9.8 Heavy metals in sediment

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Alternate attribute name: Trace metals in coastal sediment

Preamble: Pressures from human activities, such as agriculture, effluent discharges from landfill and wastewater treatment plants (WWTPs), urbanisation, and industrial wastes increase sediment metal concentrations [1]. Metals are of growing concern in terms of water quality management, as they cannot be degraded in the environment although some metal species can be transformed into other species which may be more or less toxic [1].

State of knowledge of "Trace metals in coastal sediment" attribute: Good / established but incomplete – general agreement, but limited data/studies

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

Trace metals are naturally present in the environment. Their distribution depends on the presence of natural sources (e.g., volcanoes or erosion) and human activities through extraction from ores [2]. The main anthropogenic activities resulting in the discharge of metals include fossil fuel combustion, industrial and agricultural processes and many metals are used in daily household activities [3]. It is important to recognise the types of metals. For instance, cadmium and mercury are heavy metals but other metals of environmental concern including zinc and copper are essential metals. It is estimated that one-third of all proteins requires a metal cofactor for normal functions [2]. However, even essential metals can be toxic and that depends on the concentration. This relates to the concept of essentiality as illustrated in Figure 1. For essential metals like copper, zinc and selenium, there is a "window of essentiality" which represents a range of concentrations that will maintain a level of health in an organism- as illustrated in Figure 1A. For non-essential metals like cadmium, when concentrations reach levels that overcome the defence capacity of an organism, then it becomes toxic (Figure 1, panel B). This is why using trace metals is the appropriate term to use as it covers all metals. The most appropriate term would be trace elements as arsenic is defined as an element or metalloid.

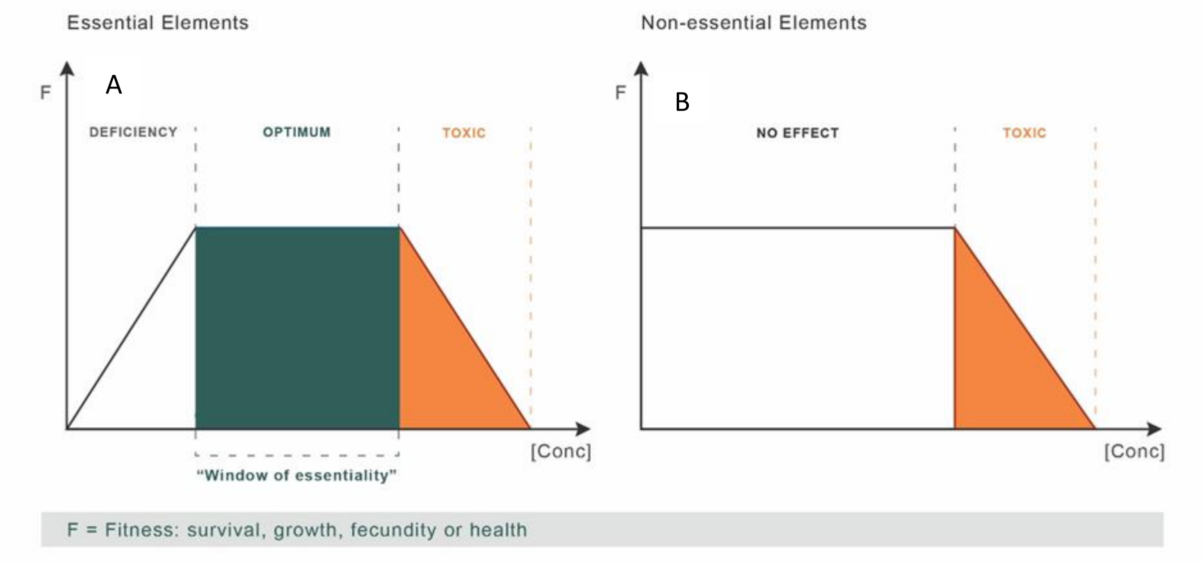

Figure 1. Conceptual diagrams illustrating the differences in concentration–response relationships with respect to organism health between A) essential metals and B) non-essential metals.

The toxicity of trace metals is well established and can impact both ecosystem and human health [4]. The relationship of metals to human and ecological health has been covered in the Attribute of trace metals in water. The hazards remain similar with sediment as another source of metal exposure with receptor species most at-risk being sediment dwelling organisms. Metals in sediment can enter the food chain through bioaccumulation posing a risk to exposed biota higher in the food chain and humans [5]. As sediment is the major compartment where metals accumulate, it is also the major source of exposure posing the highest risk [6].

