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Sediments on the move

A PROTOCOL FOR ASSESSING SEDIMENT TOXICITY IN RESERVOIRS BEFORE FLUSHING

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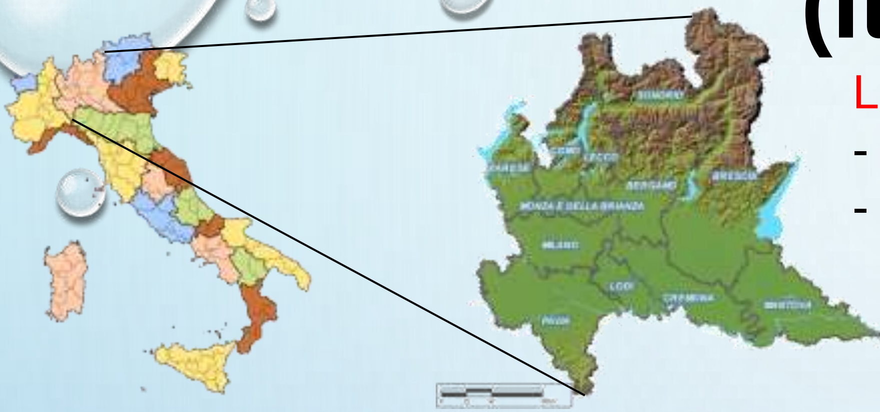
Reservoirs in Lombardy Region (Italy)



Lombardy Region:
- Large dams: about 80
- Small dams: about 600

Reservoirs accumulate huge quantities of fine sediments: sediment management is needed to maintain/recover storage capacity and to prevent clogging of outlets

Sediment flushing: scouring out of deposited sediments through the use of low-level outlets in dams to lower water levels, thereby increasing the flow velocities in the reservoir

Implications on aquatic communities in the riverine ecosystem downstream the dam:
- **physical-mechanical impact**: immediate
- **ecotoxicological effects** on aquatic organisms due to the release of toxic substances from sediments: long-term effects

Water Framework Directive 2000/60/EC

Sediments: a complex matrix … with scarse regulation

Complex matrix:

- toxicity depends on site-specific bioavailability, partitioning and chemical speciation

- flushing and sluicing techniques were proved to alter physical and chemical conditions (e.g. solid/liquid ratio, pH, redox conditions), thus determining the release of contaminants from sediments (e.g. Hug Peter et al., 2014; Fetters et al., 2016, Frémion et al., 2016)

Regulation?

- WFD 2000/60/EC
- Directive 2013/39/UE

→ **Sediment Quality Standards** are not defined for freshwater sediments

Fetters K.J., Costello D.M., Hammerschmidt C.R., Burton G.A.Jr., 2016. Toxicological effects of short-term resuspension of metal-contaminated freshwater and marine sediments. Environmental Toxicology and Chemistry, 35: 676-686.

Frémion F., Bordas F., Mourier B., Lenain J-f., Kestens T., Courtin-Nomade A., 2016. Influence of dams on sediment continuity: a study case of a natural metallic contamination. Science of the Total Environment, 547: 282-294.

Frémion F., Courtin-nomade A., Bordas F., Lenain J-f., Jugé P., Kestens T., Mourier B., 2016. Impact of sediments resuspension on metal solubilization and water quality during recurrent reservoir sluicing management. Science of the Total Environment, 562: 201-215.

Hug Peter D., Castella E., Slaveykova V.I., 2014. Effects of a reservoir flushing on trace metal partitioning, speciation and benthic invertebrates in the floodplain. Environmental Science Processes & Impacts, 16: 2692-2702.

