

Short-term recovery of inland and marine environments after the 2023 Emilia-Romagna flood

Riccardo Bentivogli^{1*}, Carlotta Carlini¹, Federica Costantini^{1,2,3,4}, Elena Fabbri^{1,3,4}, Beatrice Maria Sole Giambastiani^{1,3}, Nicolas Greggio^{1,3,4*}, Martina La Torre^{1,2}, Cristina Luccarini¹, Laura Pezzolesi^{1,2,3,4}, Alessandro Piazza^{1*}, Paola Valbonesi^{1,3}, Sonia Silvestri^{1,3}

¹Department of Biological, Geological, and Environmental Sciences, University of Bologna, Ravenna, Italy

²National Inter-University Consortium for Marine Sciences (CoNISMa), Rome, Italy

³Interdepartmental Centre for Research in Environmental Sciences (CIRSA), University of Bologna, Ravenna, Italy

⁴Interdepartmental Centre for Industrial Research in Renewable Resources, Environment, Sea and Energy (CIRI FRAME), University of Bologna, Ravenna, Italy

*Corresponding Authors:

Riccardo Bentivogli - riccardo.bentivogli4@unibo.it

Alessandro Piazza – alessandro.piazza7@unibo.it

Nicolas Greggio – nicolas.greggio@unibo.it

Supplementary Table 1 | **Hydrological and geomorphological characteristics of the rivers and drainage canals included in this study.** Lengths, basin areas, and discharge values refer to the longest available hydrological time series for rivers, and to pumping-station records for mechanical-drainage canals. Estimated discharges for May 2023 correspond to peak flood values for rivers and measured pumping rates for canals. Additional details and system-specific notes are provided below the table.

River/Canal	ID (Fig. 1)	Discharge type	Length (km)	Basin area (km ²)	Average discharge ^a	Historical max. discharge ^b	Estimated discharge May 2023 ^c	Sources	System description
Reno	RE	Natural	211 ^d	5040 ^e	95 ^d	2300 ^f	1200-1300 ^d	^d ARPAE Emilia-Romagna; ^e Autorità di Bacino Distrettuale del Fiume Po; ^f Autorità di Bacino Reno;	-
Canale Destra Reno	DxRE	Natural	133 ^g	1200 ^e	40-50 ^g	350-400 ^g	300-350 ^h	^e Autorità di Bacino Distrettuale del Fiume Po; ^g Consorzio di Bonifica Renana; ^h ARPAE-SIMC, Protezione Civile Emilia-Romagna	The Destra Reno Canal is a historic hydraulic work, designed to drain floodwaters from the Reno River and protect the agricultural and urban areas east of Bologna. It is part of the land reclamation system of the Emilia-Romagna plain, interconnected with other canals such as the Savena Abbandonato, Navile, and Idice. During the May 2023 flood, it played a critical role in managing the excess water coming from the mountain and hillside basins.
Lamone	LAM	Natural	88 ^d	675 ^e	15-20 ^d	900-1000 ^e	1000-1100 ^d	^e Autorità di Bacino Distrettuale del Fiume Po; ^d ARPAE Emilia-Romagna;	-
Cerba	CER	Mechanical drainage	11 ⁱ	62 ⁱ	1.1*10 ⁶ ⁱ	3*10 ⁶ ⁱ	5.2*10 ⁶ ⁱ	ⁱ Consorzio di Bonifica della Romagna	Not affected by the 2023 flooding only drained the rainfall in its catchment
Canala/Valtorto	CAN	Mechanical drainage	22	78	1.1*10 ⁶ ⁱ	3.7*10 ⁶ ⁱ	1.5*10 ⁷ ⁱ	ⁱ Consorzio di Bonifica della Romagna	Hugely affected by the 2023 flooding events. Pumps continuously work for over a month at the maximum discharge with the help of international agencies.
Magni/Cupa	MAG	Mechanical drainage	30	50	n.a	n.a	n.a.	ⁱ Consorzio di Bonifica della Romagna	Hugely affected by the 2023 flooding events. Pumps continuously work for over a month at the maximum discharge with the help of international agencies.

Notes:

^afor rivers is the average discharge (m³/s) of the longest timeseries, for canals is the pumping station average discharge for the month of May over the period 1992-2022 (in m³).

^b For rivers is historical max. discharge (m^3/s) of the longest timeseries, instead for canals is the max. pumping station discharge for the month of May over the period 1992-2022 (in m^3).

^c For rivers is estimated discharge (m^3/s) during May 2023 flooding, instead for canals is the measured pumping station discharge of the May 2023 (in m^3).

Supplementary Table 2 | **Summary statistics of physico-chemical and biological parameters measured in inland waters following the May 2023 flood.**
Values are reported as mean (minimum–maximum) across all inland stations for each sampling period (May, June and October 2023).

Compartment	Parameter	May (T1)	June (T2)	October (T3)
Inland	Temperature (°C)	24.2 (22.0-26.6)	24.8 (23.9-26.1)	21.9 (21.3-23.2)
Inland	Salinity	0.0 (0.0-0.0)	2.3 (0.0-7.0)	1.7 (0.0-7.0)
Inland	Dissolved Oxygen (mg L ⁻¹)	6.8 (0.3-16.1)	7.6 (4.7-12.1)	8.0 (4.7-12.4)
Inland	Depth (m)	1.4 (0.4-3.7)	1.5 (0.3-3.7)	1.7 (0.2-3.7)
Inland	N[NO ³⁻ + NO ²⁻] (mg L ⁻¹)	2.53 (0.02-7.81)	0.85 (0.27-1.91)	1.91 (0.77-6.23)
Inland	P[PO ₄ ³⁻] (mg L ⁻¹)	0.37 (0.14-0.60)	0.52 (0.37-0.87)	0.36 (0.24-0.77)
Inland	Chlorophyll a (µg L ⁻¹)	22.6 (0.-66.6)	36.6 (2.1-68.8)	30.8 (4.6-64.1)
Inland	Phaeopigments (µg L ⁻¹)	2.4 (0.2-7.4)	11.7(0.2-30.2)	8.6 (3.9-16.3)
Inland	TSS (g m ⁻³)	73.5 (24.0-150.0)	98.6 (22.5-312.0)	74.3 (43.8-120.3)
Inland	pH	7.5 (7.3-8.0)	7.5 (7.1-7.7)	7.4 (7.0-7.9)
Inland	Water depth (m)	1.4 (0.4-3.7)	1.5 (0.3-3.7)	1.7 (0.2-3.7)
Marine	Temperature (°C)	25.2 (24.8-25.8)	25.3 (24.8-26.5)	23.6 (23.4-23.8)
Marine	Salinity	12.4 (9.0-15.0)	34.9 (34.0-36.0)	34.4 (33.0-36.0)
Marine	Dissolved Oxygen (mg L ⁻¹)	14.3 (9.1-17.9)	8.7 (7.5-9.2)	10.6 (9.8-11.1)
Marine	Depth (m)	7.6 (3.9-8.8)	7.7 (4.0-9.1)	7.4 (4.3-8.8)
Marine	N[NO ³⁻ + NO ²⁻] (mg L ⁻¹)	0.25 (0.14-0.32)	0.03 (0.00-0.13)	0.05 (0.02-0.08)
Marine	P[PO ₄ ³⁻] (mg L ⁻¹)	0.006 (0.001-0.012)	0.007 (0.004-0.011)	0.009 (0.002-0.018)
Marine	Chlorophyll a (µg L ⁻¹)	19.8 (10.3-31.8)	1.6 (0.8-2.1)	9.4 (5.8-13.0)
Marine	Phaeopigments (µg L ⁻¹)	1.9 (0.9-3.1)	0.2 (0.0-0.4)	2.1 (1.1-3.1)
Marine	TSS (g m ⁻³)	24.6 (10.0-44.0)	12.6 (8.7-14.0)	16.5 (8.0-21.3)
Marine	CDOM ₄₄₀ (m ⁻¹)	1.15 (0.46-1.98)	1.12 (0.54-1.67)	0.059 (0.044-0.075)
Marine	Water depth (m)	7.6 (3.9-8.8)	7.7 (4.0-9.1)	7.4 (4.3-8.8)