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

There is strong evidence globally of the adverse effects on human metabolism resulting from exposure to metal-contaminated drinking water [3]. Exposure to non-essential metals is potentially harmful as they do not have physiological roles in the metabolism of cells. In addition, the ingestion of metals via food or water can modify the metabolism of other essential elements including zinc, copper, iron and selenium [4]. Metals and metal compounds can interfere with functions of the central nervous system (CNS), the haematopoietic system, liver and kidneys [2].

Areas of high anthropogenic activity like urban centres are more susceptible to the impacts of trace metals. Urban areas have larger areas of impervious surfaces such as roofs, roads and paved areas that are sources of metals [7]. Many urban streams and coastal zones are also the receiving environment for untreated sewage, via leakage or overflows from wastewater networks and treatment plants. The concentration and bioavailability of metals bound to estuarine sediments depends on many factors including, redox potential, pH, salinity, dissolved metal species and sediment composition [8].

It is well documented that estuaries and coastal zones have been key locations for human settlement and marine resource use. Centuries of overexploitation, habitat transformation, and pollution have led to estuarine degradation and biodiversity loss undermining their ecological resilience [9]. Local examples of estuarine and coastal ecosystems degradation have been reported. Ecological health declines in benthic community structures have been against gradients of metal contamination at concentrations below guideline thresholds (e.g., [10,11]. Ecotoxicity studies of sediment samples from the Ahuriri (Hawke's Bay) and New River (Southland) Estuaries revealed the presence of metals, including lead and zinc that were at concentrations exceeding sediment quality guideline values [12]. The situation is the same nationwide as dissolved zinc was found to be positively related to the proportion of urban land cover and imperviousness in upstream catchments [7].

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

The status quo would result in the continuous accumulation of metals in the environment as they are not biodegradable. Worldwide, in addition to the issue of anthropogenic zinc contamination in urban areas, contamination of soils with zinc has increased in some agricultural sectors, such as dairy farming and horticulture. The most significant concern for freshwater lakes relates to the partitioning of zinc to bed sediments, where over time it may gradually build up beyond ecotoxic thresholds for macroinvertebrates and other bed-dwelling organisms, which are integral components of aquatic ecosystems [13].

Yes, there is evidence that better management of trace metal sources can reverse the trends. For instance, the global phase-out of leaded petrol use has contributed to the decline of concentrations in the ocean [14]. A UK study showed that reductions in industrial activity and improved environmental controls on emissions resulted in a decline in trace metal concentrations in sediments [8].

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

A report commissioned by the PCE provided a national-level summary of the chemical contaminants including metals that Regional Councils/Unitary Authorities include in consent-based monitoring requirements and routine State of the Environment (SoE) monitoring programmes [15]. It stated that copper, zinc and lead were the most frequently listed trace metals monitored as part of consent conditions [15]. It is interesting that to date, there are no published studies that have quantitatively assessed relationships of copper and zinc with intensity of urban land use, despite these metals being key contaminants in urban streams and frequently used as indicators of stormwater inputs [7].

One important aspect that is not commonly included in current monitoring frameworks is the use of biological indicators, or bioindicators. Bioindication is the use of an organism, a part of an organism, or a community of organisms, to assess the impacts the quality of its/their environment [5]. A definition of bioindicator was suggested to be an anthropogenically induced variation in biochemical, physiological, or ecological components or processes, structures, or functions (i.e., a biomarker) that can be causally-linked to biological effects [16].

Macroinvertebrate abundance can be influenced by the level of stressors as taxon richness declines across pollution gradients. Pollution sensitive taxa respond to levels of contaminants leading to alterations to benthic macroinvertebrate assemblages (e.g., [17]).

There have been notable advances in the development of bioavailability models for assessing toxicity as a function of water chemistry in freshwater ecosystems. For instance, the biotic ligand model (BLM), the multiple linear regression model, and multimetal BLM have been developed for most of the common mono- and divalent metals. Species sensitivity distributions for many metals are available, making it possible for many jurisdictions to develop or update water quality criteria or guidelines [18]. Sediment bioavailability models are emerging including models that allow for prediction of toxicity in sediments for copper and nickel [18].

