A stochastic approach for assessing the environmental risk generated by wet-weather events from integrated urban wastewater systems

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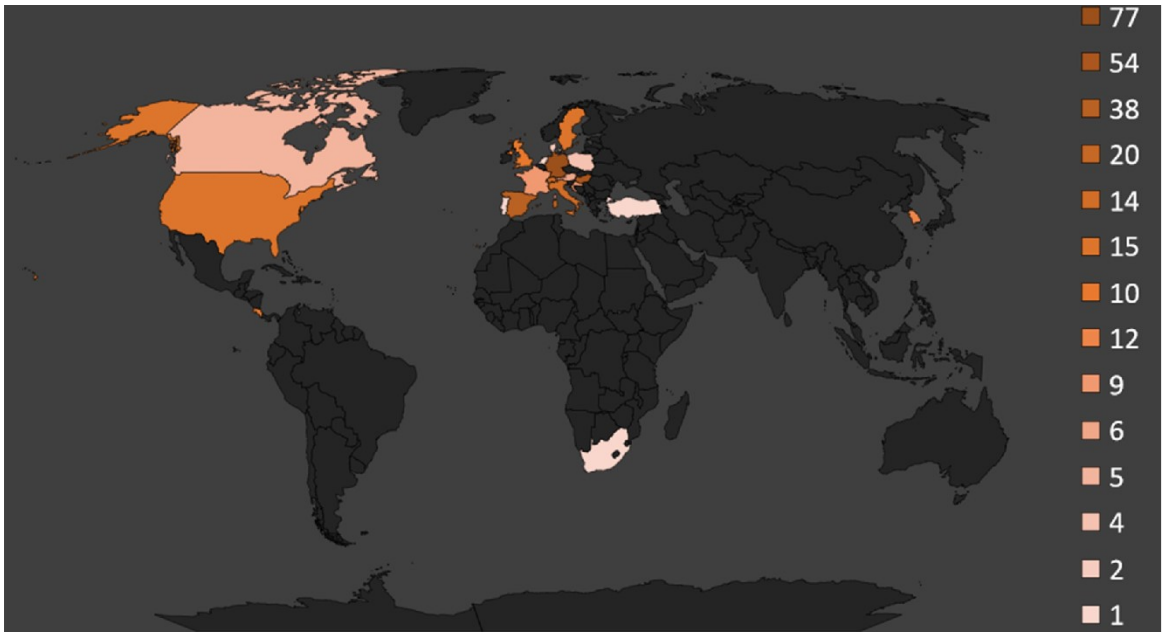


Figure S1. Number of IUWSs included in this study per each country of the world.

Table S1. Number of sewer systems with only concentration data (C), volumes data (V), and their combination (C and V) per each discharge and surface water recipient.

	CSO			***BP***			***EFF***			***Q_R***		
	C	*V*	*C&V*	*C*	*V*	*C&V*	*C*	*V*	*C&V*	*C*	*V*	*C&V*
Number of sewer systems	27	9	16	7	6	16	15	115	102		52	13
TOT		52			29			232			65	

Table S2. For V, Q_R, and C of each discharge, ranges of values, number of references used, and specific references are reported. "Values range" represents the minimum and maximum values registered for V and Q_R across all articles, while for concentrations the interval is reported as the average values of the 25th percentiles and 75th percentiles of the detected concentrations.

Variable	Discharge type	Values range	Unit	N° references	References
V	**CSO**	$9.5 \cdot 10^3 – 9.3 \cdot 10^6$	m^3/y	**13**	1–13
	BP	$6.0 \cdot 10^3 – 9.0 \cdot 10^6$	m^3/y	**14**	1, 5, 6, 14–24
	EFF	$1.8 \cdot 10^3 – 3.5 \cdot 10^9$	m^3/y	**35**	1, 10, 21, 25–56
Q_R	**RIVER**	0.01 – 7993	m^3/s	**21**	7, 9, 39, 41, 43, 45, 46, 49, 52, 56–58, 22, 59, 28, 33–38
E. Coli	**CSO**	$1.0\ 10^6$-$2.0\ 10^6$	CFU/100 mL	**3**	6, 60, 61
	BP	$1.2\ 10^6$-$3.1\ 10^6$	CFU/100 mL	**4**	6, 17, 18, 62
	EFF	1-7.4	CFU/100 mL	**2**	25, 26
TSS	**CSO**	87.5-195.3	mg/L	**11**	1, 2, 8, 9, 51, 60, 61, 63–66
	BP	76.8-148.5	mg/L	**8**	1, 18, 19, 22, 23, 51, 62, 67
	EFF	2.8-6.5	mg/L	**4**	25, 26, 30, 51
BOD_5	**CSO**	55.0-117.4	mg/L	**6**	8, 51, 61, 63, 64, 66
	BP	144.3-220.5	mg/L	**4**	22, 23, 51, 67
	EFF	5.0-6.0	mg/L	**4**	25, 28, 30, 51
COD	**CSO**	72.5-154.9	mg/L	**9**	1, 8, 9, 51, 61, 63–66