Supplementary Table 3 | **Anomalies in inland water quality parameters measured in 2023 (three post-flood sampling times: T1, T2, T3) relative to the 2010–2022 baseline at the three river stations (RE, DxRE, LAM).** Units: temperature (T, °C), electrical conductivity (EC, $\mu\text{S cm}^{-1}$), dissolved oxygen (DO, mg L^{-1}), pH (dimensionless), dissolved inorganic nitrogen ($\text{N} = \text{NO}_3^- + \text{NO}_2^-$, $\mu\text{g L}^{-1}$), and dissolved inorganic phosphate ($\text{P} = \text{PO}_4^{3-}$, $\mu\text{g L}^{-1}$). Baseline values (mean, SD, P95) were derived from all available measurements for each station ($\text{N} = 90\text{--}153$, depending on parameter and station). Z-scores quantify the deviation of each 2023 time point from the long-term baseline mean in units of SD; percentile ranks indicate the empirical position of T1–T3 values within the corresponding baseline distribution (0% and 100% indicate values outside the historical range).

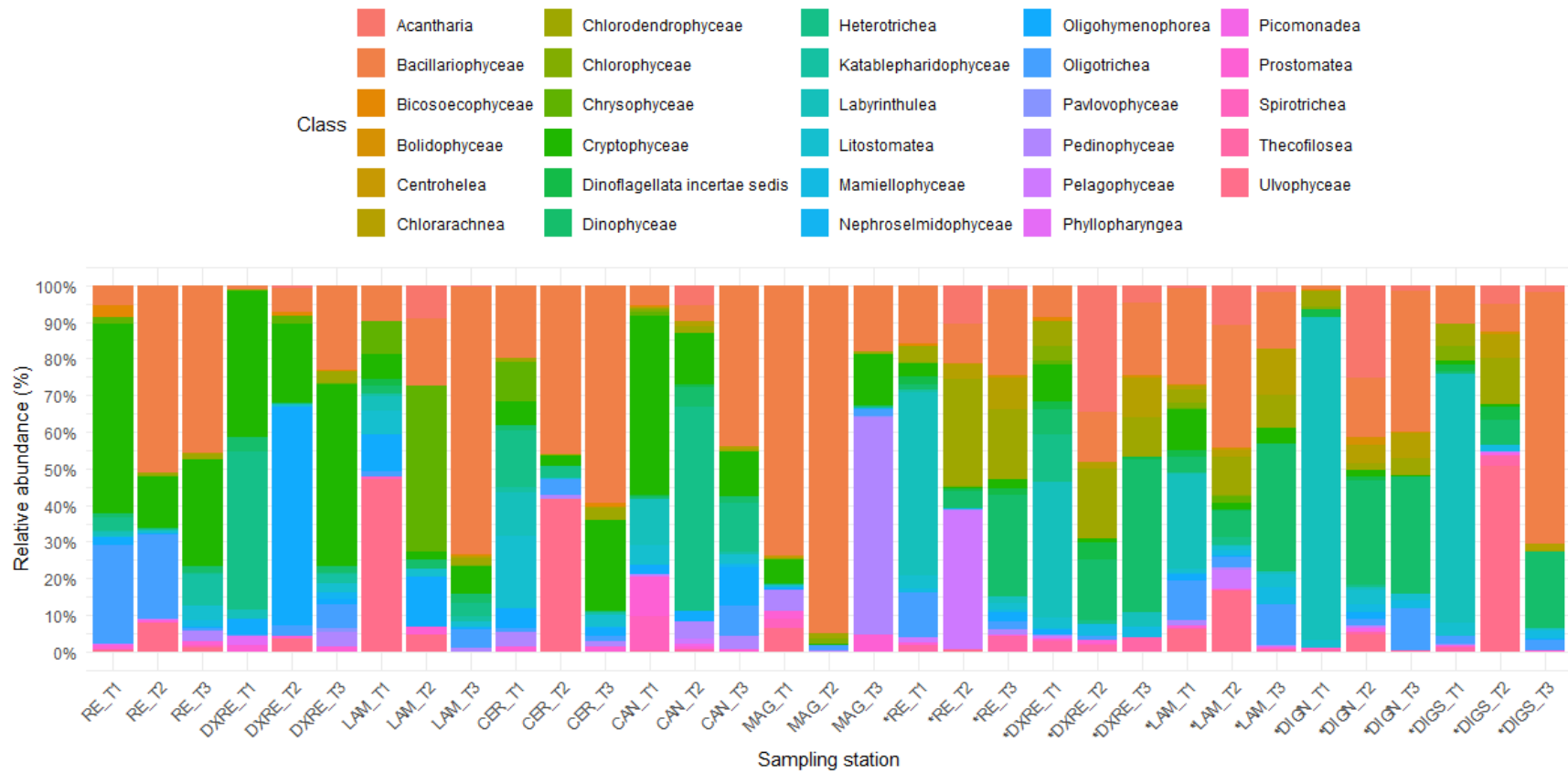
Parameter	Station	Time	Baseline mean	Baseline std	Baselinep95	2023 mean	Z_score	Percentile (%)	N baseline
T	RE	T1	16.7	8.2	28.5	22.9	0.8	68.0	153
T	RE	T2	16.7	8.2	28.5	24.1	0.9	70.6	153
T	RE	T3	16.7	8.2	28.5	21.3	0.6	64.1	153
T	DxRE	T1	17.2	8.5	28.5	24.9	0.9	72.2	90
T	DxRE	T2	17.2	8.5	28.5	26.1	1.1	76.7	90
T	DxRE	T3	17.2	8.5	28.5	21.4	0.5	62.2	90
T	LAM	T1	16.2	7.9	28.0	22.0	0.7	69.3	153
T	LAM	T2	16.2	7.9	28.0	24.2	1.0	77.8	153
T	LAM	T3	16.2	7.9	28.0	21.4	0.7	66.7	153
EC	RE	T1	568.4	139.3	734.9	100.0	-3.4	0.0	152
EC	RE	T2	568.4	139.3	734.9	800.0	1.7	96.7	152
EC	RE	T3	568.4	139.3	734.9	1000.0	3.1	98.0	152
EC	DxRE	T1	1196.2	1154.0	2752.0	100.0	-0.9	0.0	90
EC	DxRE	T2	1196.2	1154.0	2752.0	500.0	-0.6	3.3	90
EC	DxRE	T3	1196.2	1154.0	2752.0	100.0	-0.9	0.0	90
EC	LAM	T1	607.9	230.3	929.8	100.0	-2.2	0.0	153
EC	LAM	T2	607.9	230.3	929.8	300.0	-1.3	0.0	153
EC	LAM	T3	607.9	230.3	929.8	100.0	-2.2	0.0	153
DO	RE	T1	10.5	2.4	13.9	3.1	-3.1	0.0	153
DO	RE	T2	10.5	2.4	13.9	7.3	-1.3	7.2	153
DO	RE	T3	10.5	2.4	13.9	4.7	-2.4	1.3	153
DO	DxRE	T1	10.5	3.6	16.6	0.3	-2.9	0.0	90
DO	DxRE	T2	10.5	3.6	16.6	4.7	-1.6	0.0	90
DO	DxRE	T3	10.5	3.6	16.6	8.2	-0.7	26.7	90
DO	LAM	T1	10.0	2.0	13.0	7.1	-1.4	3.9	153

