Research and sampling strategy for evaluating the effectiveness of sediment erosion mitigation options for plantation forestry in the Marlborough Sounds

Christina Bright and Sarah Mager

Department of Geography, University of Otago

PO Box 56, Dunedin

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Executive Summary

Coastal sedimentation from sediment discharged from forested hillslopes in the Marlborough Sounds is a problem, with the potential to cause environmental harm. The effectiveness of sediment mitigation options from hillslopes dominated by plantation forestry in the Marlborough Sounds requires the implementation of a research programme that evaluates different mitigation efficacy. The proposed sediment mitigation options were outlined in a technical paper produced by Dr Steven Urlich at the Marlborough District Council. On the basis of the technical paper, this report describes hillslope processes and their connection to the marine environment via the hydrological network.

Sedimentation of hillslopes is comprised of organic and inorganic components. In organic rich environments, such as plantation forest, the organic contribution of suspended material can be a significant portion of overall suspended load, and has important implications on measurements of suspended sediment and turbidity. In disturbed environments, like during forest clearance, there is material transfer from the terrestrial domain, via the hydrological system, into the coastal margin, and the effects and relative significance of organic material (e.g. slash) to inorganic material (e.g. mineral soil) should be assessed. Turbidity is often used a proxy variable for determining suspended sediment concentration in rivers, but in the presence of dissolved and particulate organic material it may produce unreliable estimations of suspended sediment concentrations. Therefore, the accurate measurement of turbidity is paramount to making correct assessments of suspended sediment into the Marlborough Sounds. Furthermore, the disturbance of forest soils may contribute to greater leaching of organic acids that may interfere with turbidity readings.

A remote sensing exercise was undertaken to establish locations suitable for monitoring sites to test the effectiveness of the proposed sediment discharge mitigation measures in the Marlborough Sounds. Yncyca Bay in the Pelorus Sound, and Onepua and Opua Bay in Tory Channel both meet a series of requirements for suitable monitoring locations. The identification of suitable monitoring sites should be accompanied by undertaking a hillslope erosion analysis by using publically available datasets that characterise the key variables that drive hillslope erosion. Utilisation of this data will enable different bands of risk to be identified for future implementation of mitigation measures, as well as assist in the identification of suitable monitoring sites. Monitoring the efficacy of the proposed

mitigation measures, including distance of setbacks, and their relative use to hillslope will require expansion of current environmental monitoring in the Sounds. Implementation of this monitoring will require resourcing, either by outsourcing the project to attract external expertise and technical instrumentation, or expansion of current environmental monitoring. It is recommended that all future work assessing the flux of suspended sediment into the Marlborough Sounds should include hillslope erosion severity modelling, to establishing the links between slope and sediment generation due to erosion.

List of Figures

List of Tables

Table of Contents

1 Introduction

The Marlborough District Council (MDC) produced a report in 2015 that investigated the vulnerability of hillslopes dominated by plantation forests in the Marlborough Sounds to produce excess sediment that discharges into the coastal environment. The potential environmental harm related to sediment discharge compelled the MDC to evaluate the causes of erosion and coastal sedimentation caused by plantation forest activities, and identified potential mitigation options. The regulatory mechanisms were chosen based on their ability to reduce the amount of sediment discharged into coastal waters, and forms part of the review process in the ongoing development of the Marlborough Resource Management Planning Framework. This report follows the original report produced by the MDC, and describes a potential sampling strategy that could be used as a guide to establishing a research project or monitoring systems that will evaluate the effectiveness of the proposed sediment mitigation options.

1.1 Summary of MDC Technical Report

The review document produced by the MDC identified the causes and consequences (both ecological and physical) of plantation forestry in the Marlborough Sounds (Urlich 2015). Case studies of events where extensive sedimentation occurred in the Marlborough Sounds were used to discuss the ecological effects of seabed smothering by fine sediment, and discolouration of the water column, particularly in areas of low flow. These issues were first identified in the late 1970s and are now recognised that the Marlborough Sounds is predisposed to a greater risk of erosion and discharge of fine sediment to coastal waters. Greater risk is primarily a consequence of heavy rainfall events occurring on a weathered lithology, with steep topography, that is disturbed regularly by plantation forestry activities. The report evaluated what regulatory mechanisms could be used to reduce the region's susceptibility, and a series of mitigation options have been produced (Table 1).

Table 1: Possible management options identified by the Marlborough District Council for mitigating the discharge of fine sediment from plantation forests to the coastal area of the Marlborough Sounds. Summarised from Marlborough District Council Technical Report No: 15-009 November 2015.

Mitigation Option	Details/Reasoning
Replanting setbacks from the shoreline: 30 metre	The proposed NES requires a 30 metre setback, although this is seen an inadequate given tree length often matches this length, and fallen trees would damage any mitigation on slopes during the window of vulnerability.
100 metre	Existing 100 m setbacks exist in the sounds, and have a positive response from the public for aesthetic appearance.
200 metre	The most highly weathered, clay-rich erodible soils in the Marlborough Sounds are located between the shoreline and 200 m elevation. A 200 m setback would keep this erosion zone under continuous undisturbed vegetation cover.
Replanting setback from permanently flow streams coupled to the sea	Proposed NES for forestry identifies a setback of 5 metres from perennial streams with a width less than 3 metres, and 10 metres for streams with a width exceeding 3 metres. Riparian buffers mitigate inputs of organic debris, reduce nutrient loading, and protect bank stability.
Replanting controls on steep slopes	Limit replanting of exotic plantation forest on slopes over 30 or 35 degrees. Replanting on steep slopes could become a discretionary activity requiring consent from council, in which a case by case approach could be applied.
Post harvest replanting requirements	Reducing the window of vulnerability by i) replanting areas harvested within 12 months of harvest; ii) replanting in excess of 1000 stems per hectare.
Harvest controls	Required removal of woody material greater than 100 mm in diameter and 3 metres in length from gullies over 5000 m^2, no later than 1 month after harvest.
Earthworks requirements	Standard of road and track construction is variable across the Marlborough Sounds. Preventing erosion from poor standards improved by i) road design and construction certified by a CPENZ; and ii) loose fill (must have a grass cover established.

1.2 Scope of Report

The objective of this report is to outline a research and sampling strategy to assess the proposed sediment erosion mitigation measures described in Table 1. Section 2 provides relevant theoretical background on riverine suspended material and its analytical methods is provided in Section 2, identifying the different components of suspended material and describing the relationships between these parameters with discharge and turbidity. Section 3 introduces the proposed sampling strategy and includes descriptions of potential field sites with the equipment required. In addition, Section 3 describes a process to evaluate the affect of slope on sediment generation by assessing hillslope erosion severity. Two options are suggested for implementing a sampling strategy with descriptions of field equipment and methods, including laboratory analysis, options for additional water quality analysis and future research is also described. Section 4 provides a conclusion and final recommendation on implementing a sampling system that will test the effectiveness of the proposed sediment mitigation options.

2 Riverine Suspended Material

2.1 Theoretical Background

Mature plantation forestry is an effective management tool on steep land for limiting erosion in New Zealand (e.g. Ekanayake *et al.,* 1997; Watson *et al.,* 1999; Marden, 2016) and internationally (e.g. Stokes *et al.,* 2004; Sidle *et al.,* 2006; Kateb *et al.,* 2013). Plantation forest tree roots reduce erosion on hillslopes by increasing soil strength and slope stability. Experiments comparing soils with and without established root systems have shown that soils with established root systems can withstand greater shear stress than soils without root systems (Ekanayake *et al.,* 1997). However, during clear-felling of plantation forests, root systems are damaged and soil is significantly disturbed. Land vulnerability and how significant the loss of soil is due to erosion depends on local environmental conditions (Marden & Rowan, 2015). The conditions that predispose an environment to erosion include mechanical facets, including soil type, surface land cover, and slope, and those that are hydrological including water balance and soil permeable, and climate (Amishev *et al.,* 2014). In the Marlborough Sounds, sediment generation is enhanced by forestry activities occurring on a weathered lithology, with steep topography, in an area exposed to high intensity rainfall (Laffran *et al.,* 1985). Therefore landslips, and sheet and rill erosion are common sediment mobilising mechanisms resulting in increased sediment delivery to coastal waters (Phillips *et al.,* 1996; Urlich, 2015). Past episodes of mass movements from high intensity rainfall events have shown coastal sedimentation is significant from recently harvested land between the coast and 200 m elevation, with slopes over 30 degrees (e.g. Phillips *et al.,* 1996). It is therefore necessarily that the MDC assess how to best manage potential erosion over these conditions, and understand sediment generation and transport on steep slopes.

Sediment generation is the consequence of mass movement and surface erosion, and is mobilised and connected to the fluvial system via hydrological flow paths. Hydrological flow paths direct eroded material to receiving water bodies, where it is either held in temporary storage in the channel, mobilised and transported downstream, or deposited at the river mouth into a receiving body (lakes, estuaries, or the coastal margin). In the Marlborough Sounds, surface erosion is the consequence of overland runoff triggered by rainfall events, that subsequently transports fine material (e.g. silt and clay) originating from forestry tracks, roads and landings to streams that are coupled to the coast (Laffran *et al.,* 1985; Fahey & Coker, 1992; Gray & Spender, 2010). Intense mass movement events in the form of slips and flows are predominantly the result of intense rainfall occurring in mid to upper gully depressions with slopes over 30 degrees, transporting fine sediment, but also slash and log debris (Phillips *et al.,* 1996). The material entrained in stream flow is a mixture of inorganic and organic material comprising rock fragments, soil, and plant matter. Quantifying the amount of material entrained in stream flow is often referred to as determining the total suspended sediment concentration (TSS or SSC), however, this is inaccurate in systems where a significant portion of organic material may also be included in the suspended load of riverine systems (Bright & Mager, 2016). In instances where organic material may contribute a significant portion of the suspended material, it should be referred to as total suspended material (TSM). The following sections describe the inorganic and organic constituents that comprise TSM, stream water turbidity, suspended sediment-turbidity relationships, and the role of stream flow generation and discharge in identifying suspended sediment behaviours. Where appropriate, a description of the methods used to determine each parameter is provided.

2.1.1 Total Suspended Material

Particulate matter within streams is mobilised via bedload or in suspension, depending on the competence of the stream, which is a function of its stream flow velocity. Material that travels in suspension contains both organic and inorganic fractions (Fig. 1), and collectively form the total suspended material (TSM). The inorganic portion is derived from rocks, clay or mineral sources, and is most commonly referred to as the suspended sediment concentration (SSC). The organic portion is derived from organic matter, either as fine particulates or larger particles of plant debris, woody material, soil organic matter, algae and all other organic materials, and is collectively referred to as the particulate organic matter (POM). Particulate organic matter is often an overlooked component of suspended material, and is analytically determined in soils using a loss on ignition (LOI) method. POM includes portions of organic phosphorus, carbon and nitrogen (POP, POC, and PON respectively), with approximately half of the mass being comprised of organic carbon (Pribyl, 2010). Bright and Mager (2016) provides a detailed explanation of these two particulates that compose TSM, and the importance of measuring both variables in environments where receiving waters can have a potentially high organic matter content, such as plantation forests. The effect that POM and inorganic suspended sediment (SS) have on stream water turbidity is different, as variations in particle shape and material density between organic and inorganic particles result in alteration of the optical properties of water and the subsequent attenuation of light. A comparison study of the portion of suspended material between organic and inorganic portions was undertaken by Bright and Mager (2016) in a paired catchment study in Otago and identified that POM contributed 45% of POM in a tussock catchment and 60% in a forested catchment currently undergoing clearance. It was concluded that the presence of POM, and dissolved organic carbon (DOC) interfered with turbidity measurement, and contributed to uncertainty in deriving suspended sediment-turbidity relationships. Consequently, there was a poor predictive relationship between turbidity and the suspended sediment concentrations, which bears more broadly on the reliance of turbidity and suspended sediment relationships, which are important in sediment monitoring programmes as turbidity is often used to predict the SSC.