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

I am not in a position to comment but Regional Councils have selected sites where they monitor trends for the SoE. It is certainly possible as consent holders would also have access to sites for monitoring as part of their consent conditions. This should be part of using proper engagement practices with all stakeholders and partners.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

The analytical methods using inductively coupled plasma mass spectrometry (ICP-MS) instruments can measure elements and metals and are well established and validated. Several commercial laboratories including Hill Labs and AsureQuality can measure metals at competitive prices.

A recent investigation reported limitations that councils have identified that preventing the expansion of current monitoring programmes including the high costs for both laboratory analysis and council staff time spent doing monitoring and reporting [15]. However, it should be noted that consent holders cover agreed conditions monitoring costs.

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

We are not aware of any sediment heavy metals monitoring being regularly undertaken by iwi/hapū/rūnanga. Resourcing is difficult for iwi/hapū/rūnanga to obtain, and any monitoring by agencies is generally infrequent, inconsistent, and ad hoc, and most programmes fail to provide information on whether chemical contaminants will have impacts of concern to Māori [34]. Some of the environmental assessment frameworks being developed by/with iwi/hapū/rūnanga include “safe to eat” or “safe to swim” outcomes [35-37]. Data/indicators required to fully realise these holistic cultural assessment frameworks will require information about heavy metals in water, sediment, and/or mahinga kai species. See also [13], [19], [20].

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Contaminants are mostly found as complex mixtures of which metals are one family of pollutants at impacted sites. The issue of multiple stressors relates to the range of sources that put pressure on the receiving environment – e.g., stormwater and wastewater contain a range of other types of contaminants. Cumulative effects, through additional new marine industries, climate change and other stressors, can reduce environmental resilience and increase the risk of environmental or economic collapse [24]. The importance of sediments as stressors will depend on site ecosystem attributes and the magnitude and preponderance of co-occurring stressors [25]. Therefore, management of coastal waters must contend with multiple drivers in concert as the coordination of regulating agencies for urban and agricultural runoff is warranted as metals are only one component within a range of other contaminants that can accumulate in sediment [26].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

The information to date indicates that trace metals are accumulating in our environment, e.g., zinc was positively related to the proportion of urban land cover and imperviousness in a upstream catchments [7]. The ecotoxicological effects of trace metals and their speciation under a range of environmental conditions are well understood and documented (as per references cited above). The key anthropogenic sources are well characterised to assist the management of these contaminants. The main challenge is that the management of metals requires a holistic/system approach as there are multiple factors to consider. For instance, roof material often contains zinc that can leach overtime. Some effort is required to find alternative types of material with less impacts which needs to be underpinned by appropriate policy. There are examples of recovery following policy changes, e.g., the global phase-out of leaded petrol use has contributed to the decline of concentrations in the ocean [14].

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

Finding reference sites with low levels of anthropogenic pressure is important to provide a baseline to confirm adverse impacts of metals and other stressors on receiving ecosystems. However, it is very difficult and nearly impossible to find reference sites that experience no anthropogenic pressure.

One option to consider is to use a ranking of environmental targets in line with the ecosystems to protect. For instance, New Zealand is recognized internationally for its environmental management and innovative regulatory frameworks, as demonstrated, for example, by the implementation of the first no-take marine reserve [24].

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

Sediment quality guideline values (SQGVs) were derived and updated [27]. These values are now used as default guideline values (DGVs) for toxicants in sediment in the Australian and New Zealand Guidelines for sediment quality [1].

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

[1] https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/sediment-quality-toxicants

Yes, there are threshold value guidelines available. The ANZG DGVs have been developed to provide threshold values for metals and other contaminants. They are set to provide a range of protection as per point B3. The sediment DGVs indicate the concentrations below which there is a low risk of unacceptable effects occurring, and should be used, with other lines of evidence, to protect aquatic ecosystems. In contrast, the 'upper' guideline values (GV-high), provide an indication of concentrations at which there might already have toxicity-related adverse effects. As such, the GV-high value should only be used as an indicator of potential high-level toxicity problems, not as a guideline value to ensure protection of ecosystems.

If a DGV is exceeded or even where toxicant concentrations in the sediment are trending towards the DGV, it is recommended using multiple lines of evidence approach as part of the weight-of-evidence process to better assess the risk to the sediment ecosystem.