Variable	Discharge type	Values range	Unit	N° references	References
	BP	195.6-220.1	mg/L	**6**	1, 18, 19, 22, 23, 51
	EFF	19.0-39.4	mg/L	**6**	1, 25, 26, 28, 30, 51
NH_4	**CSO**	4.0-5.5	mg/L	**5**	1, 8, 61, 64, 66
	BP	5.5-10.9	mg/L	**4**	1, 19, 22, 62
	EFF	0.1-0.8	mg/L	**3**	1, 25, 30
NO_3	**CSO**	0.0-0.2	mg/L	**3**	1, 61, 64
	BP	0.1-0.2	mg/L	**2**	1, 19
	EFF	2.8-7.0	mg/L	**2**	1, 30
TP	**CSO**	0.7-1.3	mg/L	**5**	1, 8, 51, 64, 66
	BP	1.0-1.9	mg/L	**4**	1, 22, 51, 62
	EFF	0.4-13.4	mg/L	**4**	1, 25, 30, 51
Cd	**CSO**	0.1-0.1	µg/L	**3**	1, 64, 68
	BP	0.1-0.1	µg/L	**1**	1
	EFF	0.0-0.0	µg/L	**1**	1
Ni	**CSO**	1.7-4.3	µg/L	**3**	1, 64, 68
	BP	2.3-2.8	µg/L	**1**	1
	EFF	4.0-6.2	µg/L	**1**	1
Pb	**CSO**	2.5-8.8	µg/L	**5**	1, 63, 64, 66, 68
	BP	2.5-3.4	µg/L	**3**	1, 19, 22
	EFF	0.1-0.2	µg/L	**1**	1
CBZ	**CSO**	47.2-102.5	ng/L	**2**	1, 69
	BP	113.5-151.7	ng/L	**5**	1, 17, 18, 20, 51
	EFF	240.0-300.0	ng/L	**12**	27, 28, 56, 70, 29, 31, 32, 47, 51–53, 55
DCF	**CSO**	115.4-289.6	ng/L	**3**	1, 45, 69
	BP	186.4-322.7	ng/L	**5**	1, 17, 18, 20, 51
	EFF	590.7-625.0	ng/L	**14**	27, 28, 53, 55, 56, 70, 29–32, 45, 47, 51, 52
TCS	**CSO**	5.2-32.8	ng/L	**1**	1
	BP	30.0-42.9	ng/L	**4**	1, 20, 21, 51
	EFF	48.1-62.9	ng/L	**4**	21, 51–53
CBD	**CSO**	46.0-72.0	ng/L	**2**	1, 69
	BP	15.7-26.4	ng/L	**2**	1, 20
	EFF	17.8-41.9	ng/L	**2**	1, 71
DRN	**CSO**	54.8-137.2	ng/L	**6**	1, 8, 10, 66, 68, 69
	BP	10.7-20.0	ng/L	**2**	1, 20
	EFF	11.8-28.5	ng/L	**5**	1, 10, 27, 56, 71
TRB	**CSO**	39.8-64.8	ng/L	**3**	1, 10, 69
	BP	22.6-34.0	ng/L	**2**	1, 20
	EFF	13.4-15.0	ng/L	**3**	10, 27, 71
BaP	**CSO**	14.4-49.6	ng/L	**5**	1, 8, 64, 66, 68
	BP	14.7-26.3	ng/L	**2**	1, 20
	EFF	0.2-0.5	ng/L	**1**	1
CHR	**CSO**	29.3-74.0	ng/L	**4**	1, 64, 66, 68
	BP	26.3-51.6	ng/L	**2**	1, 20
	EFF	0.5-0.7	ng/L	**1**	1
FLU	**CSO**	42.9-110.8	ng/L	**5**	1, 8, 64, 66, 68
	BP	57.4-79.1	ng/L	**3**	1, 20, 50
	EFF	1.2-2.7	ng/L	**2**	1, 50

Table S3. Contaminants for which the chronic risk assessment was performed. The toxic level chosen was the lowest value between AA-EQS and lowest $PNEC_{chronic}$.

