2010). *Norovirus* and *Cryptosporidium parvum* were not reported, although these two pathogens are common disease-causing organisms with low infectious doses (Teunis *et al.* 2008a; Pintar *et al.* 2009); they have been assumed to be important aetiological agents for gastrointestinal illness in the assessment reported.

The most conservative estimate was applied to assess the dose. The average dilutions of waste water, swim time and ingestion load was therefore applied. A conservative estimate of the concentrations of the five reference pathogens was applied, since the literature survey showed that the pathogen concentrations may vary by several orders of magnitude (Table 2) and no measurements of the pathogenic load from the actual case was available.

Dose-response models, obtained from the literature, were used to estimate the probability of infection (Table 1).

RESULTS AND DISCUSSION

The heavy rain event

In the afternoon of 14 August 2010 unusually intense rainfall hit the eastern parts of Denmark (Figure 2). Within eight hours the rain gauge measured 58 mm of rain corresponding to a return period of 20 years and 9.5% of the yearly rain in Copenhagen, Denmark. The rain intensity peaked between 16:00 and 18:00 and 19:00 to 19:30 to reach a maximum of 1.8 and 2.4 mm per 5 min (Figure 3). The high rain intensities overloaded the sewer system of the catchment and lead to a CSO event between 17:30 and 20:00 (Figure 3). The maximum overflow intensity reached 2.84 m^3/s, corresponding to 41% of the maximal capacity of the overflow structure. In total 26,300 m^3 CSO water was discharged within a five hour period. Essentially no overflow events were recorded in the previous period

Table 1 | Dose-response models

Reference pathogen	Dose-response relationship	Model	Reference
C. jejuni	$P_{inf} = 1–(1 + D/7.59)^{-0.145}$	B-p	Medema *et al.* (1996)
E. coli and O157:H7	$P_{inf} = 1–(1 + D/45.9)^{-0.4}$	B-p	Teunis *et al.* (2008b)
G. lamblia	$P_{inf} = 1–e^{-d/0.0199}$	Exp.	Teunis *et al.* (1996)
C. parvum	$P_{inf} = 1–(1 + D/0.176)^{-0.115}$	B-p	Teunis *et al.* (2002)
Norovirus	$P_{inf} = 1–(1 + D/0.055)^{-0.04}$	B-p	Teunis *et al.* (2008a)

P_{inf}, probability of infection; D, dose ingested.
[a]B-p, Beta-poisson;
[b]Exp., exponential.

Table 2 | QMRA for the ironman 2010 competition with estimated pathogen concentration in the CSO water and recipient water applied for estimating pathogen concentration in recipient, dose, risk, disease incidence and percentage infected. For calculations, maximum literature value of pathogen concentrations was used

	Literature value conc. in waste water	CSO[f] (% waste water)	Recipient[g] (% CSO)	Conc. in recipient water (mL^{-1})	Dose[h] (org. $swim^{-1}$ mL^{-1})	Risk ($person^{-1}$)	No. of cases ($n = 1312$)	Incidence rate (%)
Pathogen								
C. jejuni	10^2–10^5 CFU/100 mL[a]	2.6	4.8	1.24×10^{-1}	5.48×10^{0}	7.58×10^{-2}	99	7.6
E. coli O157	0–5,000 MPN/L[b]	2.6	4.8	6.20×10^{-5}	2.74×10^{-3}	2.39×10^{-5}	<1	0.002
G. lamblia	20–13,600 cysts/L[c]	2.6	4.8	1.69×10^{-4}	7.46×10^{-3}	3.13×10^{-1}	410	31.3
C. parvum	<8–1,100 oocysts/L[d]	2.6	4.8	1.36×10^{-5}	6.03×10^{-4}	3.93×10^{-4}	<1	0.04
Norovirus	<1–10^6 PDU/L[e]	2.6	4.8	1.24×10^{-2}	5.48×10^{-1}	2.73×10^{-2}	36	2.7
Total							546	42

PDU: PCR detectable units.

[a] *Sources:* Höller (1988); Rechenburg & Kistemann (2009); Veldhuis *et al.* (2010).

