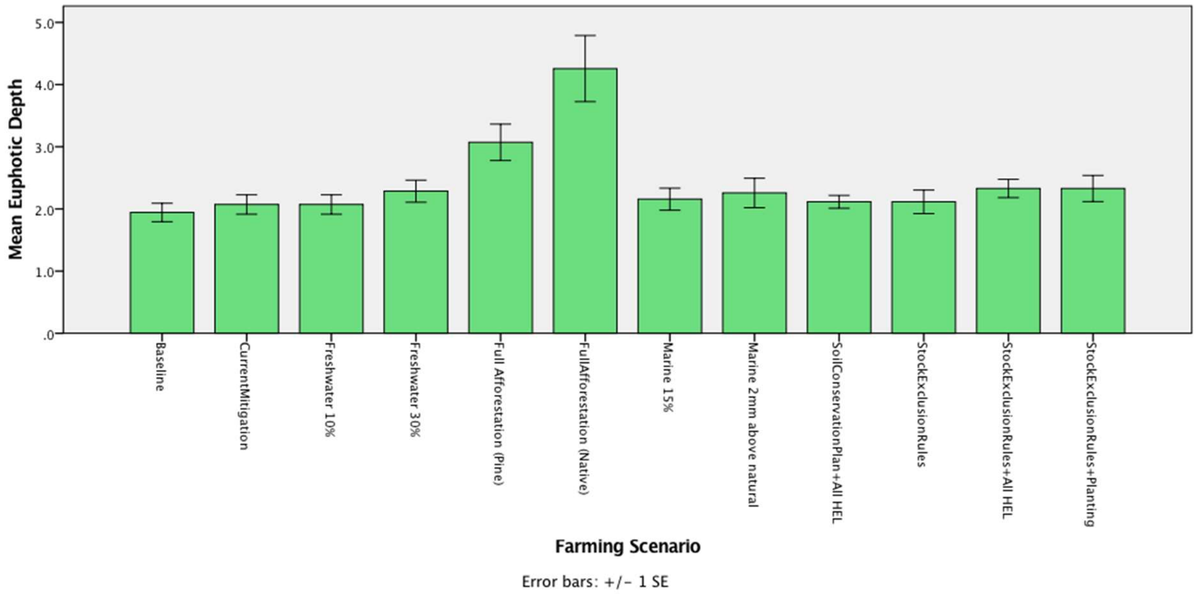
Kaipara Harbour Sediment Mitigation Study:

Narrative Assessment of

Freshwater Sediment Attribute Predictions

5 December 2017



Prepared for Northland Regional Council
&
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by

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Executive Summary

Introduction. Northland Regional Council with support from Auckland Council and Ministry for the Environment have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study (the Study). The first aim of the Study is to develop a catchment economic model for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment. The second aim of the Study is to develop a management tool for use in formulating consistent farm-scale sediment mitigation plans. The tool will be easily usable by land management advisors in the field to identify appropriate actions to mitigate critical source areas of sediment under different land uses at the farm scale.

This report. This report provides a narrative assessment of how changes in sediment attributes in freshwater in response to mitigation applied in the catchment will translate into changes in ecosystem health and functioning and certain values derived by humans from the use of water.

Background. Daigneault et al. (2017) report on the catchment economic modelling done for the Study, which was performed with the spatially explicit economic land use model, New Zealand Forest and Agriculture Regional Model (NZFARM). The model incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads into seven river subcatchments from various land uses have been estimated using the SedNetNZ model (Dymond 2016). A harbour sediment budget that takes as input those sediment loads has been constructed. Land-based mitigation costs and effectiveness in reducing sediment have been obtained from a range of sources.