Micropollutant	Abbreviation	Class	Abbreviation	Toxic Level	Unit	AA-EQS or $PNEC_{chronic}$?
Cadmium	Cd	Metals	HM	0.08	µg/L	AA-EQS
Lead	Pb			1.2	µg/L	AA-EQS
Nickel	Ni			4	µg/L	AA-EQS
Carbamazepine	CBZ	Pharmaceuticals	PHARM	50	ng/L	$PNEC_{chronic}$
Diclofenac	DCF			50	ng/L	$PNEC_{chronic}$
Triclosan	TCS			20	ng/L	$PNEC_{chronic}$
Carbendazim	CBD	Pesticides	PEST	150	ng/L	$PNEC_{chronic}$
Diuron	DRN			70	ng/L	$PNEC_{chronic}$
Terbutryn	TRB			65	ng/L	AA-EQS
Benzo(a)pyrene	BaP	Polycyclic Aromatic Hydrocarbons	PAH	0.17	ng/L	AA-EQS
Chrysene	CHR			2.9	ng/L	AA-EQS
Fluoranthene	FLU			6.3	ng/L	AA-EQS

AA-EQS from [72], $PNEC_{chronic}$ from NORMAN database..

Table S4. Statistical distributions of volumes and river flow. The parameters of each distribution and AD values resulting from Anderson-Darling goodness of fit test are reported.

VARIABLE	**BEST FITTING DISTRIBUTION: Lognormal**			
	Distribution parameters			**Goodness of fit test**
	a	**b**	**c**	**AD value**
V_{CSO}	11.23	2.40	9367.54	0.922
V_{BP}	11.36	2.15	5621.79	0.307
V_{EFF}	14.48	2.72	-	0.271
Q_R	0.04	3.21	-	1.080

Table S5. Percentiles of V_i and Q_R used for the definition of each DF scenario. V_i refers to single discharge structure, while resulting DF considers the number of structures used: 1 for BP and EFF, a random number between 2 and 20 for CSO.

SCENARIO	V_i			Q_R		DF	
	m^3/y			m^3/s		-	
Safe	**Discharge**	**15P**	**35P**	**65P**	**85P**	**5P**	**95P**
	CSO (N=25)	1.57E+04	3.94E+04	3.57	28.91	437.42	8512.34
	BP (N=22)	1.49E+04	4.30E+04			5114.46	41021.32
	EFF (N=217)	1.16E+05	6.81E+05			357.46	4092.48
Medium	**Discharge**	**40P**	**60P**	**40P**	**60P**	**5P**	**95P**
	CSO (N=25)	5.05E+04	1.47E+05	0.46	2.34	12.60	202.47
	BP (N=22)	5.53E+04	1.53E+05			158.06	909.10
	EFF (N=217)	9.76E+05	3.87E+06			6.61	46.14
Worst	**Discharge**	**65P**	**85P**	**15P**	**35P**	**5P**	**95P**
	CSO (N=25)	1.99E+05	9.06E+05	0.04	0.30	0.22	5.10
	BP (N=22)	2.01E+05	7.96E+05			3.13	28.4
	EFF (N=217)	5.54E+06	3.26E+07			0.08	0.90