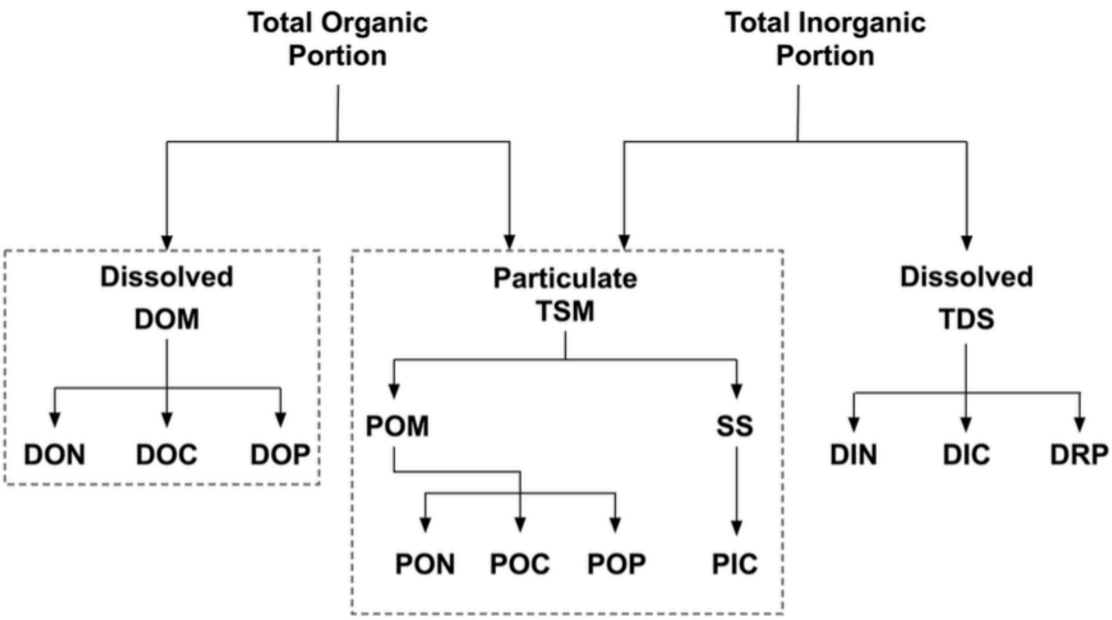

Figure 1: Total suspended material and nutrient components. Dashed boxes indicate components that also contribute to turbidity. Abbreviations: TSM = Total suspended material. D = dissolved and P = particulate when at the beginning of an acronym. O = Organic and I = inorganic, and N = nitrogen, C = carbon, P = phosphorus when at the end of an acronym. TDS = Total dissolved solids (e.g. ions), DOM = dissolved organic matter, and DRP = dissolved reactive phosphorus, which is equivalent to DIP. Source: Bright & Mager (2016).

2.1.2 Turbidity

Turbidity is a measure of the opaqueness or cloudiness of water, and increases due to the presence of suspended particles; thus turbidity is widely used as a proxy indicator for suspended sediment. The response of turbidity to the inorganic and organic components of TSM can be different, complicating the use of turbidity for determining SSC (see: Bright and Mager, 2016). Therefore, a method that allows for the determination of both organic and inorganic portions of suspended material is important to understanding the flux of material through catchments. Suspended material may be comprised of significant portions of organic matter; the effect of which may be to increase turbidity when using a tungsten-lamp type turbidity sensor (Bright and Mager, 2016), confounding the application of turbidity suspended sediment relationships, particularly if delivery of organic material is temporally variable. Turbidity is a recommended variable to monitor for the effects of land disturbance as it is proportional to water clarity, a variable identified by the National Objectives Framework as mandating observation for its effect on habitat, and cultural suitability. However, the uncertainty associated to using turbidity as a proxy for determining SSC and turbidity instrument response to the presence of organic carbon (dissolved and particulate) should not be ignored and careful choice of methods is required.

2.1.3 Suspended Sediment and Turbidity Relationships

In New Zealand turbidity is widely used in environmental monitoring, due to its relative ease of measurement, both in situ, in field or laboratory analysis. Due to the convenience of collecting turbidity data, and relatively simple laboratory methods available for determining turbidity, it is commonly used in suspended sediment monitoring by the application of relatively simple regression-based rating curves. By contrast the collection of suspended sediment concentration data is time and laboratory intensive work. For instance, samples need to be collected semi-regularly, either through manual collection or the use of a water sampler. Samples are then weighed and filtered using standard protocols which requires repeated weighing over three days. Water samples for suspended sediment concentration may also require pre-treatment to impede any nuisance growth between collection and analysis, using preservatives like mercuric chloride. Mercuric chloride is highly toxic to aquatic ecosystems and may not be suitable for use in locations where it may inadvertently make its way into the hydrosphere.

Due to the intensive processing of water samples for suspended sediment measurement, standard practice is to infer suspended sediment measurements from turbidity readings. Establishing a significant relationship between turbidity and SSC requires a range of conditions to be observed. SSC and turbidity relationships are difficult to produce from data collected only during low flow as there is insufficient range in data to produce a strong regression equation. The most common method is to collect samples during event flow when there is increased mobilisation of material and establish a SSC and turbidity regression over a range of flow conditions. It should be noted, however, that these regression relationships are bespoke to the observed catchment, and should not be used to extrapolate sediment concentrations from other catchments. Once an established relationship is produced, for any value of turbidity, the SSC can be determined for that catchment, although it should be noted that in some catchments there may be seasonally variable relationships that occur between suspended sediment and turbidity depending on sediment source, availability and the influence of organic matter on the total load of material transported. Thus, it is recommended that multiple event flows be observed at different times of year to determine the range of potential suspended sediment to turbidity relationships.

2.1.4 Suspended Material and Discharge

The amount of material suspended during event flow is contingent on two factors: the competence of the water, and the supply of material deliverable to the riverine network. Under base flow conditions the amount of suspended material is a function of competence, that is the amount of material entrained and sustained in motion depends on there being sufficient energy to initiate mobilisation of material, and the sustained energy proportional to continued momentum; mostly commonly characterised by determination of the volumetric stream flow, or discharge (typically expressed in units of $l\ s^{-1}$ or $m^3\ s^{-1}$). Under base flow conditions the system is transport-limited; however, under event-flows, the increase in stream flow concomitant with an increase in active channel, is supply-limited.

Material within the channel is mobilised proportional to increases in stream energy, however, a plot of stream discharge relative to suspended material concentration is rarely a straight line (Fig. 2). Rather, there is often a delay between peak discharge and peak sediment suspended sediment movement; as there is a delay in the delivery of allochthonous material to the riverine network (Klein, 1984). Under these conditions, a plot of stream flow relative to suspended sediment concentration may exhibit a hysteretic pattern, that is a different slope is observed between the rising and descending limbs of the hydrograph (e.g. Houser *et al*., 2006). These relationships often reveal hysteresis loops that are used to explain the mobilisation, transport, and exhaustion of sediment during flow events (e.g. Klein, 1984), and may be important when considering hillslope erosion mechanisms in the Marlborough Sounds. Virtual sediment exhaustion can occur, for instance, when two significant sized discharge events occur in quick succession to each other. During the first storm the near-field material is easily accessible and mobilised during high-flow, however, as the storm proceeds, there is a temporary reduction in available material for mobilisation, so that there may be a decline in sediment load. Any subsequent event may not sustain the same amount of sediment transport, as the near-field supply is temporarily limited. The counter may also be true, if there is a long period with low flow, the first significant event flow is likely to mobilise more suspended material. Thus, understanding the potential sources of sediment, their proximity to the stream network, as well as the role of antecedent conditions can all impart a strong influence on the flux of material through catchment systems.

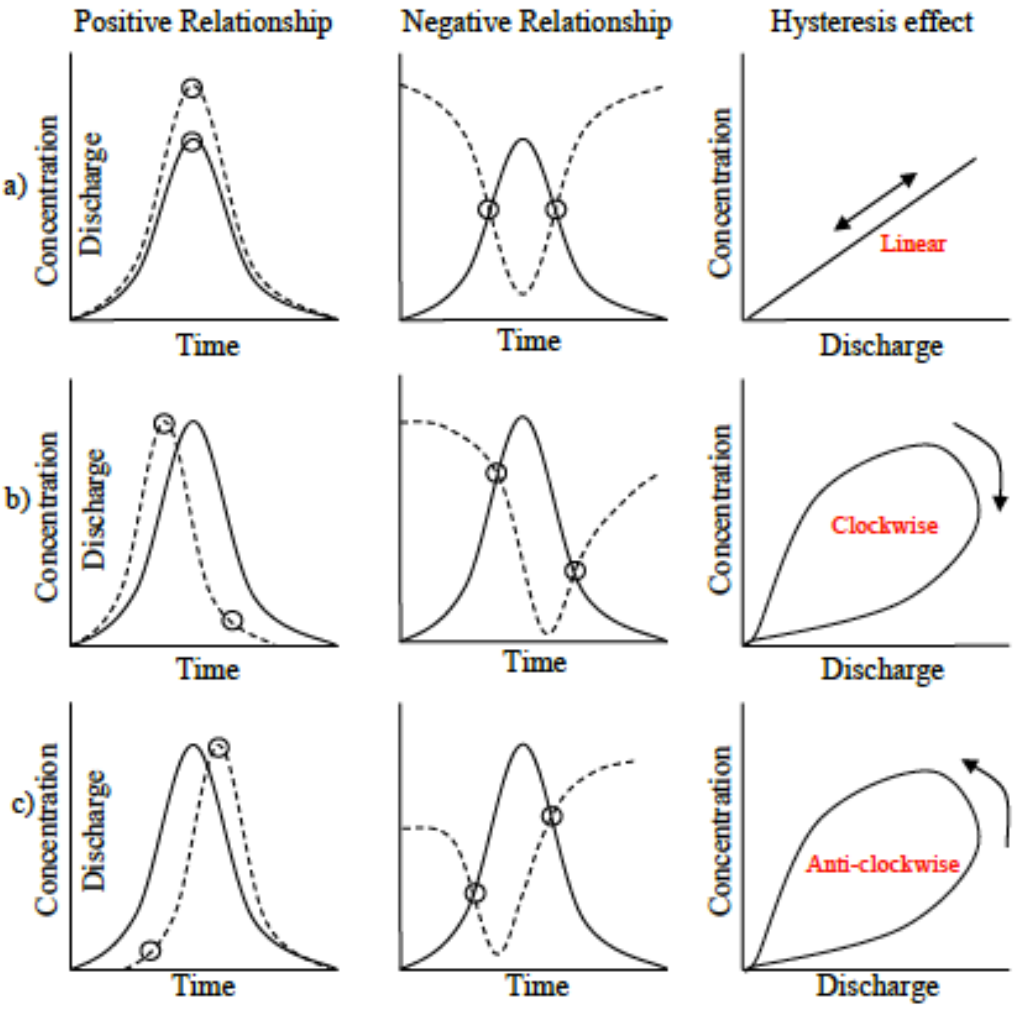

Figure 2: Theoretical hysteresis effects when plotting discharge (Q) and suspended sediment concentration (c) with positive (P) and negative (N) relationship with discharge. Possible hysteresis patterns include linear, clockwise and anticlockwise directions. a) linear relationship with discharge; b) clockwise hysteresis where concentration is higher on the rising limb; and c) anticlockwise hysteresis where concentration is lower on the rising limb.