PrATo: a protocol for assessing sediment toxicity in reservoirs before flushing

- **PrATo** includes methods for **sampling, chemical analysis and ecotoxicological evaluation** of sediments, as well as criteria for **risk assessment**, based on cross-interpretation of results

- **Sediment characterization** need to be carried out:
  - **before flushing**: sediments of the reservoir and of the downstream river will be analyzed in order to plan adequate flushing operations
  - **after flushing**: analyses will be compared with results obtained before flushing, in order to evaluate the outcomes of the operations

- It provides a practical tool for drafting **Reservoirs Management Plans**

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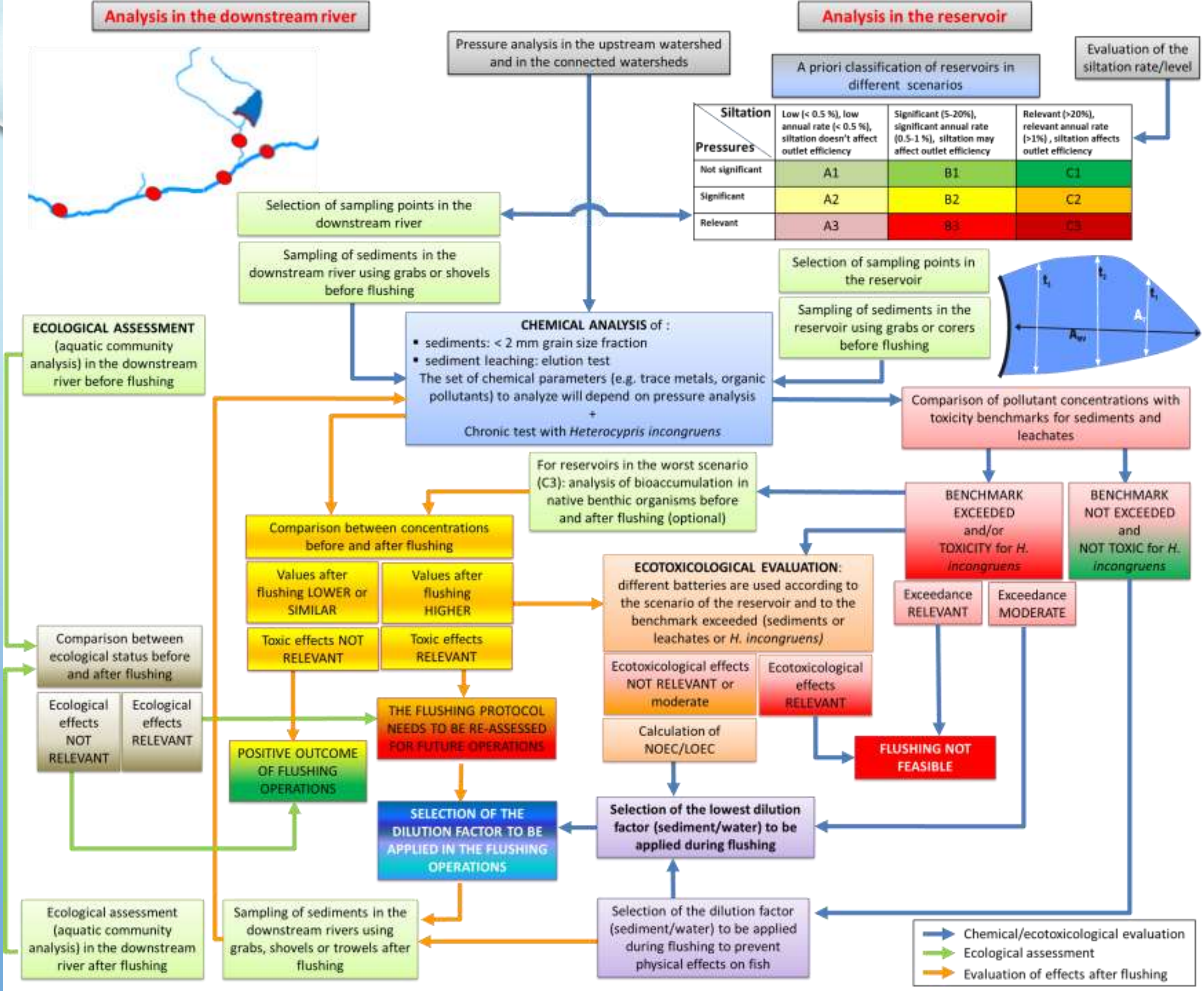
Final aim: maximizing sediment discharge minimizing environmental impacts on the downstream river