Twelve mitigation scenarios (summarized in Table ES.1 in Daigneault et al. 2017) were analysed by NZFARM to assess the costs and benefits of a range of management and mitigation approaches to reducing to sediment inputs into seven specific river subcatchments and the harbour. Environmental outcomes were expressed in terms of marine and freshwater "sediment attributes". These included three freshwater sediment attributes (suspended sediment concentration, water clarity, and euphotic depth) and one harbour sediment attribute (the annual average sedimentation rate, AASR). Besides the Baseline scenario (current land use with no mitigation practices, as in the SedNetNZ erosion model), these scenarios comprised five practice-based mitigation scenarios [Current Mitigation (scenario no. 1), Farm Management Plan on all Highly Erodible Pastoral Land (2), Stock Exclusion Rules (3), Stock Exclusion with Riparian Planting (4) and Stock Exclusion + All Highly Erodible Land Plans (5)], four outcome-based scenarios [Freshwater Node 10%, i.e. total annual sediment load in all seven freshwater subcatchments reduced by 10% (6), Freshwater Node 30% (7), Marine Deposition 15% (8), Marine Annual Average Sedimentation rate 2 mm above 'natural' state (9)]. Two large-scale afforestation scenarios (Full Afforestation with Pines (10), Full Afforestation with Native Forest plus Wetland Restoration (11)) were also modelled to establish the minimum feasible loads and best possible environmental outcomes that could be achieved in the entire catchment.

Objectives. This component of the Study focuses on narratively describing and discussing the ecological implications for stream invertebrates and fish of the changes in the three freshwater sediment attributes modelled by Daigneault et al. (2017) in their 12 mitigation scenarios. This

was done following a rigorous quantitative statistical analysis of the data, to determine which scenarios resulted in significant changes in freshwater sediment attributes. There were two specific aims:

1. Determine if the 12 mitigation scenarios affected the three sediment attributes significantly in an analysis that treated the studied seven individual river subcatchments as "replicates" of each scenario. Compared to the Baseline scenario (current land use with no mitigation practices) or the Current Mitigation scenario, several of the other mitigation scenarios should result in significant improvements in the freshwater sediment attributes. This was the main hypothesis tested by the statistical analysis.

2. Determine if overall differences in the three sediment attributes occurred among the river subcatchments (averaged across all scenarios). While such differences are of secondary interest (because they are at least partly due to regional differences including subcatchment geology and topography), the resulting information about "background variation" in the data was expected to explain some of the response patterns found for the different scenarios.

Methods. For each freshwater attribute, a two-way ANOVA without interaction term was performed, with "scenario" and "river subcatchment (sediment node)" as the fixed factors. It was not possible to include an interaction term (scenario × river) in this model because there was only a single replicate of each treatment combination. For all significant overall differences among mitigation scenarios or rivers, pair-wise comparisons using Tukey's HSD post hoc tests determined which specific scenarios or rivers differed significantly from each other.

The ANOVA models for the three freshwater sediment attributes explained 70-90% of the total variation in the data, indicating that these statistical models fitted very well, and both fixed factors, scenario and river subcatchment, had strong effects on all three sediment attributes. Consequently, the post hoc test rankings for the pair-wise comparisons were highly reliable for both factors.

Results. Suspended sediment concentration was significantly lower under Full Afforestation with Native Forest (plus Wetland Restoration) than in all other scenarios except for Full Afforestation with Pine Forest. Sediment concentration under Full Afforestation with Pine Forest was also significantly lower than in most other scenarios, apart from three: Stock Exclusion + All Highly Erodible Land Plans, Stock Exclusion Rules plus Riparian Planting, and Freshwater Node 30%. Notably, none of the 10 scenarios that did not involve full afforestation (including Baseline and Current Mitigation) differed significantly from each other, indicating that mean suspended sediment concentration was similarly high in all of them. Water clarity and euphotic depth both showed essentially the inverse response pattern to suspended sediment. Thus, clarity was significantly higher under Full Afforestation with Native Forest (plus Wetland Restoration) than in all other scenarios. None of the other 11 scenarios (including Baseline and Current Mitigation) differed significantly from each other, indicating that water clarity was similarly low in all of them. Euphotic depth was highest under Full Afforestation with Native Forest (plus Wetland Restoration), intermediate under Full Afforestation with Pine Forest, and lowest in the 10 other scenarios. Once again, none of the 10 scenarios that did not involve full afforestation (including Baseline and Current Mitigation) differed significantly from each other, indicating that euphotic depth was similar in all of them.