One of the analytical approaches to understanding the source of sediment during event flows is to use sediment tracers that mark different sediment sources in heterogeneous catchments and this type of sediment source fingerprinting analysis is occurring in the Pelorus Sound to examine benthic change and determine the causes of sediment build up (Urlich, pers. comm. 2017). However, statistical techniques, like hysteresis analysis, can also be useful for determining sediment or transport limited systems. If such statistical approaches are to be employed, then it is essential that discharge and turbidity be measured concomitantly. Measuring discharge is also important for determining the flux and yield of material being eroded from hillslopes, rather than simply a concentration. For example, the total suspended material (TSM) is measured as a concentration in units of mg L^{-1}, however, if discharge is known, it can be converted to a flux in units of kg a^{-1}, or as a specific yield in units kg a^{-1} ha^{-1}. Units of yield and flux are particularly useful for comparing different catchments and assessing the effects of different management strategies and mitigation measures in place, as it normalises the sediment data relative to runoff and/or catchment area.

2.1.5 Determining Suspended Sediment Concentration, POM, and Turbidity

To determine suspended material concentrations and fluxes, a laboratory filtration method is used (see: Gray *et al.* 2000). Discrete samples typically at least 1 L are required; although smaller volumes can be used if sufficient suspended material is present, like for instance, high suspended material during storm events. From the discrete water sample, a portion of the sample can be extracted for turbidity measurement and the remaining sample used to determine sediment concentration. The filtering process requires knowing the sample water volume that is then filtered through pre-washed and dried 0.7 µm glass fibre filters (GFF). Filters are oven dried at 105°C for 24 hours to determine total suspended material (TSM) in mg L^{-1} (Gray *et al.* 2000). Filters should be weighed on at least a 4 decimal point balance, and re-dried three times reporting the dry weight each time until 3 consecutive weights are recorded. To determine the organic portion of the sample, the glass fibre filters are then dried at 500°C for 30 minutes to determine the loss on ignition of the organic portion (POM) of the TSM (see: Heiri, 2001). Between temperatures of 500–550^{o}C organic matter is oxidized to CO_2 and ash, so that the loss of mass is proportional to the loss of organic matter. If sample weight is small, a lower temperature will avoid singeing minerals, but larger samples may require longer burn times (see: Heiri *et al.*, 2001). The filters are reweighed to determine the amount of mass loss, which is equivalent to the organic portion. The difference in mass is recorded as particulate organic matter (POM) in mg L^{-1} The employment of this method, beyond the standard suspended sediment concentration method allows for the determination of the significance, or otherwise, of the organic portion of suspended material; the latter of which can be an important component of the overall mass of material being transported in river with a dominant plantation forest land cover (Bright and Mager, 2016).

Turbidity is measured with an optical sensor, as turbidity is a measurement of the scattering of light caused by suspended particles. Optical sensors differ, but most often turbidity is measured photometrically and expressed in units of NTU (nephelometric turbidity units), or spectrophotometrically and expressed in units of FTU (formazin turbidity units). Because of the differences in turbidity measurements, careful attention is required when comparing turbidity values, however, the unit of NTU is most commonly reported. Unlike suspended sediment concentration, turbidity is relatively easy to measure and can be determined in the laboratory, or in situ with a range of instruments. These include turbidity sensors that can be left in field attached to continuous data loggers, portable probes that can be used in field, or portable turbidimeters that can be used in a laboratory. In the suggested sampling strategy, the use of both in field continuous turbidity monitoring and the use of lab-based methods are suggested. The advantage of continuous field-based turbidity measurements is that it will capture the natural variations in turbidity associated with variable flow conditions, that cannot easily be represented in systematically timed grab sample collection. For in-field conditions infra-red based nephelometers are recommended as these are less affected by the presence of dissolved organic carbon (USGS, 2005). It should also be noted that installation of turbidity meters requires careful consideration of instrument location so that they are not subject to light diffraction from other sources, and so that the equipment being used will return data that is valuable to the research needs (Fig. 3).

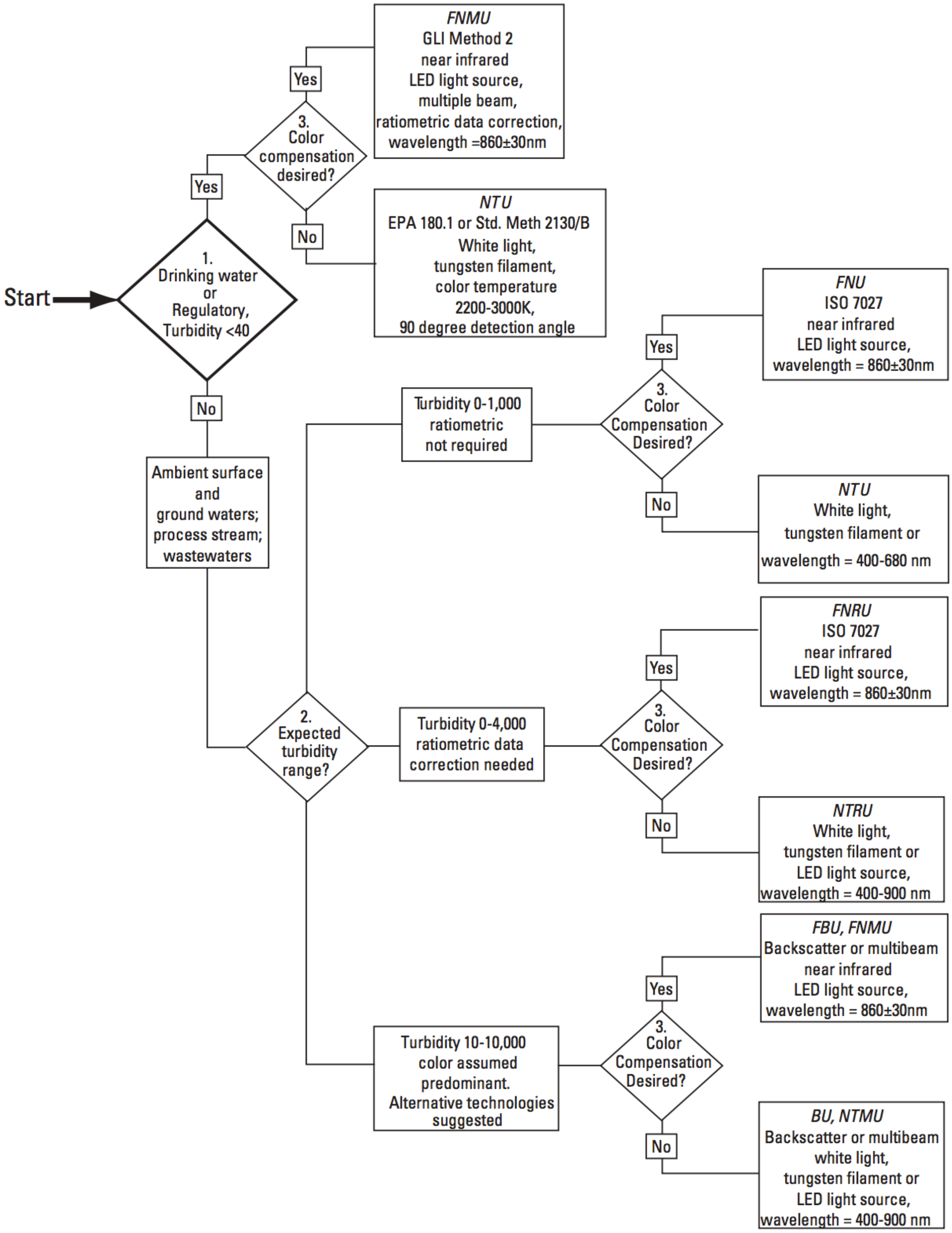

Figure 3: Decision tree to determine appropriate instrument choice for measuring turbidity as defined in the USGS Field Manual for the Collection of Water-Quality Data (USGS, 2005).

3 Research Strategy and Methods

To evaluate the effectiveness of the proposed sediment mitigation options for plantation forestry in the Marlborough Sounds, it is suggested that monitoring should focus on understanding sediment generation processes, and the degree that different mitigation measures attenuate sediment discharged to the coastal environment. Preliminary work by the MDC has suggested set back and slope control mitigation options, which are used as the basis of developing the sampling strategy (Fig. 4) described in this section. First a note about temporal and spatial scales is made followed by the sampling strategy, and a series of criteria are recommended for identifying potential monitoring sites. A description of hillslope erosion analysis is included, and is recommended for use as an analytical tool to assess the effect of slope on erosion in the Marlborough Sounds. Finally, two options for the implementation of a sampling strategy are provided with suggested field equipment and methods, and laboratory and statistical analysis described. Further to this, potential future long term monitoring of suspended sediment from plantation forests is described.

3.1 Sampling Strategy

Early in the establishment of a sampling strategy (e.g. Fig. 4), it is important to identify the temporal and spatial boundaries that define the research domain; including understanding of the processes being studied, and what data is required to observe these processes. Research scope is also restricted by the range of resources available (e.g. time, money, equipment). The MDC should direct resources to the generation and discharge of suspended sediment from hillslopes with a dominant plantation forest land cover into the coastal area of the Marlborough Sounds as a part of their broader environmental management strategies in the region. The hillslope processes vary with time (e.g. event flow versus base flow, and seasonally) and space (e.g. differences in geology, climate, and topography), hence requiring a sampling strategy that considers both dimensions is essential. It is recommended that the MDC either adopt one of two options that are described in the following sections. Both require a similar spatial scale, but differ by the time required to conduct the research, and the investment in equipment and expertise needed. Figure 4 is a generalised sampling strategy that reflects the main objectives and outcomes of both the proposed sampling systems.

What is the effectiveness of different sediment erosion mitigation measures in the Marlborough Sounds at attenuating the generation and discharge of fine sediment from plantation forests?

Mitigation Options

Set Backs from Coast	Set Backs from Streams	Slope Controls
What effect does the establishment of 30, 100 and 200 metre setbacks have on SSC and turbidity?	What effect does the establishment of 5 and 10 metre setbacks have on SSC and turbidity?	What is the risk of hillslope erosion on slopes greater than 30 and 35 degrees?
Data Required		
Continuous Turbidity (measured via infield probe) Daily/Weekly/Monthly Turbidity and TSM (SSC and POC) measured from grab samples in lab. Water Level/Discharge	Continuous Turbidity (measured via infield probe) Daily/Weekly/Monthly Turbidity and TSM (SSC and POC) measured from grab samples in lab.	Water Level/Discharge Rainfall Geology Vegetation Cover Erosion Susceptibility SSC and Turbidity
Analysis		
Statistical differences; Correlation to risk factors; Turbidity vs. Discharge; and Turbidity vs. SSC.	Statistical differences; Correlation to risk factors; Turbidity vs. Discharge; and Turbidity vs. SSC.	Desktop GIS based analysis; and spatial analysis.
Outcome		
Values of SSC and turbidity for the options, with contributing factors to sediment discharge identified.	Values of SSC and turbidity for the options, with contributing factors to sediment discharge identified.	Hillslope erosion analysis at the catchment scale (maps). Focus on that risk on slopes of 30 and 35 degrees. Links to suspended sediment generation.