Analysis in the downstream river
Analysis in the reservoir
Pressure analysis in the upstream watershed and in the connected watersheds
A priori classification of reservoirs in different scenarios
Evaluation of the siltation rate/level
Siltation
Pressures
Low (< 0.5 %), low annual rate (< 0.5 %), siltation doesn't affect outlet efficiency
Significant (5-20%), significant annual rate (0.5-1 %), siltation may affect outlet efficiency
Relevant (>20%), relevant annual rate (>1%) , siltation affects outlet efficiency
Not significant
A1
B1
C1
Significant
A2
B2
C2
Relevant
A3
B3
C3
Selection of sampling points in the downstream river
Sampling of sediments in the downstream river using grabs or shovels before flushing
Selection of sampling points in the reservoir
Sampling of sediments in the reservoir using grabs or corers before flushing
ECOLOGICAL ASSESSMENT (aquatic community analysis) in the downstream river before flushing
CHEMICAL ANALYSIS of :
• sediments: < 2 mm grain size fraction
• sediment leaching: elution test
The set of chemical parameters (e.g. trace metals, organic pollutants) to analyze will depend on pressure analysis
+
Chronic test with Heterocypris incongruens
Comparison of pollutant concentrations with toxicity benchmarks for sediments and leachates
For reservoirs in the worst scenario (C3): analysis of bioaccumulation in native benthic organisms before and after flushing (optional)
BENCHMARK EXCEEDED and/or TOXICITY for H. incongruens
BENCHMARK NOT EXCEEDED and NOT TOXIC for H. incongruens
Comparison between concentrations before and after flushing
Values after flushing LOWER or SIMILAR
Values after flushing HIGHER
Toxic effects NOT RELEVANT
Toxic effects RELEVANT
ECOTOXICOLOGICAL EVALUATION: different batteries are used according to the scenario of the reservoir and to the benchmark exceeded (sediments or leachates or H. incongruens)
Exceedance RELEVANT
Exceedance MODERATE
Ecotoxicological effects NOT RELEVANT or moderate
Ecotoxicological effects RELEVANT
Calculation of NOEC/LOEC
FLUSHING NOT FEASIBLE
Comparison between ecological status before and after flushing
Ecological effects NOT RELEVANT
Ecological effects RELEVANT
THE FLUSHING PROTOCOL NEEDS TO BE RE-ASSESSED FOR FUTURE OPERATIONS
POSITIVE OUTCOME OF FLUSHING OPERATIONS
SELECTION OF THE DILUTION FACTOR TO BE APPLIED IN THE FLUSHING OPERATIONS
Selection of the lowest dilution factor (sediment/water) to be applied during flushing
Ecological assessment (aquatic community analysis) in the downstream river after flushing
Sampling of sediments in the downstream rivers using grabs, shovels or trowels after flushing
Selection of the dilution factor (sediment/water) to be applied during flushing to prevent physical effects on fish
Chemical/ecotoxicological evaluation
Ecological assessment
Evaluation of effects after flushing

IRSA CNR

Reservoirs in Lombardy Regions

69 reservoirs were considered

High altitude, anthropic pressures not significant, low siltation, flushing operation not needed, possibly high concentrations of metals deriving from natural weathering or atmospheric deposition

Pressure analysis \ **Siltation rate/level**	Low	Significant	Relevant
Not significant	**36**	**7**	**3**
Significant	**2**	**6**	**0**
Relevant	**2**	**7**	**6**

Low altitude, anthropogenic pressures relevant, high siltation, flushing operation needed, possibly high concentrations of metals and organics deriving from anthropogenic activities

Chemical analysis of sediments

- Analysis of fine fractions (< 2 mm) and leachates
- The list of parameters varies according to pressure analysis

