9.11 Extent of mud (broad scale attribute)

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Preamble: "Mud" refers to a cohesive mixture of deposited (benthic) material consisting of water, clay minerals, silt particles, and organic matter (biopolymers). "Sediment mud content" refers to the proportion of sediment particles (i.e., percent of a sediment sample's dry weight) ≤ 63 µm. In intertidal areas, muddy sediment can be identified by its lack of firmness underfoot (e.g., how far a person sinks into the sediment when walking or standing on it). Some researchers can identify sediments with high mud content by other means, for example, by the presence of indicator species (e.g., crabs) or their traces (e.g., burrows). Note, however, that sediment muddiness is difficult to assess accurately at broad scales, especially in submerged (subtidal) habitats and using drone or satellite imagery. The "Extent of mud" in an estuarine area may be defined as the proportional area where sediment mud content is greater than a particular threshold, e.g., 25% mud content. However, Mud Extent in an estuarine area will likely be determined through interpolation of point samples of mud content (as percent mud content is not easy to determine from drone/remotely-sensed imagery or by walking/observing an estuary). Interpolation accuracy depends on the number of sampling points and their spatial distribution across estuaries. This will need to be considered when comparing Mud Extent in different estuaries.

State of knowledge of "Extent of Mud (broad scale, estuarine)" attribute: Medium / unresolved – some studies/data but conclusions do not agree

In soft-sediment habitats, sediment mud content is widely and well understood to affect many sediment parameters, including macroinvertebrate-based estuarine health metrics and human use/amenity values (such as walkability, firmness, and odour). Thus the attribute is likely important. However, knowledge of how differences in "extent of mud" relate to estuarine ecological integrity is medium / unresolved. Obtaining accurate measurements of the extent of muddy habitat at estuarine scales is challenging. Therefore, relationships between this attribute and ecological integrity remain unclear.

Part A—Attribute and method

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

Human Heath: The "Extent of mud (broad scale, estuarine)" attribute—hereafter Mud Extent—does not relate to Human Health. A possible exception is that food (e.g., shellfish) gathered from muddy sites may have higher concentrations of contaminants than food collected from sandier sites, as trace metals and other anthropogenic contaminants often bind to fine sediments. Therefore, food safety may be worse in estuaries with high Mud Extent, although this would be better assessed directly using other attributes, e.g., 'Trace metals in sediment' or 'Trace metals in water/indicator species' (report sections 9.8 and 9.9).

Ecological Integrity: Mud content is inversely related to various measures of ecological integrity. Therefore, estuaries and coastal areas with greater Mud Extent are likely to be in a poorer state of health overall. Muddy sediments, particularly when mud content exceeds 10 to 25%, are associated with significantly reduced abundance, richness, and diversity of benthic macroinvertebrates [1-4]. Muddy sediments also have fewer large-sized suspension-feeding bivalves (pipi, cockles, scallops, horse mussels, green lipped mussels) that are key contributors to ecological integrity. Ecosystem functions (benthic primary production rates, nutrient regeneration) have been shown to be affected by experimental additions of mud [5,6] and to change across natural gradients of sediment muddiness [7-9]. The resuspension of muddy sediments by waves can affect water clarity, which can in turn affect feeding by visual predators such as fish and wading birds. In conclusion—based on numerous individual experiments and observations across mud content gradients [10-13]—estuaries with high Mud Extent are likely to have lower ecological integrity than estuaries with low Mud Extent. However, Mud Extent is difficult to measure accurately and the shape/slope of the overall negative relationship between Mud Extent and ecological integrity remains unclear.

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

Although the 'natural baseline' (pre-human) state of Mud Extent is unknown, it is widely accepted that Mud Extent has increased dramatically in estuaries throughout New Zealand in modern times. Humans have greatly elevated rates of fine-sediment input into estuaries through land-use practices (e.g., widespread deforestation). The most pronounced changes in fine sediment accumulation rates (and thus muddiness and Mud Extent) have occurred during the last 100 years. Sediment accumulation rates are presently estimated to be 10 to 100 times greater than natural [14]. Some harbours that were once navigable to ships are now highly infilled. The spatial extent of coastal mangroves in North Island estuaries has expanded markedly over the last 100 years (~4% per year since the 1940s), coincident with and possibly driven by increases in Mud Extent [15]. The expansion of Mud Extent in estuaries tends to proceed from head to mouth, i.e., muddiness increases first in upper estuarine areas where rivers are introducing sediments that have eroded from land. Later, as the estuary infills, Mud Extent may expand outward from the upper estuary tidal creeks into the main body of the estuary and towards the mouth.