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

As discussed in the above sections, metals have multiple anthropogenic sources and they can continue to accumulate in various environmental compartments including sediment due to the non-degradability of metals. There are indications of degradation of coastal ecosystems globally and in New Zealand (e.g., [9-11,26]. Despite the occurrence of some extinctions, most species and functional groups persist in coastal areas but in greatly reduced numbers. The potential for recovery remains, and where remediation efforts have focused on protection and restoration, recovery has been observed but over long time periods [9].

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

It has been recognised that indigenous peoples, knowledge frameworks, and values are critical in orienting international efforts for the management of chemicals and waste that are more sustainable and equitable for all [28]. A high standard of sediment quality is an outcome sought by iwi/hapū/rūnanga. There is tikanga and mātauranga Māori relevant to informing bands, allocation options, minimally disturbed conditions and/or unacceptable degradation residing in treaty settlements, catchment/species restoration strategies, cultural impact assessments, environment court submissions, iwi environmental management plans, reports, etc.

There are one-off-studies where iwi/hapū/rūnanga are influencing research initiatives exploring the state and impacts of environmental contaminants (including heavy metals) on the outcomes they are seeking (e.g., mauri is protected, kai is safe to eat, water is safe to swim) (e.g., [38-40]).

See also [19], [20], [22], and [23].

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

The key here is to address the increasing trends of metal accumulation and come up with solutions to revert the increasing trends by developing better management frameworks for the sources. The SoE reporting for MfE highlights the level of environmental degradation in both freshwater and marine domains [9,29]. Metals are one of the multiple stressors that have been identified with sources including stormwater, municipal treated wastewater and agricultural discharges.

The toxicity and ecotoxicity of individual metals are well characterised and understood. Predicting or assessing the environmental impacts of an individual chemical is a challenge in a field situation as contaminants are often found in complex mixtures. For instance, exposure to low levels of multiple chemicals in mixtures can cause toxicity at concentrations where exposure to an individual chemical might cause no effect based on their DGVs. This is because multiple physiological processes may be affected by chemicals having different mechanisms of toxicity. This is a strong argument for the need of a system approach to the management of aquatic systems.

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

C2-(i). Local government driven and C2-(ii). Central government driven and C2-(v). Internationally driven

The Australia New Zealand guidelines for sediment quality DGVs are designed to trigger further specific site risk assessment based on a weight of evidence. In a recent survey on the type and range of chemical contaminants councils do, the emphasis was on the type of chemicals, but the implications of exceedance of DGVs was not assessed [15]. I am not aware of any follow up studies in New Zealand responding to a DGV exceedance.

C2-(iii). Iwi/hapū driven and C2-(iv). NGO, community driven

We are not aware of interventions/mechanisms being used by NGOs or iwi/hapū/rūnanga to directly affect this attribute.

<u>Part D—Impact analysis</u>

D1. What would be the environmental/human health impacts of not managing this attribute?

A business-as-usual scenario would lead to on-going increase of metals in sediment and have devastating impacts on exposed ecosystems. There is no doubt that the accumulation of anthropogenic pollutants in the environment is causing harm and scientists need to work with other stakeholders to reduce pollution [30]. Metals are not degradable so any continuous discharges will accumulate into the various environmental compartments and biota. The impacts of human activities have pushed estuarine and coastal ecosystems far from their historical baseline of rich, diverse, and productive ecosystems [9]. Managing the sources is a priority to ensure the protection of these valuable ecosystems. However, there are examples of declining metal concentrations from improved environmental controls on emissions and discharges of metals and other contaminants, e.g., [8].

There are multiple challenges to reduce the discharge of metals in urban environments, particularly non-point sources like stormwater. There are examples of options to reduce metals at the sources [13]. There are solutions to consider but their implementation would be challenging, e.g., an initiative to impose restrictions on the maximum amount of zinc in galvanised or zinc coated roofing materials [13].

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

Coastal and ocean ecosystems provide commercial, cultural, recreational and economic benefits as well as support diverse habitats and species of local and global significance [24]. It is well-recognized that healthy and thriving coastal and freshwater ecosystems are essential for economic growth and food production [24]. The key impacts from the pressure that metals place on receiving environments is the potential loss in biodiversity and disruption of ecosystem functions and services through shifts in distributions of key species. Fishery and aquaculture industries are most likely to be impacted by pressure from metal contamination. Healthy and functional ecosystems and healthy fish stocks are important for the fisheries industry [31]. There are other aspects to consider including natural beauty of our estuaries, coastal and open ocean areas that are central to our culture and national identity.