Figure 4: Strategy to test the effectiveness of potential mitigation measures to reduce the discharge of fine sediment from plantation forestry in the Marlborough Sounds.

3.2 Study Location and Field Sites

Plantation forestry is extensive throughout the Marlborough region, with a significant volume of forest in the Marlborough Sounds. Most production that occurs in the Sounds is in the Port Underwood, Queen Charlotte Sound and Tory Channel, Pelorus Sound, and Croisilles Harbour areas (Fig. 5). Due to limited resources, it is not feasible to establish field monitoring sites in each Sound, rather, systematically selecting locations that represent the variations and effects of different mitigation measures across the Sounds can be implemented. If there are only minor variations in local climatic conditions (e.g. vulnerability to storms) (Fig. 6) and minor variations in regolith across the Marlborough Sounds (Fig. 7), the major controls on slope failure can be considered homogeneous. Thus, a sampling strategy can be defined to consider the efficacy of coastal (30, 100 and 200 metres) and riparian setbacks (5 and 10 metre), in relation to variation in slope and plantation age, structure, and density. The following describes a potential process for choosing representative sampling sites within the Marlborough Sounds, and what specific environmental elements (e.g. vegetation cover, water ways, or geology) related to the proposed mitigation options should be represented. The section concludes with a description of the equipment and fieldwork requirements.

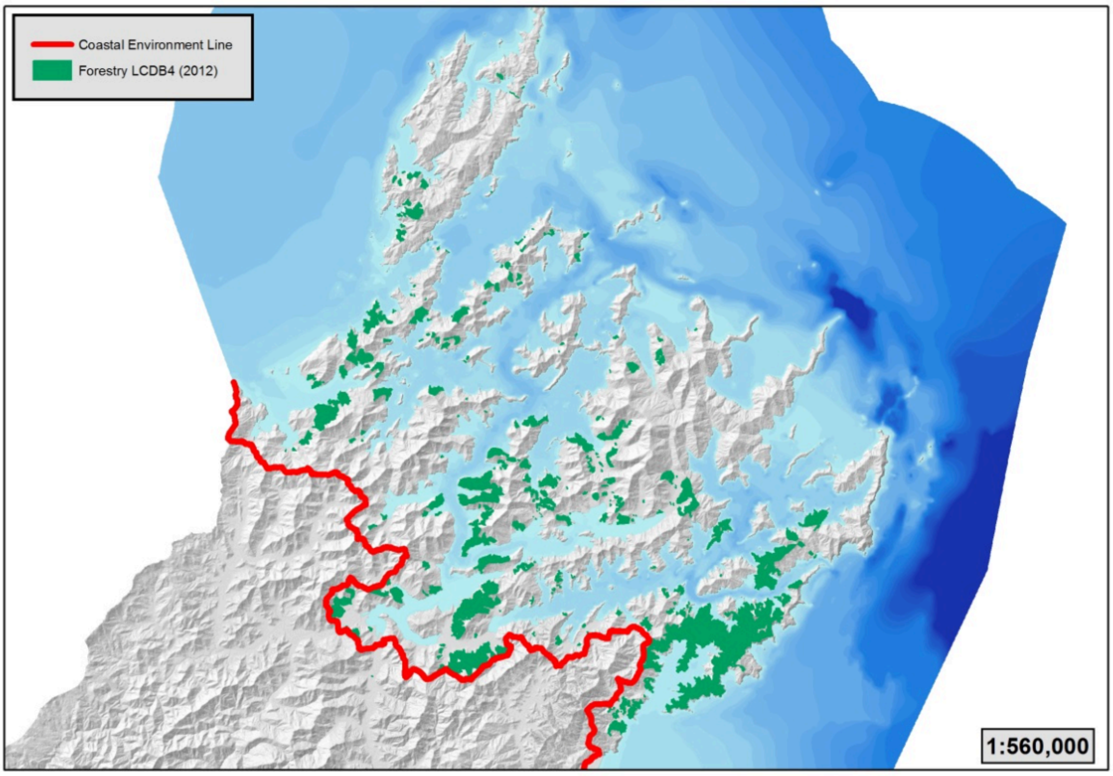

Figure 5: Map showing existing forestry in the Marlborough Sounds. Red line depicts the Coastal Environment Line, as defined in the Marlborough Environment Plan (Source: Urlich, 2015).

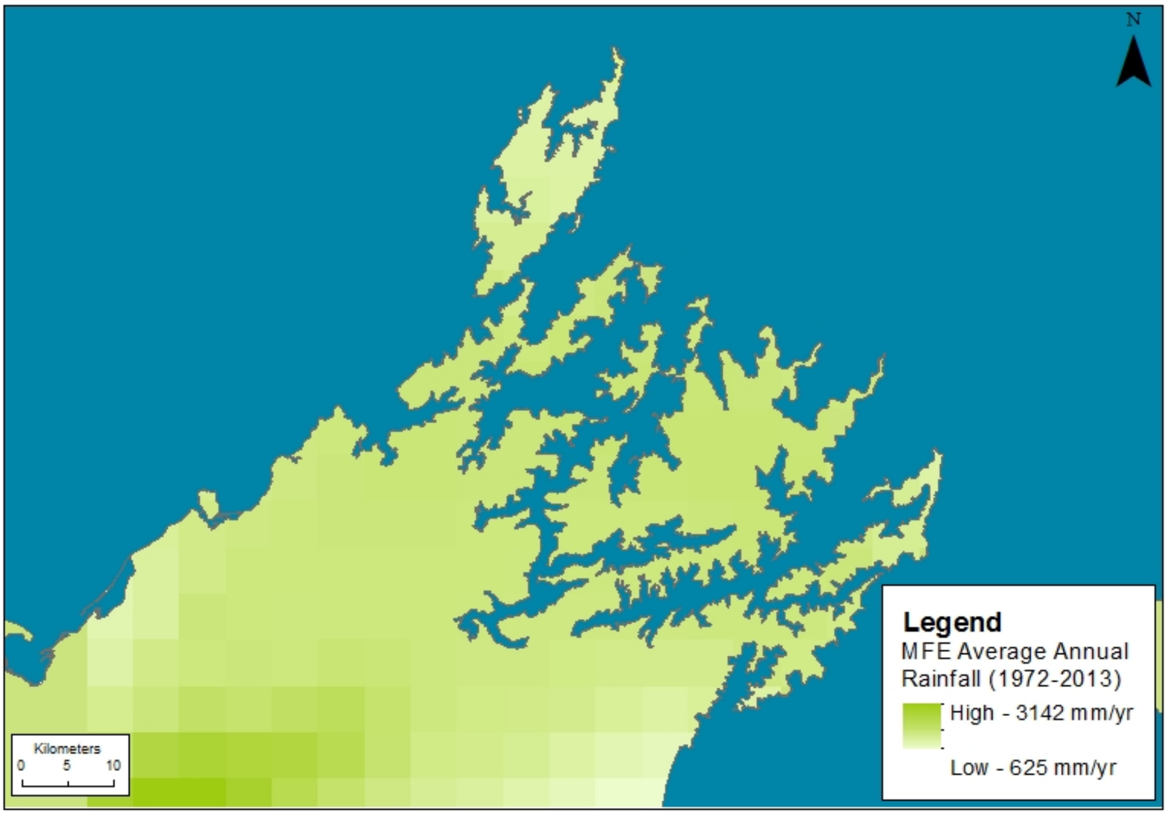

Figure 6: Mean annual rainfall distribution over the Marlborough Sounds for the period 1972 to 2013 (Source: Ministry for the Environment average annual rainfall 1972-2013 (2016)).

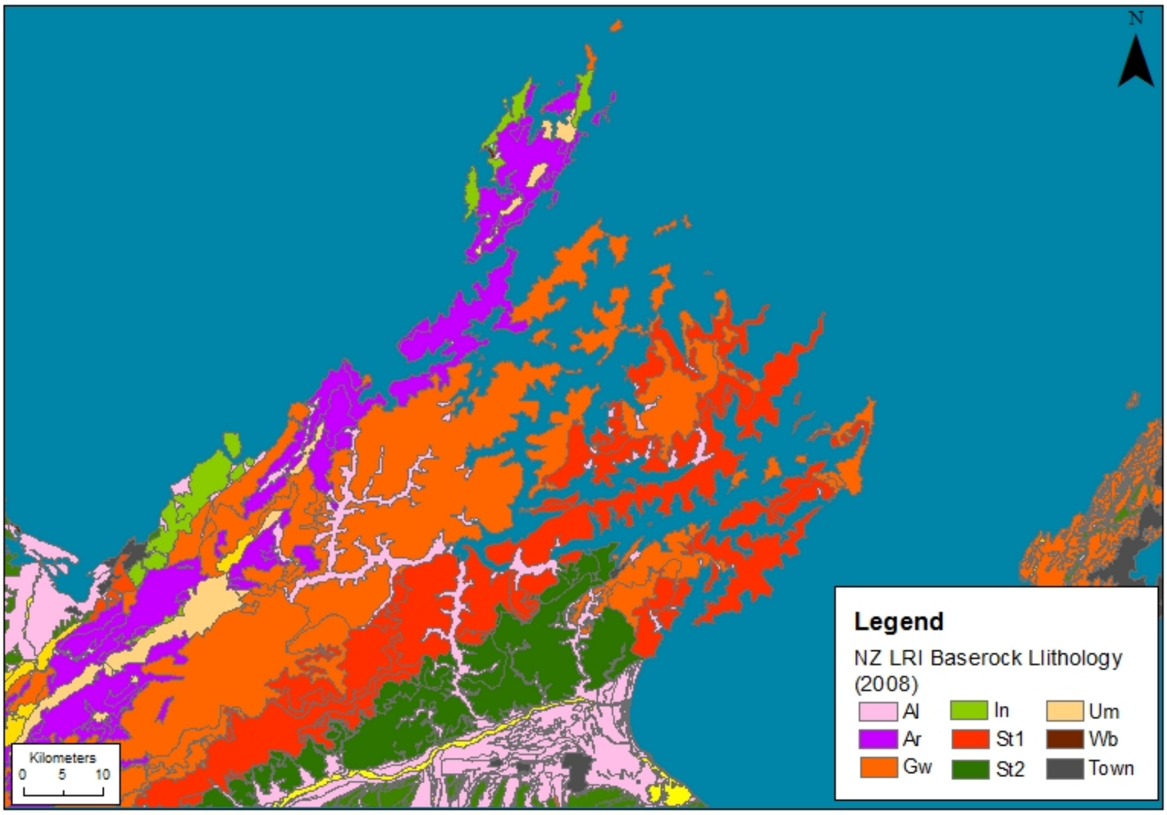

Figure 7: Lithology over the Marlborough Sounds area. Al = alluvium, Ar = argillite, Gw = greywacke, In = ancient volcanoes (dikes and sills), St1 = semi-schist, St2 = schist, Um = ultramafic, Wb = windblown sands (Source: Landcare Research NZLRI Rock (2011)).

3.2.1 Site Selection

On the basis of the Marlborough District Council review (Urlich, 2015) Yncyca Bay, Onepua Bay, and Opua Bay in the Marlborough Sounds were identified as suitable case studies for developing mitigation options. Located in the Pelorus Sound (Fig. 8 Map A), Yncyca Bay is a location where plantation forest is separated from the coastal margin with a 100 m setback, providing a useful area for monitoring the efficacy of 100 m setbacks in attenuating sediment discharge. Onepua and Opua Bays in Tory Channel contain extensive forests that form part of the largest concentration of plantation forest in the Marlborough Sounds (Fig. 8 Map B). Utilising prior knowledge of these areas, and existing literature related to plantation forests in Tory Channel (e.g. Phillips *et al.,* 1996), it is suggested that these areas are suitable for implementing future monitoring.

