9.12 Suspended sediment / water clarity / turbidity

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State of knowledge of the "Suspended sediment / water clarity / turbidity" attribute: Good / established but incomplete – general agreement, but limited data/studies

Section A—Attribute and method

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

Suspended sediment, clarity and turbidity are strongly related entities/concepts [1]. Suspended particulate matter (SPM) in waters, usually measured as total suspended solids (TSS; g/m^3), is typically the dominant light attenuating constituent in coastal waters [2] and therefore controls water clarity (transmission of light through water) and turbidity (an index of light scattering [3]). Other major light-attenuating constituents in coastal waters, in common with natural waters more generally, include coloured dissolved organic matter (CDOM), phytoplanktonic algae, and (pure) water itself [2] [4].

There are two main aspects to water clarity, and both strongly affect ecological integrity of coastal and other waters [1]:

- Penetration of (diffuse) sunlight with depth in water, and
- Visual range in water (visual clarity; visibility).

Although broadly correlated (e.g., [2]) these two aspects relate to *different* 'types' of light attenuation such that light penetration cannot be accurately predicted from visual clarity or vice versa. Penetration of sunlight into waters is quantified by the down-welling irradiance (diffuse light, usually photosynthetically available radiation, PAR) attenuation coefficient [5] [6]

$$K_d(\mathrm{PAR}) = \ln(1/T_{\mathrm{PAR}})/\Delta z \qquad (1)$$

Where z is depth below the water surface and T_{PAR} is transmission of down-welling PAR, over the depth interval Δz. A useful index of light penetration is the euphotic depth, defined as the depth of the 1% PAR level, which is given approximately by $z_{eu} = 4.6/K_d(\mathrm{PAR})$.

Visual range in waters, for humans as well as fish, marine mammals and aquatic birds, is mainly controlled by the light beam (radiance) attenuation coefficient [7] [8]

$$c = \ln(1/T)/r \qquad (2)$$

in which light beam transmission is: $T = L/L_o$ where the incident light beam (radiance) is L_o and the beam is attenuated to L over path length r. Visual range is a complicated function of reflectivity and angular size of the visual target, underwater lighting and direction of viewing [8], but a very valuable (simple) index of underwater visibility is the sighting range of an (optically large) *black body* (with zero reflectance) in the *horizontal direction* (eliminating any dependence on change of illumination with depth). A practical approach is to observe a matte black disc, for which horizontal visual range underwater is: $y_{BD} = 4.8/c(550)$, where $c(550)$ is the light beam attenuation coefficient at 550 nm (near peak sensitivity of the human eye) [9]. The coefficient of 4.8, accounts for the contrast sensitivity of the human eye, and was confirmed to high accuracy by Zanevald & Pegau [8]. Black disc visibility has been measured in New Zealand for many years, for example since 1989 in rivers [10].

A traditional index of visual clarity is the Secchi depth (sighting range of a white or black-and-white) disc viewed vertically), which is less useful as a visibility index because it depends on underwater lighting as well as light beam attenuation [11]. Furthermore, Secchi observations can be very misleading in often depth-stratified coastal waters.

Sunlight penetration largely controls depth limits of aquatic plants and benthic algae in waters [5]. For example, keystone seagrasses, including the one New Zealand species, *Zostera muelleri*, are 'light-demanding' plants that can only grow with sufficient sunlight penetration to the seabed [e.g., 12, 13]. The controlling factor is then, *not* K_d(PAR)) as such but *optical depth*: K_d(PAR)*z (dim.) – which, from the definition in Eqn 1 above, corresponds to PAR at the bed being reduced to a particular fraction of that incident on the water surface (in unstratified water). Interestingly, fine sediment affects seagrasses *both* when suspended (by attenuating sunlight) and when deposited (by exerting an oxygen demand while also reducing oxygen transfer to the substrate from overlying water). These two stressor modes of fine sediment *interact* because seagrasses need sufficient light to generate oxygen fast enough to counter deoxygenation of muddy substrate near their roots [14].