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)?

Mud Extent has not been monitored or estimated in estuarine/coastal areas until relatively recently, however, it is safe to assume that Mud Extent has increased markedly over the last 150 years since the arrival of Europeans in Aotearoa New Zealand. Road building, urban expansion, and agricultural intensification during the last 30 years has likely contributed to the highest rates of increase in Mud Extent (though this is speculative because Mud Extent is not widely measured). Under the status quo, Mud Extent will continue to increase, especially with climate change expected to increase the loadings of terrigenous sediments to coastal receiving environments, driven by more frequent and higher intensity storms. However, with large-scale afforestation, riparian planting, and exclusion of livestock from river margins, the loading of new terrigenous sediment to estuarine/coastal areas is predicted to decrease, which would in turn allow Mud Extent to slowly decrease. Mud Extent may decrease fastest at sites and in estuaries with positive net sea level rise, as increased inundation of muddy fringing habitats may help to flush muddy sediments out of estuaries, though this is speculative and requires testing/verification.

One important point is that Mud Extent can increase rapidly following major storms. For example, there was evidence of muddy deposits covering wide extents in Auckland, Waikato (Coromandel), and Hawke's Bay estuaries following the passage of Cyclone Gabrielle (NIWA Hamilton Marine Ecology team pers. obs., 2023). These increases in Mud Extent were detected in the immediate post-event period, but the persistence of the muddy areas was not well studied.

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?

Mud Extent has been assessed in many South Island estuaries, and in a few North Island estuaries. Researchers at Wriggle and Salt Ecology have used a method called "Broad scale mapping", which is intended to provide a rapid overview of estuary condition based on visible features (e.g., aerial photographs), supported by ground-truthing to validate the visible features. The usual reporting metric for Mud Extent is "Soft Mud Percent Cover", defined as "percent of available intertidal habitat with >25% mud"[16-18].

It must be noted that mud content is not generally detectable from aerial photographs, therefore, on-the-ground observations of underfoot substrate firmness by field staff and grainsize samples are used for validation. For this method, "soft mud" is identified when an adult sinks 2-5 cm, and "very soft mud" is defined when an adult sinks >5 cm. Together they are called "total soft mud" [18], or possibly "mud-elevated substrate (>25% mud content)" [Leigh Stevens, Salt Ecology Ltd., pers. comm.]. However, correlations between "firmness" and grainsize are not always clear [19]. Furthermore, from a distance, proponents acknowledge that soft mud looks visually similar to firm muddy sand, firm sandy mud, firm mud, and very soft mud. This raises questions about standardisation and the ability to measure this metric accurately.

Other types of "Rapid Habitat Assessment" techniques have been undertaken in a number of Auckland and Waikato estuaries, although these assessments are focused on biotic habitats (defined by dominant species or biological features), with Mud Extent not typically assessed directly [20-23]. The forthcoming update of the National Estuarine Monitoring Protocol may provide guidance on a standard method or consistent technique for quantifying Mud Extent. However, Mud Extent is likely a difficult variable to measure accurately at the scale of whole estuaries—particularly when the estuaries are too large for researchers to cover on foot and when the estuaries have large proportions of subtidal habitat.

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

Assessing Mud Extent requires field work to access estuarine areas that are exposed at low tide. All parts of the estuary need to be assessed (not just specific sentinel sites), meaning that boats and multiple points of access from shore will likely be required to characterise Mud Extent. Permissions may be needed to gain access from private lands. Ancestral and sacred areas, such as areas near burial grounds, are likely to be off limits for assessments (possibly even by unmanned aerial drone). It is always advisable to communicate with mana whenua to understand access issues. In general, clear communication, good relationships, and addressing concerns or impacts to landowners' property or operations is necessary. Formal access agreements may need to be established in some cases.