DO	LAM	T2	10.0	2.0	13.0	5.6	-2.2	0.7	153
DO	LAM	T3	10.0	2.0	13.0	7.4	-1.3	5.2	153
pH	RE	T1	8.1	0.2	8.6	7.4	-3.1	0.0	152
pH	RE	T2	8.1	0.2	8.6	7.3	-3.6	0.0	152
pH	RE	T3	8.1	0.2	8.6	7.0	-4.8	0.0	152
pH	DxRE	T1	8.1	0.4	8.7	7.3	-2.5	2.2	90
pH	DxRE	T2	8.1	0.4	8.7	7.1	-2.9	2.2	90
pH	DxRE	T3	8.1	0.4	8.7	7.4	-2.1	2.2	90
pH	LAM	T1	8.2	0.2	8.5	7.6	-2.8	0.0	153
pH	LAM	T2	8.2	0.2	8.5	7.5	-3.3	0.0	153
pH	LAM	T3	8.2	0.2	8.5	7.5	-3.3	0.0	153
N	RE	T1	2437.8	1581.3	5112.0	690.0	-1.1	0.0	153
N	RE	T2	2437.8	1581.3	5112.0	710.0	-1.1	0.0	153
N	RE	T3	2437.8	1581.3	5112.0	860.0	-1.0	0.0	153
N	DxRE	T1	5391.4	5171.0	16565.0	20.0	-1.0	0.0	90
N	DxRE	T2	5391.4	5171.0	16565.0	870.0	-0.9	0.0	90
N	DxRE	T3	5391.4	5171.0	16565.0	810.0	-0.9	0.0	90
N	LAM	T1	2062.0	1051.4	4180.0	1650.0	-0.4	43.1	153
N	LAM	T2	2062.0	1051.4	4180.0	1910.0	-0.1	56.2	153
N	LAM	T3	2062.0	1051.4	4180.0	1520.0	-0.5	33.3	153
P	RE	T1	48.2	44.0	148.0	460.0	9.4	100.0	153
P	RE	T2	48.2	44.0	148.0	510.0	10.5	100.0	153
P	RE	T3	48.2	44.0	148.0	770.0	16.4	100.0	153
P	DxRE	T1	99.3	89.9	305.5	390.0	3.2	98.9	90
P	DxRE	T2	99.3	89.9	305.5	400.0	3.3	98.9	90
P	DxRE	T3	99.3	89.9	305.5	350.0	2.8	98.9	90
P	LAM	T1	47.0	56.0	140.0	600.0	9.9	100.0	153
P	LAM	T2	47.0	56.0	140.0	430.0	6.8	100.0	153
P	LAM	T3	47.0	56.0	140.0	310.0	4.7	98.7	153

Supplementary Table 4 | **Seasonal anomalies of marine environmental parameters measured in 2023 relative to the ARPAE 2010–2022 baseline (station 6).** Units: salinity (psu), dissolved oxygen (DO, mg L⁻¹), chlorophyll-a (Chl-a, µg L⁻¹), dissolved inorganic nitrogen (N = NO₃⁻ + NO₂⁻, µg L⁻¹), and dissolved inorganic phosphate (P = PO₄³⁻, µg L⁻¹).

Baseline values (mean, SD, P95) were derived from historical seasonal data (N = 9–13 years). Z-scores quantify deviations of 2023 measurements from the baseline mean in units of SD; percentile ranks indicate the approximate position of 2023 values within the baseline distribution. For DO, annual (not seasonal) ARPAE means were used due to missing seasonal data; one anomalous year (2014) inflated variance and DO z-scores should therefore be interpreted with caution.

