Comparison of Freshwater Sediment Quality Guidelines (SQGs) for potentially toxic elements (PTEs): Historical Perspectives and Future Directions

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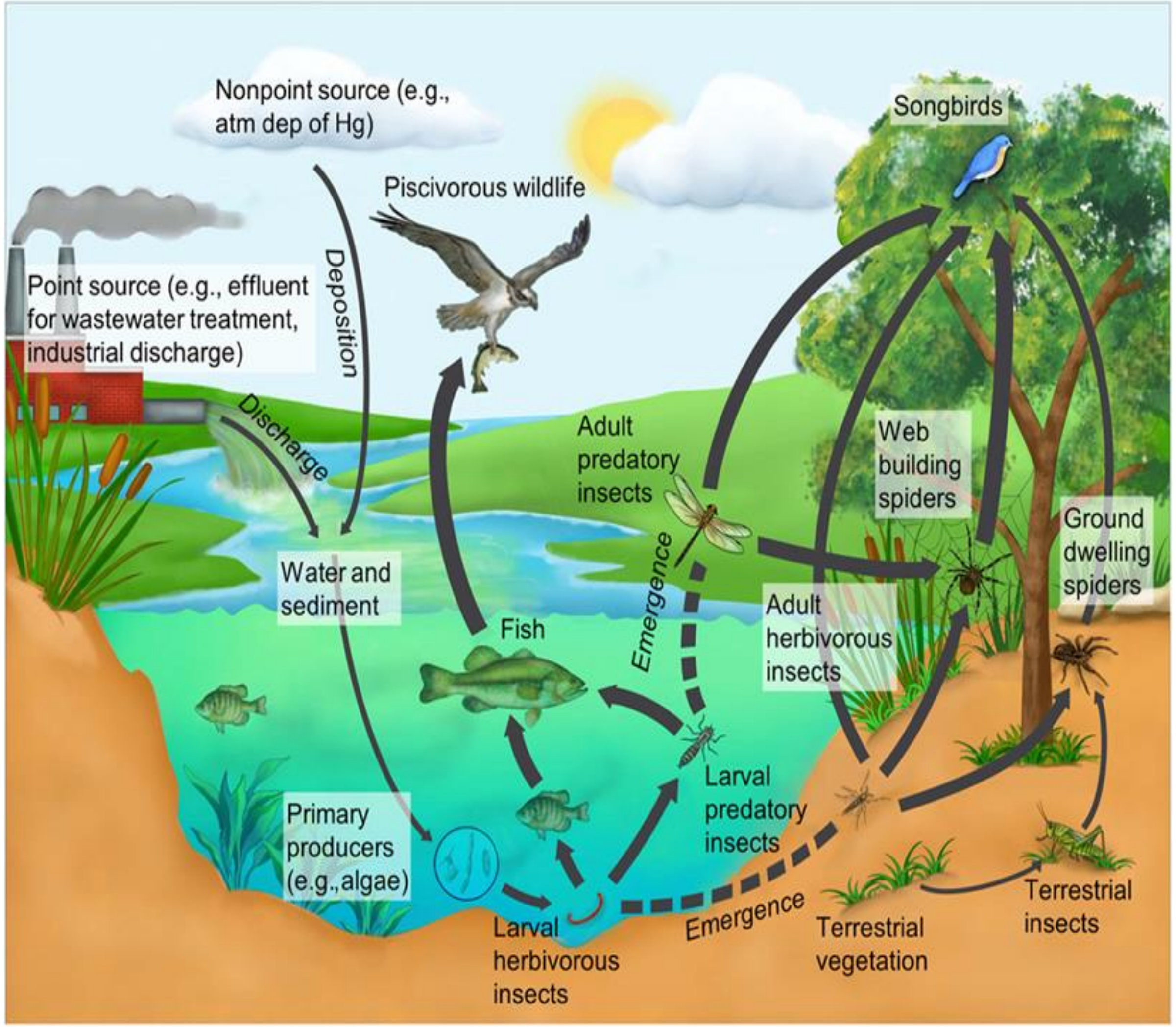
Introduction

Importance of Freshwater Ecosystems

- rivers, lakes, wetlands, and streams
  - ✓**Abiotic and biotic factors**
- are increasingly under threat from
  - ✓ **Natural sources -** weathering of rocks
  - ✓ **Anthropogenic -** Industrial discharge, agricultural runoff, urbanization
    - ❖including potentially toxic elements (PTEs), into aquatic environments (Vörösmarty et al., 2010)
- **Sediments- act as sink and sources of contaminants in aquatic systems.**
  - ✓Sediment Quality Assessment