Visual clarity strongly affects behaviour of sighted animals including fish and aquatic birds [7] Reactive distance of sighted predators is necessarily less than visual range. Some New Zealand coastal fishes, including commercially valuable snapper, are very sensitive to visual clarity being preferentially visual predators. They have to switch over to less favoured modes of prey detection when their visual range is constrained [15]. Certain aquatic birds, notably diving predators like shearwaters and gannets [16], are obliged to detect prey visually, and may be expected to be very sensitive to visual clarity – perhaps more so than fish which can augment vision with lateral line or olfactory capabilities. Marine mammals may also be very sensitive to visual habitat, although toothed whales can substitute their highly developed sonar for vision in low clarity waters, so may be *less* sensitive to visual clarity than preferential visual feeding animals.

Visual clarity also strongly affects human uses of waters, including coastal waters, as regards amenity and for recreation [17]. Although visual water clarity is often considered primarily an aesthetic concern, visual range in waters also affects contact recreation safety as regards avoidance of submerged hazards [18]. Measurement of visual clarity in tandem with bacterial indicators in beach surveillance is strongly encouraged – both because of safety concerns with low clarity water [19] and in view of the broad inverse correlation of faecal contamination and visual clarity [18]. (Refer the FIB stocktake by Davies-Colley & Stott.)

Turbidity, usually measured by nephelometry (light side scattering), has long been used as a convenient index of SPM concentration and clarity of waters. Unfortunately, nephelometric turbidity is not a 'proper' scientific quantity – being measured in 'informal' (non-SI) units *relative to formazine*. [20]. Because natural SPM scatters light very differently from formazine, measurements relative to formazine are of limited usefulness[1]. Only passing reference to 'turbidity' will be made herein – confined mainly to recognising the (continuing) utility of high-frequency nephelometers to provide a proxy for SPM concentration and water clarity in coastal waters, necessarily with local calibration.

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 evidence from laboratory experiments and field observations that the light climate affects growth (and depth limits) of coastal benthic plants such as keystone seagrasses [12]. Indirect evidence for degradation of the light climate of New Zealand's coastal waters comes particularly from the historical declines of seagrasses in some of our estuaries [13]. A range of stressors may be responsible including herbicides, unusually large storms, and substrate disturbance by boats, but an association with river-borne mud seems clear in many systems in New Zealand. For example, Pauatahanui Inlet lost most of its seagrass meadows in recent decades plausibly due to mud loading from urbanisation and pastoral farmland [13].

Evidence is less strong on ecological effects of visual range on reactive distance of fish and birds – mainly because most studies have used formazine-based turbidity as the metric rather than visual clarity (or TSS) [e.g., 15]. However, there are very good reasons for expecting strong effects of 'visual habitat' on aquatic animals [7]. Research on visual clarity tolerance of New Zealand coastal species seems highly desirable. Visual clarity is also known to strongly affect human aesthetic preference and safety for contact recreation in waters [17].

It is hard to assess the optical impact of fine sediment on coastal waters in the absence of a baseline. However, a reasonable assumption is that NZ's coastal waters are less clear than in pre-human and, particularly, pre-European, times owing to increased fine sediment concentrations reflecting forest clearance causing accelerated erosion of the NZ land mass [[21]. Several lines of evidence suggest that clearance of indigenous forest on hill land for pastoral agriculture amplifies sediment loads indefinitely by about an order of magnitude.

It is easier to assess optical impacts in rivers than in coastal waters because spatial changes down-river can be related, for example, to the confluence of turbid tributaries draining erosion prone terrain [22]. Because rivers are the main influence on coastal water quality [23], degraded river visual clarity may be expected to translate into our coastal waters. However, the 'translation' is not linear with salinity because river SPM tends to be flocculated on contact with salt ions promoting