Regarding overall differences between river subcatchments (averaged across all scenarios), suspended sediment concentration was highest in the Mangakahia River, second-highest in the Wairua River, third-highest in the Hoteo, Kaihu and Kaukapakapa rivers, and lowest in the Kaipara River. Water clarity and euphotic depth were both higher in the Kaipara River than in all other rivers. Moreover, euphotic depth was intermediate in the Hoteo, Kaihu, Kaukapakapa and Manganui rivers, and lowest in the Wairua and Mangakahia rivers.

Discussion. The first key result is that the main hypothesis, that sediment attributes are significantly improved compared to Baseline or Current Mitigation, was supported only for the two Full Afforestation scenarios. For suspended sediment and euphotic depth, Full Afforestation with Pine Forest essentially performed as well as Full Afforestation with Native Forest (plus Wetland Restoration) in significantly reducing suspended sediment concentration and increasing euphotic depth compared to the Baseline or Current Mitigation scenarios. For water clarity, only Full Afforestation with Native Forest (plus Wetland Restoration) resulted in a significant increase of clarity compared to Baseline or Current Mitigation. Thus, Full Afforestation with Pine Forest would probably be effective in improving at least two of the three freshwater sediment attributes, suspended sediment and euphotic depth, and its overall performance would be not much below the maximum attainable mitigation (which would require considerably more effort without any potential economic return).

The second key result is that none of the eight mitigation scenarios that did not involve full afforestation were able to achieve significant mean improvements in any of the three freshwater sediment attributes compared to the Current Mitigation or Baseline scenarios at the scale of the entire catchment. The statistical models explained an unusually high percentage of the total variation in the sediment attribute data (70-90%) and all overall effects of the factor 'mitigation scenario' had strong effect sizes (0.57-0.81, maximum possible effect size 1.0; note that effect sizes >0.10 indicate that the results are biologically relevant). Consequently, all findings are both statistically highly reliable and biologically relevant and show clearly that the strong overall patterns were driven only by the beneficial effects of the two full afforestation scenarios. Based on our current understanding of the impacts of suspended sediment on New Zealand fish and invertebrate species (and keeping in mind as another caveat that data are lacking for significant areas of the catchment), this second result essentially suggests that, unless the entire Kaipara Harbour catchment is fully afforested with pine forest or native bush, in-stream suspended sediment loads, water clarity or euphotic depth are unlikely to be improved to an extent that is relevant for stream invertebrate or fish communities at the scale of the entire catchment.

In spite of the two key results, which are somewhat sobering, some trends in the freshwater attribute data suggest that certain non-afforestation mitigation measures may be successful at least in some of the seven studied Kaipara Harbour subcatchments. These trends should be interpreted with a degree of caution because they cannot be underpinned by any statistical analysis (as there is only a single data point per subcatchment), but they are still worth considering. For example, the scenario Stock Exclusion + All Highly Erodible Land Plans is expected to reduce suspended sediment concentrations compared to Baseline by 51% in the Wairua, 41% in the Mangakahia, 32% in the Kaukapakapa and 28% in the Kaipara. This scenario is also expected to increase water clarity compared to Baseline by about 0.5 metres in 4 of the 7 subcatchments (Kaipara, Kaukapakapa, Manganui, Wairua), and euphotic depth by the same amount in 3 of the 7 subcatchments (Kaipara, Kaukapakapa, Wairua). For the Kaipara and Kaukapakapa subcatchments, these improvements could be due to the fact that both comprise a variety of pastoral land uses with relatively high erosion rates that could benefit from implementing a range of mitigation practices. By contrast, other Kaipara subcatchments already have relatively high proportions of forest plantations or native bush; thus, they produced minimal erosion and/or had limited mitigation potential and did not experience the same increases in water clarity and euphotic depth.