[b] *Sources:* Garcia-Aljaro *et al.* (2005); Heijnen & Medema (2006).

[c] *Sources:* Robertson *et al.* (2000); Medema & Schijven (2001); Payment *et al.* (2001); Briancesco & Bonadonna (2005); Ottoson *et al.* (2006); Robertson *et al.* (2006); Veldhuis *et al.* (2010).

[d] *Sources:* Robertson *et al.* (2000); Payment *et al.* (2001); Ottoson *et al.* (2006); Robertson *et al.* (2006).

[e] *Sources:* Lodder & Husman (2005); Pusch *et al.* (2005); Ottoson *et al.* (2006); Katayama *et al.* (2008).

[f] Result from drainage model.

[g] Result from hydrodynamic and bacteria models.

[h] Dose by average swim time of 76 min. Highest load of pathogen concentration.

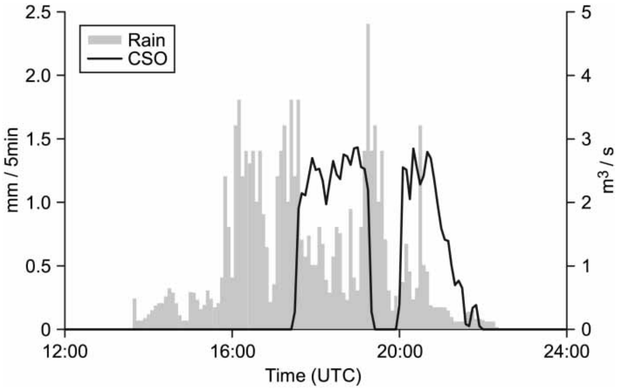

Figure 3 | Measured volumes from the rain gauge (mm/5 min) and the combined sewer overflow (CSO), (m^3/s), 14 August 2010.

of 2007–2010, which demonstrates the extremity of this heavy rain event.

Dilution factor

To assess the dilution of waste water from the drainage system in the bathing water, dynamic modelling was applied since actual measurements of the bathing water quality were unavailable. The dilution of the waste water by rainwater in the combined drainage system was determined by applying rain data as input to the drainage model (Mark *et al.* 1998). In the drainage system, the average dilution factor was estimated to be in the range 26.8–45.5 with an average of 38.5 within the time of the rain event. This corresponded to 2.2–3.7% waste water with an average of 2.6% (Table 2).

The dilution in the recipient water was determined by applying online flow data from the CSO as input to the 3D hydrodynamic model, resulting in a dilution factor of 21. This corresponded to 4.8% CSO water on average in the recipient at the time of the ironman competition (Table 2), with a 0.5% variation within the time of the competition (Figure 4). By combining the outputs of the two models, a total of 0.13% of waste water was present in the recipient at the time of the ironman competition, showing that the waste water was highly diluted by the rainwater and in the bathing water.

One of the major uncertainties of QMRA is the dilution from source to recipient and therefore the water quality at the time of exposure, which typically has to be assumed. However, the use of dynamic models made it feasible to assess the dilution in different waters in the absence of water quality measurements. This approach of combining a drainage model and a hydrodynamic and bacterial

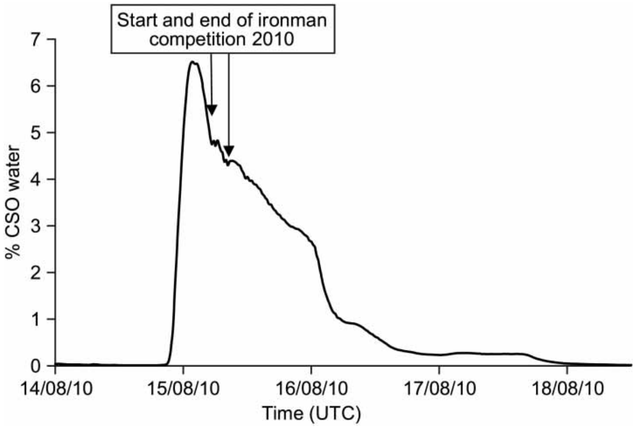

Figure 4 | Model output of percentage CSO water in measurement point 375 (location S4). Start (05:00) and end (08:00) of the ironman competition are marked by arrows.

model for estimating the dilution factor in a QMRA has not been described previously.