Several health and safety indications need to be considered for fieldwork. Use of boats and kayaks generally requires health & safety training and Worksafe qualifications. Sinking into deep mud or traversing channels on incoming tides can be fatally hazardous if this risk is not managed.

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).

Costs of assessing the Mud Extent attribute will vary widely depending on estuary size and morphology. Costs will be determined by the staff time required to safely and thoroughly assess all parts of an estuary. It may be possible to gather information from local people (and possibly enlist their help in surveys) to determine Mud Extent while limiting cost. In most cases, Mud Extent would be just one of many attributes measured (therefore, costs could be shared). It is possible that use of UAVs (aerial drones) will increase estuarine coverage and measurement accuracy, provided that standard protocols for operation and processing are developed. Use of drones will require upfront costs (drone purchase, training).

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

We are unaware of any iwi or hapū that have assessed mud extent in estuaries in their rohe moana. It is highly likely, however, that knowledge about estuarine muddiness and extent is held by mana whenua and could facilitate quantification of this attribute. An assessment of co-developing appropriate indicators for estuarine mahinga kai was co-led with a rūnaka within the takiwā of Ngāi Tahu ki Murihiku, which highlighted the importance of sediment characteristics as key to mahinga kai ecosystems [56]. As such, an additional scope to the project had led to working with Environment Southland to incorporate a significant site for sediment monitoring as part of the annual assessment, and which whānau will additionally monitor at key periods to align with seasonal relevance [56].

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

Bed sediment muddiness is correlated with a range of other attributes, e.g., heavy metals in sediment (positively), water clarity/turbidity (positively), and macroinvertebrate community composition (negatively). However, Mud Extent—percent of available intertidal habitat with >25% soft mud—is probably most closely correlated with other estuary scale attributes such as mangrove extent and quality (positively), seagrass extent and quality (negatively), and shellfish bed extent and quality (negatively). While the correlated attributes should not necessarily be grouped, it may be possible for them to be assessed together (to save costs and provide a greater range of information).

Part B—Current state and allocation options

B1. What is the current state of the attribute?

Our understanding of Mud Extent attribute (broad scale in estuaries) is moderate at the National Scale. Mud Extent has been quantified in many South Island estuaries and a few lower North Island estuaries. Mud Extent has not, to our knowledge, been estimated in any Auckland, Waikato, or Northland estuaries. Where it has been assessed, questions remain about the accuracy/repeatability of the estimates. Mud extends into subtidal areas but the attribute is only assessed in intertidal habitats. Mud Extent is calculated as percent of available intertidal area *excluding saltmarsh*, but no guidance has been presented to date on whether to exclude mangroves (which are only distributed in central and upper North Island estuaries). Thus, in summary, there are gaps and potential issues in using this attribute as an estuarine health indicator. However, with guidance on how to standardise the assessment technique, and with the incorporation of new technologies such as aerial drones, the Mud Extent attribute has promise for use as a national indicator, particularly if it can be shown to drive or correlate with changes in other spatial attributes such as Shellfish extent/quality and Seagrass extent/quality.

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

There are no known reference states for this attribute. Oral histories and sediment cores 20-50 cm deep (with deeper layers of sediment being progressively older) may be able to fill this information gap. It should be noted that some estuaries and parts of estuaries are likely to have been dominated by fine sediments / soft mud even in their natural state (e.g., for example in protected estuary arms and downstream of catchments with silt-clay dominated soils).

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)

The following bands have been circulated by researchers at Wriggle and Salt Ecology:

Very Good – Band A	Soft mud **<1%** of intertidal substrate outside of saltmarsh
Good – Band B	Soft mud **1-5%** of intertidal substrate outside of saltmarsh
Moderate – Band C	Soft mud **5-15%** of intertidal substrate outside of saltmarsh
Poor – Band D	Soft mud **>15%** of intertidal substrate outside of saltmarsh

The evidence/justification provided for the setting of these bands was:

> *"Soft Mud Percent Cover. Soft mud (>25% mud content) has been shown to result in a degraded macroinvertebrate community (Robertson et al. 2015, 2016), and excessive mud decreases*

water clarity, lowers biodiversity and affects aesthetics and access. Because estuaries are a sink for sediments, the presence of large areas of soft mud is likely to lead to major and detrimental ecological changes that could be very difficult to reverse. In particular, its presence indicates where changes in land management may be needed". [from 16]

Percent vs hectares. It should also be noted that, in large estuaries with hundreds of hectares of intertidal habitat, low "Soft Mud Percent Cover" values may equate to a relatively large areal extent (many hectares) of soft mud—a factor that may need to be considered when evaluating health (as it is for some other estuarine attributes).