[1] Turbidity has long been known to be instrument-specific, such that different turbidity sensors give different responses on the *same* waters. In one laboratory study (Rymszewicz et al. 2017) a five-fold range of output was measured across 12 different turbidity sensors on the *same* river. Even turbidity sensors of the same principle differ in response due to subtle design differences combined with differing natural SPM optics. Davies-Colley et al. (2021) reported a two-fold range for six nephelometric turbidity sensors compliant with the international standard (ISO7027; specifying 90° scattering of near-infrared radiation) that are commonly used in NZ. These authors asserted that (1) turbidity is not suitable for environmental standards, (2) turbidity should not be used as a measure of SPM effects on aquatic life, and (3) formazine-based turbidity should be abandoned and replaced by light beam attenuation.

settling [2] [24]. That is, estuarine mixing of river and seawaters is typically strongly *non-conservative* (non-linearly related to salinity).

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 pace and direction of change in the optical water quality of NZ's coastal waters is largely unknown because only recently has monitoring of appropriate metrics been standardised [25].

Fortunately, NZ has been 'evolving' towards a better understanding of SPM and its relationship to light attenuation in waters over recent years, culminating in standards for protecting freshwaters from fine sediment damages in terms of visual clarity [26] [27]. Advances have also been made in optics of NZ coastal waters [2]. In future we may expect increased direct monitoring of visual clarity in coastal waters backed up with beam transmissometry [25] Likewise, increased monitoring of (sun)light penetration of waters is expected, particularly with PAR sensors mounted on CTD/sondes for convenient depth profiling [25].

Extreme weather events produce severe erosion and sediment delivery and cause temporarily increased 'muddiness' of rivers and coastal receiving waters. For example, the Hudson River Estuary exhibited hysteresis of suspended sediment and resulting turbidity for at least two years following tropical cyclones in 2011 [28] Similarly Cyclone *Gabrielle* (14 February 2023) may be expected to increase muddiness of rivers and coastal receiving waters for several years, particularly in the strongly impacted regions of Gisborne and Hawkes Bay.

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?

There are no NZ *standards* for SPM or related optical metrics applicable to coastal waters. However, the Ministry for the Environment [29] gives *guidelines* as follows: a black disc visibility of 1.6 m is recommended for swimming in coastal waters as well as freshwaters (for safety as well as amenity protection). Visual clarity should not be changed by more than 20%, and euphotic depth (index of light penetration) should not be changed by more than 10%, to avoid changes, respectively, to 'visual habitat' of aquatic animals (and people) and light climate for benthic plants. Clearly an appropriate baseline is required from which to gauge *change* in these optical metrics, but such baselines are not generally available for NZ coastal waters.

Standards have recently been promulgated for visual clarity to protect river ecosystems from sediment damage (NPS-FM2020: Table 8) [26]. Implementation of these standards in freshwaters has implications for downstream receiving coastal waters and the river standards themselves might be broadly applicable in coastal waters at least until refined by research.

Most monitoring of SPM and clarity (both aspects) of NZ estuaries and coastal waters is carried out by regional councils as part of SoE reporting [23]. The NEMS for discrete coastal water quality monitoring [25] is a very valuable guide that is improving cross-regional comparability and should eventually improve national reporting on NZ's coastal water quality. Depth profiling with sondes is increasingly conducted in coastal monitoring, so we can expect increasing deployment of PAR sensors on these multi-parameter devices to quantify PAR penetration [25] [2]. Visual clarity can be indexed by Secchi or black disc observations, backed up where necessary, if not actually substituted, by field deployment of beam transmissometers [25] or laboratory measurement of light beam attenuation [20]

High-frequency optical monitoring of coastal waters on moorings or structures is potentially very informative, notably. for ‘sea-truthing’ of remote sensing, and for capturing ‘events’ like wind-wave disturbance, and plumes from river stormflows or dredging. However, high-frequency optical monitoring in coastal waters is quite challenging. Nephelometric turbidity sensors are probably best for this purpose due to relatively low cost, wide dynamic range (up to 1000-fold) and comparative resistance to biofouling. But, for nephelometric turbidity data to be useful, *local calibration* to better metrics (TSS, visual clarity, light penetration) is needed [20]. Fairly frequent (e.g., monthly) visits are required, for sensor cleaning as well as on-site calibration and sampling.