Contamination

Routine monitoring and the hydrodynamic and bacterial model showed that the recipient water was of excellent quality a few days before and after the CSO event (Table 3). At the time of the ironman competition, the hydrodynamic and bacterial model forecasted that the water from the CSO had been directed to the swimming area for the competition (Figure 5). Bacterial counts for the centre of the lagoon (sampling point S4) were estimated in terms of most probable number (MPN) to be $1.7–2.6 \times 10^4$ MPN/100 mL *E. coli* (mean 2.2×10^4 MPN/100 mL, standard deviation (SD) 2.6×10^3 MPN/100 mL) and $5.1–6.4 \times 10^3$ MPN/100 mL enterococci (mean 5.8×10^3 MPN/100 mL, SD 400 MPN/100 mL) was estimated (Table 3). The EU limits for good water quality (Directive 2006/7/EC) of 200 MPN/100 mL enterococci and 500 MPN/100 mL *E. coli* for coastal and transitional waters were therefore greatly exceeded. No measurements were available for comparison.

When the ironman competition was repeated in 2011 and no CSO took place, the monitoring and the model showed excellent bathing water quality, except at 10:00 hours where 347 MPN/100 mL enterococci spp. were detected (Table 3). The concentration of *E. coli*, coliforms and ammonia was unchanged supporting the absence

Table 3 | Bathing water quality, monitored and modelled, before, for the duration and after the ironman competitions and estimation of disease rate and incidence rate for the duration of the ironman competitions in 2010 and 2011

		Monitoring[a]		**Modelling**[b]			
Date	**Time**	***E. coli*** **MPN/100 mL**	**Enterococci MPN/100 mL**	***E. coli*** **MPN/100 mL**	**Enterococci MPN/100 mL**	**No. of cases of disease (monitored/modelled)**[c]	**Incidence rate (%; monitored/modelled)**
2010						$n_{2010} = 1312$[d]	
11 August	12:15	30	2	3	34	–	–
15 August	07:00	n.m.	n.m.	25,800	6,400	–/1,312	–/100
	10:00	n.m.	n.m.	16,800	5,100	–/1,222	–/90
18 August	12:20	<10	5	<1	2	–	–
2011						$n_{2011} = 1{,}365$[d]	
10 August	15:43	44	35	<1	<1	–	–
14 August	07:00	94	98	<1	<1	24/–	1.8/–
14 August	10:00	113	347	<1	<1	87/ –	6.3/ –
17 August	12:57	<10	<1	<1	<1	–	–

– Values cannot be calculated as there was no monitoring.
[a] Sampling point S3.
[b] From 3D hydrodynamic model at sampling point S3.
[c] Calculated from Prüss (1998), WHO (2003) and Kay *et al.* (2004); 104 MPN/100 mL enterococci equals 19/1000 persons with disease.
[d] Competitors (male and female), completing the whole ironman distance.
n.m., not measured.