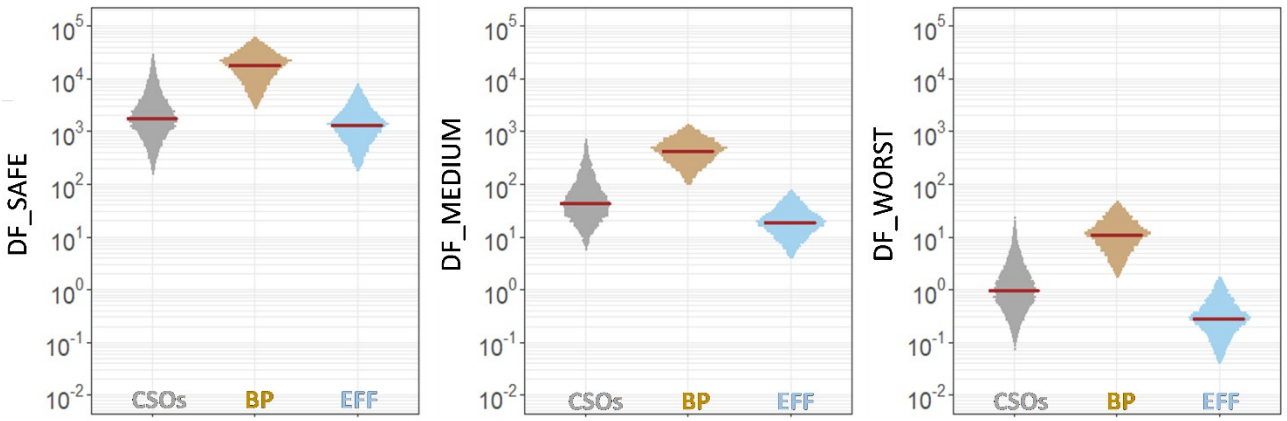
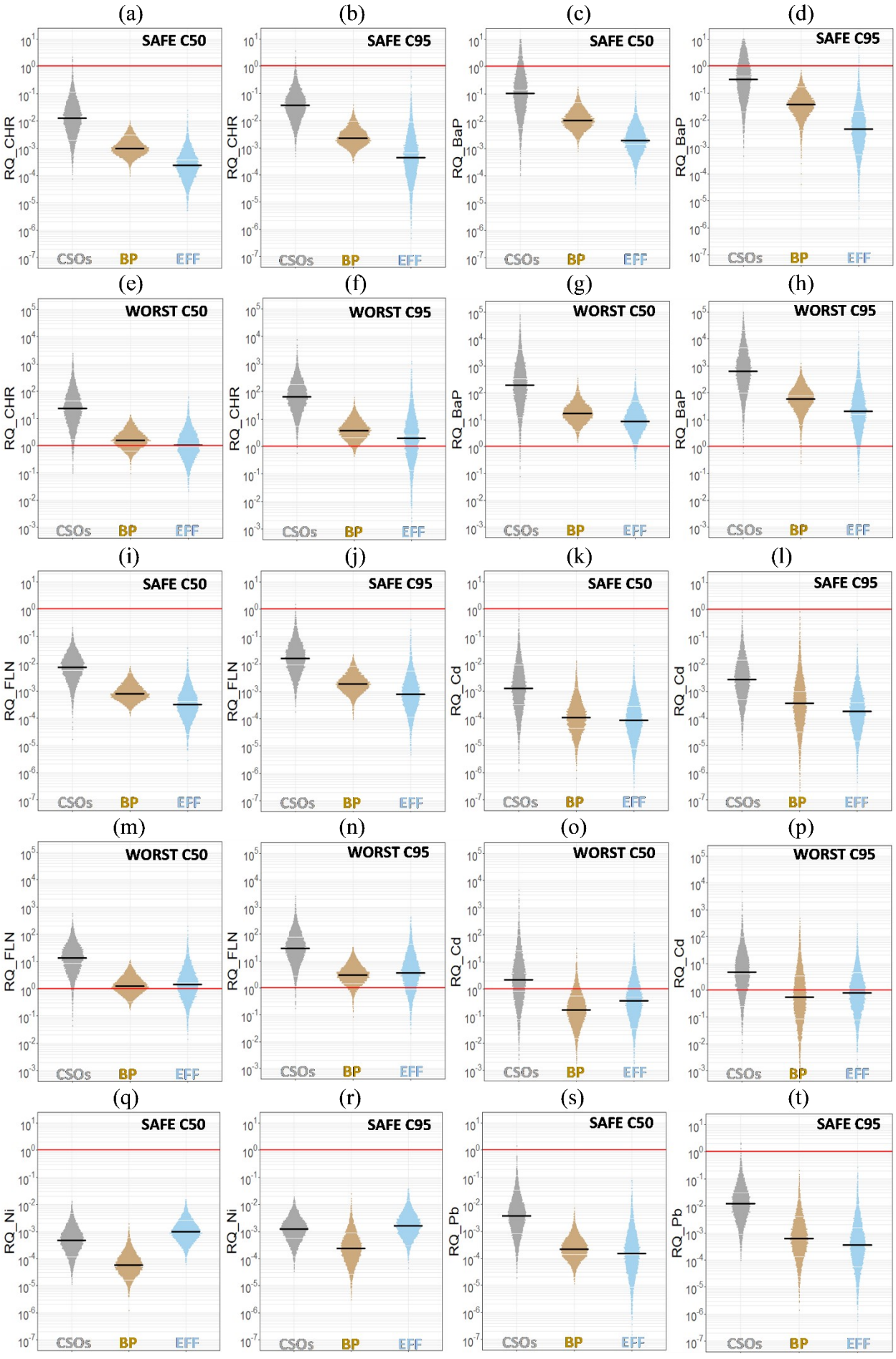


Figure S2. DF values for each DF scenario and each discharge type.

Table S6. Pollution levels of river water expressed by Macro-descriptors Pollution Level (LIM)

MACRO-DESCRIPTORS	QUALITY LEVEL				
	1	**2**	**3**	**4**	**5**
100-DO (%)	<|10|	<|20|	<|30|	<|50|	>|50|
N-NO_3	<0.3	<1.5	<5	<10	>10
N-NH_4	<0.03	<0.1	<0.5	<1.5	>1.5
Total P	<0.07	<0.15	<0.3	<0.6	>0.6
BOD_5	<2.5	<4	<8	<15	>15
COD	<5	<10	<15	<25	>25
E. Coli	<100	<1000	<5000	<20,000	>20,000
Single score	**80**	**40**	**20**	**10**	**5**
LIM - Total score	**480-560**	**240-475**	**120-235**	**60-115**	**<60**
LIM - Score interpretation	**Excellent**	**Good**	**Sufficient**	**Scarce**	**Bad**