Analytes	**Anthropic pressures not significant**	**Anthropic pressures significant or relevant**	**Analytes**	**Anthropic pressures not significant**	**Anthropic pressures significant or relevant**
Sediment characteristics			**Organics**		
Particle size distribution	x	X	Anthracene		x
Humidity	x	X	Fluorene		x
TOC	x	X	Naphthalene		x
			Phenanthrene		x
			Benzo(a)anthracene		x
Trace elements			Benzo(a)pyrene		x
Arsenic	x	X	Chrysene		x
Cadmium	x	X	Dibenzo(a,h)anthracene		x
Total chromium	x	x	Fluoranthene		x
Chromium VI		x	Pyrene		x
Manganese		x	Total PAHs	x	x
Antimony		x	Total PCBs	x	x
Copper	x	x	Chlordane		x
Lead	x	x	Dieldrin		x
Mercury		x	p,p’-DDD		x
Nickel	x	x	p,p’-DDE		x
Zinc	x	x	p,p-DDT		x
Beryllium		x	Total DDTs		x
Cobalt		x	Endrin		x
Selenium		x	Heptachlor epoxide		x
Tin		x	Lindane (gamma-BHC)		x
Vanadium		x	C > 12	x	x

Benchmarks for sediments

- **Sediments: Threshold Effect Concentrations (TECs) and Probable Effect Concentrations (PECs)** (MacDonald et al., 2000)

Pollutant	TEC	PEC	Pollutant	TEC	PEC
Trace elements (mg/kg p.s.)					
Arsenic	9.79	**33**	Lead	35.8	**128**
Cadmium	0.99	**4.98**	Mercury	0.18	**1.06**
Chromium	43.4	**111**	Nickel	22.7	**48.6**
Copper	31.6	**149**	Zinc	121	**459**
Polycyclic aromatic hydrocarbons (µg/kg p.s.)			**Polycyclic biphenyls (µg/kg p.s.)**		
Anthracene	**57.2**	845	Total PCBs	**59.8**	676
Fluorene	**77.4**	536	**Organochlorine pesticides (µg/kg p.s.)**		
Naphthalene	**176**	561	Chlordane	**3.24**	17.6
Phenanthrene	**204**	1170	Dieldrin	**1.9**	61.8
Benzo(a)anthracene	**108**	1050	p,p'-DDD	**4.88**	28
Benzo(a)pyrene	**150**	1450	p,p'-DDE	**3.16**	31.3
Chrysene	**166**	1290	p,p-DDT	**4.16**	62.9
Dibenzo(a,h)anthracene	**33**		Total DDTs	**5.28**	572
Fluoranthene	**423**	2230	Endrin	**2.22**	207
Pyrene	**195**	1520	Heptachlor epoxide	**2.47**	16
Total PAHs	**1610**	22800	Lindane (gamma-BHC)	**2.37**	4.99

MacDonald D.D., Ingersoll C.G. & Berger T.A. 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Arch. Environ. Contam. Toxicol., 39: 20–31.

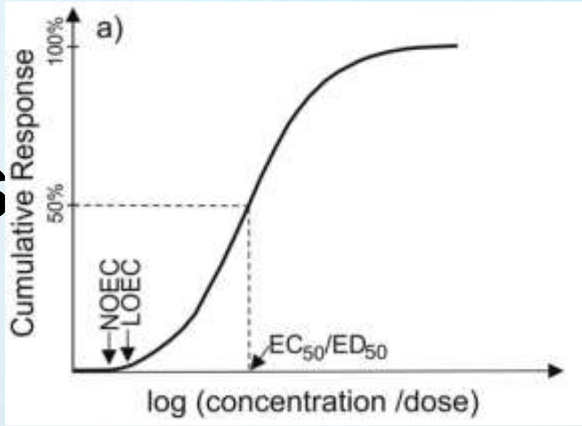
- **Leachates: concentrations from existing national legislation (e.g.** D.M. 05/04/2006, D.M. 27/09/2010 and D. Lgs. 152/2006, allegato 5, parte IV, tabella 2)