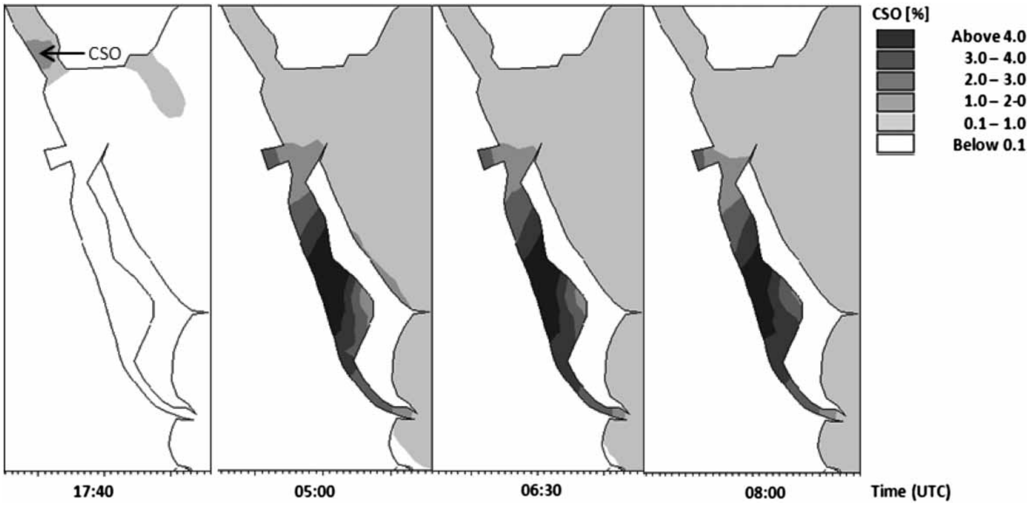

Figure 5 | Model output of percentage CSO water in the bathing water August 14–15 2010, start of overflow (17:40), and start (05:00), middle (06:30) and end (08:00) of the ironman competition.

of faecal contamination (results not shown) and that the presence of the swimmers did not affect the water quality.

Waste water quality

Concentrations of the indicators *E. coli* and enterococci spp. were investigated to estimate the waste water quality in the drainage system of Kloevermarkens catchment. To avoid the impact of the weekday and to mimic the seasonal conditions of the system, waste water was collected on two independent Saturdays, with hourly sampling from 17:00 to 19:00, the time of the CSO event in 2010 (Figure 2). The *E. coli* and enterococci spp. concentrations were in the range of 10^5–10^6 MPN/100 mL (Figure 6). The variation within the hourly sampling was minor, 0–7% for *E. coli* and 0.5–8.7% for enterococci. Within the sampling days, the difference in concentrations was ten-fold for *E. coli* and five-fold for enterococci, exemplifying the difficulty in classifying waste water quality. In conclusion, the indicator levels are similar to other studies of waste water (Kim *et al.* 2009; Soller *et al.* 2010).

Risk assessment

To assess the risk of disease, a QMRA was conducted by applying the results from the dynamic models and exposure data from the ironman competition. The QMRA was conducted by a conservative estimate of average values of dilution factor and swimming times. The total incidence rate, when analysing for five reference pathogens and the average swim time of 76 min, was 42%, corresponding to 546 competitors out of 1313 acquiring disease (Table 2). In the epidemiological study of the related outbreak, the incidence rate was 55% among the competitors (Harder *et al.* 2010). Similar studies related to water contamination by CSO or treated waste water have shown that compromised water quality of the recipient waters correlate with an increased risk of disease (Donovan *et al.* 2008; Åström *et al.* 2009; Dura *et al.* 2010; Passerat *et al.* 2011).

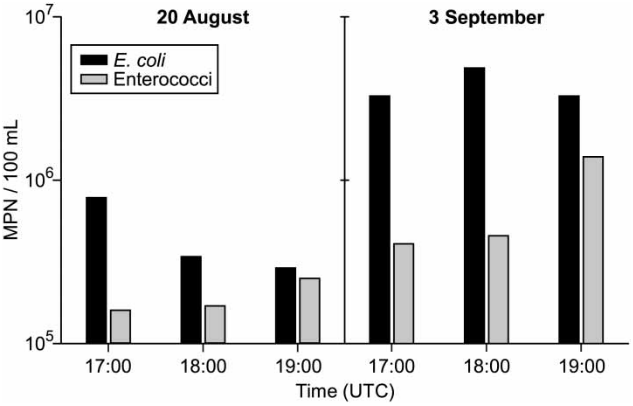

Figure 6 | Indicator concentrations in waste water at sampling point (S3) for the duration of dry weather conditions, 20 August and 3 September 2011.

The average values from the two dynamic models were applied to estimate the dilution of waste water to the recipient water. Uncertainty of the model outputs due to hydraulics may lead to less dilution and thereby a lower dose estimate than the actuality, shown by the lower incidence rate found in this study than the one found in the epidemiological study. Furthermore, the output of the 3D hydrodynamic model showed that the contamination was highest at the beginning of the ironman competition and lowest at the end (Figure 4). Also the concentrations of the pathogens were uncertain, with no actual measurements or knowledge of the decay of the pathogens. Finally, the health issues of the ironmen themselves, due to their physical fitness and the extreme physical challenge of the competition, may influence the incidence rate whereby more complaints of gastrointestinal disease occur (Jeukendrup *et al.* 2000).