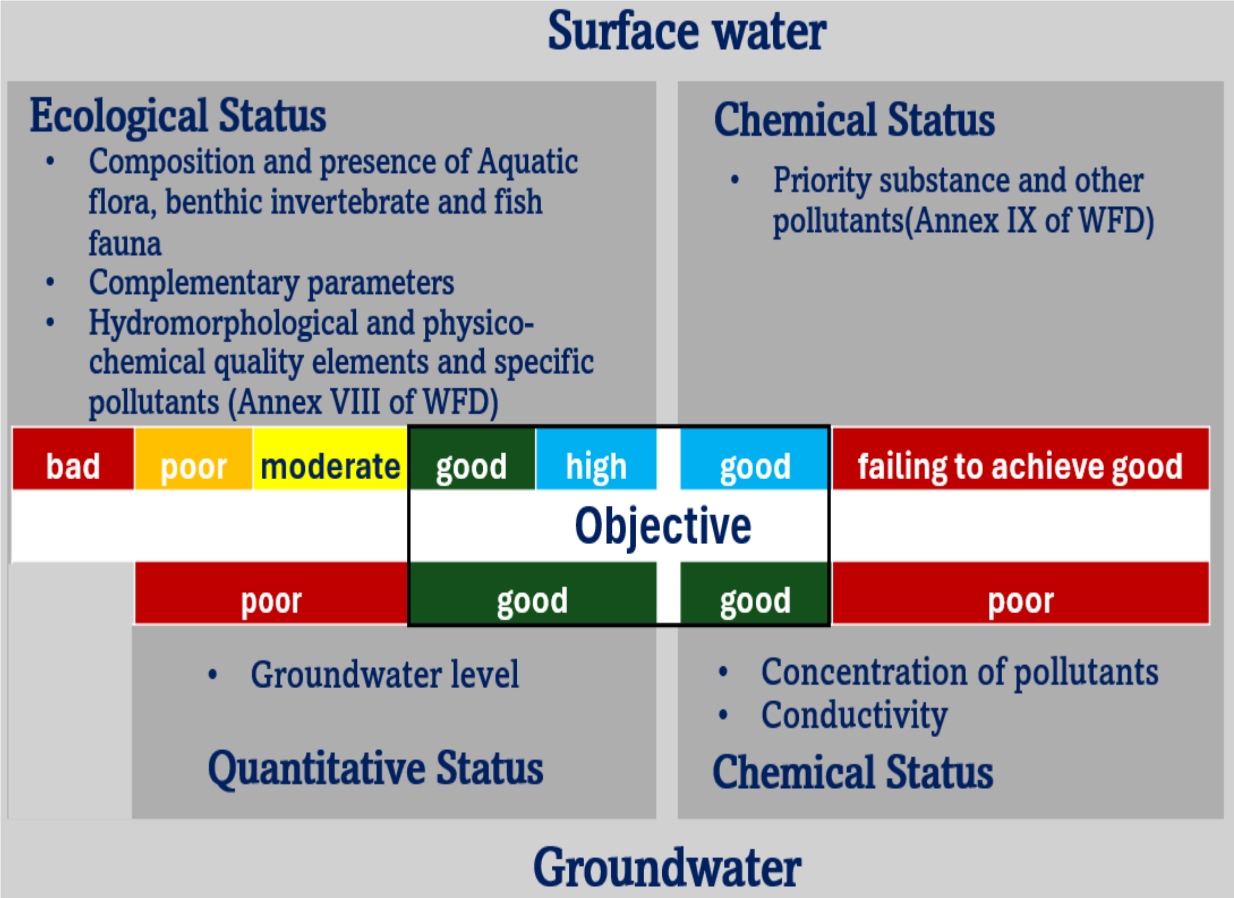


(Chumchal et al. 2022)

The Role of The EU Water Framework Directive (EU-WFD)

The **EU Water Framework Directive (WFD)** is aimed at protecting and improving **the chemical** and **ecological quality** of European water bodies. It establishes:

- ✓ **Environmental Quality Standards (EQS)** for potential toxic substances
- ✓ **Monitoring and assessment requirements** surface water, groundwater, and sediments
- ✓ **Transboundary cooperation mechanisms**, requiring countries to collaborate on pollution reduction and sustainable water management
- ✓ **Regulatory measures to control pollution sources**, including industry, agriculture, and urban development



(Miccoli, Lombardo and Cicolani 2013)

Classification of Sediment quality guidelines (SQGs)