(a)
SAFE C50
RQ_CHR
CSOs
BP
EFF
(b)
SAFE C95
RQ_CHR
CSOs
BP
EFF
(c)
SAFE C50
RQ_BaP
CSOs
BP
EFF
(d)
SAFE C95
RQ_BaP
CSOs
BP
EFF
(e)
WORST C50
RQ_CHR
CSOs
BP
EFF
(f)
WORST C95
RQ_CHR
CSOs
BP
EFF
(g)
WORST C50
RQ_BaP
CSOs
BP
EFF
(h)
WORST C95
RQ_BaP
CSOs
BP
EFF
(i)
SAFE C50
RQ_FLN
CSOs
BP
EFF
(j)
SAFE C95
RQ_FLN
CSOs
BP
EFF
(k)
SAFE C50
RQ_Cd
CSOs
BP
EFF
(l)
SAFE C95
RQ_Cd
CSOs
BP
EFF
(m)
WORST C50
RQ_FLN
CSOs
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(n)
WORST C95
RQ_FLN
CSOs
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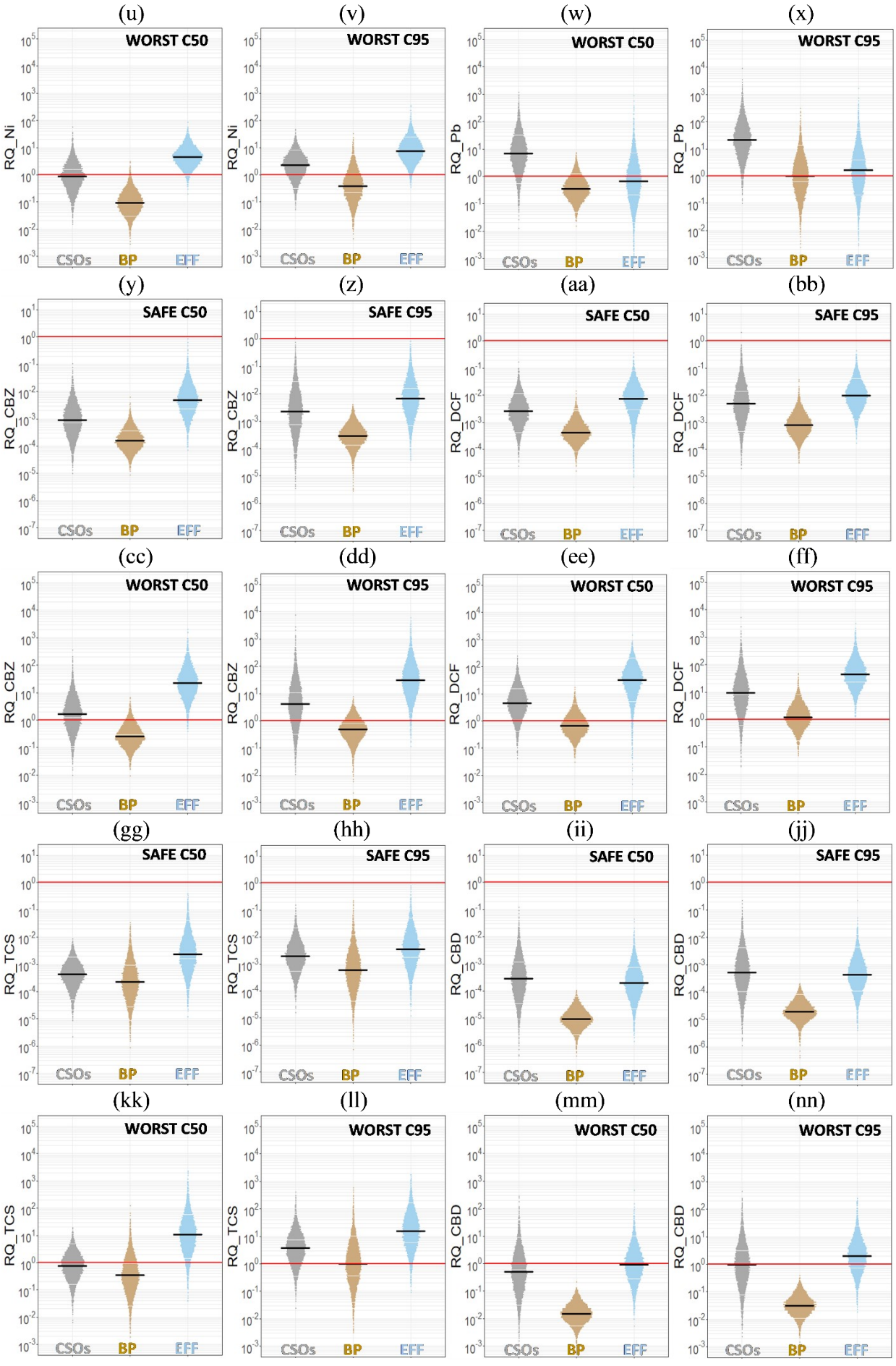
(o)
WORST C50
RQ_Cd
CSOs
BP
EFF
(p)
WORST C95
RQ_Cd
CSOs
BP
EFF
(q)
SAFE C50
RQ_Ni
CSOs
BP
EFF
(r)
SAFE C95
RQ_Ni
CSOs
BP
EFF
(s)
SAFE C50
RQ_Pb
CSOs
BP
EFF
(t)
SAFE C95
RQ_Pb
CSOs
BP
EFF