An increase of euphotic depth by 0.5 m would allow benthic periphyton (where streambed substrata are suitable) and/or macrophyte communities to increase primary production in deep river waters, with potentially beneficial flow-on effects on higher trophic levels such as invertebrates or fish (due to increased locally produced energy available for the entire stream food web). This advantage would probably become relevant mainly in the deepest river sections (because even at Baseline euphotic depth is already 1.5-2.6 m). While no specific research is available to determine whether an increase in water clarity by 0.5 m (starting from a Baseline clarity of 0.8-2.1 m) represents a biologically relevant improvement for visually feeding stream fish, such an improvement seems possible in some subcatchments, especially the Wairua and Manganui where Baseline clarity was < 1 m. Consequently, on balance, the scenario Stock Exclusion + All Highly Erodible Land Plans has the potential to yield beneficial outcomes for the running-water ecosystems in certain Kaipara Harbour subcatchments, which could be prioritized for mitigation efforts based on all components of the Study.

In the context of subcatchment-specific patterns and trends, it is important to note that NRC has no sampling sites in the lower Northern Wairoa River, therefore water quality or MCI data are lacking for what is likely to be the most impacted area considering cumulative effects of agricultural stressors on stream organisms.

Implications for human contact recreation. The findings for visual clarity in several of the mitigation scenarios that did not involve full afforestation have encouraging implications for human contact recreation, which is affected (safety, aesthetics) by visual clarity in rivers. Existing guidelines recommend that visual clarity should be > 1.6 m for contact recreation. In the Kaipara Harbour catchment, mean water clarity in the Baseline scenario (1.24 m) and the Current Mitigation scenario (1.37 m) are below that threshold, indicating that the current mean visual clarity is too low for rivers to be generally suitable for contact recreation. However, in four of the 10 non-afforestation mitigation scenarios, mean visual clarity would increase to values at or slightly above the 1.6 m guideline. These are Freshwater Node 30% (1.60 m), Marine Annual Average Sedimentation rate 2 mm above 'natural' state (1.64 m), Stock Exclusion + All Highly Erodible Land Plans (1.66 m), and Stock Exclusion Rules plus Riparian Planting (1.67 m). These increases in visual clarity may be a benefit for those people living in the Kaipara catchment who would enjoy swimming in these rivers.

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Introduction

Northland Regional Council (NRC) and Auckland Council (AC) have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study (henceforth abbreviated as "the Study").

The first aim of the Study is to develop a catchment economic model for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment. Sediment mitigation applied in the catchment reduces sediment runoff, which translates into changes in "sediment attributes" such as suspended-sediment concentration, water clarity and euphotic depth in freshwater, and sedimentation rate and seabed muddiness in the harbour. Changes in sediment attributes in turn will translate into changes in ecosystem health and functioning and certain values derived by humans from the use of water, for example, kaimoana gathering and swimming. The catchment economic model will estimate the cost of applying sediment mitigation in the catchment and the reduction in sediment runoff and the associated changes in sediment attributes that will result from the application of the mitigation. Model predictions will assist NRC and AC when making decisions about managing sources of sediment in the Kaipara Harbour Catchment.

The second aim of the Study is to develop a management tool for use in formulating consistent farm-scale sediment mitigation plans. The tool is intended to be easily used by land management advisors in the field to identify appropriate actions to mitigate critical source areas of sediment under different land uses at the farm scale.

This report

This report provides a narrative assessment of how changes in freshwater sediment attributes in response to different mitigation scenarios applied in the Kaipara Harbour catchment may translate into changes in stream ecosystem health (based on stream fish and invertebrate communities) and in certain values derived by humans from the use of water. This narrative assessment was done following a rigorous quantitative statistical analysis of the modelled mitigation scenario data, to determine which scenarios resulted in significant changes in freshwater sediment attributes.

Background

Anthropogenic sediment inputs have been recognised as having negative impacts on stream and river ecosystems in New Zealand (reviews by Ryan, 1991; Clapcott et al., 2011) and worldwide (e.g., reviews by Newcombe and MacDonald, 1991; Wood and Armitage, 1997). Affected freshwater organisms include fish, benthic (streambed-dwelling) invertebrates and algae.