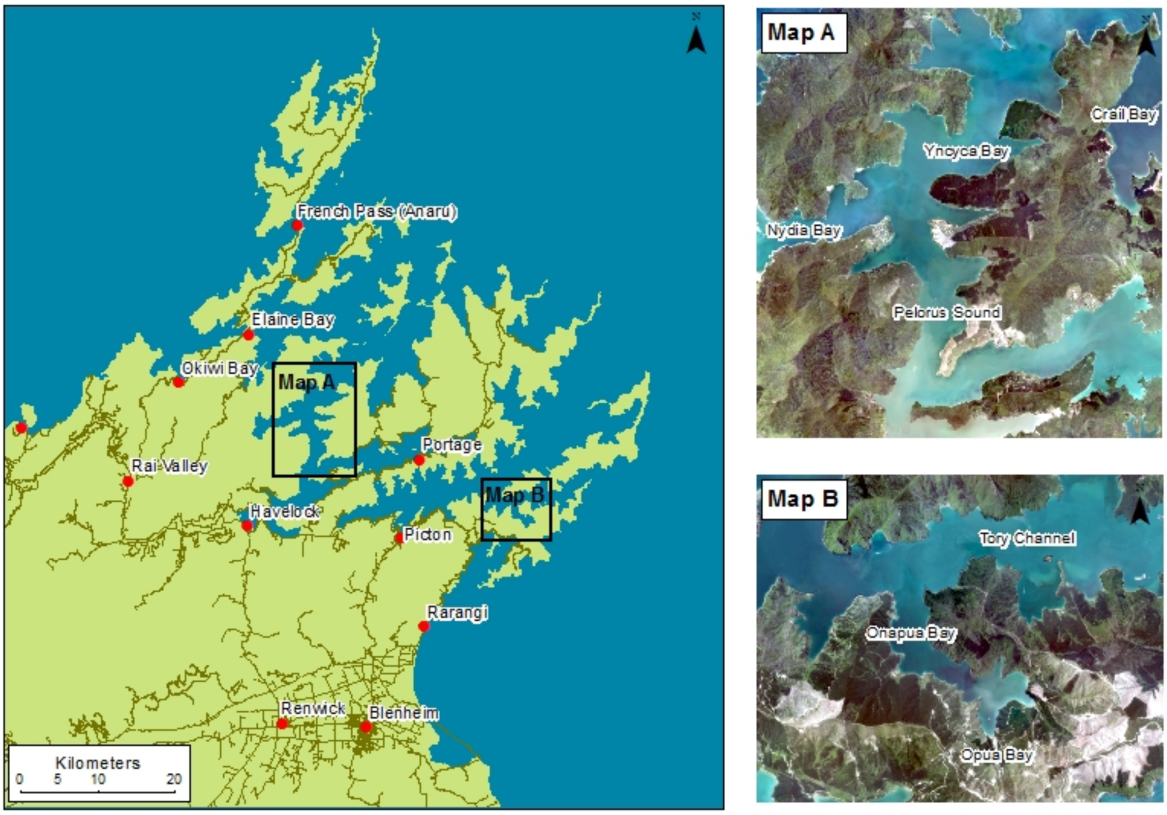

Figure 8: Map of Marlborough Sounds identifying the two areas of interested identified in Urlich (2015) as potential areas to assess mitigation measures. Maps A and B show the areas of Yncyca Bay in the Pelorus Sound, and Onepua and Opua Bays in the Queen Charlotte Sound.

Remote sensing has been carried out to investigate the suitability of Yncyca, Onepua and Opua Bays as monitoring sites. The following resources (Table 2) were used to assess site suitability, and it is recommended that a ground-truthing investigation be undertaken and these criteria re-evaluated during that process, with subsequent approval of the location for use as a monitoring site. The MDCs forestry spatial data identifies that Yncyca Bay is principally *Pinus radiata* with an age ranging from 25 to 30 years. In Onepua and Opua Bay areas, the forest is predominantly *Pinus radiata* with a variety of ages, including older plantings greater than 25 years, and plantings of 10 to 20 years. In both areas the forests present are approaching harvestable age, and an opportunity exists now to monitor sediment discharge prior to harvest (providing baseline data), and during the forest clearance phase.

From the above remote sensing is it suggested that three sites in both areas (Yncyca Bay, Onepua and Opua Bays) be selected for monitoring, one in each location which is continuously monitored for turbidity with *in situ* turbidity sensors, and other locations that are visited regularly for collection of turbidity and suspended sediment concentration samples. The three sites need representative examples where, 30, 100 and 200 metre coastal setbacks are present, riparian setbacks of 5 or 10 metres are present, and slopes between 0 and 30 degrees, 30 to 35 degrees, and slopes greater than 35 degree exist (Table 3). In addition to these monitoring sites, a control site should be established (Table 3). It is important to note that providing for all combinations of these variables would require extensive resources, and rather the suggestion of three sites per location allows representative data to be collected across the possible mitigation options, and will aid decision makers with research supporting the development of mitigation measures in the Marlborough Sounds.

Table 2: Resources used in a remote sensing exercise investigating the suitability of Yncyca Bay and Onepua and Opua Bays for suspended sediment monitoring, for the purposes of evaluating potential mitigation measures.

	Yncyca Bay	**Onepua and Opua Bay**
Aerial Imagery	Plantation forest is the dominant land cover.	Plantation forest is the dominant land cover. Current stands and intense forest clearance has occurred in the past.
Topographic Maps	Using topographic contours, approx. 30, 100 and 200 m setbacks from the coast may exist. Streams/water ways appear to be present in these areas, and are directly coupled to the coast.	Using topographic contours, coastal setbacks that are approx. 200 m may exist, also 30 to 100 m. Streams/water ways appear to be present in these areas, and are directly coupled to the coast. NB: These streams are not necessary dominated by only one land use.
MDC maps and preliminary site analysis	Analysis by MDC shows that: • Existing 100 m setbacks in places. • Slopes over 30 degrees, and over 35 degrees exist. • Forestry is *Pinus radiata* with an age class of 25 to 30 years.	Analysis by MDC shows that: • Slopes over 30 degrees, and over 35 degrees exist. • Forestry is *Pinus radiata* with a variety of age classes, 10 to >25 years.
Spatial Data • MfE Data Service • LRIS Data Portal • MDC	River flow suggests that streams may have flows acceptable for sampling. e.g. annual flows[1] of 9 to 103 L s^{-1} (mean annual low flows[2] range 1 to 20 L s^{-1}). Catchment size – order 1 approx. 0.4 km^2 or 40 ha Geology – Greywacke	River flow suggests that streams have flows acceptable for sampling. e.g. annual flows[1] of 15 to 72 L s^{-1} (mean annual low flows[2] range 2 to 20 L s^{-1}). Catchment size – order 1 approx. 0.3-0.6 km^2 or 30-60 ha; order 2 approx. 1.6 km^2 or 160 ha. Geology – Semi-schist
Accessibility	Boat access would be most effective.	Boat access would be most effective. Access by forestry tracks from main Port Underwood Road would be possible.

[1],[2] Minimum mean annual streamflow and low streamflow as modelled may be highly variable on an annual scale. Suitable sites should have a mean annual flow of, or greater than, 0.050 m^3 s^{-1} (50 L s^{-1}), as flows lower than this may not have sufficient depth suitable for year-round monitoring of turbidity, collection of water samples, or sufficient depth to quantify discharge.

Table 3: Site requirements that are needed to collect data evaluating the effectiveness of sediment discharge mitigation measures.

Sites	Requirements
Site 1: a) Yncyca b) Onepua and Opua Bay	30 metre coastal setback Riparian setback (5 or 10 metres) Slopes: <30 degrees; 30–35 degrees; >35 degrees Mean annual stream flow greater than 50 L s^{-1}.
Site 2: a) Yncyca b) Onepua and Opua Bay	100 metre coastal setback Riparian setback (5 or 10 metres) Slopes: <30 degrees; 30–35 degrees; >35 degrees Mean annual stream flow greater than 50 L s^{-1}.
Site 3: a) Yncyca b) Onepua and Opua Bay	200 metre coastal setback Riparian setback (5 or 10 metres) Slopes: <30 degrees; 30-35 degrees; >35 degrees Mean annual stream flow greater than 50 L s^{-1}.
Control Site (options)	Either: • Native land cover with stream coupled directly to the coastal area, with slope considered; • Established plantation forestry with no setbacks (coastal or riparian) and stream coupled directly to coastal area, with slope considered; or • Established plantation forestry with no setbacks. (coastal or riparian) that is undergoing forest clearance, and with stream directly coupled to the coastal area, with slope considered. • Mean annual stream flow greater than 50 L s^{-1}.

3.2.2 Control Sites

Control sites are essential in experimental studies, and are particularly useful in research that consider catchments as environmental units, as well as useful tools for statistically determining the differences between a treatment catchment and a control (e.g. land use, land cover, slope, geology). Potential control sites were identified from the remote sensing exercise, subject to ground truthing to assess viability. Careful selection of the control site characteristics is required to ensure representativeness of the control catchment environmental unit, relative to plantation forestry (Table 3). Remote sensing has identified the areas around Te Weka Bay and Tawa Bay in the Onepua and Opua Bay area as potential control sites, and in the head of Yncyca Bay; on the south side of the bay there is an area without plantation forestry, and a stream coupled to the coast. These potential control sites are described below, two sites in the Onepua and Opua Bay areas (note three catchments identified in (Fig. 9), and one site in Yncyca Bay (Fig. 10)).

3.2.2.1 Te Weka Bay

Te Weka Bay is located near Onepua and Opua Bays and analysis of satellite imagery of the area suggests that Te Weka is mostly indigenous forest, and largely absent of dense plantation forestry. The New Zealand Land Cover Database version 4.1 (LCDB v4.1, 2015) classes the vegetation in this areas as being predominantly gorse and broom in the upper catchment, with indigenous forest lower in the catchment (Fig. 9). The stream located in Te Weka Bay drains a first order catchment (0.37 km^2 or 37 ha) that could be used for monitoring as a control site. The stream has a mean annual flow of 10 $l\ s^{-1}$ and a mean annual low flow (MALF) of 11 $l\ s^{-1}$ (Ministry for the Environment River Flows data layer, 2016). Based on these modelled flow values, discharge from this stream is well below the recommended 50 $L\ s^{-1}$; suggesting that the runoff in this area may not be sufficient for long-term monitoring of discharge, although the stream may be suitable for manual water sample collection. The hillslopes of the area surrounding Te Weka Bay are steep with slope angles ranging 26 to 35 degrees and underlain with semi-schist geology, as classified by the NZ LRI (Fig. 9).

3.2.2.2 Tawa Bay.

Tawa Bay is location within Onepua Bay and near Opua Bay. The vegetation cover determined from aerial imagery appears to be indigenous scrub and or forest, and largely absent of dense plantation forestry. The vegetation in this area contains portions of broadleaf indigenous hardwood forest, maturing exotic forest and harvested forest, with gorse and broom (Fig. 9) (LCDB v4.1, 2015). The stream located in Tawa Bay drains a first order catchment (0.58 km^2 or 58 ha) that could be used for monitoring as a control site. The stream has a mean annual flow of 15 L s^{-1}, and a mean annual low flow of 2 L s^{-1} (Ministry for the Environment River Flows data layer, 2016). Based on these modelled flow values, the 50 L s^{-1} that is suggested for monitoring purposes is not satisfied, and at low flows there is likely insufficient water to adequately collect manual samples for suspended sediment analysis without risk of disturbing the bed or stream banks and contaminating the sample. The hillslopes of the area surrounding Tawa Bay are steep with slope angles ranging 26 to 35 degrees and underlain with semi-schist geology, as classified by the NZ LRI (Fig. 9).