Ecotoxicological analysis

- **Whole-sediment chronic test with the ostracod** *Heterocypris incongruens* as screening test (all samples)
- Test batteries with **chronic tests** focused on sediments or leachates according to benchmark exceedance (selected sample)

			Anthropic pressure analysis		
			Not significant	**Significant**	**Relevant**
Toxicity for *H. incongruens*	**and/or exceedance of benchmarks**	**for whole-sediments**	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***
				2) Whole-sediment test with **higher plants**	2) Whole-sediment test with **higher plants**
					3) Whole-sediment test with ***Chironomus***
		for leachates	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***	1) Test on leachates with ***Ceriodaphnia*** or ***Daphnia***
				2) Test on leachates with ***Raphidocelis subcapitata***	2) Test on leachates with ***Raphidocelis subcapitata***
					3) Test on leachates with **higher plants**

Final aim of toxicity tests



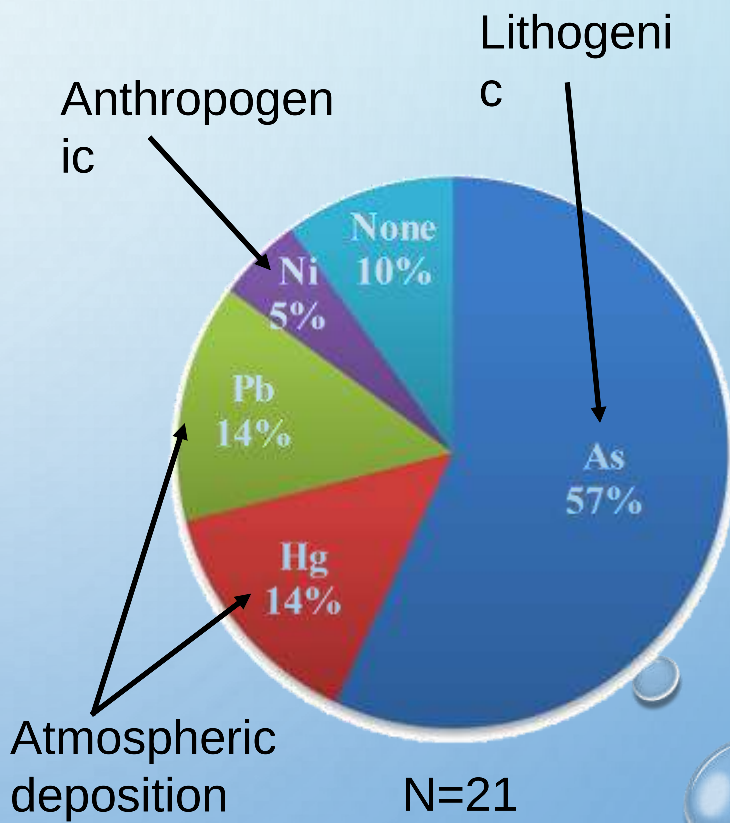
- **Tests on leachates**: **NOEC and LOEC** can be calculated in order to define a proper sediment:water dilution factor to be applied during flushing which should minimize long-term toxic effects on aquatic organisms in the downstream river ecosystem

- **Test on sediments** (% effects): in case of significant sediment toxicity, some additional measures will be needed during and after flushing in order to prevent massive sediment deposition in the downstream river, e.g. additional washing operations after flushing, limitation of flushing operations in terms of sediment volumes flushed downstream at each event or frequency of flushing operations

Results from case studies

- Most reservoirs showed **exceedance of benchmarks for trace elements in sediments**
- No exceedance for organics