Suspended fine sediment in streams and rivers increases water turbidity and reduces both visual water clarity and euphotic depth, and these physical changes can result in a number of ecological effects. Reduced visual clarity can impair the foraging efficiency of visually hunting fish and birds (e.g., Julian et al., 2013; Davies-Colley et al., 2014), may cause certain migratory fish species to avoid highly turbid rivers (e.g., Boubée et al., 1997; Rowe and Dean, 1998), and can increase drift rates of benthic invertebrates (e.g., Shaw and Richardson, 2001; Bond and Downes, 2003; Larsen and Ormerod, 2010). Suspended sediment can damage the gills of freshwater fish, which can limit fish growth and make them more susceptible to disease (Waters, 1995). Reduced euphotic depth can result in the decline of benthic plants (Davies-Colley and Smith, 2001; Julian et al., 2013) and negatively affect growth rates of periphyton and macrophytes on the river bed (e.g., Julian et al., 2013; Davies-Colley et al., 2014).

Deposited fine sediment may smother river beds and degrade benthic habitats in running waters (Conroy et al., 2016; Wood and Armitage, 1997). Regarding the ecological effects of deposited fine sediment, more information is available in New Zealand on quantitative relationships between deposited sediment and benthic invertebrates (summarized in Table 4-1 in Clapcott et al., 2011) than for stream fish or benthic algae. In these studies, elevated sediment levels affected invertebrate community composition, diversity and abundance of EPT taxa (pollution-sensitive mayfly, stonefly and caddisfly larvae), density of common individual invertebrate taxa, and invertebrate drift. Anywhere between 10% and 10-fold increases in fine sediment resulted in noticeable invertebrate responses, with changes amplified by increasing exposure time to the sediment. The most commonly inferred mechanism driving the responses of benthic invertebrates to deposited fine sediment is a change in habitat (Clapcott et al., 2011).

Daigneault et al. (2017) report on the catchment economic modelling done for the Study, which was performed with the spatially explicit economic land use model, New Zealand Forest and Agriculture Regional Model (NZFARM). The model incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads into rivers from various land uses in the Kaipara Harbour catchment were estimated using the SedNetNZ model (Dymond, 2016), and a harbour sediment budget that takes as input those sediment loads was constructed by Green et al. (2017). Land-based mitigation costs and effectiveness in reducing sediment were obtained from a range of sources and summarized by Basher (2017). Twelve scenarios were analysed by NZFARM (see Table ES.1 in Daigneault et al., 2017) to assess the costs and benefits of a range of management and mitigation approaches to reducing sediment inputs into seven specific river subcatchments and the harbour. The scenarios included practice-based approaches (e.g. fencing all streams for stock exclusion) as well as outcome-based approaches (e.g. meeting sediment load reduction targets in specific river sub-catchments and harbour depositional basins). Two large afforestation scenarios were also modelled to establish the minimum feasible loads and best possible environmental outcomes that could be achieved in the entire catchment. Environmental outcomes were expressed in terms of marine and freshwater "sediment attributes". These included three freshwater sediment attributes (suspended sediment concentration, water clarity, and euphotic depth) and one harbour sediment attribute (the annual average sedimentation rate, AASR).

This component of the Study focuses on interpreting the predictions by Daigneault et al. (2017) of the three freshwater sediment attributes. The general aim is to narratively describe and discuss the implications for stream invertebrates and fish of the modelled changes in the freshwater sediment attributes. To ensure the narrative was based on a rigorous quantitative statistical analysis, this component of the Study had two specific aims:

1. Determine if the 12 mitigation scenarios modelled by Daigneault et al. (2017) affect the three sediment attributes significantly in a statistical analysis that regarded the studied seven individual river subcatchments within the Kaipara Harbour catchment as "replicates" of each scenario. Compared to the Baseline scenario (current land use with no mitigation practices) or the Current Mitigation scenario, one would expect several of the other scenarios that included mitigation to result in significant improvements in the three freshwater sediment attributes. This was the primary hypothesis that was tested with the analysis.