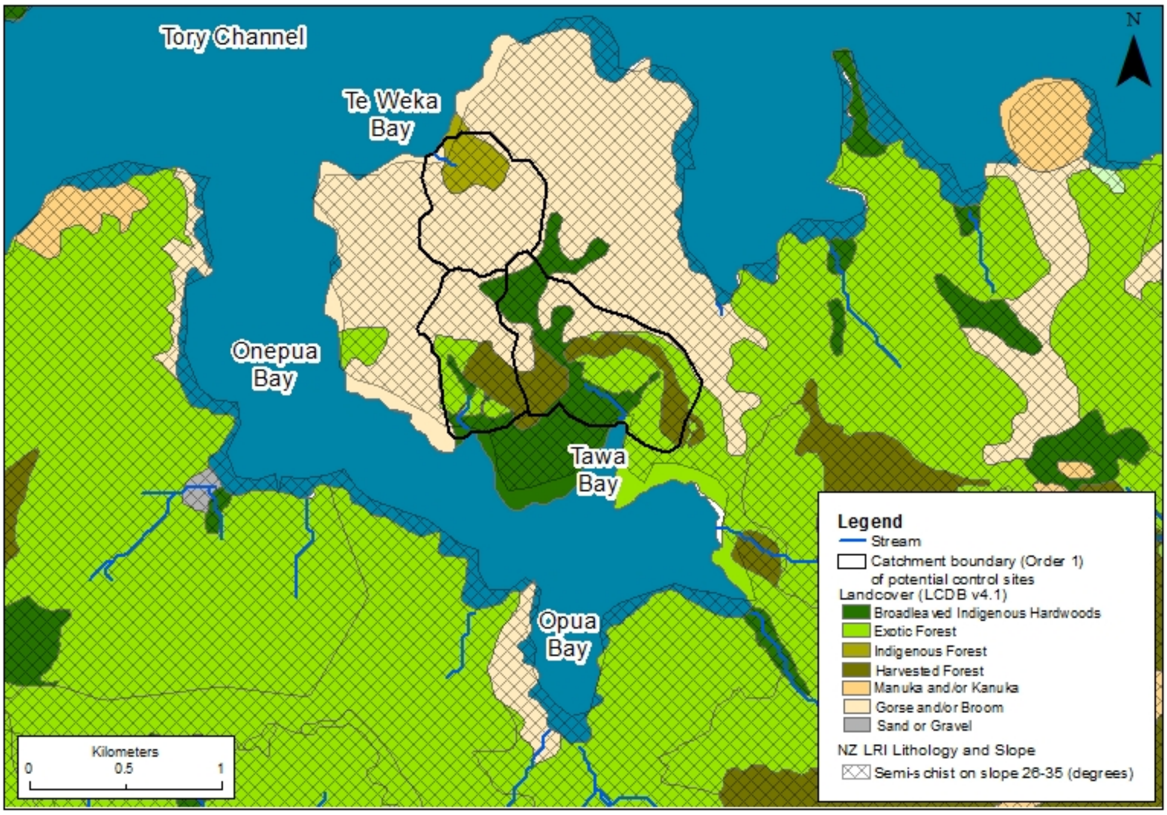

Figure 9: Environmental characteristics of potential monitoring control sites in the Onepua and Opua bay areas (Sources: Ministry for the Environment; River Flows, and River Environment Classification Catchment Order 1 (2010). Landcare Research; Land Cover Database version 4.1, NZ LRI Rock, NZLRI Slope).

3.2.2.3 Yncyca Bay

A portion of the southern side of Yncyca Bay appears to have native vegetation cover and is free of dense planation forestry. The vegetation in this area as being predominantly exotic forest with small portions of broadleaf indigenous hardwood forest and high producing exotic grassland (Fig. 10) (LCDB v4.1, 2015). The stream drains a first order catchment (0.43 km^2 or 43 ha) and could be used for monitoring as a control site (Fig. 10). The hillslopes of this part of Yncyca Bay are steep with slope angles 26 to 35 degrees and underlain with greywacke geology, as classified by the NZ LRI (Fig. 10). The stream has a mean annual flow of 45 L s^{-1} and mean annual low flow of 9 L s^{-1} (Ministry for the Environment River Flows data layer, 2016). Based on these modelled flow values, a mean annual flow of 45 L s^{-1} is close to the recommended 50 L s^{-1}, and warrants investigation as a potential control site from a field visit as modelled flow values can have an uncertainty of ±25% in ungauged catchments (Booker and Woods 2014).

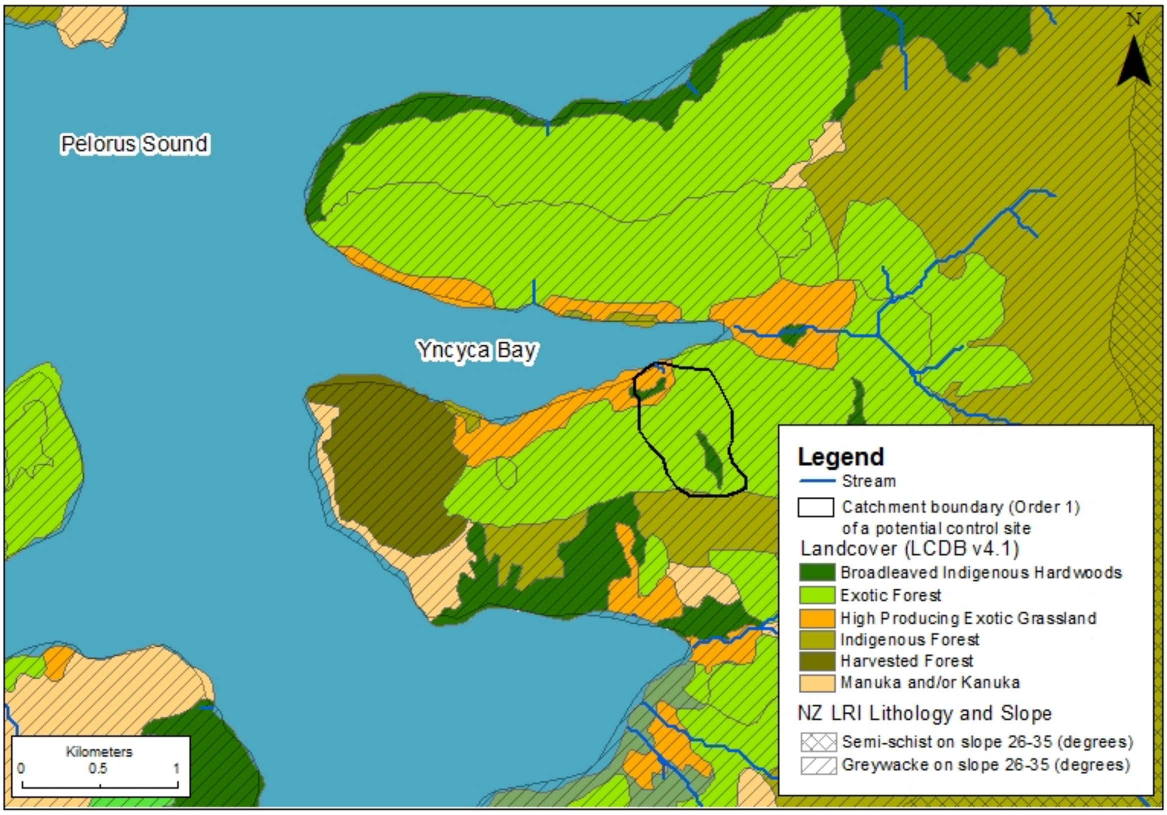

Figure 10: Environmental characteristics of a potential monitoring control site in Yncyca Bay (Sources: Ministry for the Environment; River Flows, and River Environment Classification Catchment Order 1 (2010). Landcare Research; Land Cover Database version 4.1, NZLRI Rock, NZLRI Slope).

3.3 Hillslope Erosion Severity

Hillslopes play an important role in the delivery of material to rivers, lakes, and the coast. How susceptible hillslopes are to erosion is controlled many variables, including, but not limited to; soil type, lithology, land cover, and topography including slope, aspect, drainage pattern, and landform type (Bloomberg *et al.,* 2011). The Marlborough District Council have identified slope as a key variable that should be considered when evaluating mitigation options for sediment discharge to the coastal area. In addition, a technical paper produced for the Ministry for Primary Industries by Amishev *et al.* (2014) assessed the options for terrain stability and landscape hazard mapping at the operational scale, and the role of these analyses in minimising post-harvest erosion impacts. It is, therefore, necessary that the MDC determine how they will conduct their own assessments of erosion severity on steep slopes in the Marlborough Sounds. It is recommended that the MDC utilise existing data services from the Ministry for the Environment and Landcare Research to assess erosion susceptibility and severity on hillslopes in the Marlborough Sounds.

Landcare Research provides scientific data through the Land Resource Information Systems Portal (LRIS) that allows access to environmental data in Geographic Information System (GIS) applications. Within the LRIS, a Land Use Capability (LUC) system exists, that was designed to promote sustainable land development and management. A component of the LUC system includes the New Zealand Land Resource Inventory (LRI). The LRI is a spatial database containing map units as polygons with information on each relating to five main land type attributes; rock type, soil, slope angle, erosion type and severity, and vegetation cover (see: Lynn *et al.,* 2009). In addition, the Ministry for the Environment provide an erosion susceptibility classification database that supported the development of the National Environmental Standard for Plantation Forestry. The objective of developing forestry specific classification system was to enable analysis of the erosion risk, sedimentation and environmental harm associated with plantation forests (Bloomberg *et al.,* 2011). Erosion susceptibility is defined by the predisposition of a land unit to erode (determined by soil, lithology and topographic characteristics), preparatory factors (e.g. forest clearance), and the likely severity of an erosion event and any consequences (see: Ministry for the Environment 2012 Erosion Susceptibility 4 Classes 2012 metadata). The data package incorporates erosion severity data from the LRI and LUC to produce an erosion susceptibility class (ESC), with four categories of susceptibility; low, moderate, high, and very high. The categories are based on the LRI erosion classification system, however, Bloomberg *et al.* (2011) reclassified the LRI classes to make these specific to plantation forestry, and this has been used to define the level of control for different plantation forest activities (Basher *et al.,* 2016).

Further to this, following public submission on the proposed National Environmental Standard for Plantation Forestry, concerns were raised about the suitability of the ESC and whether the level of control on land in the high and very high categories was adequate. The Ministry for Primary Industries (MPI) has since provided a more comprehensive description of the dominant erosion processes, rock type, and topography in the high and very high ESC categories, and further refined the categories of ESC (Basher *et al.,* 2016). A terrain classification was developed, consisting of 21 classes, and provides structure distinguishing the terrain types (dominant erosion, rock type, and topography) in the high and very high ESCs. The MDC should consider how these erosion classification categories could be used in the assessment of erosion and subsequent sediment discharge in the Marlborough sounds.