The estimated incidence rate was expected to be higher than that observed due to the application of a conservative estimate of waste water dilution along with the conservative scenario for pathogen concentration and the dose-response. However, the estimated disease rate was lower than observed, possibly because the models estimate too high a dilution or because waste water contains a broad diversity of parasites, bacteria and virus (Vestergaard *et al.* 2007) and therefore other pathogens than the five reference ones evaluated here would contribute to the disease rate of the outbreak. One example is the outbreak in Koege, Denmark, in 2007 where tap water was contaminated with waste water. *C. jejuni*, norovirus and *E. coli* (A/EEC; attaching and effacing *E. coli*) were the major disease-causing organisms and several other parasites and bacteria were detected (Vestergaard *et al.* 2007). Another potential disease-causing organism is adenovirus, which has been found to be prevalent in waste water, influent and effluent of a treatment plant (Hata *et al.* 2013).

The estimated incidence rate of 7.6% of *C. jejuni* corresponded to the 6% found in the epidemiological study where *Campylobacter* spp. was investigated in faecal samples (Harder *et al.* 2010). This was not surprising since *Campylobacter* spp. is one of the most frequently detected waterborne pathogenic organisms in Denmark. The incidence rate of norovirus was 2.7%, thereby acting as a minor contributor to the incidence rate. *G. lamblia* constituted the highest risk with an estimated incidence rate of 31% and *C. parvum* less than 1% (Table 2). This was not surprising since *C. parvum* typically is of lower prevalence than *G. lamblia* (Rijal *et al.* 2009). It is not obligatory to report disease caused by *G. lamblia*, *C. parvum* and norovirus in Denmark, so it is difficult to categorise their typical prevalence.

Although gastrointestinal infections by *E. coli* are common, dose response models of each subtype of *E. coli* do not exist as such except for *E. coli* O157 (Table 1). But the natural habitat for this subtype is the intestines of cattle (Heijnen & Medema 2006), and it may not be representative of urban areas. In this study the *E. coli* O157 contribution was minor, probably because the waste water came from an urban area. Furthermore, in outbreaks related to waste water in Denmark occurrence of *E. coli* O157 has not been documented.

The QMRA indicated a causal relation between CSO and disease by underlining the fact that swimming in bathing water contaminated by as little as 0.0013% of waste water can pose a substantial risk of disease.

Incidence rate estimated from indicators

The health impact of swimming in contaminated and non-contaminated marine bathing water was investigated by using data from WHO (2003), Kay *et al.* (2004) and Prüss (1998) on the dose-response relationship, where 104 enterococci/100 mL caused 19 gastrointestinal illnesses per 1,000 swimmers in marine water impacted by waste waters. From the results of the enterococci concentrations estimated by the hydrodynamic bathing water model and assuming a linear relation between indicator concentration and disease rate, a total of 90–100% of the 1,312 competitors at the ironman competition 2010 would acquire disease (Table 3). These results do not reflect the results of the epidemiological study by Harder *et al.* (2010), but overestimate the disease rate, most likely because a linear relationship between high indicator concentrations and disease rate does not exist, as also pointed out in a meta-analysis by Wade *et al.* (2003).

Based on the enterococci monitoring, the incidence rate of swimming in marine bathing water, without CSO contamination was 1.8–6.3% at the ironman competition 2011

(Table 3). Asperen *et al.* (1998) found similar results in an epidemiological study of the incidence rate at a triathlon competition performed in freshwater, meeting the current Dutch and European bathing water standards. Here 0.4–5.2% of the swimmers, depending on the case definition, developed gastroenteritis. Schets *et al.* (2011) found that 3% of adult swimmers had health complaints after swimming in seawater.

CONCLUSION

This study demonstrated the link between gastrointestinal disease and CSO caused by an extreme rain event through a QMRA that included knowledge of exposure data and the dilution factor from the source to the recipient waters. Dilution factors were estimated by combining the outputs of two dynamic models, an approach not described previously. The hydraulics were shown to a useful tool for risk assessment when combined with exposure and microbial data since the results of the QMRA were comparable to epidemiologically based incidence rates. This study has contributed to a new generation of QMRA with reduced uncertainties due to estimating dilution factor. However, the QMRA still has uncertainties within the model outputs and the pathogen concentrations.