2. Determine, using the same statistical analysis, if overall differences in the three freshwater sediment attributes occur among the river subcatchments (when averaged across all 12 modelled scenarios). Such differences are of secondary interest compared to the effects of the scenarios because they are at least partly due to regional differences, including subcatchment geology, topography, etc. Nevertheless, this analysis may contribute useful information about the existing "background variation" in the data, which may help explain some of the patterns found for the different scenarios.

Methods

Freshwater sediment attributes

As stated in Daigneault et al. (2017; Section 2.4.1), water clarity and euphotic depth are estimated to have an inversely related and non-linear response to changes in sediment loads, while changes in suspended sediment concentration are perfectly correlated to load. Dymond (2016) provides more details on how the three freshwater attributes were estimated for seven subcatchments in the Kaipara Harbour Catchment. These subcatchments are shown in Figure 3 in Daigneault et al. (2017) (also copied onto the next page).

Mitigation scenarios

No explicit targets for the freshwater sediment attributes were addressed by Daigneault et al. (2017). Instead, the NZFARM model predicts the impacts on the freshwater attributes of specific management practices or sediment load targets, rather than trying to achieve a particular freshwater attribute state. However, all mitigation scenarios were designed so that the freshwater sediment attributes will always be "maintained or improved" (i.e., no scenario produced more erosion or sediment than the 'no mitigation' Baseline scenario in any given subcatchment).