Parameter	Season	Baseline mean	Baseline SD	Baseline p95	2023 mean	Z- score	Percentile (%)	N baseline
S	Spring	29.1	2.8	33.5	12.4	-5.9	0	11
	Summer	32.3	2.2	35.0	34.9	1.2	88	11
	Autumn	28.6	3.2	32.5	34.4	1.9	97	11
Chl-a	Spring	8.0	3.2	12.8	19.8	3.7	100	9
	Summer	7.2	3.3	12.2	1.6	-1.7	4	9
	Autumn	7.0	1.5	9.0	9.4	1.6	95	9
N(NO ₃ ⁻ +NO ₂ ⁻)	Spring	291.3	219.3	715.4	248.0	-0.2	42	13
	Summer	53.9	34.7	96.7	32.6	-0.6	27	13
	Autumn	523.8	205.3	832.5	49.6	-2.3	1	13
P(PO ₄ ³⁻)	Spring	4.2	4.0	12.3	5.5	0.3	63	13
	Summer	2.6	1.6	5.1	7.3	3.0	100	13
	Autumn	7.7	3.8	13.1	9.0	0.4	64	13



Supplementary Figure 1 | **Relative abundance of taxa grouped by "Class" level.**

Supplementary Table 5 | **Levels of 7 pharmaceuticals at river and canal sampling sites (ng L⁻¹).**

Pharmaceuticals		Diclofenac	Ketoprofen	Ibuprofen	Naproxen	Furosemide	Hydrochlorothiazide	Paracetamol
May 2023	RE	15.59	50.12	3.21	1.64	<LOD	0.73	0.78
	*RE1	11.06	9.26	2.41	0.54	<LOD	0.21	1.23
	*RE2	5.34	12.93	1.05	0.20	<LOD	<LOQ	0.54
	DxRE	2.50	14.78	4.95	0.46	<LOD	0.19	3.88
	*DxRE1	0.78	10.20	3.48	0.36	<LOD	0.20	5.46
	*DxRE2	1.71	8.31	2.50	0.32	<LOD	0.13	1.66
	LAM	14.21	21.31	15.43	1.76	0.64	0.84	16.18
	*LAM1	2.23	6.55	2.22	0.22	<LOD	<LOQ	0.65
	*LAM2	11.97	6.59	1.35	0.23	<LOD	<LOQ	0.49
	CER	3.46	5.94	11.39	2.06	0.13	0.42	12.04
	CAN	1.09	8.18	4.63	0.49	<LOD	<LOQ	1.44
	MAG	239.30	19.54	21.85	14.96	19.34	60.92	19.64
	*DIGN	1.92	10.97	2.27	0.30	<LOD	<LOQ	1.14
	*DIGS	1.83	9.47	1.47	0.20	<LOD	<LOQ	0.88
June 2023	RE	9.18	8.64	4.42	1.78	<LOD	1.09	2.09
	*RE1	3.82	6.04	0.58	<LOQ	<LOD	<LOQ	<LOQ
	*RE2	4.54	6.02	0.52	<LOQ	<LOD	<LOQ	<LOQ
	DxRE	3.28	9.92	6.17	0.74	<LOD	0.80	1.80
	*DxRE1	4.28	4.87	0.50	<LOQ	<LOD	<LOQ	<LOQ
	*DxRE2	2.47	4.68	0.55	<LOQ	<LOD	<LOQ	<LOQ
	LAM	12.66	17.58	43.88	8.72	3.06	2.70	22.65
	*LAM1	2.58	8.87	1.30	<LOQ	<LOD	<LOQ	0.49

	*LAM2	4.86	5.05	0.70	<LOQ	<LOD	<LOD	<LOQ
	CER	2.10	13.02	20.40	0.78	<LOD	<LOQ	1.82
	CAN	3.10	12.78	16.20	1.15	<LOD	0.26	2.54
	MAG	21.03	8.78	2.87	1.98	<LOD	6.77	0.98
	*DIGN	7.66	5.97	0.49	<LOQ	<LOD	<LOD	<LOQ
	*DIGS	5.40	4.30	0.61	<LOD	<LOD	<LOD	<LOQ
October 2023	RE	8.75	20.45	2.56	1.61	<LOD	1.51	<LOD
	*RE1	1.90	8.11	< LOQ	<LOQ	<LOD	<LOQ	<LOQ
	*RE2	2.25	4.34	< LOQ	<LOQ	<LOD	<LOD	<LOQ
	DxRE	3.00	9.41	5.44	1.87	<LOD	1.03	<LOD
	*DxRE1	1.26	8.47	0.66	<LOQ	<LOD	<LOQ	<LOQ
	*DxRE2	1.17	10.90	1.05	0.17	<LOD	<LOD	<LOD
	LAM	6.33	8.11	25.73	2.27	<LOQ	1.49	0.79
	*LAM1	<LOD	7.87	0.47	<LOQ	<LOD	<LOQ	<LOQ
	*LAM2	0.69	8.50	0.99	<LOQ	<LOD	<LOQ	<LOQ
	CER	4.02	7.87	23.73	1.96	<LOQ	0.84	0.98
	CAN	2.70	8.14	10.41	2.70	<LOQ	0.94	5.03
	MAG	259.51	13.41	2.36	7.30	40.36	72.71	<LOD
	*DIGN	0.71	7.54	0.43	<LOQ	<LOD	<LOQ	<LOQ
	*DIGS	0.59	3.34	<LOQ	<LOQ	<LOD	<LOQ	<LOQ
	LOQ (ng L ⁻¹)	0.25	0.40	0.17	0.57	0.13	0.50	0.58
	RSD %	3.51	2.31	5.43	6.18	1.95	0.43	4.39

Supplementary Table 6 | **Detailed performance metrics for chlorophyll-a (CHL, $\mu\text{g L}^{-1}$) retrieval algorithms applied to Sentinel-2 and Sentinel-3 imagery.** For each model, minimum and maximum in situ and estimated values are reported, along with Mean Absolute Error (MAE), Root Mean Square Error (RMSE), bias, and their corresponding percentage values calculated with respect to the average in situ concentration. The algorithm with the lowest MAE for each date is highlighted as the best-performing model.