Parameter	Unit	Min	Max	Median	TEC/PEC
Altitude	m a.s.l.	237	2987	1051	
Siltation rate	cm/year	0.1	74.1	5.6	
Siltation level	% volume	0.001	8.6	0.4	
Volume	m^3x10^6	0.05	63	0.35	
Surface	m^2x10^6	0.02	2.18	0.04	
Depth	m	9	86	27	
Fine fraction	% < 2mm	15	100	91	
TOC	mg/kg d.w.	58	107753	13036	
As	mg/kg d.w.	1.0	694.7	27.9	33
Cd	mg/kg d.w.	0.03	2.00	0.22	4.98
Cr	mg/kg d.w.	6.8	65.3	21.6	111
Hg	mg/kg d.w.	0.01	1.20	0.04	1.06
Ni	mg/kg d.w.	2.7	46.4	19.3	48.6
Pb	mg/kg d.w.	1.0	150	18.1	128
Cu	mg/kg d.w.	1.4	91.5	25.5	149
Zn	mg/kg d.w.	28.3	356	88.2	459

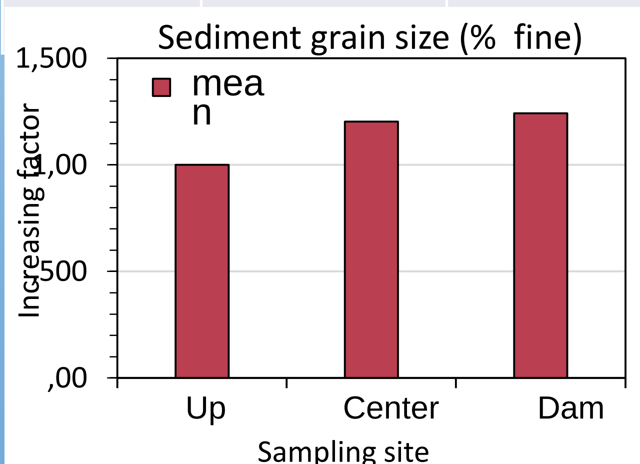


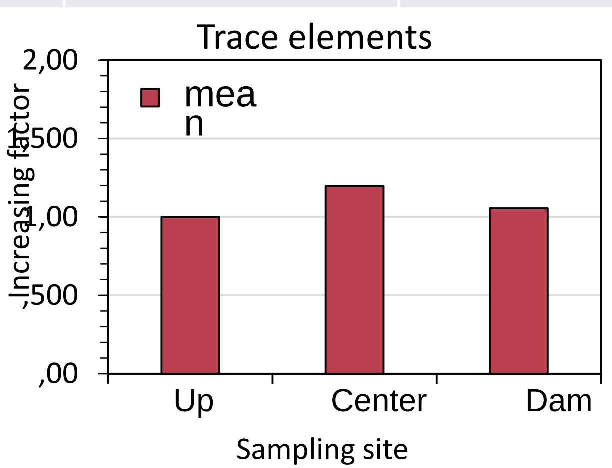
Results from case studies

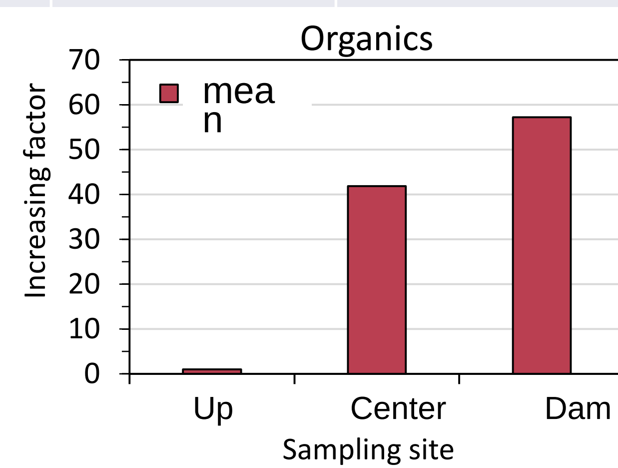
- Chronic test batteries were tested only for 5 reservoirs (2015-16)
- In general, leachates did not exert toxic effects, while **frequent toxicity was found in whole-sediment tests**