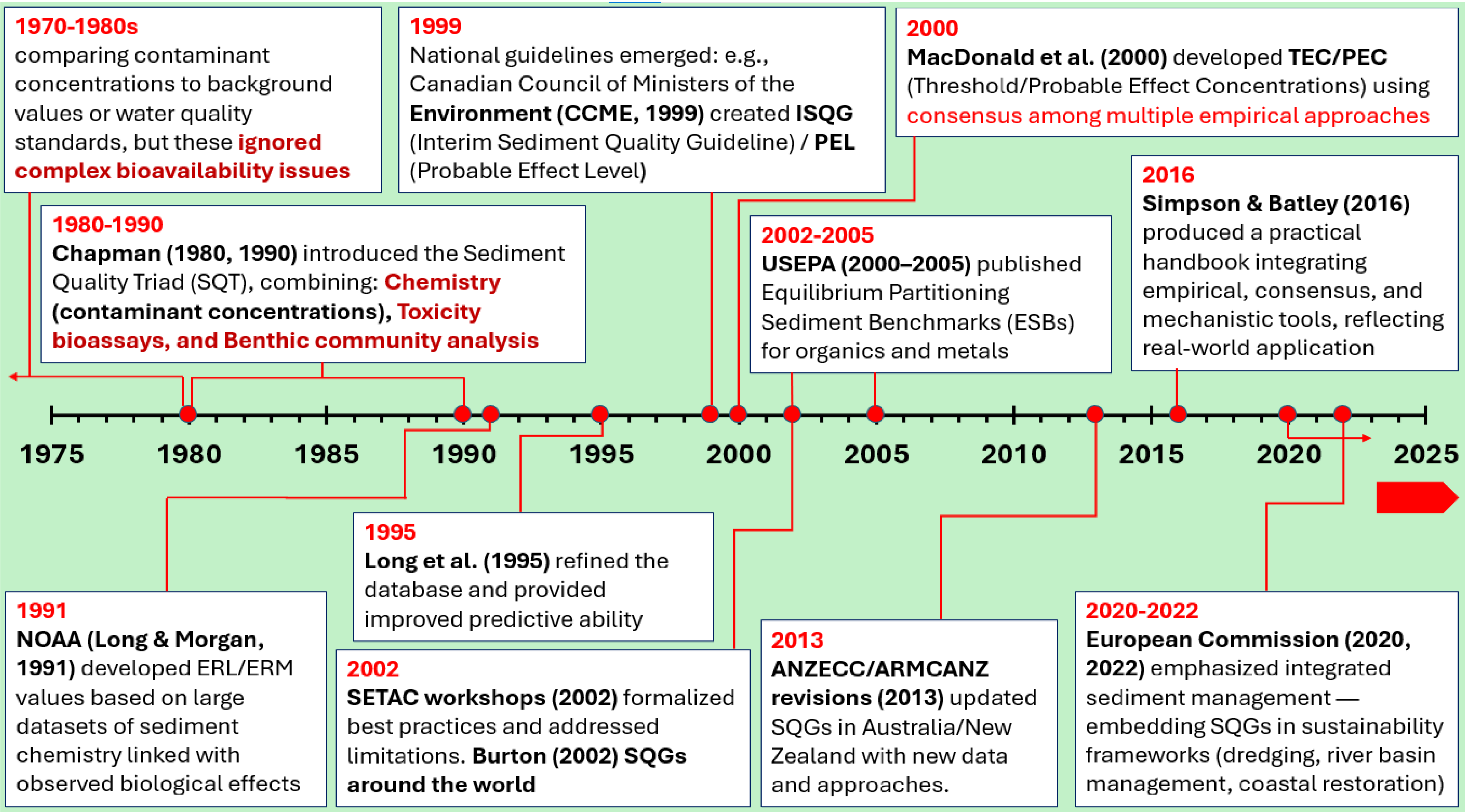
SQG Category	Approach	References/Developers
Mechanistic or Theoretical	Equilibrium Partitioning Approach (EqPA)	Di Toro, Mahony et al. (1991), Di Toro, Zarba et al. (1991) Ankley et al. (1996), NYSDEC (1998), Di Toro and McGrath (2000)
Empirical	Screening-Level Concentration Approach (SLCA) ✓ Lowest Effect Level - LEL ✓ Severe Effect Level - SEL ✓ Minimal Effect Threshold – MET ✓ Toxic Effect Threshold – TET	Persaud et al. (1993) Von Stackelberg and Menzie (2002) EC and MENVI Q (1992)
	Effect – Range - Approach (ERA) ✓ Effects Range Low - ERL ✓ Effects Range Median - ERM	Long et al. (1995) USEPA (1996), Long and Morgan (1991)
	Effect- level- Approach (ELA) ✓ Threshold Effects Level - TEL ✓ Probable Effects Level - PEL	MacDonald et al. (1996) Smith et al. (1996), USEPA (1996)
	Apparent-Effects - Threshold - Approach (AETA) ✓ Apparent Effect Threshold - AET	Barrick et al. (1988) Ginn and Pastorok (1992) , Cubbage et al. (1997)
	Consensus-Based - Approach (CBA)	Swartz (1999) , MacDonald et al. (2000a, 2000b)
	Logistic - Regression - Modeling - Approach (LRMA)	Field et al. (1999, 2002)

(MacDonald et al., 2000)

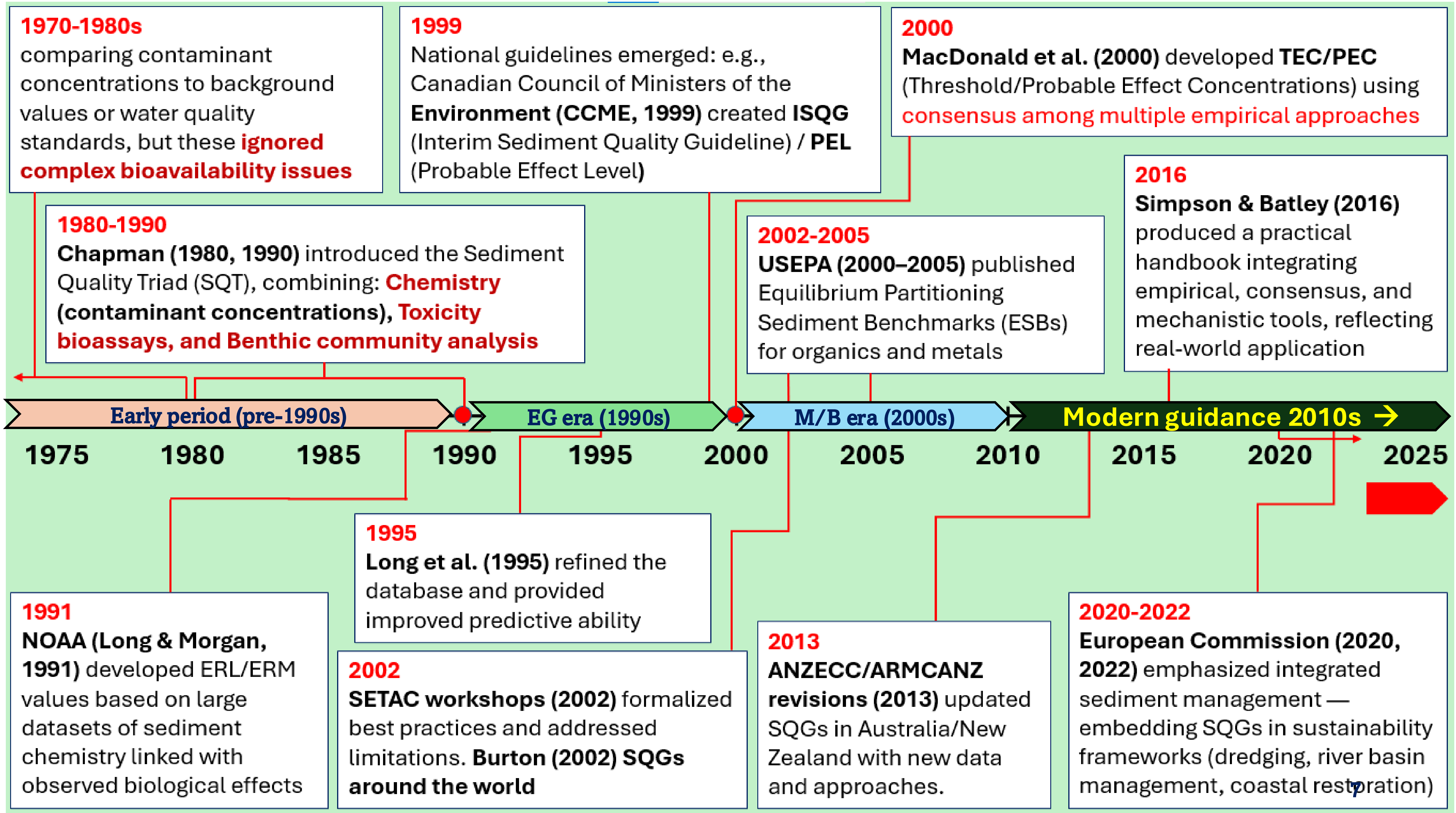
SQGs - based on their derivation approach:

- ✓ **Theoretical or Mechanistic Approach - ** the **effect of sediment organic carbon** or **sulfides** on the equilibrium partitioning of contaminants (Pavlou 1987, Di Toro et al., 1991 and 1999)
- ✓ **The Empirical Approach -** based on **statistical analysis** of large databases of matched sediment chemistry and **toxicity data**

Schematic Timelines of Historical Perspective of Freshwater SQGs



- **Early period (pre-1990s)**
- **Empirical guideline era (1990s)**
- **Mechanistic / bioavailability era (2000s onward)**
- **Modern guidance (2010s– present)**


1970-1980s
comparing contaminant concentrations to background values or water quality standards, but these ignored complex bioavailability issues
1999
National guidelines emerged: e.g., Canadian Council of Ministers of the Environment (CCME, 1999) created ISQG (Interim Sediment Quality Guideline) / PEL (Probable Effect Level)
2000
MacDonald et al. (2000) developed TEC/PEC (Threshold/Probable Effect Concentrations) using consensus among multiple empirical approaches
1980-1990
Chapman (1980, 1990) introduced the Sediment Quality Triad (SQT), combining: Chemistry (contaminant concentrations), Toxicity bioassays, and Benthic community analysis
2002-2005
USEPA (2000–2005) published Equilibrium Partitioning Sediment Benchmarks (ESBs) for organics and metals
2016
Simpson & Batley (2016) produced a practical handbook integrating empirical, consensus, and mechanistic tools, reflecting real-world application
Early period (pre-1990s)
EG era (1990s)
M/B era (2000s)
Modern guidance 2010s →
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
1995
Long et al. (1995) refined the database and provided improved predictive ability
1991
NOAA (Long & Morgan, 1991) developed ERL/ERM values based on large datasets of sediment chemistry linked with observed biological effects
2002
SETAC workshops (2002) formalized best practices and addressed limitations. Burton (2002) SQGs around the world
2013
ANZECC/ARMCANZ revisions (2013) updated SQGs in Australia/New Zealand with new data and approaches.
2020-2022
European Commission (2020, 2022) emphasized integrated sediment management — embedding SQGs in sustainability frameworks (dredging, river basin management, coastal restoration)

Research Objectives

The main objectives are:

- ✓ To undertake **a comprehensive comparison of existing Freshwater Sediment Quality Guidelines (SQGs)** for potentially toxic elements (PTEs) such as: As, Cd, Cr, Cu, Hg, Pb, Ni, and Zn across various regions and countries
- ✓ To identify similarities and differences in the **methodologies and thresholds** applied across these regions
- ✓ To address the historical prospectives and to propose **recommendations** for improving SQGs and addressing unmet needs

(Photo by: Victor Mello ICPDR , 2021)

Results: Freshwater Sediment Quality Guidelines, FSQGs

Table 1. Freshwater Sediment Quality Guidelines, SQGs, i.e., threshold effect concentrations, TECs and probable effect concentrations, PECs, mg kg-1. DW (55)