Date	Sensor	Spatial Resolution (m)	Processor/Product	Algorithm	In-Situ min-max ($\mu\text{g L}^{-1}$)	Estimated min-max ($\mu\text{g L}^{-1}$)	MAE	RMSE	Bias
May 2023	Sentinel 2	20	C2Nets	C2RCC	10.3–31.8	7.8-16.8	48.9% (9.7 $\mu\text{g L}^{-1}$)	57.5% (11.4 $\mu\text{g L}^{-1}$)	-9
				C2X		20.1-29.6	46.4% (9.2 $\mu\text{g L}^{-1}$)	52.4% (10.4 $\mu\text{g L}^{-1}$)	5.4
				C2XCOMPLEX		19.0-28.5	34.3% (6.8 $\mu\text{g L}^{-1}$)	41.3% (9.2 $\mu\text{g L}^{-1}$)	4.9
			ACOLITE	chl_oc2		10.8-17.5	37.3% (7.4 $\mu\text{g L}^{-1}$)	49.4% (9.8 $\mu\text{g L}^{-1}$)	-6.5
				chl_oc3		16.7-24.8	31.8% (6.3 $\mu\text{g L}^{-1}$)	36.3% (7.2 $\mu\text{g L}^{-1}$)	-0.5
				chl_re_gons		29.9-44.5	85.2% (16.9 $\mu\text{g L}^{-1}$)	95.3% (18.9 $\mu\text{g L}^{-1}$)	16.9
				chl_re_gons740		29.6-43.7	83.2% (16.5 $\mu\text{g L}^{-1}$)	93.3% (18.5 $\mu\text{g L}^{-1}$)	16.5
				chl_re_moses3b		36.9-64.7	165.9% (32.9 $\mu\text{g L}^{-1}$)	176.0% (34.9 $\mu\text{g L}^{-1}$)	32.9
				chl_re_mishra		19.3-29.5	35.8% (7.1 $\mu\text{g L}^{-1}$)	43.9% (8.7 $\mu\text{g L}^{-1}$)	4
			Sentinel 3 OLCI	chl_nn		5.0-6.5	75.6% (15.0 $\mu\text{g L}^{-1}$)	83.7% (16.6 $\mu\text{g L}^{-1}$)	-15
				chl_oc4me		NaN	NaN	NaN	NaN
June 2023	Sentinel 2	20	C2Nets	C2RCC	0.8-2.1	4.9-10.2	410.3% (6.4 $\mu\text{g L}^{-1}$)	423.1% (6.6 $\mu\text{g L}^{-1}$)	6.4
				C2X		9.1-20.0	884.6% (13.8 $\mu\text{g L}^{-1}$)	910.3% (14.2 $\mu\text{g L}^{-1}$)	13.8
				C2XCOMPLEX		8.5-17.2	692.3% (10.8 $\mu\text{g L}^{-1}$)	724.4% (11.3 $\mu\text{g L}^{-1}$)	10.8
			ACOLITE	chl_oc2		4.2-7.9	243.6% (3.8 $\mu\text{g L}^{-1}$)	262.8% (4.1 $\mu\text{g L}^{-1}$)	3.8
				chl_oc3		5.8-12.5	435.9% (6.8 $\mu\text{g L}^{-1}$)	461.5% (7.2 $\mu\text{g L}^{-1}$)	6.8
				chl_re_gons		10.6-20.9	865.4% (13.5 $\mu\text{g L}^{-1}$)	903.8% (14.1 $\mu\text{g L}^{-1}$)	13.5

Ocotber 2023				chl_re_gons740		11.1-20.9	871.8% (13.6 µg L ⁻¹)	910.3% (14.2 µg L ⁻¹)	13.6
				chl_re_moses3b		4.4-22.5	647.4% (10.1 µg L ⁻¹)	801.3% (12.5 µg L ⁻¹)	10.1
				chl_re_mishra		8.1-13.9	576.9% (9.0 µg L ⁻¹)	596.2% (9.3 µg L ⁻¹)	9
	Sentinel 3 OLCI	300	SENTINEL 3	chl_nn		2.8-6.1	179.5% (2.8 µg L ⁻¹)	185.9% (2.9 µg L ⁻¹)	2.8
				chl_oc4me		16.1-68.2	2961.5% (46.2 µg L ⁻¹)	3205.1% (50.0 µg L ⁻¹)	46.2
	Sentinel 2	20	C2Nets	C2RCC	6.9-13.0	2.9-8.1	55.1% (5.2 µg L ⁻¹)	60.3% (5.7 µg L ⁻¹)	-5.2
				C2X		4.6-11.7	46.6% (4.4 µg L ⁻¹)	50.8% (4.8 µg L ⁻¹)	-3.6
				C2XCOMPLEX		5.0-11.0	19.1% (1.8 µg L ⁻¹)	26.5% (2.5 µg L ⁻¹)	-1.6
			ACOLITE	chl_oc2		3.3-14.5	46.6% (4.4 µg L ⁻¹)	54.0% (5.1 µg L ⁻¹)	-2.6
				chl_oc3		2.4-5.6	62.5% (5.9 µg L ⁻¹)	65.6% (6.2 µg L ⁻¹)	-5.9
				chl_re_gons		7.2-13.3	20.1% (1.9 µg L ⁻¹)	24.4% (2.3 µg L ⁻¹)	0.9
				chl_re_gons740		7.9-13.5	20.1% (1.9 µg L ⁻¹)	24.4% (2.3 µg L ⁻¹)	1.1
				chl_re_moses3b		2.7-16.8	46.6% (4.4 µg L ⁻¹)	51.9% (4.9 µg L ⁻¹)	0.9
				chl_re_mishra		6.4-9.8	23.3% (2.2 µg L ⁻¹)	27.5% (2.6 µg L ⁻¹)	-2
						2.2-4.8	64.6% (6.1 µg L ⁻¹)	66.7% (6.3 µg L ⁻¹)	-6.1
						10.6-63.6	165.2% (15.6 µg L ⁻¹)	230.8% (21.8 µg L ⁻¹)	15.3
	Sentinel 3 OLCI	300	SENTINEL 3	chl_nn					
				chl_oc4me					

Supplementary Table 7 | **Detailed performance metrics for total suspended sediment (TSS, g m^{-3}) retrieval algorithms applied to Sentinel-2 and Sentinel-3 imagery.** The table reports the in situ and estimated value ranges, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), bias, and their respective percentage values, computed using the average in situ TSS concentration. The algorithm with the lowest MAE for each date is highlighted as the best-performing model.