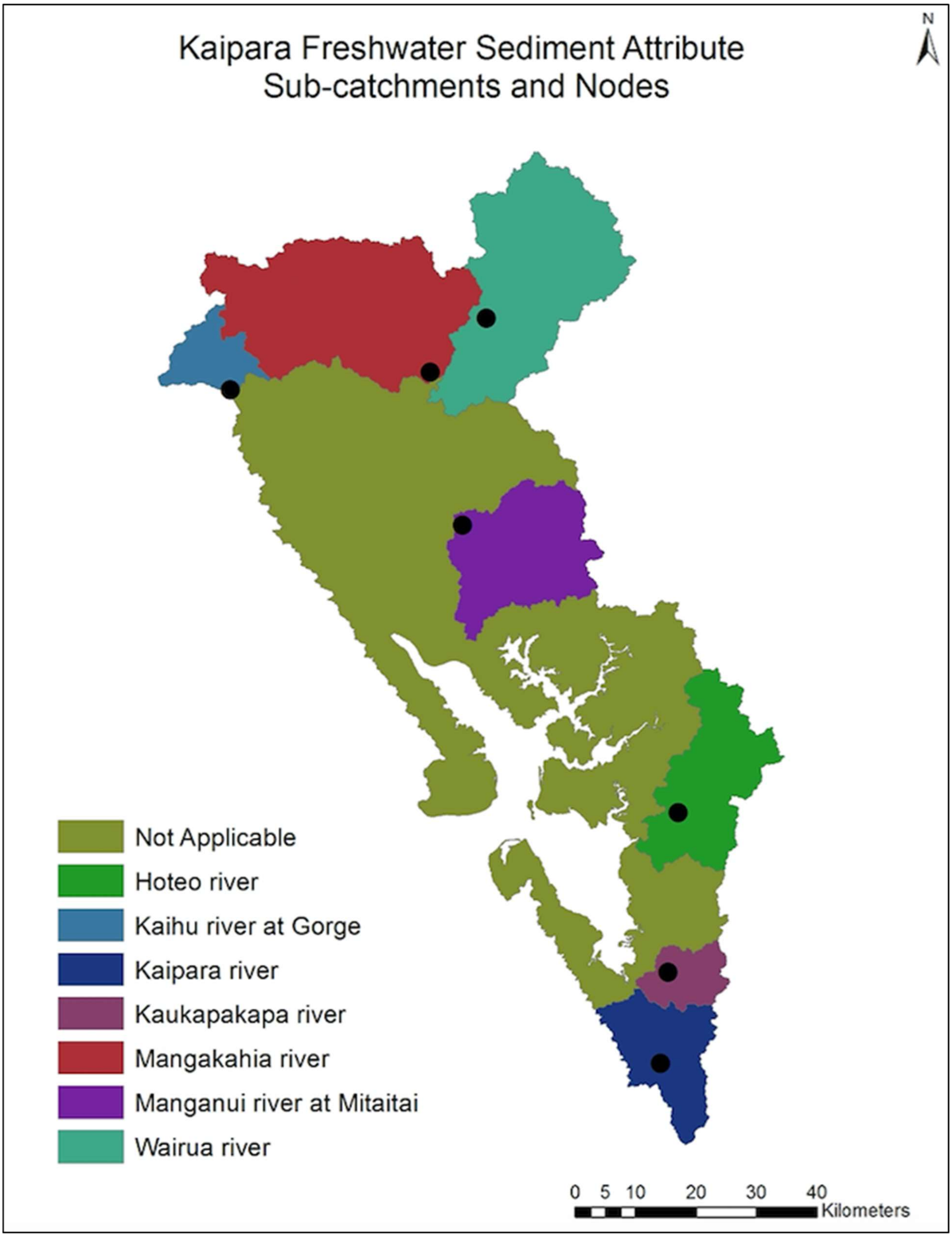

Figure 3 from Daigneault et al. (2017): Kaipara Harbour catchment freshwater subcatchments. The black dots indicate the exact location of each 'node of importance' that Dymond (2016) used to estimate the baseline figures for each sub-catchment. These nodes were primarily chosen because they are located near environmental monitoring stations where sediment rating curves could be developed so that quantitative relationships between sediment loads and attributes could be established. See Section 2.6.2 in Daigneault et al. (2017) for more information.

NZFARM provides several options for managing sediment from different land uses that range from intensive pasture to native bush, for example, implementing farm management plans, fencing streams, and constructing wetlands and sediment bunds.

Twelve scenarios were analysed using NZFARM (see Table ES.1 in Daigneault et al., 2017, copied onto the next page). These included practice-based approaches (e.g. fencing all streams for stock exclusion) plus outcome-based approaches (e.g. meeting sediment load reduction targets in specific freshwater subcatchments or coastal basins). Two large afforestation scenarios were also modelled to establish the minimum feasible loads and best possible attribute states that could be achieved. In all scenarios, mitigation costs were annualised and assumed to be accrued for 25 years. Besides assessing the cost and effectiveness for practices and policies that could reduce catchment sediment loads, NZFARM also estimated changes in marine (annual average sedimentation rate, AASR) and freshwater sediment attributes (suspended sediment concentration, water clarity, euphotic depth), with the latter being the subject of this analysis and discussion.

Table ES.1 from Daigneault et al. (2017): NZFARM scenarios for the Kaipara Harbour catchment.