Finally measurements of indicator organism level, combined with dose-response relationships, showed reasonable results at low indicator levels, whereas at high levels of indicators, estimated by application of the 3D hydrodynamic model after the CSO event, the indicators overestimate the disease rate if the same dose-response relationship was applied.

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REFERENCES

Ahern, M., Kovats, R. S., Wilkinson, P., Few, R. & Matthies, F. 2005 Global health impacts of floods: Epidemiologic evidence. *Epidemiol. Rev.* **27**, 36–46.

Andersen, H. S., Tamašauskas, H. & Mark, O. 2004 The full urban water cycle – Modeling with MIKE URBAN. *Proceedings of the 7th International Conference on Urban Drainage Modelling*, Dresden, Germany.

Asperen, I. A. V., Medema, G., Borgdorff, M. W., Sprenger, Marc J. W. & Havelaar, A. H. 1998 Risk of gastroenteritis among triathletes in relation to faecal pollution of fresh waters. *Int. J. Epidemiol.* **27**, 309–315.

Åström, J., Pettersson, T. J. R., Stenström, T. A. & Bergstedt, O. 2009 Variability analysis of pathogen and indicator loads from urban sewer systems along a river. *Water Sci. Technol.* **59**, 203–212.

Briancesco, R. & Bonadonna, L. 2005 An Italian study on *Cryptosporidium* and *Giardia* in wastewater, fresh water and treated water. *Environ. Monitor. Assess.* **104**, 445–457.

Curriero, F. C., Patz, J. A., Rose, J. B. & Lele, S. 2001 The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *Am. J. Public Health* **91**, 1194–1199.

Donovan, E., Unice, K., Roberts, J. D., Harris, M. & Finley, B. 2008 Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River. *Appl. Environ. Microbiol.* **74**, 994–1003.

Dura, G., Pándics, T., Kádár, M., Krisztalovics, K., Kiss, Z., Bodnár, J., Asztalos, A. & Papp, E. 2010 Environmental health aspects of drinking water-borne outbreak due to karst flooding: case study. *J. Water Health* **8**, 513–520.

European Union 2006 Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC.

Garcia-Aljaro, C., Bonjoch, X. & Blanch, A. R. 2005 Combined use of an immunomagnetic separation method and immunoblotting for the enumeration and isolation of *Escherichia coli* O157 in wastewaters. *J. Appl. Microbiol.* **98**, 589–597.

Garsdal, H., Mark, O., Dørge, J. & Jepsen, S. E. 1995 MOUSETRAP: Modelling of water quality processes and interaction of sediments and pollutants in sewers. *Water Sci. Technol.* **31**, 33–41.

Gutiérrez, E., Malgrat, P., Suñer, D. & Otheguy, P. 2010 Real time management of bathing water quality in Barcelona. *Novatech 2010 – 7th International Conference on Sustainable Techniques and Strategies for Urban Water Management*, Lyon, France, June 2010. Available from:

http://documents.irevues.inist.fr/bitstream/handle/2042/35734/33912-284GUT.pdf?seq.

Harder, N. M., Ethelberg, S., Kuhn, K. G. & Mølbak, K. 2010 *To udbrud af Gastroenteritis, EPI-NYT week 42/43, 2010*. Statens Serum Institute, Department of Epidemiology, Copenhagen.

Hata, A., Kitajima, M. & Katayama, H. 2013 Occurrence and reduction of human viruses, F-specific RNA coliphage genogroups and microbial indicators at a full-scale wastewater treatment plant in Japan. *J. Appl. Microbiol.* **114**, 545–554.

Heijnen, L. & Medema, G. 2006 Quantitative detection of *E. coli*, *E. coli* O157 and other Shiga toxin producing *E. coli* in water samples using a culture method combined with real-time PCR. *J. Water Health* **4**, 487–498.