Date	Sensor	Spatial Resolution (m)	Processor/Product	Algorithm	In-Situ min-max (g m^{-3})	Estimated min-max (g m^{-3})	MAE	RMSE	Bias
May 2023	Sentinel 2		C2Nets	C2X	11.0-44.0	10.7-16.9	53.6% (13.2 g m^{-3})	73.1% (18.0 g m^{-3})	-11.7
				C2XCOMPLEX		8.8-14.8	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-13.5
			ACOLITE	SPM_Nechad2010_665		8.8-14.4	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-14.1
				SPM_Nechad2016_665		8.3-13.5	59.7% (14.7 g m^{-3})	80.4% (19.8 g m^{-3})	-14.7
				SPM_Nechad2010_Ave_665		8.4-13.8	59.3% (14.6 g m^{-3})	80.0% (19.7 g m^{-3})	-14.5
				SPM_Novoa2017		8.8-14.4	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-14.1
	Sentinel 3 OLCI	300	SENTINEL 3	tsm_nn		19.1-26.4	59.3% (14.6 g m^{-3})	60.9% (15.0 g m^{-3})	-0.5
June 2023	Sentinel 2	20	C2Nets	C2RCC	9.0-14.0	3.5-7.5	52.0% (6.5 g m^{-3})	53.6% (6.7 g m^{-3})	-6.5
				C2X		7.5-15.7	18.4% (2.3 g m^{-3})	25.6% (3.2 g m^{-3})	-0.1
				C2XCOMPLEX		5.9-12.4	21.6% (2.7 g m^{-3})	26.4% (3.3 g m^{-3})	-2.3
			ACOLITE	SPM_Nechad2010_665		4.6-14.0	23.2% (2.9 g m^{-3})	27.2% (3.4 g m^{-3})	-2.1
				SPM_Nechad2016_665		4.4-13.1	24.8% (3.1 g m^{-3})	30.4% (3.8 g m^{-3})	-2.7
				SPM_Nechad2010_Ave_665		4.4-13.4	24.0% (3.0 g m^{-3})	28.8% (3.6 g m^{-3})	-2.5
				SPM_Novoa2017		4.6-14.0	23.2% (2.9 g m^{-3})	27.2% (3.4 g m^{-3})	-2.1
	Sentinel 3 OLCI	300	SENTINEL 3	tsm_nn		4.8-23.5	52.0% (6.5 g m^{-3})	55.2% (6.9 g m^{-3})	-3.3
October 2023	Sentinel 2	20	C2Nets	C2RCC	8.0-21.0	2.3-4.0	81.8% (13.5 g m^{-3})	85.5% (14.1 g m^{-3})	-13.5
				C2X		6.6-12.9	49.1% (8.1 g m^{-3})	55.2% (9.1 g m^{-3})	-8.1

C2XCOMPLEX				4.6-13.3	60.0% (9.9 g m ⁻³)	66.1% (10.9 g m ⁻³)	-9.9
ACOLITE			SPM_Nechad2010_665	2.7-7.4	71.5% (11.8 g m ⁻³)	73.3% (12.1 g m ⁻³)	-11.8
			SPM_Nechad2016_665	2.6-7.0	72.7% (12.0 g m ⁻³)	75.2% (12.4 g m ⁻³)	-12
			SPM_Nechad2010_Ave_665	2.6-7.1	72.1% (11.9 g m ⁻³)	74.5% (12.3 g m ⁻³)	-11.9
			SPM_Novoa2017	2.7-7.4	71.5% (11.8 g m ⁻³)	73.3% (12.1 g m ⁻³)	-11.8
Sentinel 3 OLCI	300	SENTINEL 3	tsm_nn	3.0-12.7	56.4% (9.3 g m ⁻³)	63.0% (10.4 g m ⁻³)	-8.9

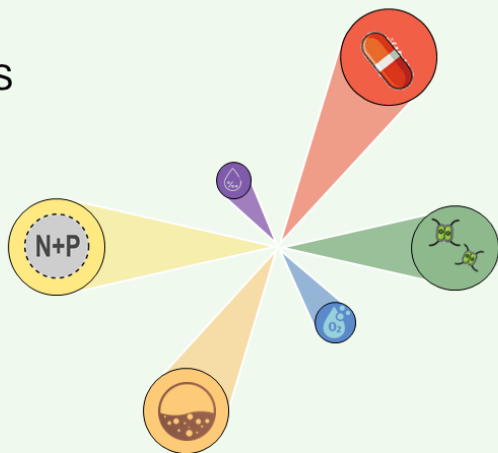
Supplementary Table 8 | **Detailed performance metrics for Chromophoric Dissolved Organic Matter (CDOM, m^{-1}) retrieval algorithms applied to Sentinel-2 and Sentinel-3 imagery.** The table reports the in situ and estimated value ranges, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), bias, and their respective percentage values, computed using the average in situ CDOM concentration.

Date	Sensor	Spatial Resolution (m)	Processor/ Product	Algorithm	In-Situ min-max (m^{-1})	Estimated min-max (m^{-1})	MAE	RMSE	Bias
May 2023	Sentinel 2	20	C2Nets	C2rcc_iop_agelb	0.5-2.0	0.4-0.6	58.4% (0.7 m^{-1})	67.8% (0.8 m^{-1})	-0.7
				c2rcc_iop_adg		0.9-1.4	34.2% (0.4 m^{-1})	40.6% (0.5 m^{-1})	0.0
				C2x_iop_agelb		0.6-4.5	134.0% (1.5 m^{-1})	168.6% (1.9 m^{-1})	0.9
				c2x_iop_adg		0.8-4.9	147.0% (1.7 m^{-1})	181.7% (2.1 m^{-1})	1.3
				C2xcomplex_iop_agelb		0.4-0.9	65.3% (0.7 m^{-1})	71.6% (0.8 m^{-1})	-0.6
				c2xcomplex_iop_adg		0.5-1.2	55.8% (0.6 m^{-1})	64.5% (0.7 m^{-1})	-0.4
	Sentinel 3 OLCI	300	SENTINEL 3	tsm_nn		4.7-6.3	490% (4.6 m^{-1})	567.6% (4.6 m^{-1})	4.6
June 2023	Sentinel 2	20	C2Nets	C2rcc_iop_agelb	0.5-1.7	0.3-0.4	67.7% (0.8 m^{-1})	74.7% (0.8 m^{-1})	-0.8
				c2rcc_iop_adg		0.7-0.9	36.3% (0.4 m^{-1})	45.5% (0.5 m^{-1})	-0.4
				C2x_iop_agelb		0.7-0.9	33.7% (0.4 m^{-1})	45.4% (0.5 m^{-1})	-0.3
				c2x_iop_adg		1.0-1.5	32.9% (0.4 m^{-1})	40.3% (0.5 m^{-1})	0.1
				C2xcomplex_iop_agelb		0.3-0.6	62.2% (0.7 m^{-1})	69.2% (0.8 m^{-1})	-0.7
				c2xcomplex_iop_adg		0.5-0.8	44.1% (0.5 m^{-1})	52.6% (0.6 m^{-1})	-0.5
	Sentinel 3 OLCI	300	SENTINEL 3	tsm_nn		0.4-0.9	42.6% (0.5 m^{-1})	49.0% (0.5 m^{-1})	0.7

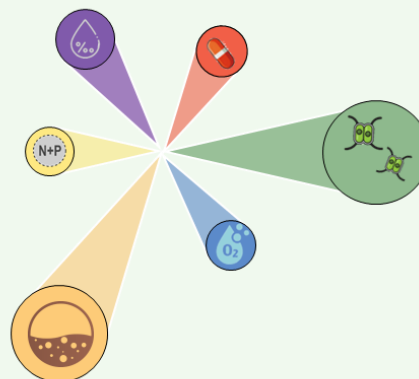
Note: It is important to note that the comparison was limited to the available CDOM products, specifically the inherent optical properties (IOP) from the Sentinel-2 C2RCC processor and the ADG_NN product from Sentinel-3 OLCI. Unlike for TSS and Chl-a, no CDOM estimates are provided by the

ACOLITE processor, and therefore ACOLITE-derived products were not included in this assessment. No CDOM performance evaluation was conducted for T3 due to the high proportion of invalid in situ measurements.

