

Long-Term Detection of SPM Concentration and Water Colour in Gravel and Sand Pit Lakes through Landsat and Sentinel-2 Imagery

Nicola Ghirardi ^{1,2,3*}, Monica Pinardi ¹, Daniele Nizzoli ², Pierluigi Viaroli ², Mariano Bresciani ¹

¹ CNR – Institute for Electromagnetic Sensing of the Environmental, Via A. Corti 12, 20133 Milan, Italy; ghirardi.n@irea.cnr.it (N.G.); bresciani.m@irea.cnr.it (M.B.); pinardi.m@irea.cnr.it (M.P.)

² Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 33/A, 43124 Parma, Italy; nicola.ghirardi@unipr.it (N.G.); daniele.nizzoli@unipr.it (D.N.); pierluigi.viaroli@unipr.it (P.V.)

³ CNR – Institute of BioEconomy, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy; nicola.ghirardi@ibe.cnr.it

* Correspondence: ghirardi.n@irea.cnr.it

Supplementary Materials

PLs	Pit lakes
SPM	Suspended Particulate Matter
λ_{dom}	Dominant wavelength
EO	Earth Observation
FUI	Forel-Ule Index
Rrs	Remote Sensing Reflectances
VIS-NIR	Visible-Near infrared
TO	Turin
OR	Po and Orba River Park
MI	Milan
TR	Trezzo sull'Adda
BS	Brescia
MN	Mantua
MO	Modena
PO	Po River shaft
L5	Landsat-5
L7	Landsat-7
S2	Sentinel-2
TM	Thematic Mapper
ETM+	Enhanced Thematic Mapper
VIS-SWIR	Visible-Short Wavelength InfraRed
MSI	MultiSpectral Instrument
L1	Level-1
WFD	Water Framework Directive
DSF	Dark Spectrum Fitting
AOD ₅₅₀	Aerosol Optical Depth at 550 nm
L_u	Water radiance
L_{sky}	Sky radiance
E_d	Downwelling irradiance
ROIs	Regions of Interest
R^2	Determination coefficient
MAE	Mean Absolute Error
RMSE	Root Mean Square Error
MAPE	Mean Absolute Percentage Error
SA	Spectral Angle
FWHM	Full Width Half Maximum
PLS _{low}	PLs characterized by low mean values of SPM and λ_{dom}
PLS _{high}	PLs characterized by high mean values of SPM and λ_{dom}
CDOM	Colored Dissolved Organic Matter

Table S1. Landsat-5 (L5, red), Landsat-7 (L7, blue) and Sentinel-2 (S2, green) satellite images processed for subsample pit lake analysis. Turin (TO), Po and Orba River Park (OR), Milan (MI), Trezzo sull'Adda (TR), Brescia (BS), Mantua (MN), Modena (MO), and along the Po River shaft (PO). The seasons follow the WFD protocol: winter (Win.; January 1 - March 20), spring (Spr.; April 1 - May 15), spring-summer (Spr. – Sum.; May 16 - June 15), summer (Sum.; July 1 - August 31), summer-autumn (Sum. – Aut.; September 1 - October 1) and autumn (Aut.; October 2 - November 31).