In addition to using the spatial data from Landcare Research's New Zealand LRIS Portal and the Ministry for the Environment's Data Service, data related to tree root strength, stocking rates, and other hillslope stabilising parameters of plantation forests should be used at the catchment scale to assess the methods required to mitigate potential erosion from steep hills slopes, and the subsequent discharge of suspended material to waterways and the cost. Forests provide a range of erosion mitigation benefits, for example, canopy interception of rainfall, maintenance of soil moisture by evapotranspiration, and root tensile strength (Watson *et al.,* 1999; Stokes *et al.,* 2004; Bloomberg *et al.,* 2011). Tree roots offer effective hillslope stability, although this also depends on the magnitude of the soil-root strength, modification of the soil water regime, and the time to reach maximum root occupancy. The temporal nature of root stability over plantation forestry cycles affect hillslope stability, forest clearance dramatically reduces the erosion mitigation benefits of vegetation, and soil-root reinforcement relationships can take up to six years after replanting to establish and depend on the planting density of trees (Watson *et al.,* 1999). Planting density for *Pinus radiata*, New Zealand's most popular exotic plantation species, is typically 1250 stems ha^{-1}, at lower densities trees provide less stability over a longer period (Watson *et al.,* 1999).

Spatial data from Landcare Research and the Ministry for the Environment can be used to assess how planting of forestry on hillslopes in the Marlborough Sounds should be managed to reduce the risk of erosion. Maps can be produced at the catchment scale, displaying information about erosion severity (e.g. Fig. 11 and 12). It is recommended that the MDC develop of series of categories that represent stocking rate, potential root strength of the planted species, and any other relevant variables, that in conjunction with an assessment of erosion susceptibility can be used during the consenting process for forest development or harvest to assess what type of planting and re-planting is permitted on hillslopes. This would require information from forests managers about forest stands, to gather information on stocking density, and a theoretical understanding of root strength by species could be applied (see: Stokes *et al.,* 2004).

As an example, erosion susceptibility and erosion type for an area in the Port Underwood of the Marlborough Sounds is described. Figures 11 and 12 show erosion type and severity data for the Robertson Point area, in the Port Underwood, Marlborough Sounds. Erosion is different on either side of the east west divide (Port Underwood versus Cook Strait) of the ridgeline in the centre of the maps. Closer inspection of the data, and using Tables 4 and 5, spatial data reveals that the western side has a very high susceptibility to erosion as per the MfE ESC, and severe sheet erosion (3Sh), with portions of moderate sheet erosion (2Sh) as the dominant erosion types of erosion and severity as classified in the NZ LRI database. However, the eastern side has portions that are classed as very high erosion susceptibility, dominated predominantly by moderate sheet erosion and soil slips (2Sh Ss), but also severe sheet erosion with soil slips (3Sh Ss). The differences in erosion type and severity may require different regulatory management considerations during consenting processes. Importantly, the slope of this area is variable (Fig. 13), and relevant to the resulting erosion classifications. Table 6 describes the slopes associated to the NZ LRI code symbols used in Figure 13. The area has slopes greater than 30 degrees, of which the MDC has highlighted as being of primary concern during harvest operations (Urlich, 2015).

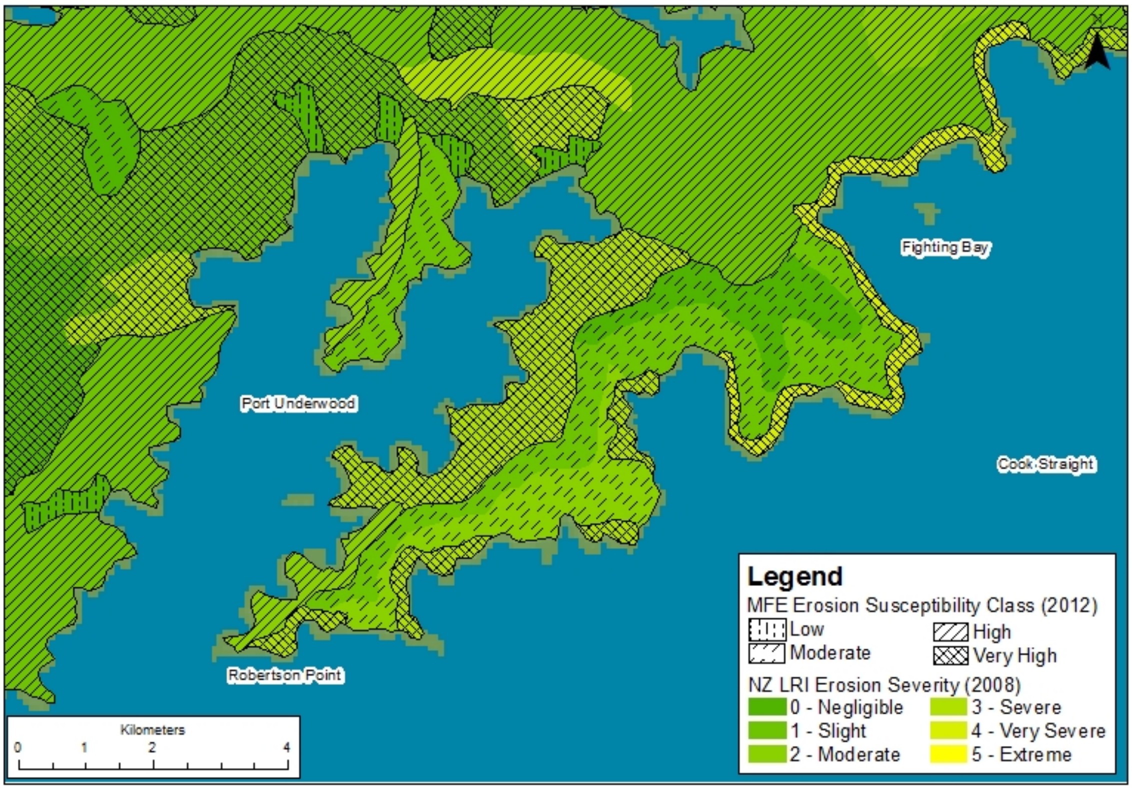

Figure 11: Erosion severity categories from the NZLRI Erosion Severity data layer, and the Ministry for the Environment Erosion Susceptibility 4 Classes data layer for the port underwood, Marlborough Sounds (Sources: Landcare Research NZLRI Erosion Severity and Type, and Ministry for the Environment Erosion Susceptibility 4 Classes).

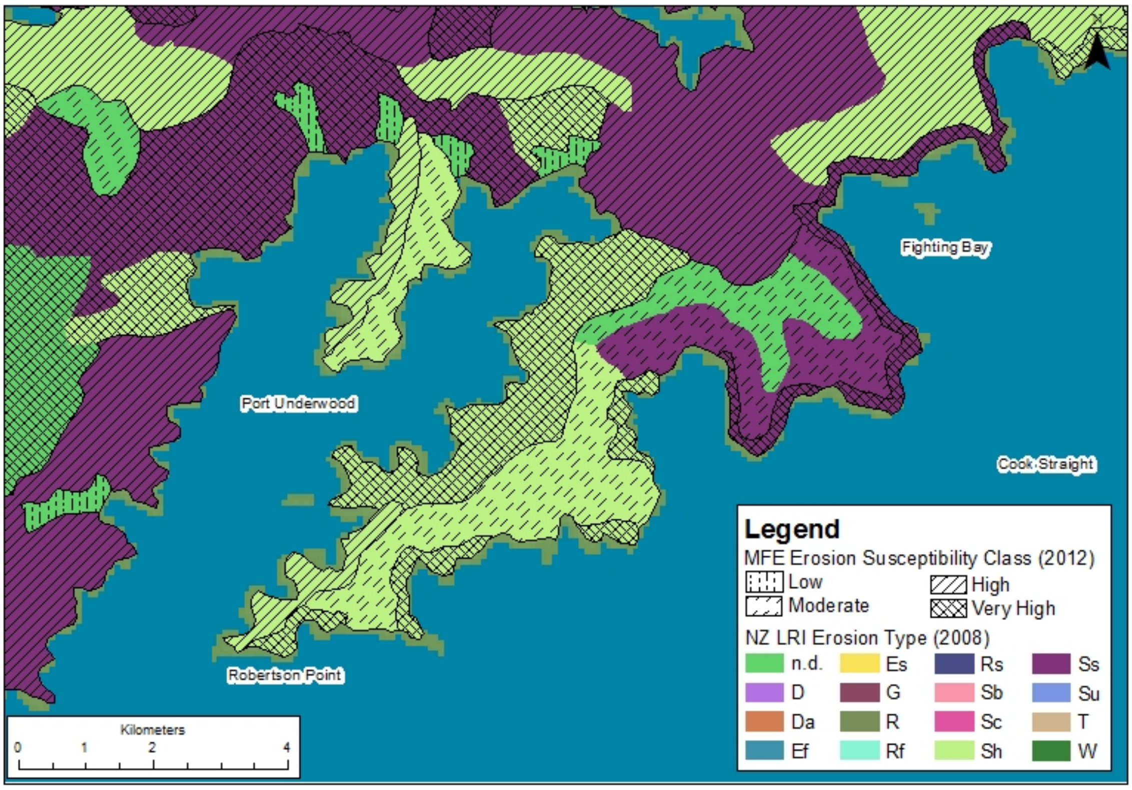

Figure 22: Erosion type categories from the NZLRI Erosion Severity data layer, and the Ministry for the Environment Erosion Susceptibility 4 Classes data layer for the Port Underwood, Marlborough Sounds. Legend defined in Table 4 (below). (Sources: Landcare Research NZLRI Erosion Severity and Type, and Ministry for the Environment Erosion Susceptibility 4 Classes).

Table 4: Descriptions for the types of erosion defined in the New Zealand LRI (Source: Newsome et al., 2008).

Erosion Code	Erosion Form Name	Erosion Code	Erosion Form Name
Da	Debris avalanche	Rf	Rockfall
Ef	Earthflow	Rs	Riparian slip
Es	Earth slip	Sb	Streambank
Mf	Mudflow	Su	Slump
Ss	Soil slip	T	Tunnel gully
D	Deposition	Sc	Scree
G	Gully	Sh	Sheet
R	Rill	W	Wind
estu	estuary	ice	icefield
lake	lake	rive	river
quar	quarry, mine, earthworks	town	urban area

Table 5: Descriptions for the erosion severity of hillslopes defined in the New Zealand LRI (Source: Newsome et al., 2008).