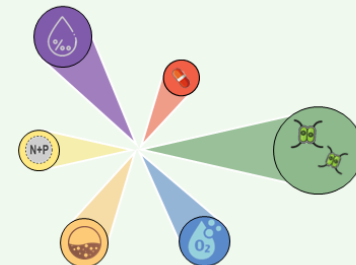
INLAND WATERS



T1

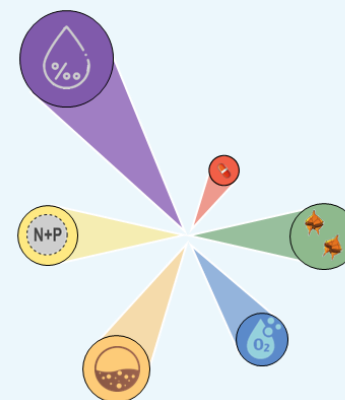
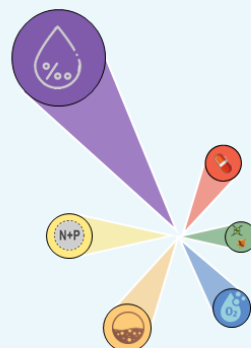
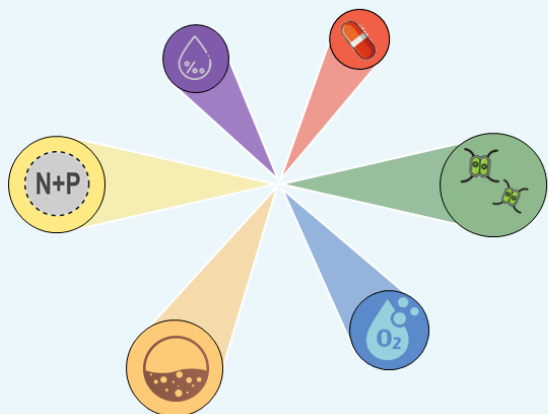


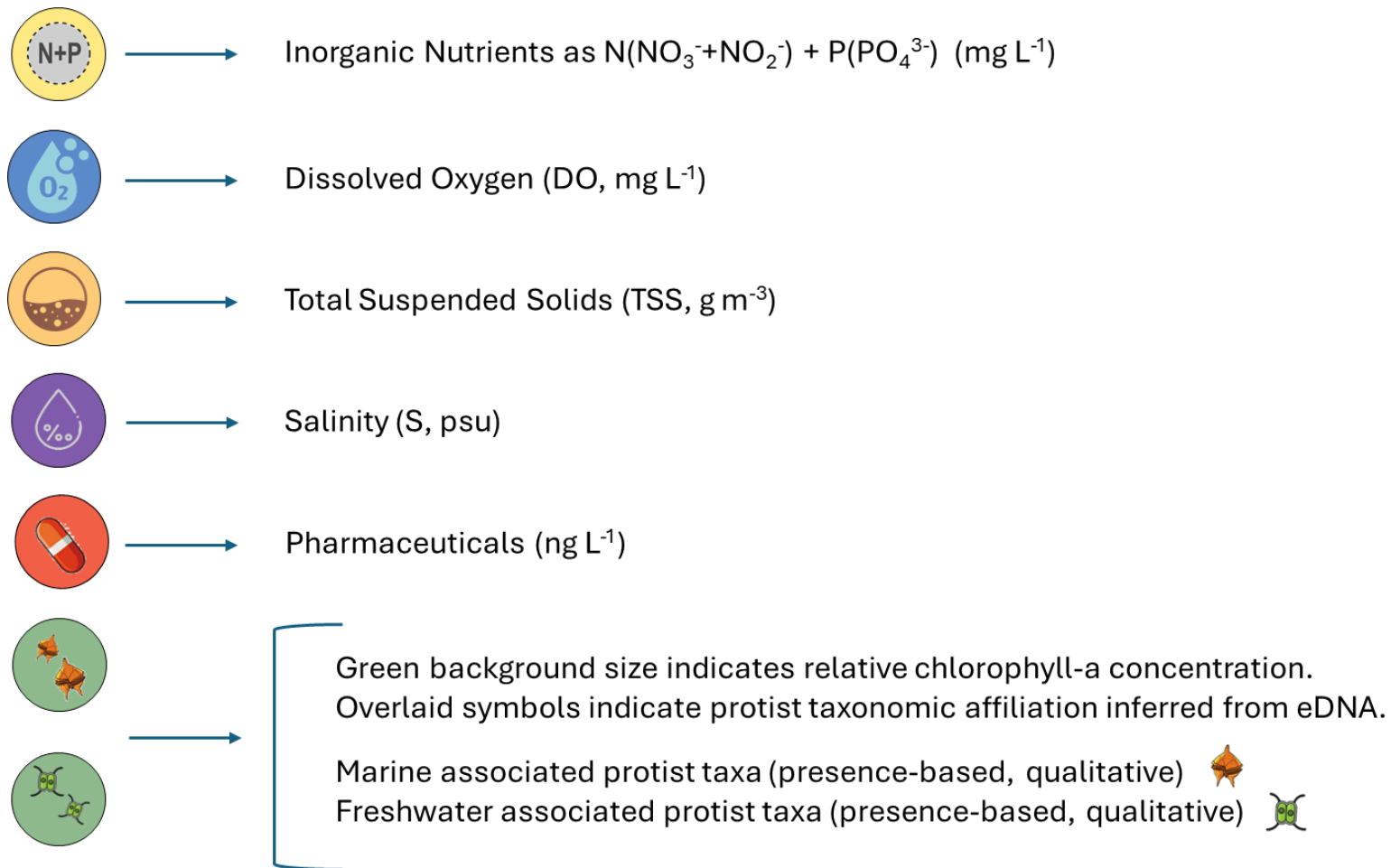
T2



T3

MARINE WATERS





Supplementary Figure 2 | **Conceptual summary of flood-driven responses across the river-to-sea continuum.** Qualitative overview integrating physical, chemical and biological patterns observed across inland, transitional and marine compartments following the May 2023 flood. Symbol size represents the relative magnitude of key chemical and physical parameters, with larger symbols indicating higher values (for example nutrients, total suspended solids, dissolved oxygen and pharmaceuticals). The size of the green background reflects relative chlorophyll-a concentrations. Overlaid symbols indicate the presence of protist taxa typically associated with marine or freshwater environments, inferred from eDNA metabarcoding data and representing qualitative, presence-based information rather than abundance.