Höller, C. 1988 Quantitative and qualitative studies of *Campylobacter* in a sewage treatment plant. *Zentralbl. Bakteriol. Mikrobiol. Hyg.* **185**, 326–339.

Jeukendrup, A. E., Vet-Joop, K., Sturk, A., Stegen, H. J. C. & Senden, J. 2000 Relationship between gastro-intestinal complaints and endotoxaemia, cytokine release and the acute-phase reaction during and after a long-distance triathlon in highly trained men. *Clin. Sci.* **98**, 47–55.

Kaas, H., Erichsen, A. C. & Roberts, C. 2011 Early warning of bathing water quality – an operational water forecast service. *Water New Zealand Annual Conference*, 9–11 November 2011.

Katayama, H., Haramoto, E., Oguma, K., Yamashita, H., Tajima, A., Nakajima, H. & Ohgaki, S. 2008 One-year monthly quantitative survey of noroviruses, enteroviruses, and adenoviruses in wastewater collected from six plants in Japan. *Water Res.* **42**, 1441–1448.

Kay, D., Bartram, J., Prüss, A., Ashbolt, N., Wyer, M. D., Fleisher, J. M., Fewtrell, L., Rogers, A. & Rees, G. 2004 Derivation of numerical values for the World Health Organization guidelines for recreational waters. *Water Res.* **38**, 1296–1304.

Kim, W. J., Managaki, S., Furumai, H. & Nakajima, F. 2009 Diurnal fluctuations of indicator microorganisms and intestinal viruses in combined sewer system. *Water Sci. Technol.* **60**, 2791–2801.

Lodder, W. J. & Roda Husman, A. M. de 2005 Presence of noroviruses and other enteric viruses in sewage and surface waters in the Netherlands. *Appl. Environ. Microbiol.* **71**, 1453–1461.

Mark, O. & Erichsen, A. 2007 Towards implementation of the new EU Bathing Water Directive – Case studies: Copenhagen & Aarhus, Denmark. *Novatech 2007 – 6th International Conference on Sustainable Techniques and Strategies in Urban Water Management*, Lyon, France, June 2007; oral presentation session 8.3. Available from: http://documents.irevues.inist.fr/bitstream/handle/2042/25226/1705_306mark.pdf.

Mark, O., Wennberg, C., Kalken, T. van, Rabbi, F. & Albinsson, B. 1998 Risk analyses for sewer systems based on a numerical modelling and GIS. *J. Safety Sci.* **30**, 99–106.

Medema, G. J. & Schijven, J. F. 2001 Modelling the sewage discharge and dispersion of *Cryptosporidium* and *Giardia* in surface water. *Water Res.* **35**, 4307–4316.

Medema, G. J., Teunis, P. F. M., Havelaar, A. H. & Haas, C. N. 1996 Assessment of the dose-response relationship of *Campylobacter jejuni*. *Int. J. Food Microbiol.* **30**, 101–111.

Miljoeforvaltningen, Teknik-og. 2008 Koebenhavns kommunes Spildevandsplan 2008. Technical report, Copenhagen municipality.

Ottoson, J., Hansen, A., Björlenius, B., Norder, H. & Stenström, T. A. 2006 Removal of viruses, parasitic protozoa and microbial indicators in conventional and membrane processes in a wastewater pilot plant. *Water Res.* **40**, 1449–1457.

Passerat, J., Ouattara, N. K., Mouchel, J.-M., Rocher, V. & Servais, P. 2011 Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. *Water Res.* **45**, 893–903.

Payment, P., Plante, R. & Cejka, P. 2001 Removal of indicator bacteria, human enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts at a large wastewater primary treatment facility. *Can. J. Microbiol.* **47**, 188–193.

Pintar, K. D. M., Pollari, F., Waltner-Toews, D., Charron, D. F., McEwen, S. A., Fazil, A. & Nesbitt, A. 2009 A modified case-control study of cryptosporidiosis (using non-*Cryptosporidium*-infected enteric cases as controls) in a community setting. *Epidemiol. Infect.* **137**, 1789–1799.

Pusch, D., Oh, D.-Y., Wolf, S., Dumke, R., Schröter-Bobsin, U., Höhne, M., Röske, I. & Schreier, E. 2005 Detection of enteric viruses and bacterial indicators in German environmental waters. *Arch. Virol.* **150**, 929–947.