Year	Season	TO	OR	MI	TR	BS	MN	MO	PO*
1990	Win.	23/02	23/02	-	-	-	-	-	-
	Spr.	12/04	12/04	12/04	12/04	07/05	07/05	07/05	07/05 + 30/04
	Spr. – Sum.	15/06	15/06	-	-	-	-	-	-
	Sum.	02/08	02/08	-	-	-	-	-	-
	Sum. – Aut.	10/09	-	-	-	-	-	-	-
	Aut.	05/10	06/11	-	-	-	-	-	-
1994	Win.	-	-	-	-	-	-	19/01	11/02 + 04/02
	Spr.	30/04	07/04	07/04	07/04	02/05	02/05	02/05	02/05 + NA
	Spr. – Sum.	-	-	-	-	-	-	27/05	19/06 + 27/05
	Sum.	-	-	-	-	-	-	30/07	06/08 + 30/07
	Sum. – Aut.	-	-	-	-	-	-	07/09	07/09 + NA
	Aut.	-	-	-	-	-	-	25/10	-
1999	Win.	-	31/01	15/01	15/01	24/01	24/01	-	25/02 + NA
	Spr.	05/04	05/04	05/04	05/04	29/03	-	30/04	30/04 + NA
	Spr. – Sum.	-	23/05	23/05	23/05	01/06	01/06	-	17/06 + 10/06
	Sum.	-	26/07	26/07	26/07	04/08	04/08	-	03/07 + 05/08
	Sum. – Aut.	-	12/09	12/09	12/09	13/09	14/09	-	13/09 + 14/09
	Aut.	-	23/11	23/11	23/11	24/11	07/10	-	07/10 + 08/10
2000	Win.	26/01	26/01	-	-	-	-	-	-
	Spr.	01/05	01/05	01/05	01/05	08/04	08/04	08/04	08/04 + 03/05
	Spr. – Sum.	09/06	02/06	-	-	-	-	-	-
	Sum.	28/08	21/08	-	-	-	-	-	-
	Sum. – Aut.	22/09	22/09	-	-	-	-	-	-
	Aut.	08/10	08/10	-	-	-	-	-	-
2003	Win.	-	-	-	-	-	-	21/02	28/02 + 21/02
	Spr.	24/04	24/04	24/04	24/04	17/04	17/04	01/04	01/04 + NA
	Spr. – Sum.	-	-	-	-	-	-	28/05	19/05 + 28/05
	Sum.	-	-	-	-	-	-	08/08	30/07 + 08/08
	Sum. – Aut.	-	-	-	-	-	-	16/09	16/09 + 25/09
	Aut.	-	-	-	-	-	-	11/10	-
2006	Win.	10/02	10/01	-	-	-	-	-	-
	Spr.	-	08/04	08/04	08/04	11/05	11/05	03/05	03/05 + NA
	Spr. – Sum.	10/06	11/06	-	-	-	-	-	-
	Sum.	30/08	30/08	-	-	-	-	-	-
	Sum. – Aut.	-	-	-	-	-	-	-	-
	Aut.	02/11	02/11	-	-	-	-	-	-
2007	Win.	-	05/01	15/02	30/01	30/01	06/01	-	-
	Spr.	27/04	27/04	20/04	20/04	20/04	20/04	20/04	20/04 + 29/04
	Spr. – Sum.	-	-	22/05	30/05	30/05	22/05	-	-
	Sum.	-	16/07	16/07	16/07	25/07	25/07	-	-
	Sum. – Aut.	-	18/09	02/09	02/09	11/09	12/09	-	-
	Aut.	-	29/11	21/10	29/11	-	21/10	-	-