(u)
WORST C50
RQ_Ni
(v)
WORST C95
RQ_Ni
(w)
WORST C50
RQ_Pb
(x)
WORST C95
RQ_Pb
(y)
SAFE C50
RQ_CBZ
(z)
SAFE C95
RQ_CBZ
(aa)
SAFE C50
RQ_DCF
(bb)
SAFE C95
RQ_DCF
(cc)
WORST C50
RQ_CBZ
(dd)
WORST C95
RQ_CBZ
(ee)
WORST C50
RQ_DCF
(ff)
WORST C95
RQ_DCF
(gg)
SAFE C50
RQ_TCS
(hh)
SAFE C95
RQ_TCS
(ii)
SAFE C50
RQ_CBD
(jj)
SAFE C95
RQ_CBD
(kk)
WORST C50
RQ_TCS
(ll)
WORST C95
RQ_TCS
(mm)
WORST C50
RQ_CBD
(nn)
WORST C95
RQ_CBD
CSOs
BP
EFF

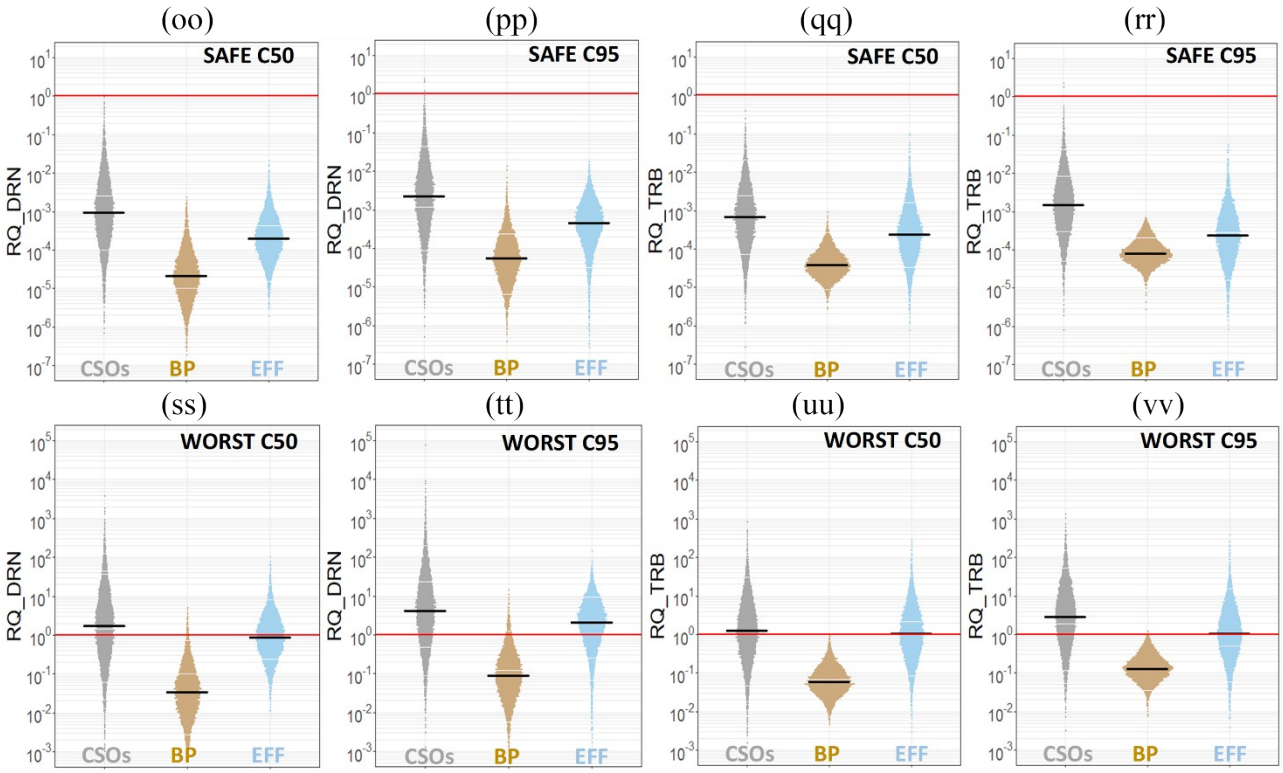


Figure S3. RQ values for each micropollutant (C50 and C95 scenarios) for each discharge in Safe and Worst scenarios.