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Climate change will have multiple effects in modulating the accumulation and bioavailability of metals. Climate change increasingly affects the variation in volume and frequency of stormwater events and runoff which can increase resuspension and direct exposure of sediments in water bodies [1]. The key concern with the effects of climate change on the risks associated with metal contamination is that changes to temperature and pH can modulate the speciation of metals or basically, their bioavailability. The importance of metal speciation cannot be overstated as it modulates the bioavailability and toxicology of trace metals. The simplest feature of speciation is whether the metal is in the dissolved or particulate form. Originally, environmental regulations were based on total metals present in the water as assayed by hot acid digestion of the samples. However, there has been a gradual change in many jurisdictions to regulations based on the dissolved component only. This reflects the general recognition that particulate metals exhibit negligible toxicity and bioavailability to aquatic organisms relative to dissolved metals [2]. Increases in temperature was correlated with increasing toxicity of metals to aquatic organisms [32]. As such, temperature should be accounted in risk assessment, because it may modify the effects of chemicals on the structure and functioning of aquatic communities, especially at higher levels of biological organization [33].

References:

1. Chon, H.S.; Ohandja, D.G.; Voulvoulis, N. The role of sediments as a source of metals in river catchments. Chemosphere 2012, 88, 1250-1256, doi:10.1016/j.chemosphere.2012.03.104.
2. Wood, C.M. 1 - An introduction to metals in fish physiology and toxicology: basic principles. In Fish Physiology, Chris M. Wood, A.P.F., Colin, J.B., Eds.; Academic Press: 2011; Volume Volume 31, Part A, pp. 1-51.

3. Fu, Z.S.; Xi, S.H. The effects of heavy metals on human metabolism. Toxicology Mechanisms and Methods 2020, 30, 167-176, doi:10.1080/15376516.2019.1701594.

4. Florea, A.M.; Büsselberg, D. Occurrence, use and potential toxic effects of metals and metal compounds. Biometals 2006, 19, 419-427, doi:10.1007/s10534-005-4451-x.

5. Stankovic, S.; Kalaba, P.; Stankovic, A.R. Biota as toxic metal indicators. Environmental Chemistry Letters 2014, 12, 63-84, doi:10.1007/s10311-013-0430-6.

6. Zhang, C.; Yu, Z.G.; Zeng, G.M.; Jiang, M.; Yang, Z.Z.; Cui, F.; Zhu, M.Y.; Shen, L.Q.; Hu, L. Effects of sediment geochemical properties on heavy metal bioavailability. Environment International 2014, 73, 270-281, doi:10.1016/j.envint.2014.08.010.

7. Gadd, J.; Snelder, T.; Fraser, C.; Whitehead, A. Current state of water quality indicators in urban streams in New Zealand. New Zealand Journal of Marine and Freshwater Research 2020, 54, 354-371, doi:10.1080/00288330.2020.1753787.

8. Duquesne, S.; Newton, L.C.; Giusti, L.; Marriott, S.B.; Stärk, H.J.; Bird, D.J. Evidence for declining levels of heavy-metals in the Severn Estuary and Bristol Channel, UK and their spatial distribution in sediments. Environmental Pollution 2006, 143, 187-196, doi:10.1016/j.envpol.2005.12.002.

9. Lotze, H.K.; Lenihan, H.S.; Bourque, B.J.; Bradbury, R.H.; Cooke, R.G.; Kay, M.C.; Kidwell, S.M.; Kirby, M.X.; Peterson, C.H.; Jackson, J.B.C. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 2006, 312, 1806-1809, doi:10.1126/science.1128035.

10. Hewitt, J.E.; Anderson, M.J.; Hickey, C.W.; Kelly, S.; Thrush, S.F. Enhancing the Ecological Significance of Sediment Contamination Guidelines through Integration with Community Analysis. Environmental Science & Technology 2009, 43, 2118-2123, doi:10.1021/es802175k.