SQGs around the world	SQGCC	SQGCCN	SQGCat	SQGCatC	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Atlantic RBCA EQS -Freshwater sediment	ARBCA	1	High	2	17	3.5	90	197	0.486	75	91.3	315
Australian ISQG-High	AU_ISQGH	2	High	2	70	10	370	270	1	52	220	410
Australian ISQG-Low												
Belgium Flanders-Consensus-1												
Belgium Flanders-Consensus-2												
Belgium Flanders-LEL												
Belgium Flanders-PEL												
Belgium Flanders-SEL												
Belgium Flanders-TEL												
Canada British Colombia-SQCSS												
Canada British Colombia-SQCTS												
Canada CCME-ISQG/TEL												
Canada CCME-PEL												
China Dianchi Lak-SQG												
China Poyang Lake-CCC												
China Poyang Lake-CMC												
China Taihu Lake-TEL												
China Taihu Lake-PEL												
Final Flemish-SQG												
German Elbe Class II												
German Elbe-Lower Limit												
German Elbe-Upper limit												
Hungarian-Geological media												
Illinois Elevated stream sedimen												

SQGs around the world	SQGCC	SQGCCN	SQGCat	SQGCatC	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Illinois Extreme Elevated stream sediments	IS_EEISS	25	High	2	28	20	60	200	0.3		100	300
Illinois Highly Elevated stream sediments	IS_HEISS	26	High	2	17	2	38	100	0.17		60	170
Illinois Slightly Elevated stream sediments	IS_SESS	27	Low	1	8	0.5	16	38	0.07		28	80
Korea-PEL	KR_PEL	28	High	2	44.7	1.87	224	228	0.67	87.5	154	1170
korea-TEL	KR_TEL	29	Low	1	7	0.4	112	48	0.05	40	59	363
Netherland-Target Value-TV	NL_TV	30	Low	1	29	0.8	100	35	0.3	35	85	140
Netherlands-QO	NL_QO	31	High	2	55	2	380	35	0.5	35	530	480
USA Florida-LEL	FL_LEL	32	Low	1	6	0.6	26	16	0.2	16	31	120
USA Florida-PEL	FL_PEL	33	High	2	17	3.5	90	197	0.49	36	91.3	315
USA Florida-SEL	FL_SEL	34	High	2	33	10	110	110	2	75	250	820
USA Florida-TEL												
USA MacDonald 2000a-Consensus Based-PEC												
USA MacDonald 2000a-ERM												
USA MacDonald 2000a-Consensus-Based-TEC												
USA MacDonald 2000a-ERL												
USA MacDonald 2000a-LEL												
USA MacDonald 2000a-MET												
USA MacDonald 2000a-PEL												
USA MacDonald 2000a-PEL-HA28												
USA MacDonald 2000a-SEL												
USA MacDonald 2000a-TEL												

SQGs around the world	SQGCC	SQGCCN	SQGCat	SQGCatC	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
USA MacDonald 2000a-TEL-HA28	MD_TEL_HA28	46	Low	1	11	0.59	36	28		20	37	98
USA MacDonald 2000a-TET	MD_TET	47	High	2	17	3	100	86	1	61	170	540
USA NOAA-LEL	NOAA_LEL	48	Low	1	6	0.6	26	16	0.2	16	31	120
USA NOAA-SEL	NOAA_SEL	49	High	2	33	10	110	110	2	75	250	820
USA NOAA-PEC	NOAA_PEC	50	High	2	33	4.98	111	147	1.06	48.6	128	459
USA NOAA-PEL	NOAA_PEL	51	High	2	17	3.53	90	197	0.486	36	91.3	315
USA NOAA-TEC	NOAA_TEC	52	Low	1	9.79	0.99	43.4	31.6	0.18	22.7	35.8	121
USA NOAA-TEL	NOAA_TEL	53	Low	1	5.9	0.596	37.3	35.7	0.174	18	35	123
USA Puget Sound-FSQS -CO	PGS_CO	54	Low	1	14	2.1	72	400	0.66	26	360	3200
USA Puget Sound-FSQS-CSLCC	PGS_CSLCC	55	High	2	120	5.4	88	1200	0.8	110	1300	4200

The Variations of the different Freshwater TECs SQGs for each potentially toxic Elements