Beach surveillance typically emphasises faecal indicator bacterial (FIB) measurement (usually weekly through the bathing season). Visual clarity measurement at times of beach surveillance is strongly recommended [19] – because visual clarity also affects swimmability (safety as well as aesthetics) and because a rough, but useful, inverse correlation typically exists for these variables [18] such that clear water reliably indicates uncontaminated water that is safe for recreation.

The guideline for visual clarity to protect contact recreation of 1.6 m [29] (still) applies to coastal waters – just as it does in rivers and lakes. The 1994 guidelines also recommend no more than 20% reduction in visual clarity and no more than 10% reduction in euphotic depth – while acknowledging the difficulty of establishing the relevant baseline from which to measure change.

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

Boat access is usually most appropriate for monitoring coastal water quality at central (relatively deep) sites [25], including for TSS, visual clarity and light penetration. Measurement of surface visual clarity can be conducted from a boat in tandem with sampling of SPM. Depth profiling, including for PAR penetration, requires access to deep waters, and typically can’t be done from the shore unless a suitable structure such as a bridge or jetty is available. Shore (wading) access is, however, usual and appropriate for beach sampling for swimming water quality,

Several regional councils conduct coastal water quality sampling by helicopter [25] which is unsuitable for depth profiling (including of light penetration) and direct visual clarity observations. If the water is sufficiently turbid (visibility < 0.6 m) a SHMAK tube could be used for direct visibility observations on helicopter samples [25], else visual clarity, can be estimated from light beam attenuation measurements on the water samples in the laboratory.

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).

Boat access to deep central sites will normally be required for measurement of a wide range of water quality variables in coastal waters [25], and boat operation is recognised as a major cost item. However, once boat sampling is underway there is little *marginal* extra cost to conducting on-site measurements of visual clarity and PAR penetration and obtaining (relatively large volume) samples for laboratory processing for TSS (costing $40/sample). If a CTD/sonde (costing perhaps $30,000 per unit, depending on optional sensors (such as turbidity, Chla-fluorescence, DO, PAR) is used for depth profiling [25], K_d(PAR) can be estimated from the simultaneous PAR profile for no extra on-site time. Alternatively, paired PAR sensors displaced by a known (adjustable) depth interval, with two-channel logger readout, of the type used by Gall et al. [2], currently costs about $5-7000, but requires extra on-site time (perhaps 5-10 minutes) for dedicated PAR profiling.

Visual clarity is best measured on-site by the black disc method [25] A float attached to the black disc target at the end of a telescoping pole makes for easier observations (but still challenging in choppy water) when the sighting range is longer than the boat length. A closely equivalent alternative to direct observation [8] is to deploy a beam transmissometer in the field (sensor plus logger costing about $20,000) or commission measurements of beam-c on water samples in the laboratory ($30/sample). A SHMAK tube is convenient to use on-site or back at the laboratory to give black disc visibility when this is low (< 600 mm) [25].

The traditional (vertical) Secchi depth is a useful index of visual clarity that is somewhat easier to measure from a boat than the black disc (horizontal) visibility, but Secchi observations can be misleading in the optically stratified water commonly encountered in estuaries. Secchi depth (in vertically mixed, i.e., unstratified water) is about 25-30% higher than horizontal black disc visibility [30]. Observer time (perhaps 5 minutes per observation) is the main cost component for visibility observations since equipment costs are low.

Increasing deployment of CTD/sondes on fixed structures or moorings may be expected in future in NZ coastal waters so as to provide high-frequency records that 'capture' events. However, there are significant costs associated with maintaining optical sensors on such platforms including turbidity sensors as convenient proxies for TSS, visual clarity and/or light penetration. These monitoring platforms do not obviate the need for fairly frequent (e.g., monthly) and ongoing (so costly) site visits for removal of biofouling, plus sampling and on-site measurements for calibration and validation of high frequency sensors.