11. Tremblay, L.A.; Clark, D.; Sinner, J.; Ellis, J.I. Integration of community structure data reveals observable effects below sediment guideline thresholds in a large estuary. Environmental Science: Processes and Impacts 2017, 19, 1134-1141, doi:10.1039/c7em00073a.

12. Boehler, S.; Strecker, R.; Heinrich, P.; Prochazka, E.; Northcott, G.L.; Ataria, J.M.; Leusch, F.D.L.; Braunbeck, T.; Tremblay, L.A. Assessment of urban stream sediment pollutants entering estuaries using chemical analysis and multiple bioassays to characterise biological activities. Science of the Total Environment 2017, 593-594, 498-507, doi:10.1016/j.scitotenv.2017.03.209.

13. PCE. Parliamentary Commissioner for the Environment. Knowing what's out there - Regulating the environmental fate of chemicals; 2022.

14. Pinedo-González, P.; West, A.J.; Tovar-Sanchez, A.; Duarte, C.M.; Sañudo-Wilhelmy, S.A. Concentration and isotopic composition of dissolved Pb in surface waters of the modern global ocean. Geochimica Et Cosmochimica Acta 2018, 235, 41-54, doi:10.1016/j.gca.2018.05.005.

15. Conwell, C. State of knowledge, management and risks; IA235200; Jacobs: Wellington, 2021; p. 86.

16. Adams, S.M.; Giesy, J.P.; Tremblay, L.A.; Eason, C.T. The use of biomarkers in ecological risk assessment: recommendations from the Christchurch conference on Biomarkers in Ecotoxicology. Biomarkers 2001, 6, 1-6.

17. Rawson, C.A.; Lim, R.P.; Tremblay, L.A.; Warne, M.S.; Ying, G.G.; Laginestra, E.; Chapman, J.C. Benthic macroinvertebrate assemblages in remediated wetlands around Sydney, Australia. Ecotoxicology 2010, 19, 1589-1600, doi:10.1007/s10646-010-0544-6.

18. Adams, W.J.; Garman, E.R. Recommended updates to the USEPA Framework for Metals Risk Assessment: Aquatic ecosystems. Integrated Environmental Assessment and Management 2023, doi:10.1002/ieam.4827.

19. Kaiser, B.A.; Hoeberechts, M.; Maxwell, K.H.; Eerkes-Medrano, L.; Hilmi, N.; Safa, A.; Horbel, C.; Juniper, S.K.; Roughan, M.; Lowen, N.T.; et al. The Importance of Connected Ocean Monitoring Knowledge Systems and Communities. Frontiers in Marine Science 2019, 6, doi:10.3389/fmars.2019.00309.

20. Harmsworth, G.R.; Young, R.G.; Walker, D.; Clapcott, J.E.; James, T. Linkages between cultural and scientific indicators of river and stream health. New Zealand Journal of Marine and Freshwater Research 2011, 45, 423-436, doi:10.1080/00288330.2011.570767.

21. Dick, J.; Stephenson, J.; Kirikiri, R.; Moller, H.; Turner, R. Listening to the kaitiaki: consequences of the loss of abundance and biodiversity of coastal ecosystems in Aotearoa New Zealand. Mai Journal 2012.

22. Rewi, L.; Hastie, J.L. Community resilience demonstrated through a Te Ao Maori (Ngati Manawa) lens: The Rahui. Aotearoa New Zealand Social Work 2021, 33, 65-76.

23. McAllister, T.; Hikuroa, D.; Macinnis-Ng, C. Connecting Science to Indigenous Knowledge: kaitiakitanga, conservation, and resource management. New Zealand Journal of Ecology 2023, 47, 1-13, doi:10.20417/nzjecol.47.3521.

24. Tremblay, L.A.; Chariton, A.A.; Li, M.S.; Zhang, Y.; Horiguchi, T.; Ellis, J.I. Monitoring the Health of Coastal Environments in the Pacific Region-A Review. Toxics 2023, 11, doi:10.3390/toxics11030277.

25. Burton, G.A.; Johnston, E.L. Assessing contaminated sediments in the context of multiple stressors. Environmental Toxicology and Chemistry 2010, 29, 2625-2643, doi:10.1002/etc.332.

26. Halpern, B.S.; Walbridge, S.; Selkoe, K.A.; Kappel, C.V.; Micheli, F.; D'Agrosa, C.; Bruno, J.F.; Casey, K.S.; Ebert, C.; Fox, H.E.; et al. A global map of human impact on marine ecosystems. Science 2008, 319, 948-952, doi:10.1126/science.1149345.