2008	Win.	-	-	-	-	-	-	10/02	10/02 + 19/02
	Spr.	04/04	05/04	08/05	07/05	-	08/05	08/05	08/05 + 09/05
	Spr. – Sum.	-	-	-	-	-	-	10/06	09/06 + 10/06
	Sum.	-	-	-	-	-	-	20/07	11/07 + 04/07
	Sum. – Aut.	-	-	-	-	-	-	-	-
	Aut.	-	-	-	-	-	-	-	-
2012	Win.	11/01	11/01	11/01	11/01	21/02	21/02	-	21/02 + 13/01
	Spr.	31/03	-	31/03	31/03	25/04	25/04	04/05	11/05 + NA
	Spr. – Sum.	25/05	19/06	19/06	19/06	-	05/06	-	27/05 + 21/06
	Sum.	22/08	22/08	22/08	22/08	15/08	30/07	-	30/07 + 08/08
	Sum. – Aut.	14/09	07/09	07/09	07/09	16/09	09/09	-	16/09 + 09/09
	Aut.	25/10	25/10	09/10	09/10	02/10	02/10	-	02/10 + NA
2014	Win.	-	-	-	-	-	-	25/01	25/01 + NA
	Spr.	28/03	-	06/04	06/04	15/04	01/05	01/05	01/05 + 24/04
	Spr. – Sum.	-	-	-	-	-	-	11/06	17/05 + 11/06
	Sum.	-	-	-	-	-	-	05/08	05/08 + 14/08
	Sum. – Aut.	-	-	-	-	-	-	06/09	06/09 + 15/09
	Aut.	-	-	-	-	-	-	24/10	24/10 + 02/11
2015	Win.	-	-	-	-	-	-	-	-
	Spr.	-	-	-	-	-	-	-	-
	Spr. – Sum.	-	-	-	-	-	-	-	-
	Sum.	-	06/08	06/08	06/08	06/08	06/08	-	06/08 + 13/08
	Sum. – Aut.	-	25/09	25/09	25/09	25/09	25/09	-	25/09 + 12/09
	Aut.	-	24/11	24/11	24/11	24/11	24/11	-	24/11 + 22/10
2016	Win.	-	-	-	-	-	-	-	-
	Spr.	12/04	12/04	22/04	22/04	22/04	22/04	29/04	22/04 + 29/04
	Spr. – Sum.	-	-	-	-	-	-	-	-
	Sum.	-	-	-	-	-	-	-	-
	Sum. – Aut.	-	-	-	-	-	-	-	-
	Aut.	-	-	-	-	-	-	-	-
2017	Win.	07/01	-	-	-	-	-	24/01	16/02 + 14/01
	Spr.	07/04	07/04	17/04	17/04	17/04	17/04	14/05	17/04 + 14/05
	Spr. – Sum.	17/05	-	-	-	-	-	03/06	27/05 + 03/06
	Sum.	06/07	-	-	-	-	-	08/07	06/07 + 08/07
	Sum. – Aut.	12/09	-	-	-	-	-	26/09	NA + 26/09
	Aut.	14/10	-	-	-	-	-	16/10	18/11 + 16/10
2018	Win.	11/02	02/01	22/01	22/01	24/01	19/01	-	22/01 + 14/01
	Spr.	17/04	17/04	22/04	22/04	22/04	22/04	24/04	22/04 + 19/04
	Spr. – Sum.	01/06	01/06	01/06	01/06	24/05	19/05	-	01/06 + 03/06
	Sum.	26/07	26/07	31/07	31/07	31/07	31/07	-	31/07 + 28/07
	Sum. – Aut.	19/09	19/09	24/09	24/09	24/09	24/09	-	04/09 + 06/09
	Aut.	24/10	24/10	24/10	24/10	19/10	24/10	-	24/10 + NA
2019	Win.	-	-	-	-	-	-	-	-
	Spr.	15/04	17/04	17/04	17/04	17/04	17/04	19/04	17/04 + 19/04
	Spr. – Sum.	-	-	-	-	-	-	-	-
	Sum.	-	-	-	-	-	-	-	-
	Sum. – Aut.	-	-	-	-	-	-	-	-
	Aut.	-	-	-	-	-	-	-	-

2020	Win.	12/01	12/01	12/01	12/01	12/01	12/01	29/01	12/01 + 29/01
	Spr.	06/04	11/04	11/04	11/04	11/04	11/04	08/04	11/04 + 08/04
	Spr. – Sum.	26/05	21/05	21/05	21/05	02/06	23/05	23/05	21/05 + 23/05
	Sum.	25/07	25/07	25/07	25/07	25/07	25/07	27/07	25/07 + 27/07
	Sum. – Aut.	13/09	13/09	13/09	13/09	13/09	13/09	15/09	13/09 + 15/09
	Aut.	13/10	08/10	28/10	28/10	28/10	28/10	10/10	28/10 + 10/10
2021	Win.	26/01	16/01	16/01	16/01	25/02	16/01	13/01	16/01 + 13/01
	Spr.	06/04	06/04	06/04	16/04	08/04	08/04	08/04	21/04 + 08/04
	Spr. – Sum.	19/05	10/06	10/06	31/05	28/05	28/05	18/05	15/06 + 18/05
	Sum.	10/07	10/07	10/07	10/07	22/07	10/07	22/07	10/07 + 07/07
	Sum. – Aut.	13/09	13/09	13/09	13/09	13/09	13/09	20/09	13/09 + 20/09
	Aut.	18/10	18/10	18/10	18/10	18/10	18/10	15/10	18/10 + 15/10

* Two different images are needed for the PO area because of its size.

Table S2. In situ measurement campaigns to validate remote sensing (RS) products from Sentinel-2 satellite images.