Supplementary Table 9 | **Summary of the main algorithms used to estimate chlorophyll-a (Chl a) and total suspended solids (TSS) from Sentinel-2 and Sentinel-3 satellite data. Processing chains include C2Nets, ACOLITE, and OLCI-WFR products.** The Algorithm type column specifies the nature of the model (empirical, semi-empirical, neural network), while the Notes column details the parameter settings, such as IOP training ranges for neural networks or the spectral bands and coefficients used for empirical algorithms. Relevant literature references are provided for each algorithm.

Satellite Sensor	Processor	Algorithm	Estimated Parameter	Algorithm type	Notes
Sentinel-2	C2Nets	C2RCC-Nets ^{1,2}	Chl <i>a</i> , TSS, CDOM	Neural Network (RTM-based inversion)	IOP ranges: a_pig [0–5.3], a_det [0–5.9], a_CDOM [0–1.0], b_wit [0–60.0], b_part [0–60.0]
	C2Nets	C2X-Nets ²	Chl <i>a</i> , TSS, CDOM	Neural Network (RTM-based inversion)	IOP ranges: a_pig [0–51.0], a_det [0–60.0], a_CDOM [0–60.0], b_wit [0–590.0], b_part [0–590.0]
	C2Nets	C2XC-Nets ²	Chl <i>a</i> , TSS, CDOM	Neural Network (RTM-based inversion)	IOP ranges: a_pig [0–30.81], a_det [0–17.0], a_CDOM [0–4.25], b_tot [0–1000.0]
	ACOLITE	Chl_oc2 ³	Chl <i>a</i>	Empirical (Ocean Color 2-band algorithm)	Bands 443, 560 nm
	ACOLITE	Chl_oc3 ³	Chl <i>a</i>	Empirical (Ocean Color 3-band algorithm)	Bands 443, 490, 560 nm
	ACOLITE	Chl_re_gons ⁴	Chl <i>a</i>	Empirical (Red-Edge, spectral regression)	Bands 705, 740, 783 nm
	ACOLITE	Chl_re_gons740 ⁴	Chl <i>a</i>	Empirical (Red-Edge regression – band 740 nm)	Band 740 nm
	ACOLITE	Chl_re_moses_3b ⁵	Chl <i>a</i>	Semi-empirical (multiband regression)	Bands 665, 705, 740 nm
	ACOLITE	Chl_re_mishra ⁶	Chl <i>a</i>	Empirical (Red-Edge linear regression)	Bands 705, 740 nm

	ACOLITE	SPM_Nechad2010_665 ⁷	TSS	Empirical (Single band)	Band 665 nm, coefficients Nechad 2010
	ACOLITE	SPM_Nechad2016_665 ⁷	TSS	Empirical (updated version)	Band 665 nm, updated coefficients
	ACOLITE	SPM_Nechad2010A_ve_665 ⁷	TSS	Empirical (Empirical (multi-environment average coefficients)	Band 665 nm
	ACOLITE	SPM_Novoa2017 ⁸	TSS	Semi-empirical (multiband regression)	Bands 560, 665, 705 nm
Sentinel-3 OLCI	OLCI-WFR	CHL_NN ⁹	Chl <i>a</i>	Neural network (RTM-trained)	Internal RTM-based inversion
	OLCI-WFR	CHL_OC4ME ⁹	Chl <i>a</i>	Empirical (OC4 algorithm adapted for OLCI)	Bands 412, 443, 490, 510 nm
	OLCI-WFR	TSM_NN ⁹	TSS	Neural network (RTM-trained)	Internal RTM-based inversion

Supplementary References

1. Doerffer, R., & Schiller, H. (2007). The MERIS Case 2 water algorithm. *International Journal of Remote Sensing*, 28(3-4), 517-535. <https://doi.org/10.1080/01431160600821127>
2. Brockmann, C., Doerffer, R., Peters, M., Kerstin, S., Embacher, S., & Ruescas, A. (2017). Evolution of the C2RCC neural network for Sentinel 2 and 3 for the retrieval of ocean colour products in normal and extreme optically complex waters. In *Living Planet Symposium* (Vol. 740, p. 54).
3. O'Reilly, J. E., Maritorena, S., Mitchell, B. G., Siegel, D. A., Carder, K. L., Garver, S. A., ... & McClain, C. (1998). Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research: Oceans*, 103(C11), 24937-24953. <https://doi.org/10.1029/98JC02160>
4. Gons, H. J., Rijkeboer, M., & Ruddick, K. G. (2002). A chlorophyll-retrieval algorithm for satellite imagery (Medium Resolution Imaging Spectrometer) of inland and coastal waters. *Journal of Plankton Research*, 24(9), 947-951. <https://doi.org/10.1093/plankt/24.9.947>
5. Moses, W. J., Gitelson, A. A., Berdnikov, S., Saprygin, V., & Povazhnyi, V. (2012). Operational MERIS-based NIR-red algorithms for estimating chlorophyll-a concentrations in coastal waters—The Azov Sea case study. *Remote Sensing of Environment*, 121, 118-124. <https://doi.org/10.1016/j.rse.2012.01.024>

6. Mishra, S., & Mishra, D. R. (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment*, 117, 394-406. <https://doi.org/10.1016/j.rse.2011.10.016>
7. Nechad, B., Ruddick, K. G., & Park, Y. (2010). Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. *Remote Sensing of Environment*, 114(4), 854-866. <https://doi.org/10.1016/j.rse.2009.11.022>
8. Novoa, S., Doxaran, D., Ody, A., Vanhellemont, Q., Lafon, V., Lubac, B., & Gernez, P. (2017). Atmospheric corrections and multi-conditional algorithm for multi-sensor remote sensing of suspended
9. EUMETSAT. (2024, July 19). *Sentinel-3 ocean colour level 2 data guide* (Version 1.2). Retrieved from <https://user.eumetsat.int/>