SCENARIOS			$n_{RQ_{i,j}>1}$		
			CSOs	BP	EFF
DF	CP	RQP			
SAFE	C50	RQ50	0	0	0
		RQ75	0	0	0
		RQ95	1	0	0
	C75	RQ50	0	0	0
		RQ75	0	0	0
		RQ95	1	0	0
	C95	RQ50	0	0	0
		RQ75	1	0	0
		RQ95	1	0	0

SCENARIOS			$n_{RQ_{i,j}>1}$		
			CSOs	BP	EFF
DF	CP	RQP			
MEDIUM	C50	RQ50	1	0	0
		RQ75	2	0	1
		RQ95	4	1	3
	C75	RQ50	1	0	0
		RQ75	2	1	1
		RQ95	7	1	4
	C95	RQ50	2	1	0
		RQ75	4	1	2
		RQ95	9	1	4

SCENARIOS			$n_{RQ_{i,j}>1}$		
			CSOs	BP	EFF
DF	CP	RQP			
WORST	C50	RQ50	9	3	8
		RQ75	12	4	12
		RQ95	12	7	12
	C75	RQ50	11	3	10
		RQ75	12	6	12
		RQ95	12	7	12
	C95	RQ50	11	6	11
		RQ75	12	6	12
		RQ95	12	8	12

Figure S4. Number of pollutants exceeding the threshold $RQ_{i,j}=1$ per each discharge type and per each scenario.

Table S7. P-value of the Mann-Whitney tests performed to compare the RQ values obtained with different combinations of CP and RQP. Results refer to the Worst scenario. The p-values below 0.1 are reported in red, the p-values below 0.05 are reported in bold red.

WORST SCENARIO		C50			C75			C95		
		RQ50	RQ75	RQ95	RQ50	RQ75	RQ95	RQ50	RQ75	RQ95
CSOs										
C50	RQ50	-	0.141	**0.004**	0.436	-	-	0.126	-	-
	RQ75	0.141	-	**0.035**	-	0.47	-	-	0.112	-
	RQ95	**0.004**	**0.035**	-	-	-	0.47	-	-	**0.023**
C75	RQ50	0.436	-	-	-	0.112	**0.003**	0.312	-	-
	RQ75	-	0.47	-	0.112	-	**0.035**	-	0.371	-
	RQ95	-	-	0.47	**0.003**	**0.035**	-	-	-	0.312
C95	RQ50	0.126	-	-	0.312	-	-	-	0.100	**0.003**
	RQ75	-	0.112	-	-	0.371	-	0.100	-	**0.026**
	RQ95	-	-	**0.023**	-	-	0.312	**0.003**	**0.026**	-
BP										
C50	RQ50	-	0.453	0.100	0.624	-	-	0.237	-	-
	RQ75	0.453	-	0.248	-	0.544	-	-	0.157	-
	RQ95	0.100	0.248	-	-	-	0.507	-	-	0.141
C75	RQ50	0.624	-	-	-	0.083	0.083	0.371	-	-
	RQ75	-	0.544	-	0.083	-	0.248	-	0.436	-
	RQ95	-	-	0.507	0.083	0.248	-	-	-	0.341
C95	RQ50	0.237	-	-	0.371	-	-	-	0.453	0.073
	RQ75	-	0.157	-	-	0.436	-	0.453	-	0.225
	RQ95	-	-	0.141	-	-	0.341	0.073	0.225	-
EFF										
C50	RQ50	-	0.126	**0.009**	0.403	-	-	0.214	-	-
	RQ75	0.126	-	**0.04**	-	0.371	-	-	0.126	-
	RQ95	**0.009**	**0.040**	-	-	-	0.312	-	-	**0.046**
C75	RQ50	0.403	-	-	-	0.089	**0.009**	0.403	-	-
	RQ75	-	0.371	-	0.089	-	**0.030**	-	0.312	-
	RQ95	-	-	0.312	**0.009**	**0.03**	-	-	-	0.157
C95	RQ50	0.214	-	-	0.403	-	-	-	0.078	**0.002**
	RQ75	-	0.126	-	-	0.312	-	0.078	-	**0.035**
	RQ95	-	-	**0.046**	-	-	0.157	**0.002**	**0.035**	-