Pit lakes	Sampling	Coordinate N	Coordinate E	Date – <i>in situ</i>	Date – RS
Laghi di Cavallara 1	I	44.99801	10.63943	11/04/2022	11/04/2022
Laghi di Cavallara 2	I	44.99971	10.63958	11/04/2022	11/04/2022
Laghi di Cavallara 3	I	44.99921	10.64321	11/04/2022	11/04/2022
Laghi di Cavallara 4	I	44.99815	10.64325	11/04/2022	11/04/2022
Cava Baita	I	44.93918	10.64777	11/04/2022	11/04/2022
	II	44.93559	10.64306	11/04/2022	11/04/2022
Polo Belgrado Fogarino 1	I	44.94800	10.67448	11/04/2022	11/04/2022
Polo Belgrado Fogarino 2	I	44.95198	10.66959	13/04/2022	13/04/2022
	II	44.95303	10.67153	13/04/2022	13/04/2022
	III	44.95168	10.67151	13/04/2022	13/04/2022
Isola degli Internati	I	44.91544	10.61520	13/04/2022	13/04/2022
Cava Malaspina	I	44.91118	10.62320	13/04/2022	13/04/2022
	II	44.91263	10.62333	13/09/2022	13/09/2022
Ca' Morta	I	45.06416	9.77108	20/06/2022	20/06/2022
Lago Verde	I	45.06013	9.77499	20/06/2022	20/06/2022
Ca' Stanga	I	45.05852	9.79616	20/06/2022	20/06/2022
Bella Venezia	I	45.05166	10.03599	28/09/2022	23/09/2022
	II	45.05327	10.03595	28/09/2022	23/09/2022
	III	45.05080	10.03601	15/06/2023	15/06/2023

	IV	45.05248	10.03609	15/06/2023	15/06/2023
	V	45.05457	10.03616	15/06/2023	15/06/2023
Polesine Sud	I	45.02177	10.06836	28/09/2022	23/09/2022
	II	45.02237	10.06633	28/09/2022	23/09/2022
	III	45.02200	10.06744	15/06/2023	15/06/2023
	IV	45.02269	10.06664	15/06/2023	15/06/2023
Polesine Nord	I	45.02463	10.06557	28/09/2022	23/09/2022
	II	45.02523	10.06797	15/06/2023	15/06/2023
	III	45.02463	10.06671	15/06/2023	15/06/2023

Table S3. Mean SPM concentrations (gm^{-3}) divided into the four categories (location, dimension, season and quarrying activity) and into the eight subsample areas: Turin (TO), Po and Orba River Park (OR), Milan (MI), Trezzo sull'Adda (TR), Brescia (BS), Mantua (MN), Modena (MO), and along the Po River shaft (PO). Small (S.), medium (M.) and Large (L.). Winter (Win.; January 1 - March 20), spring (Spr.; April 1 - May 15), spring-summer (Spr. – Sum.; May 16 - June 15), summer (Sum.; July 1 - August 31), summer-autumn (Sum. – Aut.; September 1 - October 1) and autumn (Aut.; October 2 - November 31).

		TO	OR	MI	TR	BS	MN	MO	PO	Active	Ceased	TOT
Location	<i>Isolated</i>	6.4	9.7	7.0	7.4	9.3	14.1	9.1	16.8	12.4	8.9	10.0
	<i>Proximity</i>	7.7	13.4	8.2	7.1	-	8.7	14.6	18.7	14.5	12.8	13.2
	<i>Connected</i>	5.5	-	-	-	-	6.5	-	18.8	21.4	15.7	16.5
Dimension	<i>Small (<5 ha)</i>	7.4	9.3	7.3	8.2	9.2	13.6	14.4	20.1	18.2	11.4	12.6
	<i>Medium (5-10 ha)</i>	7.0	14.8	6.9	-	11.0	9.5	12.1	15.4	14.3	9.3	10.8
	<i>Large (>10 ha)</i>	7.6	9.6	7.1	5.2	8.3	6.7	11.9	17.0	10.7	9.7	10.1
Season	<i>Winter</i>	9.4	12.1	9.4	8.0	11.9	11.1	12.3	18.5	15.1	11.4	12.4
	<i>Spring</i>	6.6	12.8	6.8	7.8	8.3	12.0	12.8	18.4	12.8	10.5	11.2
	<i>Spring – Summer</i>	7.5	10.1	5.8	6.7	7.3	10.9	12.9	14.3	11.6	9.0	9.7
	<i>Summer</i>	6.6	7.8	6.1	5.7	9.1	10.9	12.4	17.1	12.2	9.6	10.4
	<i>Summer – Autumn</i>	7.5	11.6	7.7	6.6	9.0	13.4	16.2	17.1	11.7	11.8	11.7
	<i>Autumn</i>	7.6	12.4	7.0	8.3	10.2	13.2	16.5	20.5	14.4	12.1	12.7
Quarrying activity	<i>Active</i>	8.9	15.0	8.3	6.7	12.0	-	-	20.4			13.3
	<i>Ceased</i>	6.4	9.7	6.4	8.4	7.5	9.7	13.6	16.6			10.6