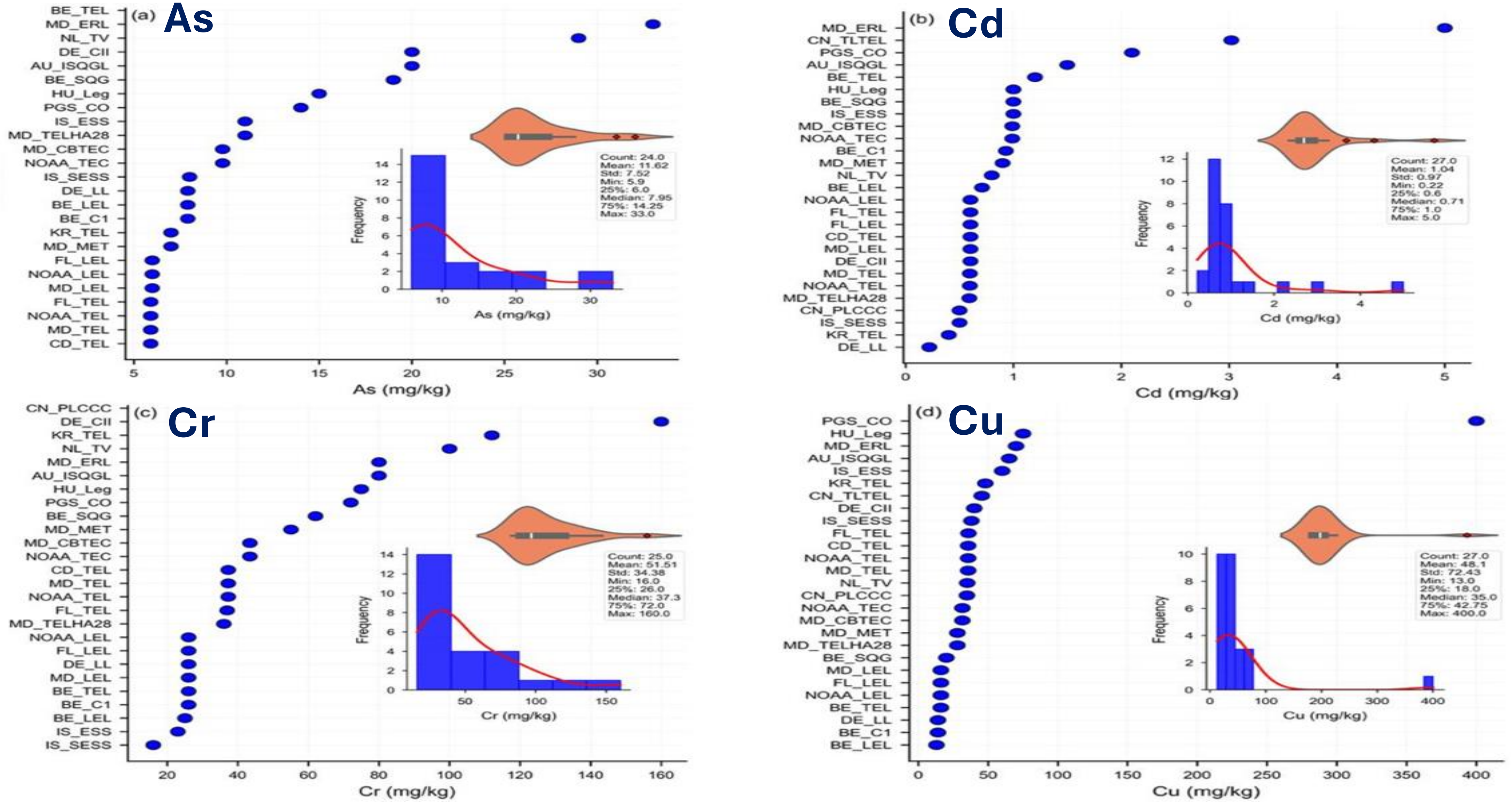
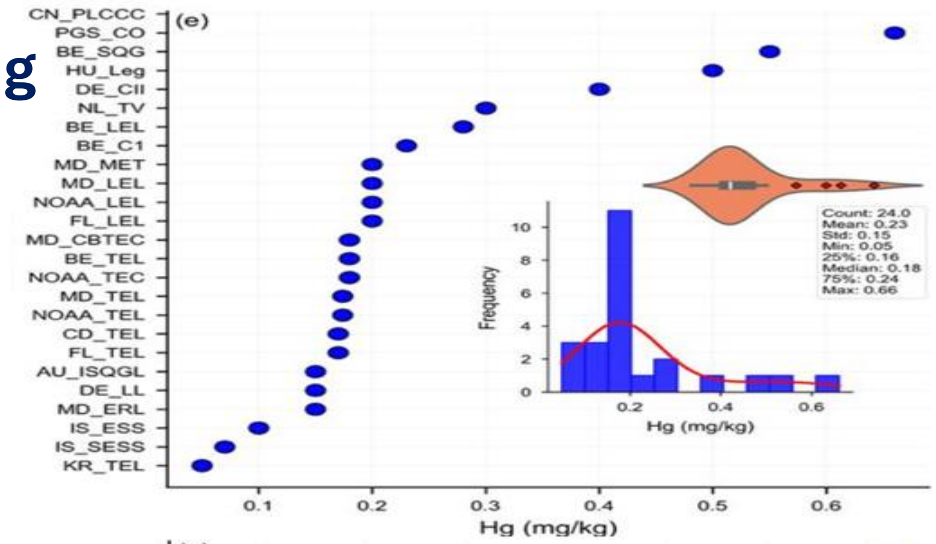


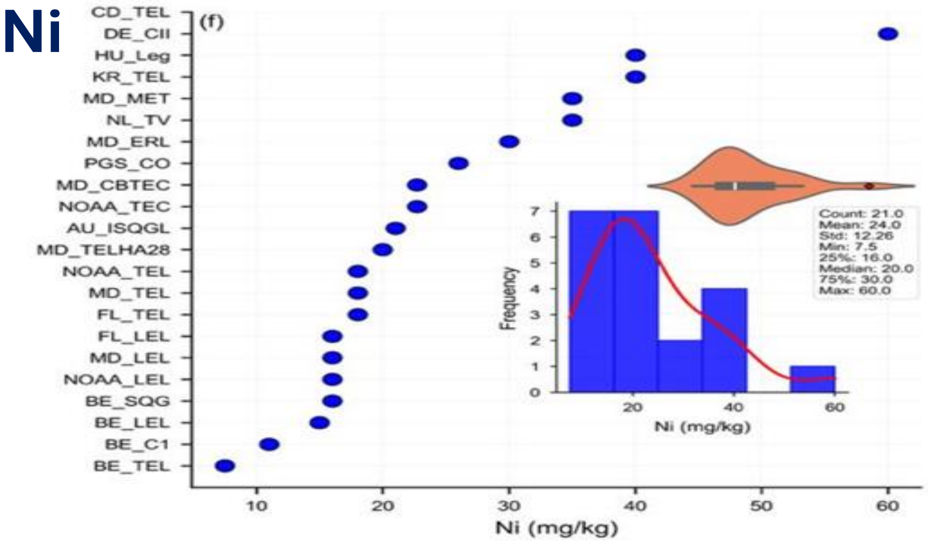
Figure 1. (a)-(h)The Box-and-Whisker plot overlaid scatter plot of TECs for As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn

Contin,,,,,

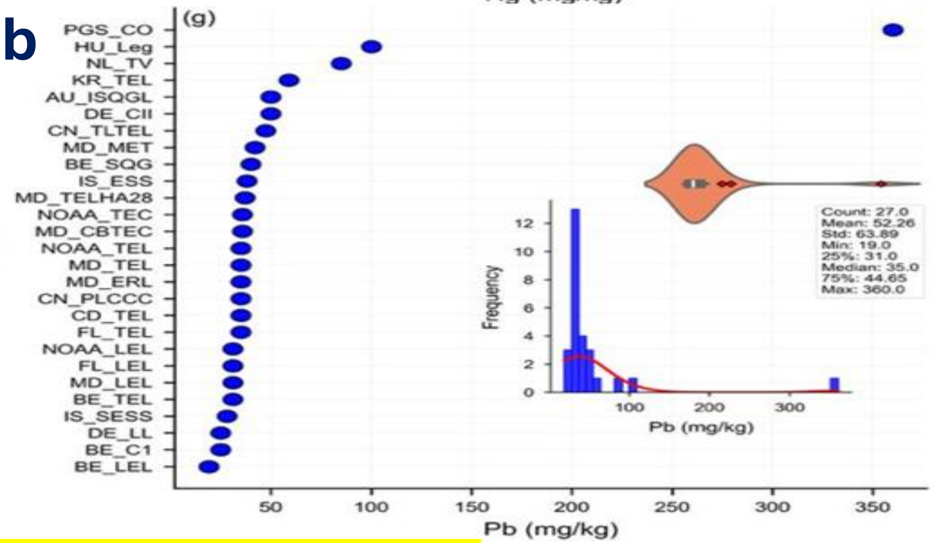
Hg



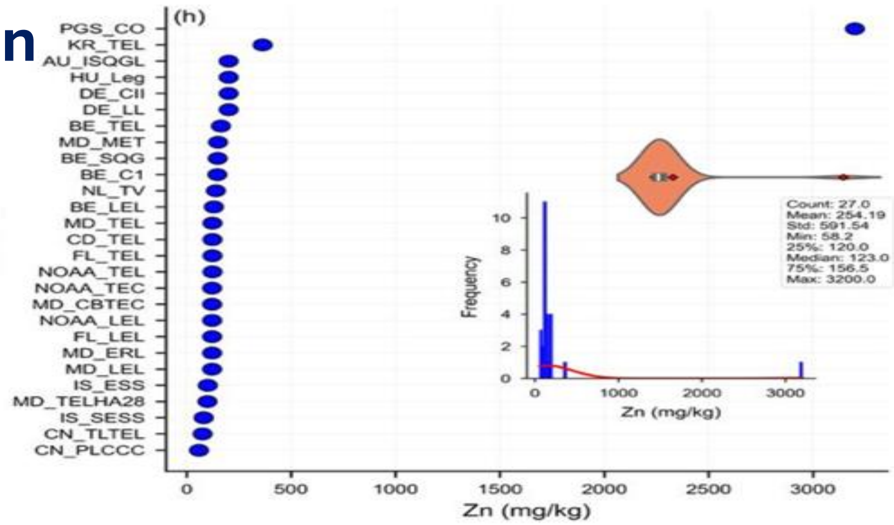
Ni



Pb



Zn



The (MAD/Median)* 100:

Pb (11.43 %) < Hg (16.67 %) < Zn (18.70 %) < Ni (20.00 %) < As (25.79 %) < Cd (29.58 %) < Cr (30.29 %)< Cu (37.14 %)