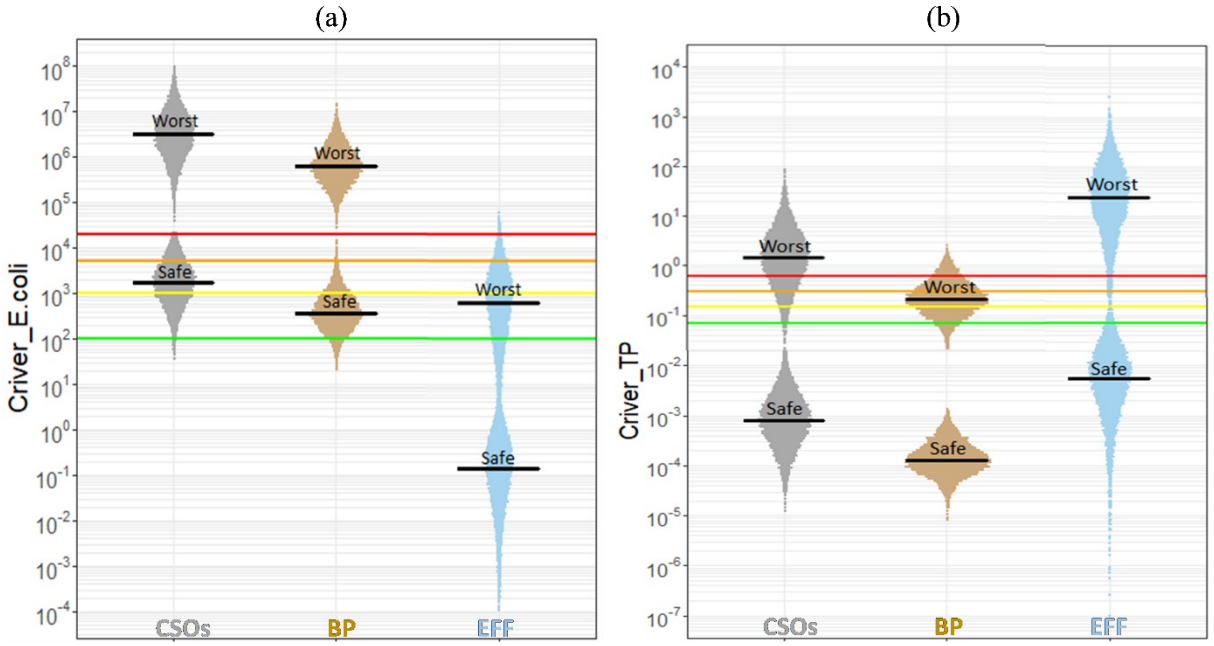


Figure S5. Concentration in the river in Safe and Worst scenario using C75 for *E. coli* (a) and TP (b). The 5 quality level classes are enclosed in the graphs between lines with different colors, where green line represent the threshold between class 1 and 2.

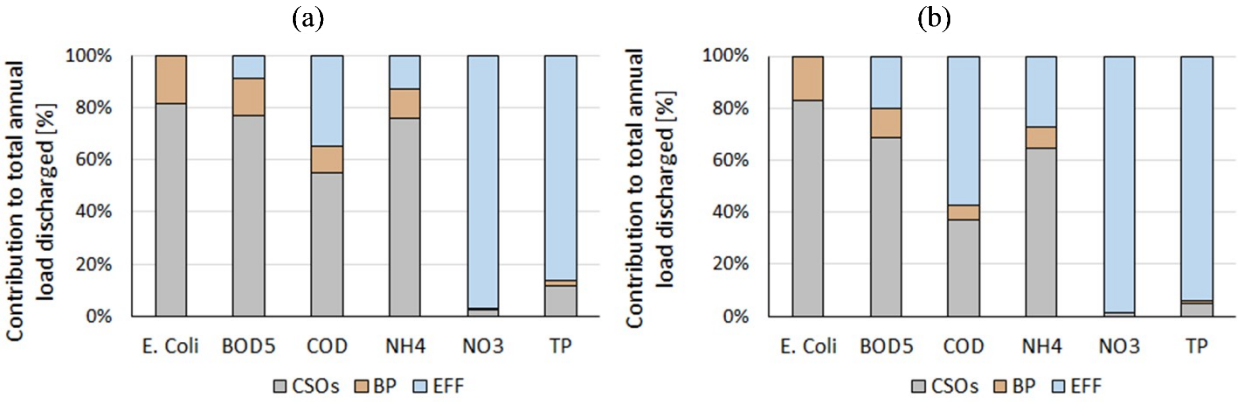


Figure S6. (b) Apportionment of the total annual load discharged to the river in (a) Safe and (b) Worst scenario.

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