Table S4. Mean λ_{dom} (nm) divided into the four categories (location, dimension, season and quarrying activity) and into the eight subsample areas: Turin (TO), Po and Orba River Park (OR), Milan (MI), Trezzo sull'Adda (TR), Brescia (BS), Mantua (MN), Modena

(MO), and along the Po River shaft (PO). Small (S.), medium (M.) and Large (L.). Winter (Win.; January 1 - March 20), spring (Spr.; April 1 - May 15), spring-summer (Spr. – Sum.; May 16 - June 15), summer (Sum.; July 1 - August 31), summer-autumn (Sum. – Aut.; September 1 - October 1) and autumn (Aut.; October 2 - November 31).

		TO	OR	MI	TR	BS	MN	MO	PO	Active	Ceased	TOT
Location	<i>Isolated</i>	571	569	568	562	565	571	573	569	564	569	567
	<i>Proximity</i>	570	570	567	563	-	571	571	570	568	571	570
	<i>Connected</i>	570	-	-	-	-	572	-	571	572	571	571
Dimension	<i>Small (<5 ha)</i>	573	570	571	563	566	571	572	570	565	571	570
	<i>Medium (5-10 ha)</i>	570	569	569	-	566	570	570	570	568	569	569
	<i>Large (>10 ha)</i>	567	569	566	561	560	571	569	568	565	568	566
Season	<i>Winter</i>	573	572	571	568	569	572	572	571	569	572	571
	<i>Spring</i>	569	568	567	558	563	570	570	568	564	569	567
	<i>Spring – Summer</i>	569	567	565	555	557	570	570	569	562	567	565
	<i>Summer</i>	568	568	565	560	564	570	572	568	564	569	567
	<i>Summer – Autumn</i>	570	571	569	566	566	571	573	570	567	571	569
	<i>Autumn</i>	571	571	571	567	568	573	572	571	568	571	570
Quarrying activity	<i>Active</i>	567	569	566	559	562	-	-	568			566
	<i>Ceased</i>	572	569	569	566	567	571	571	570			570