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

To our knowledge, there are no known examples of thresholds or tipping points for the Mud Extent attribute. The bands have been determined based on observations of experts who have worked in many estuaries (albeit mostly southern estuaries without mangroves). There do not appear to be any step changes or tipping points across the defined band boundaries.

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?

It has likely taken several decades for Mud Extent to build to its current levels. Contraction of Mud Extent will also likely take many decades. In other words, yes, historical legacies must be considered.

Reductions of catchment sediment loading rates are likely to first reduce sediment deposition/accretion rates, with bed sediment muddiness much slower to change. The speed and patterns of Mud Extent contraction will likely depend on local estuarine morphology (degree of exposure of estuarine areas to wind-waves and ocean flushing). The effects of mangroves or other biogenic structures that reduce wind-wave energy may need to be considered.

Mud Extent may decrease fastest at sites and in estuaries with positive net sea level rise, as increased inundation of muddy habitats may help to flush muddy sediments out of estuaries. However, sediment loading to estuaries is predicted to increase with climate change associated increases in rainfall intensity/frequency, thus mitigations on land are likely going to be required just to stop Mud Extent from expanding.

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.

Mātauranga Māori and extensive knowledge of estuarine spaces that have been handed down over generations is likely to be useful in defining the natural state of mud extent in estuaries. Iwi and hapū observations and knowledge of how muddiness (and other sediment characterisation) has changed over time along with other practices (e.g., shellfish collection) could help with the setting of bands. It is also highly likely that knowledge of the current state of estuarine muddiness and extent is held by mana whenua and could facilitate quantification of this attribute. Mana whenua should be asked to participate in estuarine surveys and information gathering as part of Mud Extent attribute evaluation and band refinement.

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?

With Mud Extent, relationships between environmental state and stressors are generally understood. Land-cover change (conversion of native forested hillslopes into pastureland or rotationally harvested pine) has greatly accelerated hillslope and streambank erosion, in turn leading to 10-100 fold increases in sediment accumulation rates estuaries [14]. Sediment-source tracing using compound specific stable isotope (CSSI) techniques has demonstrated the presence of terrigenous sediments with pine and streambank signatures in estuarine receiving environments [24]. Relationships between rainfall levels (river discharge volumes) and sediment loading rates are also relatively well understood, as are predictions of future loading under various climate change scenarios [25,26].

There are dozens of New Zealand studies demonstrating the deleterious effects of terrigenous fine sediments (mud) on biodiversity and ecosystem functioning in estuaries—so the consequences of the expansion of muddy habitats in our estuarine spaces is well understood [1-13,27-44].

The options for mitigating sediment loading to estuaries are known [25,26], and many of these options are already being exercised (e.g., exclusion of stock from stream and riverbanks; riparian planting; afforestation; sediment retention ponds/sumps at construction sites; controls on logging and road building).

Key knowledge gaps are knowing (1) where the greatest gains in sediment retention can be made with catchment mitigations and (2) how to evaluate the effectiveness of catchment mitigations given that positive responses in estuaries may take many years and be far from where mitigations were implemented. With the Mud Extent attribute, where quantification (identifying "soft mud" across whole estuaries) is problematic and where responses to mitigations are likely to be extremely slow/lagged, evaluating mitigation effectiveness will be extremely difficult.

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?

Many of the interventions/mechanisms for controlling the erosion and discharge of sediments from land to sea are collaborative and cross-cutting, i.e., involving iwi/hapū, local government, NGOs, and/or central government.