27. Simpson, S.; Batley, G.; Chariton, A. Revision of the ANZECC/ARMCANZ sediment quality guidelines. CSIRO Land and Water Report 2013, 8, 128.

28. Ataria, J.M.; Murphy, M.; McGregor, D.; Chiblow, S.; Moggridge, B.J.; Hikuroa, D.C.H.; Tremblay, L.A.; Öberg, G.; Baker, V.; Brooks, B.W. Orienting the Sustainable Management of Chemicals and Waste toward Indigenous Knowledge. Environmental Science & Technology 2023, 57, 10901-10903, doi:10.1021/acs.est.3c04600.

29. MfE. Ministry for the Environment & Stats NZ. New Zealand's Environmental Reporting Series: Our freshwater 2023. Retrieved from environment.govt.nz.; 2023.

30. Jesus, F.; Tremblay, L.A. Key Challenges to the Effective Management of Pollutants in Water and Sediment. Toxics 2022, 10, doi:10.3390/toxics10050219.

31. MfE. Ministry for the Environment & Stats NZ. New Zealand's Environmental Reporting Series: Our marine environment 2022. Retrieved from environment.govt.nz.; 2022.

32. Nin, C.J.; Rodgher, S. Effect of a temperature rise on metal toxicity for the aquatic biota: a systematic review. Revista Brasileira De Ciencias Ambientais 2021, 56, 710-720, doi:10.5327/z217694781010.

33. Van de Perre, D.; Roessink, I.; Janssen, C.R.; Smolders, E.; De Laender, F.; Van den Brink, P.J.; De Schamphelaere, K.A.C. The combined and interactive effects of zinc, temperature, and phosphorus on the structure and functioning of a freshwater community. Environmental Toxicology and Chemistry 2018, 37, 2413-2427, doi:10.1002/etc.4201.

34. PCE (2022) Focusing Aotearoa New Knowing what's out there Regulating the environmental fate of chemicals. March 2022: 186.

35. Williamson, B., Quinn, J., Williams, E., van Schravendijk-Goodman, C. 2016. Pilot Waikato River report card: methods and technical summary. Prepared for Waikato River Authority. Hamilton, NIWA. Hamilton: Waikato River Authority, NIWA.

36. Kaitiaki Contributors, Herangi, N., Ratana, K. (2023) Te Mauri o Waiwaia: A Maniapoto Freshwater Cultural Assessment Framework. Science Communication Summary Report prepared for Te Nehenehenui. Published by National Institute of Water and Atmospheric Research (NIWA) Ltd, Hamilton, New Zealand. NIWA Information Series 96¨February 2023. Link: https://niwa.co.nz/sites/default/files/Phase%20II%20-%20Te%20Mauri%20o%20Waiwaia_Online_RGB%20for%20web.pdf

37. Kitson, J., Cain, A. 2023. Integrated landscape approaches from a Ngai Tahu ki Murihiku perspective. Report prepared for the Parliamentary Commissioner for the Environment. Hokonui Rūnanga, Gore. April 2023: 62. Link: Integrated Landscape Approaches from a Ngāi Tahu ki Murihiku perspective (pce.parliament.nz)

38. Phillips, N. R., Stewart, M., Olsen, G., & Hickey, C. W. (2014). Human Health Risks of Geothermally Derived Metals and Other Contaminants in Wild-Caught Food. *Journal of Toxicology and Environmental Health, Part A*, *77*(6), 346–365. https://doi.org/10.1080/15287394.2013.866915

39. Stewart, M., Phillips, N.R., Olsen, G., Hickey, C.W., Tipa, G. (2011) Organochlorines and heavy metals in wild caught food as a potential human health risk to the indigenous Maori population of South Canterbury, New Zealand. *Science of The Total Environment*, 409(11): 2029–2039.

40. Stewart, M., Tipa, G., Williams, E., Home, M., Olsen, G. & Hickey, C. 2014. Impacts of Bioaccumulative Contaminants in the Te Waihora Catchment on Mahinga Kai Gatherers: Data Report and Risk Assessment. NIWA Client Report for Te Waihora Management Board & Environment Canterbury Regional Council.