Prüss, A. 1998 Review of epidemiological studies on health effects from exposure to recreational water. *Int. J. Epidemiol.* **27**, 1–9.

Rechenburg, A. & Kistemann, T. 2009 Sewage effluent as a source of *Campylobacter* sp. in a surface water catchment. *Int. J. Environ. Health Res.* **19**, 239–249.

Rijal, G., Petropoulou, C., Tolson, J. K., DeFlaun, M., Gerba, C., Gore, R., Glymph, T., Granato, T., O'Connor, C., Kollias, L. & Lanyon, R. 2009 Dry and wet weather microbial characterization of the Chicago area waterway system. *Water Sci. Technol.* **60**, 1847–1855.

Robertson, L. J., Hermansen, L. & Gjerde, B. K. 2006 Occurrence of *Cryptosporidium* oocysts and *Giardia* cysts in sewage in Norway. *Appl. Environ. Microbiol* **72**, 5297–5303.

Robertson, L. J., Paton, C. A., Campbell, A. T., Smith, P. G., Jackson, M. H., Gilmour, R. A., Black, S. E., Stevenson, D. A. & Smith, H. V. 2000 Giardia cysts and Cryptosporidium oocysts at sewage treatment works in Scotland, UK. *Water Res.* **34**, 2310–2322.

Schets, F. M., Schijven, J. F. & Husman, A. M. de Roda 2011 Exposure assessment for swimmers in bathing waters and swimming pools. *Water Res.* **45**, 2392–2400.

Soller, J. A., Schoen, M. E., Bartrand, T. & Ravenscroft, J. E. 2010 Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water Res*. **44**, 4674–4691.

Soerensen, S. & Andersen, N. K. 2005 Alarm system for bathing water in the harbour of Copenhagen. *Conference Proceedings 10th International Conference on Urban Drainage, 21–26 August, 2005*, pp. 1–8.

Teunis, P. F. M., Chappell, C. L. & Okhuysen, P. C. 2002 *Cryptosporidium* dose response studies: variation between isolates. *Risk Anal*. **22**, 175–183.

Teunis, P. F. M., Moe, C. L., Liu, P., Miller, S. E., Lindensmith, L., Baric, R. S., Pendu, J. L. & Calderon, R. L. 2008a Norwalk Virus: How infectious is it? *J. Med. Virol.* **80**, 1468–1476.

Teunis, P. F. M., Ogden, I. D. & Strachan, N. J. C. 2008b Hierarchical dose response of *E. coli* O157:H7 from human outbreaks incorporating heterogeneity in exposure. *Epidemiol. Infect*. **136**, 761–770.

Teunis, P. F. M., van der Heijden, O. G., van der Giessen, J. W. B. & Havelaar, A. H. 1996 The dose response relation in human volunteers for gastro-intestinal pathogens. Technical Report 284550002, RIVM, Bilthoven.

Veldhuis, J. A. E. ten, Clemens, F. H. L. R., Sterk, G. & Berends, B. R. 2010 Microbial risks associated with exposure to pathogens in contaminated urban flood water. *Water Res*. **44**, 2910–2918.

Vestergaard, L. S., Mølbak, K., Olsen, K., Stensvold, R., Böttiger, B. & Adelhardt, M. 2007 *EPI-NYT, week 10, 2007*. Statens Serum Institute, Department of Epidemiology, Copenhagen.

Viau, E. J., Lee, D. & Boehm, A. B. 2011 Swimmer risk of gastrointestinal illness from exposure to tropical coastal waters impacted by terrestrial dry-weather runoff. *Environ. Sci. Technol.* **45**, 7158–7165.

Wade, T. J., Pai, N., Eisenberg Jr, J. N. S. & Colford, J. M. 2003 Do U.S. Environmental Protection Agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic reviewand meta-analysis. *Environ. Health Perspect*. **111**, 1102–1109.

WHO 2003 *Guidelines for Safe Recreational Water Environments. Volume 1: Coastal and fresh waters*. World Health Organization, Geneva.

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