Erosion Severity Code	Erosion Severity Description
0	negligible
1	slight
2	moderate
3	severe
4	very severe
5	extreme

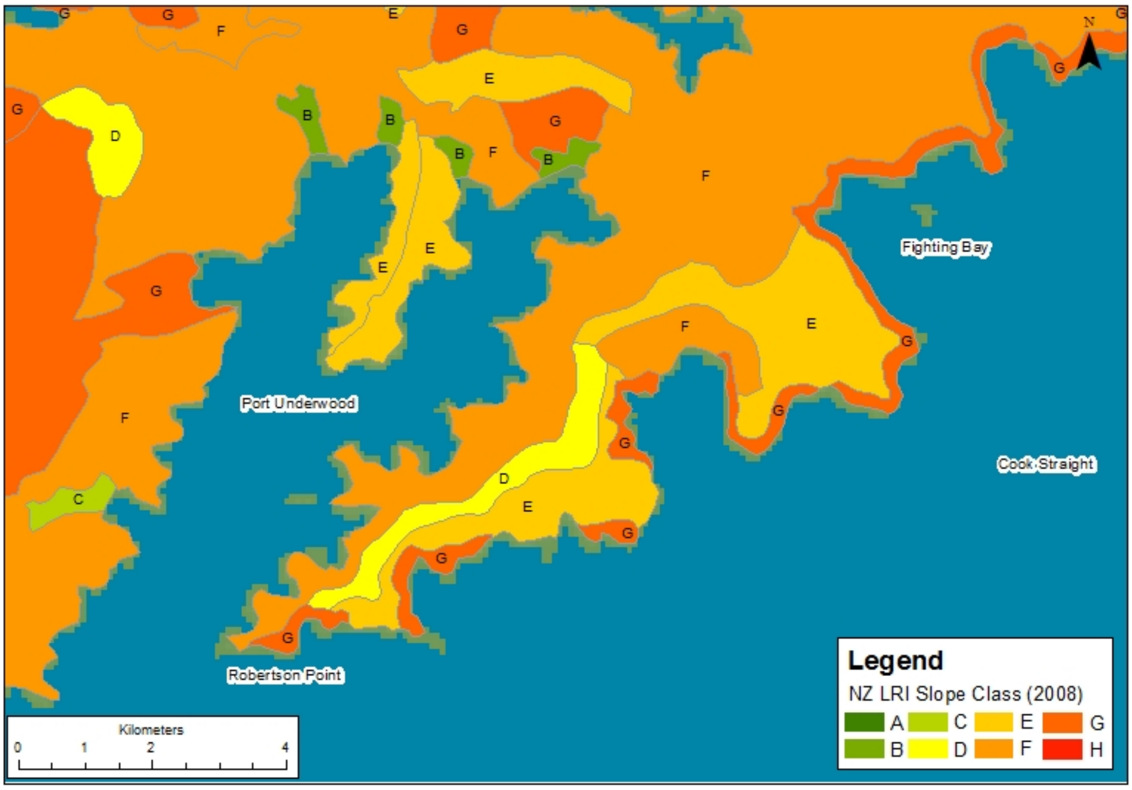

Figure 13: Slope categories from the NZLRI slope data layer for the Port Underwood, Marlborough Sounds. Legend classes defined in Table 6 (below). (Sources: Landcare Research NZLRI Slope).

Table 6: Descriptions of slope defined in the New Zealand LRI (Source: Newsome et al., 2008).

Slope Code	Slope Description	Slope value range
A	Flat to gently undulating	0–3°
B	Undulating	4–7°
C	Rolling	8–15°
D	Strongly rolling	16–20°
E	Moderately steep	21–25°
F	Steep	26–35°
G	Very steep	>35° (36–42°)
H	Precipitous	(>42°)

3.4 Field Work Requirements, Equipment and Analysis

It is recommended that the Marlborough District Council review the following two sampling options, and based on the site location analysis (Table 2) and requirements for site suitability (Table 3) adopt one option. It is suggested that with both of the sampling options that the details of tables 2 and 3 be considered. The two options are different in terms of the time and equipment required, and the level of technical expertise needed.

3.4.1 Option 1: Outsourcing equipment and technical expertise

It is suggested that the MDC outsource a research project that considers the recommendations of this report. Outsourcing will provide access to the equipment and technical expertise required to effectively assess the behaviour of sediment discharge from hillslopes dominated by forests in the Marlborough Sounds. A series of requirements for the project to be carried out should be defined to specify the equipment choices and sampling frequency. The following should be considered when requesting a project be carried out by an independent agency, and the outcome should be a report prepared for the MDC that describes the assessment of the sediment discharged from the different mitigation options. The use of this equipment to continuously collect data should reduce the effort required from human resources, and allow the project to be conducted faster.

- Installing two sondes with infra-red nephelometer turbidity sensors (refer Figure 3) for continuous monitoring of turbidity at two locations, that meet the study requirements set by MDC based on the assessments of site suitability in Tables 2 and 3;

- Installing automatic water samplers in the same location as the sondes to collect regular (recommended weekly) water samples for analysis of TSM and turbidity using USGS field methods. In addition, the following may be useful; National Environmental Monitoring Standards for Turbidity Recording (currently under review), and Suspended Sediment (currently under development);
- Episodic sampling of events either by grab samples using standardised field methods, or by programming automatic water samplers to be triggered by flow;
- Water samples to be sampled for; suspended sediment, particulate organic mater, and turbidity;
- Install water level loggers at the sites where sondes are installed. Water logger depth should be converted to discharge using a rating curve equation by either installing v-notch weirs on the stream, or to manually create a rating curve by repeated in situ discharge measurements; and
- Seek other data (e.g. climatic) from national databases.

The use of this equipment should allow data to be collected over both event and base flow, and be defined in any outsourced research project. Data over both event and base flow is important as discharge of sediment over base flow is small in comparison to the concentration of sediment discharged over event flow; however, both are equally important to understanding annual sediment behaviour.

3.4.2 Option 2: Investment from the Marlborough District Council

If outsourcing is not a valid option for the MDC, it is then suggested that monitoring for suspended sediment be incorporated into existing monitoring programmes. This will likely require exploration of what sites exist in current monitoring programmes that possibly meet some of the requirements set out in Table 3. This report can serve as a guide to determine what should be considered when looking at existing monitoring sites. As a minimum the following should be considered.

- Installing infra-red nephelometer turbidity sensors (refer Figure 3) for continuous monitoring of turbidity at two locations, that meet the study requirements set my MDC based on the assessments of site suitability in Tables 2 and 3;
- Periodic monthly grab sampling;
- Episodic sampling of events;
- Water samples to be sampled for; suspended sediment, particulate organic matter, and turbidity;
- Either utilising national databases for modelled discharge on ungauged rivers and validate modelled flow estimations with periodic river gaugings to estimate annual flow; or install vented water level loggers and convert to discharge measurements by either installing a small v-notch weir, or undertaking a manual rating curve by using repeated measurements of discharge under a range of stage conditions; and
- Seek other data (e.g. climatic) from national databases.

Incorporating this monitoring of total suspended material and turbidity into existing monitoring systems will likely require a longer sampling period than option one, as a monthly sampling system is unlikely to capture the same level of detail than the suggested sampling system with option 1.

3.4.3 Additional Water Quality Analysis

In addition to determining the concentration of riverine suspended material (SS, POM, turbidity), other water quality variables may be of use to the MDC. It should be considered whether the analysis of additional water quality parameters would help understand the potential sediment mitigation from hillslopes in the Marlborough Sounds. For example, dissolved organic carbon (DOC) may prove useful in the assessments of organic contributions from forests to the coastal area, as DOC and POC (described in Section 2.1.1) are both important water quality variables for ecosystem health, and understanding carbon flux. If implementing a new monitoring site for the suspended sediment flux, then it may also be valuable to include a number of key water quality parameters that are measured at other locations (e.g. nutrients, pH, salinity and phytoplankton) (Tiernan, 2012). The addition of these variables to the site will also indicate non-sediment related changes in water quality that occur concomitant with vegetation change, forest clearance and landscape disturbance. For example, during forest clearance biogeochemical changes in nutrient cycling occur as less nutrients are uptaken by plant cover, and as a result there can be increases in the amount of nutrients discharged to the coastal margin, which can augment existing stressors in the marine environment. An excess of nutrients, especially nitrogen and phosphorus can lead to nuisance plant growth, promote algal growth and displace endemic diatom populations in the coastal margin (Chang *et al.,* 2008; Abell *et al.,* 2010). Monitoring of changes in chlorophyll may also be valuable for indicating alteration of the aquatic chemistry, particularly in the coastal water of the Marlborough Sounds subject to intense land use change by forest clearance (Broekhuizen, 2013). It is recommended that given these monitoring systems exist in other parts of the region, and the existence of historical data for comparison, that the MDC should consider additional monitoring of certain water quality variables that are indicative of land disturbance in both coastal and fresh waters, in conjunction with suspended inorganic material and turbidity of coastal waters, and freshwater assessments of SS, POM, DOC, and turbidity from streams directly coupled to coastal areas, and draining forested hillslopes.

3.4.4 Recommended Laboratory Methods and Data Analysis

It is important that the MDC review the various options for laboratory work, and decide on a method that accurately assesses the sediment mitigation potential. Water samples either need to be analysed for suspended sediment concentration (SSC) only using the filtration method described by Gray (2000), or a modified approach that measures both SSC and particulate organic matter (POM) by adding an additional loss on ignition step (see: Heiri, 2001). Choosing between the two methods depends on the suspended material composition of stream flow, and a preliminary assessment of both stream flow particulates would distinguish whether organic material is significant enough to justify use of a loss on ignition method to account for POM. In addition, POM is likely to have an impact on coastal environments, and these impacts are largely unknown in Marlborough. It should also be considered how turbidity is measured, and it is recommended the MDC utilise the USGS decision tree (Fig. 3) for identifying appropriate in field turbidity sensors, and choice of laboratory method for deriving turbidity from grab samples. If choosing to add in addition water quality assessments, the MDC should use existing methods to ensure comparability of results between current research and historical data sets.

As a minimum data analysis should consider the differences between each variable measured and the different sediment mitigation options, and include statistical analysis of:

- SSC-turbidity relationships to establish whether turbidity can be used as a predictive tool to determine SSC. Analysis should also consider POM-turbidity relationships if POM comprises a significant portion of total suspended load;
- SSC-discharge relationships over multiple events to establish if hysteresis patterns reveal sediment generation and transport behaviour valuable to assessments of the sediment mitigation options; and
- If measured, identifying the significance or otherwise of other water quality variables that indicate land disturbance.

3.4.5 Ongoing and Future Research

In addition to collecting data to make an assessment of the effectiveness of different sediment mitigation measures, the MDC should consider establishing a long term monitoring site to continuously monitor sediment discharge from forestry in the Marlborough Sounds. Identifying two catchments, one dominated by an exotic plantation forest that has reached maturation and is to be harvested, and another catchment that can act as a control (characteristics of the control catchment will be defined by study requirements for baseline data). These catchments should reflect some of the sediment mitigation options described in Table 1. It is important to capture baseline data of SSC, POM, and turbidity data before harvest operations have started, and then collect data at a regular frequency for an extended period time, along with any other water quality variables considered important. This provides the opportunity to understand sediment generation in a catchment dominated by exotic forest, and a catchment undergoing clearance, but also provides an opportunity to study other processes related to land use change in the Marlborough Sounds, with the potential to add studies focused on the effects of roads, earthworks, and other forestry activities. The MDC should look at existing paired catchment studies in New Zealand for guidance on establishing something similar in the Marlborough Sounds (e.g. the Glendhu Experimental Catchments, see Fahey & Payne, 2015; the Maimai Catchments, see Rowe & Pearce, 1994; and the Donald Creek experimental catchments, see Pearce *et al.,* 1982).

4 Conclusion

It is recommended that a hillslope modelling exercise be undertaken in the Marlborough Sounds to identifying how slope and erosion susceptibility controls the generation of sediment in catchments with exotic forest land cover disturbed by forestry activities. A preliminary assessment of potential monitoring sites, as well as areas vulnerable to potential hill slope failure should be identified initially using a desktop-study using existing databases that are publically available from the Ministry for the Environment and Landcare Research. Combining this theoretical understanding with knowledge about catchments the preliminary analysis undertaken in this report has identified potential monitoring sites in Yncyca, Onepua, and Opua bays. These potential sites should be investigated further to assess their suitability with a pilot investigation to assess their suitability for the monitoring programme. Undertaking the monitoring phase of the project will require investment; and two options are suggested: outsourcing the project to buy in technical expertise and equipment; or investment by the MDC into integrating the sampling into exiting environmental monitoring programmes. It is recommended that the MDC invest in outsourcing a research project that will address the sampling suggestions defined in this report, which will enable quicker resolution of the efficacy of the different mitigation measures, so that these mitigation strategies can be implemented in planning documents expeditiously.

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