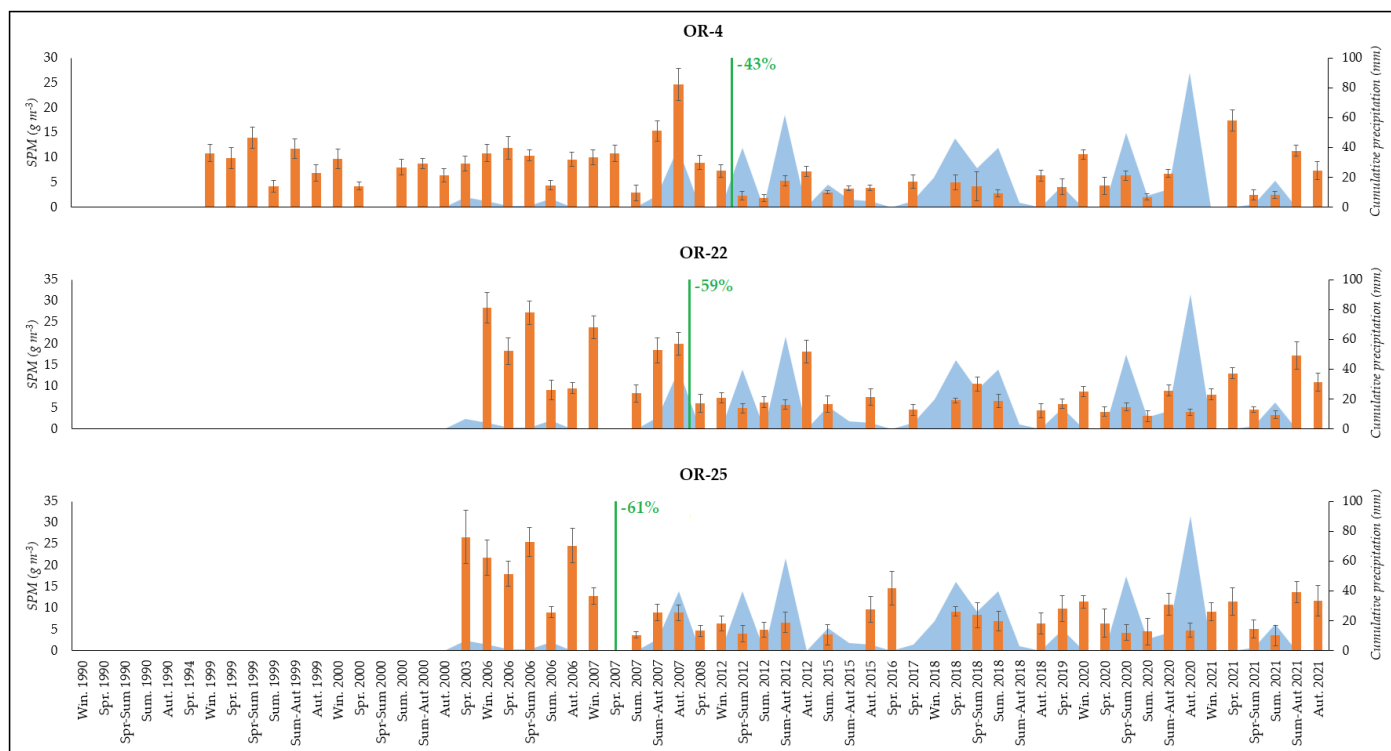


Figure S1. Temporal evolution of SPM concentration (orange columns) in some pit lakes in the OR area (Po and Orba River Park) in relation to cumulative precipitation (blue polygons) in the 7 days prior to satellite acquisitions. The green line indicates the end of quarrying activities and the mean percentage decrease in SPM concentrations after that event.