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

The SHMAK equipment set, including equipment and methods for black disc visual clarity observations, can easily be used in coastal waters as well as fresh waters by community monitors, and practical guidance is given in the estuary monitoring toolkit [31].

Water clarity is one of forty important environmental indicators provided by hapū and iwi in association with estuarine ecosystems throughout Waitaha (a.k.a. Canterbury) [49]. Visual clarity in freshwater is also one of the eight key indicators of the cultural health indicators, which are part of the wider state of the takiwā monitoring programme [50,51]. Visual clarity is measured within the freshwater area that feed into to significant estuaries, and contributes to the overall monitoring of estuary and its catchments [50,51].

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

Visual clarity correlates strongly, inversely, with measures of SPM, such as TSS [2]. Vant [32] showed that the ratio of light beam attenuation to TSS (known as 'optical cross-section' in view of the units), is appreciably lower for estuarine waters (about 0.4 m^2/g) than freshwaters (averaging about 1 m^2/g) – plausibly due to the flocculation of river fines on contact with salt ions in estuaries.

Sunlight penetration into coastal water also correlates with SPM, usually somewhat more weakly [2]. Kirk [33] showed why PAR attenuation with depth depends *non-linearly* on TSS – typically following a power law with exponent in the range 0.5-1.0 depending on the ratio of light absorption to light scattering by the SPM [2]. Light penetration and visual clarity are broadly correlated, but the contrasting definitions of these quantities (Eqn 1 versus Eqn 2) shows why estimating one from the other should not be attempted without local optical data. Nephelometric turbidity is not very useful in itself [20], but can provide a valuable (local, high-frequency) proxy for both TSS and optical parameters [2].

Visual clarity is often very usefully, inversely, correlated with faecal contamination of river waters [18]. This has important practical ramifications because bathers can protect themselves from exposure to faecal pathogens by avoiding low clarity water. The correlation of these variables in rivers is expected to also apply to coastal receiving waters, given that rivers are the main influence on water quality in estuarine and coastal waters [23]. For example, visual clarity, TSS, salinity and *E. coli* were all strongly inter-correlated in a stormflow plume from the Hutt River within Wellington Harbour, and nephelometric turbidity provided a valuable local proxy for these variables across the plume [24].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

Currently we have only a patchy national picture of optical water quality of the New Zealand coastal zone because of the lack of in-water monitoring in several regions [23]. However, more effort on coastal monitoring is being encouraged by the NEMS for discrete coastal water quality monitoring [25], so the quality and quantity of the national dataset should improve over time into the future.

Seas, Coasts and Estuaries NZ (SCENZ), based on satellite imagery, probably gives a reasonable overall picture of certain remote sensing 'products' (including TSS, K_d(PAR), black disc visibility and Secchi depth) [34], despite very limited 'sea-truthing'. Visual clarity of coastal waters is extremely variable with time in response to meteorological forcing. River stormflows 'inject' large quantities of muddy water as plumes [e.g., 24], and wind-driven wave action over shallow waters resuspends flocculated fine sediment from the seabed [e.g., 35].

Visual clarity data is available for coastal water in some NZ regions, but not others and Dudley et al. [23] were forced to use (less satisfactory) nephelometric turbidity to attempt a national picture. These authors showed that water quality generally, including turbidity, of our estuaries and coastal waters is strongly affected by river inflows such that water quality increases with increasing salinity. Visual clarity is often highest (sometimes exceeding 40 m) in coastal waters remote from major river inflows and after prolonged periods of dry calm weather. Visual clarity is episodically degraded by phytoplankton in eutrophied estuaries and coastal waters, particularly in spring when growth is accelerated by nutrient availability combined with increasing day length and warming waters.

Visual clarity is certainly capable of being adopted as a national indicator – and arguably should be so adopted given its widespread use as a freshwater indicator in NZ and multiple useful correlations (e.g., with TSS and light penetration as well as salinity). Black disc (horizontal) visibility is more useful than Secchi depth as an index of visibility, not least because the latter can be confounded by optical stratification. Black disc visibility also has the virtue of being precisely related to light beam attenuation [8] and independent of sunlight conditions so is more useful for optical modelling.