Contin,,,,,

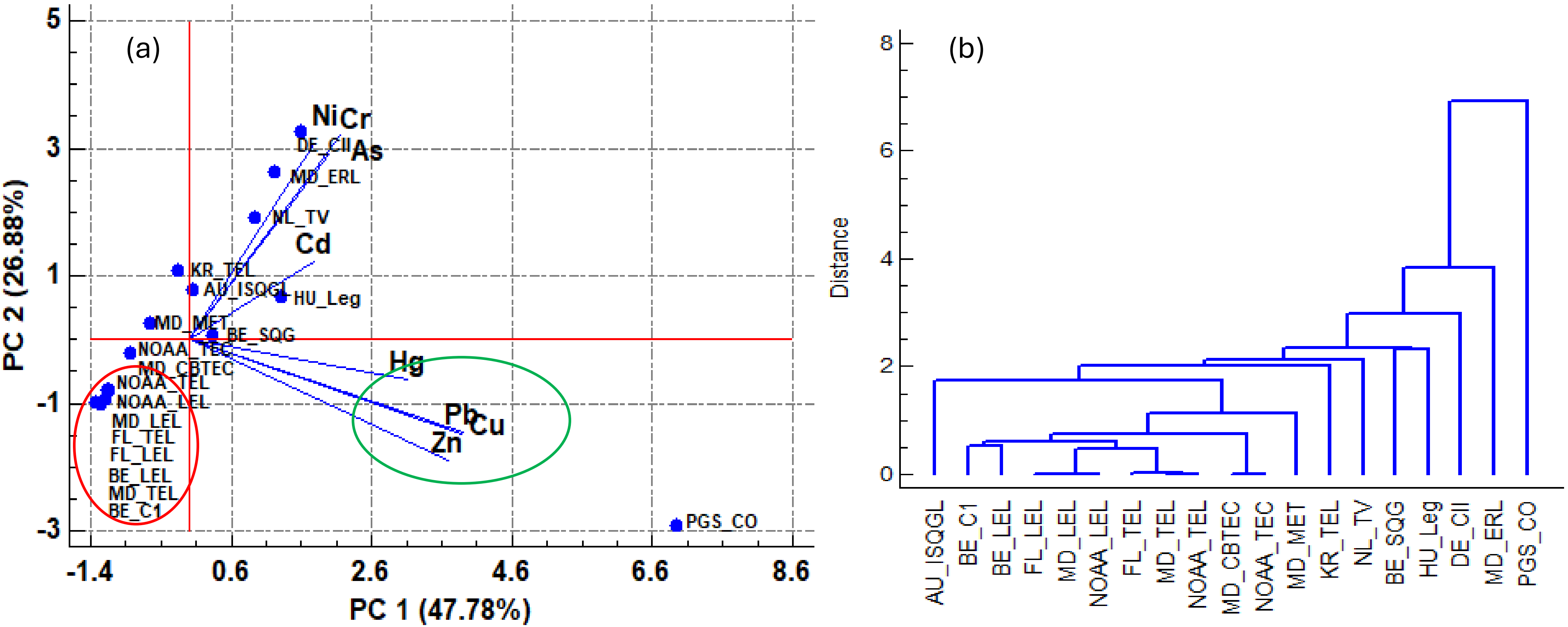


Figure 4. (a) and (b) are principal component analysis, PCA and cluster analysis, CA of the TECs SQGs, respectively

Summary

- ✓ **Hg and Zn** are with the **lowest and the highest values** in all the SQGs which corresponds the **most toxic and least toxic elements**, respectively
- ✓ **Cu** was found with the highest variability in the TECs SQGs followed by **Cr and Cd** whereas **Pb** is the least variable in the TECs
- ✓ In the **PECs SQGs and TECs SQGs** some guidelines donot have data for some elements this lack of SQGs data may lead to insufficient risk assessment procedure of these elements
- ✓ **Further investigation in literature** is required for each Freshwater SQGs

Future Directions of Freshwater SQGs

Global harmonization

- ✓ Many developing regions lack SQGs. International cooperation (e.g., through UNEP, EU directives) is needed (Batley & Warne, 2017)
- ✓ Move toward **global baseline SQGs**, adaptable to regional contexts

Site-specific and adaptive SQGs

- ✓ Incorporate local sediment geochemistry, organic carbon, Acid volatile sulphides (AVS) and redox conditions (Burgess et al., 2013)

Integration with new scientific tools

- ✓ Passive samplers to measure bioavailable contaminant fractions

Better treatment of contaminant mixtures

- ✓ Development of SQGs that consider cumulative risks from metals + PAHs + PCBs together

Climate change context

- ✓ Changing hydrology and temperature may alter contaminant mobilization and bioavailability. Future SQGs must be flexible under climate-driven shifts

Recommendations for Future Research and Action

- **A comprehensive methodological review of Freshwater SQGs for Potentially toxic elements (PTEs) around the world is required to implement as a baseline for management strategies**

- **Enhanced Transboundary Collaboration and Data Sharing**
  Strengthening transboundary cooperation. This can be achieved through:

  - ✓ **Establishing joint monitoring programs** to ensure consistent data collection and harmonization across countries (ICPDR, 2021).
  - ✓ Creating **platforms for data sharing and knowledge exchange**, such as the **ICPDR's TransNational Monitoring Network (TNMN)** (Sommerwerk et al., 2017).
  - ✓ Developing **regional agreements** that promote equitable responsibility and shared **accountability for pollution control** (Vuković et al., 2020).

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Summary of the different derivation methods of Freshwater SQGs

Methodology	Approach	Citation
(Canada, USA) – TEL/ PEL	✓ Empirical approach based on statistical analysis of field data	(MacDonald et al., 2000) (Jin et al., 2021)
(Norway & Netherlands) - **f-SSD Approach, NL_TV, & NL_QO**	✓ Hybrid approach combining field data and species sensitivity distributions	(Kwok et al., 2007) (Bjørgesæter et al., 2008)
(Korea) - TEL, PEL, AET	✓ Based on local sediment toxicity data	(Jin et al., 2021)
(USA & Canada) – **MD_CBTEC/ PEC** **CDBC_SQCSS/ CTS**	✓ Based on sediment chemistry and sediment toxicity data	(MacDonald et al., 2000) (Jin et al., 2021) (Ingersoll et al., 2001)
(Belgium- Flanders) – BE_C1 ,BE_C2, LEL/ SEL , & TEL/ PEL	✓ Based on ecological effects and ecotoxicological endpoints	(Deckere et al., 2011)
(Australia/ New Zealand) – ISQGL/ H	✓ Adapted NOAA guidelines with local validation focusing on bioavailability and toxicity testing	(Maher, 2001) (Birch & Taylor, 2002)
(USA) - NOAA_LEL/ SEL **NOAA_TEL/ PEL** **NOAA_TEC/ PEC** **PGS_CO/ CSLCC**	✓ Based on sediment chemistry as well as ecological effects and ecotoxicological endpoints ✓ EqP and empirical data with local validation	(Hoke et al., 1995) (Burton, 2002) (Zhenke, 2005)