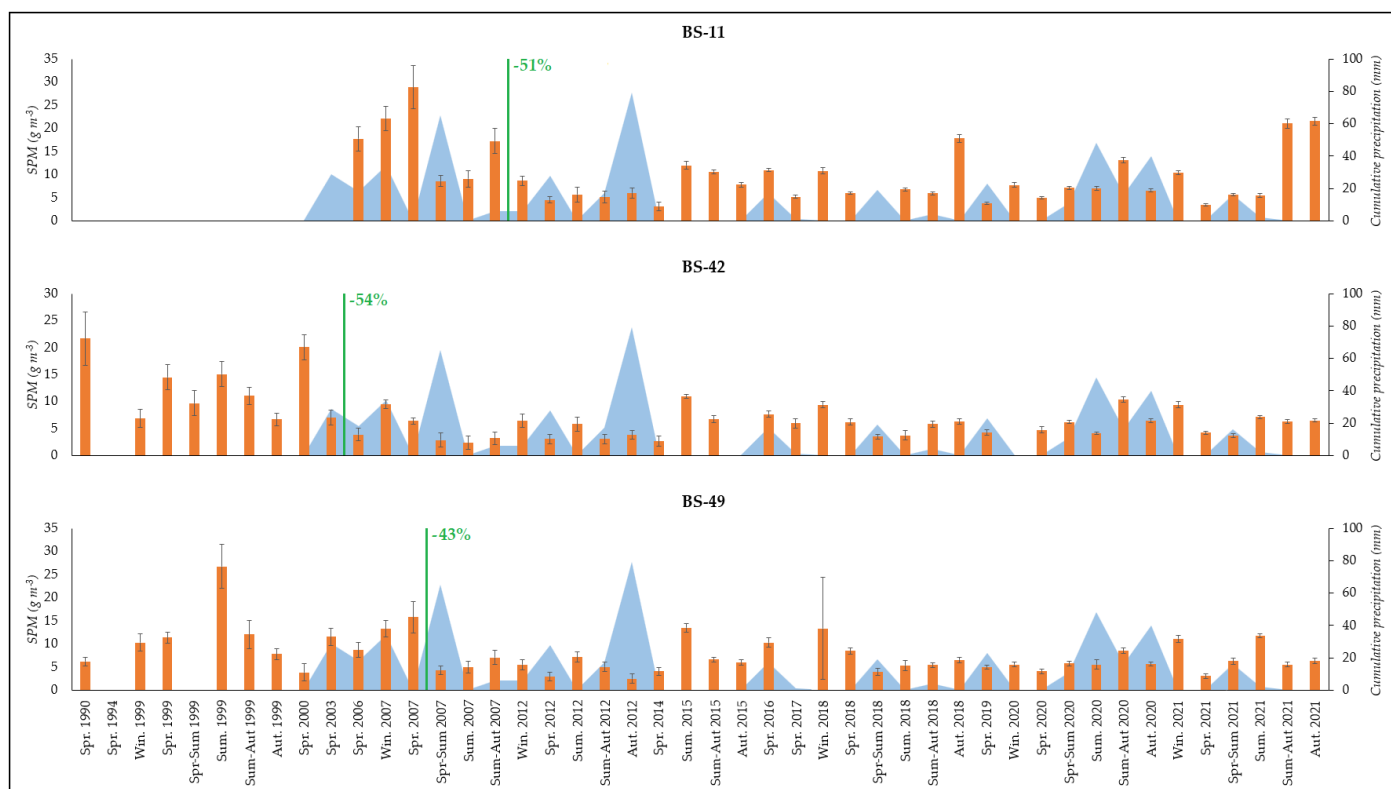


Figure S2. Temporal evolution of SPM concentration (orange columns) in some pit lakes in the BS area (Brescia) in relation to cumulative precipitation (blue polygons) in the 7 days prior to satellite acquisitions. The green line indicates the end of quarrying activities and the mean percentage decrease in SPM concentrations after that event.

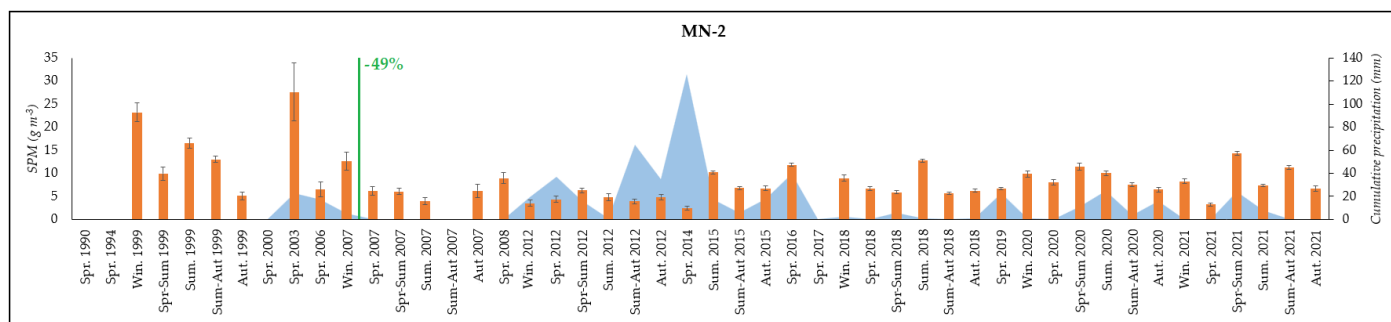


Figure S3. Temporal evolution of SPM concentration (orange columns) of MN-2 pit lake in the MN area (Mantua) in relation to cumulative precipitation (blue polygons) in the 7 days prior to satellite acquisitions. The green line indicates the end of quarrying activities and the mean percentage decrease in SPM concentrations after that event.

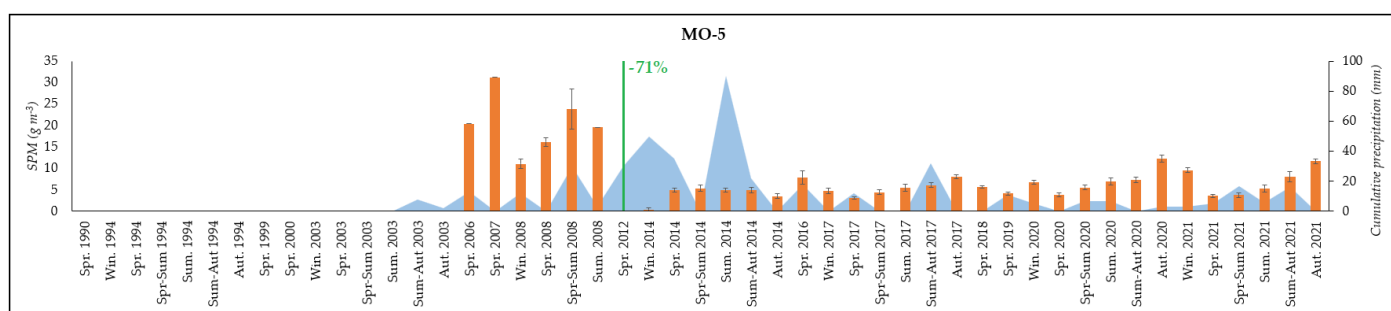


Figure S4. Temporal evolution of SPM concentration (orange columns) of MO-5 pit lake in the MO area (Modena) in relation to cumulative precipitation (blue polygons) in the 7 days prior to satellite acquisitions. The green line indicates the end of quarrying activities and the mean percentage decrease in SPM concentrations after that event.