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

The clearest seawaters on earth are those in oceanic 'desert' waters such as the SE Pacific gyre between Tahiti and Rapanui [36]. The euphotic depth (depth at which PAR irradiance is reduced to 1% of that incident on the water surface) is about 100 m within the clearest waters. Visual clarity in such clear ocean waters has not been measured *directly* so far as we are aware [37], but black disc range would probably approach the estimated 80 m for distilled water. Such extremely high visibility has actually been measured in some remarkably clear freshwater, such as Blue Lake/*Rotomairewhenua* [37] and inferred in others from instrumental measurements (e.g., Waikoropupu Springs).

In extremely clear waters, almost devoid of suspended particles [37], a slight increase in SPM concentration greatly reduces visual range and light penetration. For example, marine waters around NZ are probably more typically about 40 m visibility (regarded as "very clear' by divers), and coastal waters even this clear are uncommon owing to river suspended sediment inputs and wave disturbance of the bed, plus seasonal phytoplankton blooms.

Because inflowing rivers strongly affect water quality of receiving waters, NZ's coastal waters remote from river mouths and with adjacent land in conservation estate may be among the clearest. Indeed, Dudley et al.[23] found strong evidence for the influence of livestock agriculture and urban land on NZ estuarine and coastal water quality.

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)

There are no numeric or even narrative target attributes states in NZ for SPM metrics such as TSS. Collins et al. [38] reviewed standards for fine suspended sediments and related metrics in other countries. Turbidity is the metric most commonly used, although this is arguably very inappropriate given the 'informal (non-SI) units and weak numerical comparability of different sensors [20].

Numeric attribute states have been defined for visual clarity in NZ freshwaters (NPS-FM2020 Table 8; [26]) – with 'bottom lines' ranging from 0.61-2.22 m, depending on classification of the sediment regime. Turbidity was originally proposed for the NPS, but dropped after our laboratory tank experiments ([20] showed 'uncomfortably' weak numeric agreement among different nephelometers. These target attribute states for visual clarity to protect freshwater ecology might be a starting point for coastal receiving waters – at least until appropriate research is conducted.

As mentioned above, *guidelines* (rather than *standards*) for visual clarity and euphotic depth (light penetration) have been enumerated by MfE [29]. No more than 10% change in euphotic depth is recommended to protect the light climate of benthic plants, and no more than 20% change in visual clarity to protect the visual field of aquatic animals (and humans). A visual clarity of 1.6 m is recommended for swimming – on the basis that swimmers need to be able to avoid submerged hazards when wading in chest-deep water [29].

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

Thresholds for light 'starvation' resulting in extinction of keystone benthic plants like seagrasses are fairly well defined in theory and practice [12]. Laboratory experiments or field measurements at depth limits can establish numeric light thresholds (PAR in mol/m^2/day or % of surface average PAR) [e.g., 39]. For seagrasses, thresholds are known to *increase* in muddy systems owing to the *interaction* of light extinction by fine suspended sediment and deoxygenation under deposited fines [14].

In some coastal ecosystems, light starvation may result in 'tipping' in the classic 'catastrophe theory' sense of change to a new metastable state. Seagrass meadows are known to be vulnerable to 'tipping' to a devegetated seabed where plant recovery may be precluded by substrate muddiness [13].

Thresholds, but not tipping points, are expected for visual clarity as it affects behaviour of aquatic animals such as fish, as shown for snapper in NZ by Lowe et al. [15]. However, visibility thresholds are poorly known for NZ coastal species suggesting the need for indigenous research.

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?

Lag effects occur in coastal waters due to flocculation and settling of inflowing river sediment on contact with salt ions. This settled, flocculated sediment, sometimes referred to as a 'nepheloid layer, is easily resuspended by wind waves or other hydraulic disturbance of the bed. So, terrigenous fine sediment, delivered mainly by river stormflows, may go through multiple cycles of settling and resuspension before being "winnowed'' from coastal waters.