Example …

Sample	Benchmark exceedance for leachates	Benchmark exceedance for sediments	Test on leachates		Whole-sediment test	
			Ceriodaphnia	*P. subcapitata*	Higher plants	*H. incongruens*
Upstream		As	-	Growth -66%	-	Growth -26%
Center		As	-	Growth -66%	-	Growth -30%
Dam	Sulphates	As	Reproduction -	Growth -71%	Germination	Mortality



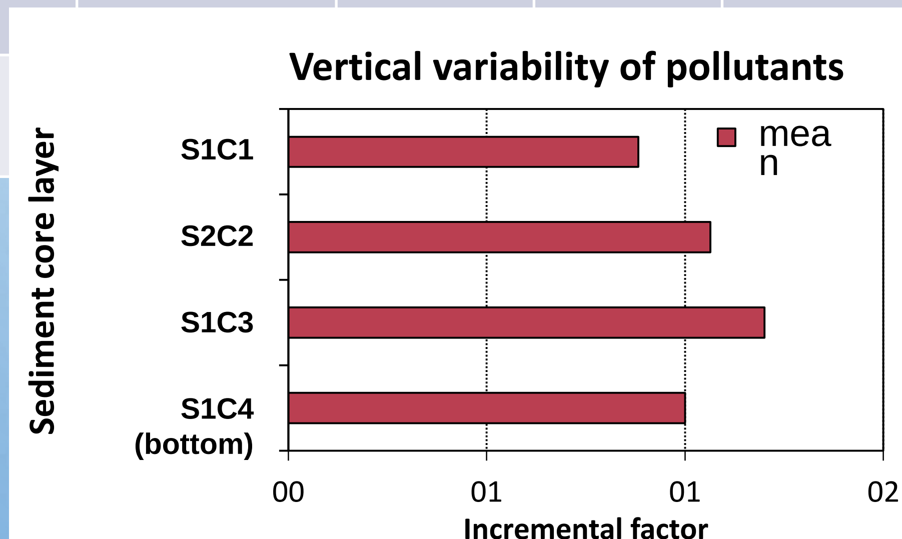




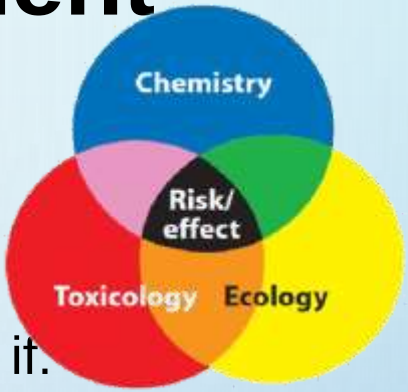
Example …

Sediment core layer	Benchmark exceedance for leachates	Benchmark exceedance for sediments	Test on leachates			Whole-sediment test	
			Daphnia magna			*H. incongruens*	
			Mortality %	Hatching %	Growth %	Mortality %	Growth %
S1C1 0-30 cm	Hg 3 µg/L, COD	As	0	-9	-3	22	-2
S1C2 30 cm-2 m	COD	As	0	-15	-8	27	-10
S1C3 2 m-5 m	As 66 µg/L, COD 54 mg/L	As 312 mg/kg	0	-10	-5	12	-18
S1C4 5 m-7 m	COD					18	-28

depth



Evaluation of flushing operations for a better management



TRIAD approach

Flushing operations need remodulation/improvement if:

- **Chemical analysis**: contaminant concentrations in the downstream river show significant increase after flushing (es. 50% increase, or new exceedance of benchmarks)

- **Ecotoxicological analysis**: toxicity in the downstream river shows significant increase (es. significant increase of % effect, or new positive tests)

- **Ecological analysis**: ecological status in the downstream river shows a significant decrease after flushing

Conclusion

PrATo is a practical and efficient tool for a sustainable management of the flushing activities

PrATo will be adopted in Lombardy Region as part of technical guidelines for drafting Reservoir Management Plans: **Direttive tecniche per la predisposizione, l'approvazione e l'attuazione dei Progetti di Gestione degli invasi** (DGR 5736/2016 Regione Lombardia)