C2-(i). Local government driven

Most resource consents for land development (housing, construction, road building) that are considered by Councils require sediment controls to prevent entry of (especially) fine sediments into waterways. Councils can oppose plans that they think do not sufficiently protect against adverse effects. Lengthy consent timeframes (35 years) sometimes prevent local governments from mitigating potentially adverse effects (e.g., cannot prevent logging of steep coastal hillslopes if the activity was consented many years prior). Some of the Jobs for Nature initiatives (while Central government driven) are being implemented locally, but efficacy in terms of reducing Mud Extent is not yet known. Some of the 'local' initiatives are being undertaken on relatively large scales (e.g., the

$100m Kaipara Moana Remediation project; [45]). The Waikato River Authority funded riparian planting, and other councils have also likely undertaken similar initiatives.

C2-(ii). Central government driven

Central government agencies such as MfE and DOC have sediment-related strategies and plans [46,47]. Updates to MfE's National Policy Statement for Freshwater Management [48] and urging from PCE [49] have emphasised a more holistic and integrated land-to-sea approach to estuarine management. The Jobs for Nature programme (administered by five central government agencies) has directed hundreds of millions of dollars towards riparian planting in catchments to prevent sediments from entering freshwater and coastal receiving environments downstream. Fisheries New Zealand has funded studies on the effects of land-based stressors (including sediments) on coastal fisheries [40]. MPI funded a response to the major sediment loading events to the coastal zone off Hawke's Bay and Gisborne following Cyclone Gabrielle.

C2-(iii). Iwi/hapū driven

Iwi and hapū are aware of the deleterious effects of mud in estuaries and have reported changes in muddiness over time. Iwi and hapū have been heavily involved in Jobs for Nature projects across New Zealand. Iwi and hapū are also leading estuarine restoration initiatives in partnership with Councils and National Science Challenge researchers from various universities, CRIs, and other research institutes/providers [50,51]. Mana whenua have also co-led tangata whenua approaches to improve estuarine mahinga kai management, that includes the importance of sediment characteristics, and are important to developments of attribute decisions [56].

C2-(iv). NGO, community driven

There are catchment care groups and other local groups that are working on riparian planting and other sediment control measures. The Nature Conservancy is involved in catchment planting and restoration.

C2-(v). Internationally driven

We are unaware of any internationally driven initiatives that are specifically designed to address Mud Extent in estuarine/coastal ecosystems of New Zealand.

Part D—Impact analysis

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

Estuaries are vital to Aotearoa-NZ's socio-cultural identity and economy [49,52]. Many of Aotearoa-NZ's estuaries and coastal environments have been devastatingly degraded, in part due to the loading of terrigenous sediments entering via freshwater, which has greatly increased Mud Extent—impacting amenity values, decreasing native biodiversity, increasing invasions by non-indigenous species, affecting key ecosystem functions, and decreasing food for fish and bird species. If we do not manage this attribute, our estuaries are likely to continue to degrade (i.e., healthy estuarine area will shrink).

A range of culturally and commercially important shellfish species are found in estuaries, including mussels, scallops, cockles, and pipi. Increased Mud Extent and degraded estuarine health are barriers to iwi/hapū food security and wellbeing aspirations, and are likely to limit job and business opportunities for Māori and other New Zealanders (e.g., mussel and oyster aquaculture; scallop fisheries).

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 areas of economic impact related to Mud Extent would be on customary fisheries, mussel and oyster aquaculture businesses*, on- and in-water tourism enterprises (such as kayak rentals, scuba charters, glass bottom boating), and potential new Blue Carbon initiatives. There is some suggestion that severe infilling and expansion of Mud Extent can affect navigation by sea into city centres (case in point Invercargill City). Investment in activities that reverse estuarine degradation is a potential economic growth area (i.e., development of Restorative Marine Economies).

*Note that oysters are relatively mud tolerant and note that commercial oysters and mussels are both cultured above the bed, not on it, so impacts on these activities from increased mud extent in the upper arms of estuaries may be small.

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

Climate change is predicted to result in more frequent and higher intensity storms, which will likely elevate rates of terrigenous sediment input to estuaries [26], thus exacerbating issues of high Mud Extent. In contrast, sea level rise [53] may increasingly inundate currently muddy intertidal flats and potentially ameliorate high Mud Extent by resuspending mud from the edges of estuaries [54,55].

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