Petersen et al. [40] showed that seabed lighting could be much more strongly shaded by nepheloid layers than calculated from extrapolating the water column light gradient – which may explain, in part, the legacy effect of seagrasses often failing to recolonise after extinction by mud loading. Transplantation experiments in NZ were successful in former seagrass meadow sites in Whangarei Harbour [41] but not in Pautahanui Inlet (despite apparently sufficient bed PAR) – apparently because of mud deposition and intrusion into the substrate in the latter estuary [13].

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.

Visual clarity of waters is of high concern to Māori – as demonstrated, for example, by the close inverse correlation of visual clarity and cultural health reported by Harmsworth et al. [42]. Furthermore, the broad inverse correlation of FIB and visual clarity [18] provides a means to avoid contact with faecal contamination, simply by avoiding low clarity waters. In practice, if visual clarity is close to or better than the MfE [29] guideline of 1.6 m for swimming, the risk of infection by faecal pathogens is very low [18]. Low clarity coastal water is best avoided in view of the difficulty of detecting submerged hazards [29] even if demonstrably free of faecal contamination.

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 main pressure on optical water quality of coastal waters is mobilisation of fine sediment from adjacent land with conveyance to the coast via rivers, notably during storm flow events [43]. However, the relationship between the *pressure* (land erosion) and coastal optical water quality is highly complex because of:

- Displacement in space of land sources from coastal receiving waters
- Variation in time, particularly with river flow conditions and coastal plume hydrodynamics,
- Uptake and storage of fines (and faecal microbes) in the hyporheic zone of rivers [44].
- Flocculation of fine sediment on contact with salt ions from seawater, with subsequent settling to the seabed[1].

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?

Because most fine sediment loading on NZ's coastal waters comes from erosion of adjacent land, the interventions must focus on land. Such interventions are underway in NZ, focussed mainly on general water quality (including nutrients and faecal contamination as well as fine sediment) of *rivers* rather than coastal waters.

C2-(i). Local government driven

Regional councils are the agencies most actively intervening to improve water quality in NZ, including optical water quality – by promoting soil conservation and stream fencing (to reduce cattle ingress) and riparian setbacks (to trap sediment in overland flow). Such land management has been shown to improve stream water quality. For example, integrated catchment management at Whatawhata generally improved sediment loads and stream water quality [45-47], and improved visual clarity and reductions in *E. coli* have been reported for catchments with land management action in Horizons Region [48]. These water quality improvements can be expected to 'translate' downstream to coastal receiving waters.

Regional councils are keen to inform the recreating public of swimming suitability of waters. In future, modelling of visual clarity informed by high-frequency turbidity monitoring could, in principle, be used to 'now-cast' swimming suitability. NIWA currently has 'Smart Idea' funding of a project (WaiSpy MBIE contract: C01X2204) that is attempting to develop a system for nowcasting 'swimmability' of rivers – most strongly affected by faecal contamination and visual clarity. The approach can potentially be translated to downstream coastal receiving waters.

C2-(ii). Central government driven

[1] Resulting nepheloid layers are easily resuspended by hydraulic disturbance, notably wind wave exposure over tidal flats. Nepheloid layers consolidate over time, but leave the substrate 'muddier' than previously, more subject to deoxygenation, degraded as habitat, and less suitable for re-establishment of keystone seagrasses.

C2-(iii). Iwi/hapū driven

Iwi and hapū are aware of the deleterious effects of suspended sediment in estuarine and coastal waters and have reported changes in this attribute over time. Iwi and hapū have been heavily involved in Jobs for Nature projects across New Zealand (many of which address sediment and nutrient entry into waterways, which are related to this attribute) and are leading estuarine restoration initiatives in partnership with Councils and National Science Challenge researchers from various universities, CRIs, and other research institutes/providers.