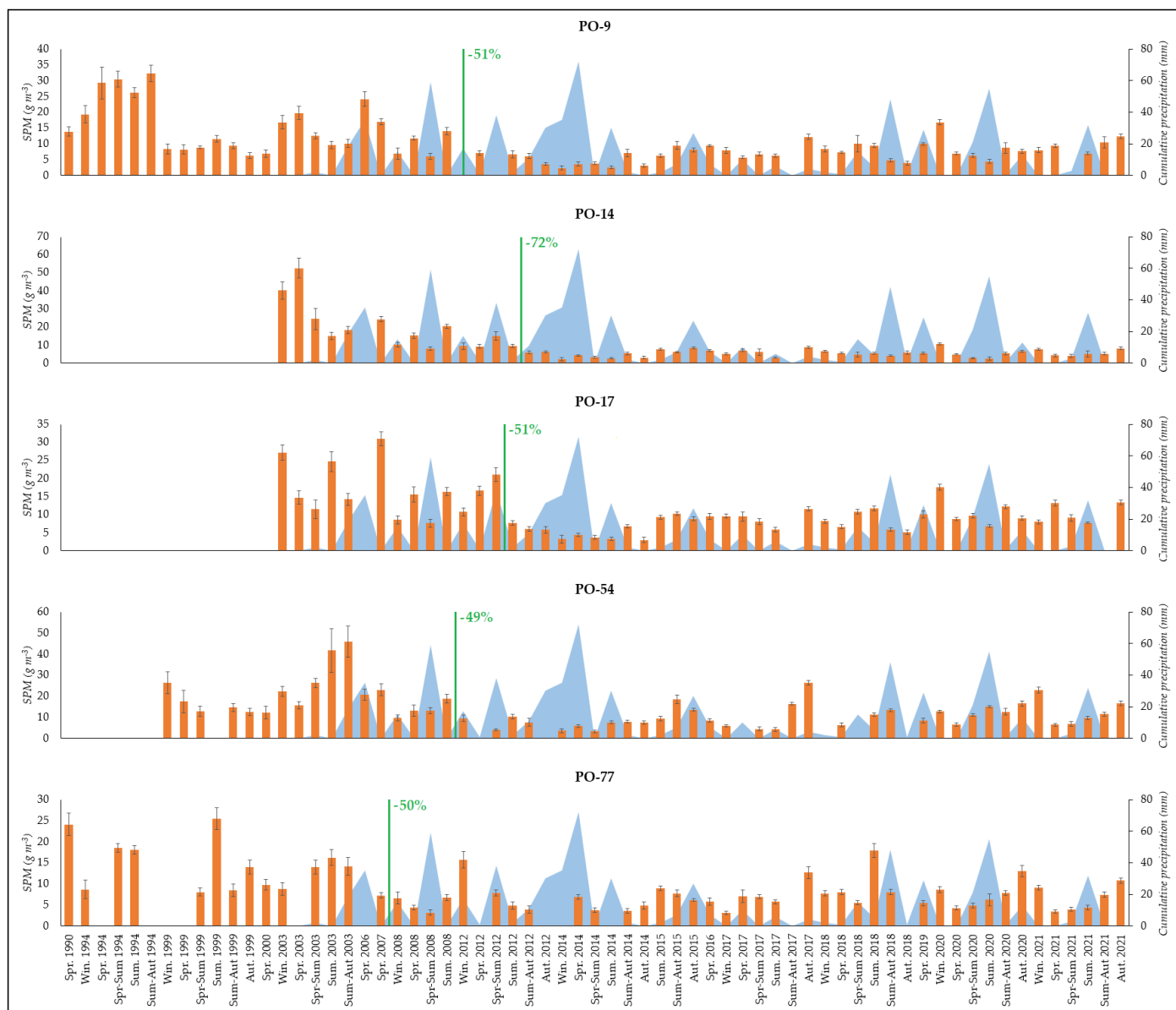


Figure S5. Temporal evolution of SPM concentration (orange columns) of some pit lakes in the PO area (Po River shaft) in relation to cumulative precipitation (blue polygons) in the 7 days prior to satellite acquisitions. The green line indicates the end of quarrying activities and the mean percentage decrease in SPM concentrations after that event.