C2-(iv). NGO, community driven

Community-driven initiatives such as catchment care groups and 'Mountains to Sea' mobilise community interests in stream fencing, restoration planting and water monitoring. These efforts should reduce the burden of fine sediment loading of rivers and downstream coastal waters. We are not aware of improved coastal water quality in NZ being explicitly linked to land management, however such connections have been established overseas. Improved coastal water quality is difficult to attribute to land management because of the complexity of land-coastal connections (Refer C1).

C2-(v). Internationally driven

Part D—Impact analysis

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

Not managing sediment load to coastal waters and resulting degradation of optical water quality is likely to lead to decreased recreational amenity and swimming suitability, and downgraded perception of NZ as 'clean and green' among tourist visitors. Not managing fine sediment and water clarity (both aspects) is also likely to severely impact coastal ecosystems – reducing visual range of fish and birds and degrading the light climate of benthic plants. Seagrass meadow ecosystems, in particular, seem particularly vulnerable to 'tipping' by muddy stormflow plumes into a new de-vegetated state with no guarantee of eventual seagrass recovery [12].

Managing optical water quality of coastal waters requires, mainly, management of sediment loads of inflowing rivers – in turn by reducing land erosion. So, land activities that mobilise sediment, primarily livestock agriculture, plantation forestry and urban land use, need to be isolated so far as possible from waters. Important controls on sediment mobilisation include:

- *In livestock pasture:* soil conservation activities (e.g., poplar space-planting) and fencing to exclude livestock from waters, plus riparian fencing and planting to entrap sediment in overland flow,
- *In plantation forestry:* care with roading and culverting to prevent erosion, slash management and riparian set-backs to avoid slash entry and minimise sediment entry to streams.
- *In urban areas:* street-sweeping to reduce mobilisation of fines and associated contaminants in stormwaters, and detention of roof and paved area runoff to prevent bank erosion of urban streams by high peak flows.

To *manage* optical water quality of coastal waters requires its *measurement* – which, currently, is not adequate in NZ because sampling is mainly discrete at a sparse distribution of sites. What is needed for improved management is *modelling* to fill in the measurement gaps in time and space – ideally informed by high-frequency instrumental monitoring (in contributing rivers as well as coastal receiving waters) or new modelling approaches using satellite remote sensing such as SCENZ [34]. The 'Coastwatch' research programme, proposed by NIWA to the MBIE Endeavour fund, would integrate relevant sources of monitoring data (notably coastal satellite imagery and high-frequency river monitoring) within an artificial intelligence (AI) framework for a 'quantum leap' in NZ's coastal management capability.

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)

The main economic impact of *not* managing coastal water optical quality would be on NZ's tourist industry – which trades strongly on NZ's image as a 'clean green', environmentally responsible country. Loss of aquatic species of conservation concern is also possible, including marine mammals and birds. Commercially valuable fish species, such as snapper, could be reduced in abundance by poor visual habitat and loss of 'nursery' seagrass meadow habitat.

The general public of NZ would be impacted in a difficult-to-quantify way if our coastal waters were increasingly perceived by NZ citizens as of degraded optical water quality, resulting in reduced recreational opportunity for fear of underwater hazards (and, likely, faecal contamination) and reduced sport fishing opportunity and biodiversity values.

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

Increased storminess due to global warming may be expected to decrease optical water quality of coastal water, by increasing SPM concentrations and light attenuation. More frequent large storms are forecast to cause more land erosion [21], resulting in increased fine sediment loads conveyed by rivers with associated degradation of habitat and recreational amenity in coastal receiving waters. Neverman et al. [21] modelled erosion response to global warming from the NZ land mass under defined IPCC scenarios, and predict that sediment yield from soft-rock areas (such as Gisborne, and Hawkes Bay) could double by 2090.

Higher summer temperatures with global warming may be expected to drive people to swim and recreate more often in NZ's coastal waters despite poor visual clarity (and more frequent faecal contamination). Higher summer temperatures will also exacerbate deoxygenation in coastal substrates under deposited (flocculated) river fines – which exert an oxygen demand as well as reducing oxygen transfer from overlying water.

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