Scenario #	Scenario Name	Scenario Description
0	Baseline	Current land use with no mitigation practices to match same assumption as SedNetNZ erosion model.
		Practice-based Scenarios
1	Current Mitigation	Current land use with likely proportion of mitigation practices implemented today. Assumes 80% of streams and rivers on dairy farms and 30% of streams and rivers on other pastoral land are fenced to exclude livestock (dairy cattle, dairy support cattle, beef cattle and deer) and 10% of pastoral land area with 1.0 t/ha/yr or higher erosion rates (i.e., highly erodible land, HEL) has soil conservation measures.
2	Farm Management Plan on all Highly Erodible Pastoral Land	Current land use with farm management plans (predominately promoting soil conservation by planting poplar or willow poles) implemented on all HEL.
3	Stock Exclusion Rules	Current land use with riparian fencing of River Environment Classification 2 (REC2) or larger permanent streams for stock exclusion on all pastoral land meeting the NZ Government's proposed stock exclusion regulations (2017).
4	Stock Exclusion with Riparian Planting	Current land use with riparian fencing for stock exclusion on all pastoral land meeting the NZ Government's (2017) proposed stock exclusion regulations on REC2 or larger permanent streams, but also with 5m stream buffer with planted vegetation.
5	Stock Exclusion + All HEL Plans	Combination of scenarios 2 and 3.
		Outcome-based Scenarios
6	Freshwater Node 10%	Total annual sediment load reduced in all seven freshwater zones reduced by 10%.
7	Freshwater Node 30%	Total annual sediment load reduced in all seven freshwater zones reduced by 30%.
8	Marine Deposition 15%	Total annual sediment load reduced in all nine marine sediment deposition basins reduced by 15%.
9	Marine AASR 2mm above 'natural' state	Average annual sedimentation rate (AASR) from catchment-based erosion is no more than 2mm greater than AASR under 'natural' land conditions (Scenario 11).
		Afforestation Scenarios
10	Full Afforestation (Pine)	All non-forest land (e.g., pasture, arable, lifestyle blocks) is planted with radiata pine. Used to estimate maximum attainable mitigation while maintaining a 'productive' land use.
11	Full Afforestation (Native) & Wetland Restoration	All non-forest land is planted with native bush and likely extent of pre-human wetlands are restored. Used to estimate 'natural' erosion loads in the catchment and thus maximum attainable mitigation.

Statistical analysis

The NZFARM model predictions of the three freshwater sediment attributes were analysed using SPSS 23 (IBM SPSS Statistics; IBM Company, Chicago, IL, U.S.A.). For each attribute, a two-way ANOVA without interaction term was performed, with "scenario" and "river subcatchment (sediment node)" as the fixed factors. For water clarity and euphotic depth, the ANOVA model was intercept (d.f. 1) + scenario (11) + river (6) + error (66, n = 84). For suspended sediment concentration (where data were available for six of the seven rivers), the ANOVA model was intercept (d.f. 1) + scenario (11) + river (5) + error (55, n = 72). It was not possible to include an interaction term (scenario × river) in this model because there was only a single replicate of each treatment combination (12 scenarios × 6 rivers = 72 data points for suspended sediment, and 12 scenarios × 7 rivers = 84 data points for water clarity and euphotic depth – see Fig. 18 and Appendix 5 in Daigneault et al., 2017).

In all cases where significant overall differences among scenarios or rivers were found, pair-wise comparisons using Tukey's HSD post hoc tests were conducted to determine which specific scenarios or rivers differed significantly from each other.

Since null hypothesis significance testing does not provide any estimates of the magnitude of an effect of interest (Nakagawa and Cuthill, 2007), standardized effect sizes for all results were calculated with $P \leqslant 0.10$ to allow for evaluating the biological relevance of all significant findings (partial eta² values, range 0-1; effect size categories after Nakagawa and Cuthill, 2007: weak >0.10, moderate >0.30, strong >0.50; please note that all effects >0.10 are likely to be biologically relevant, whereas effects <0.10 are likely to be biologically unimportant).

When interpreting the findings of these analyses, potential differences between scenarios (averaged across all 6-7 river catchments) were of primary interest and are discussed in depth. Potential overall differences between river catchments (averaged across all 12 mitigation scenarios), by contrast, are of secondary interest and will thus be discussed more briefly.

Results

Fig. 18 in Daigneault et al. (2017, copied onto the next page) shows the patterns for the three freshwater sediment attributes across the 12 modelled mitigation scenarios in each of the 7 river subcatchments (6 for suspended sediment).

Figure 18 from Daigneault et al. (2017): Freshwater sediment attributes by scenario and catchment node. Units for each sediment attribute are based on the median flow percentile of each node. No suspended sediment data were available for Manganui River at Mitaitai.

The subsequent figures and table complement Fig. 18 in Daigneault et al. (2017) and illustrate the results of the statistical analysis. Overall differences among the 12 mitigation scenarios (averaged across all river subcatchments) are presented first, then the findings of secondary interest, overall differences among the 6-7 subcatchments (averaged across all scenarios).

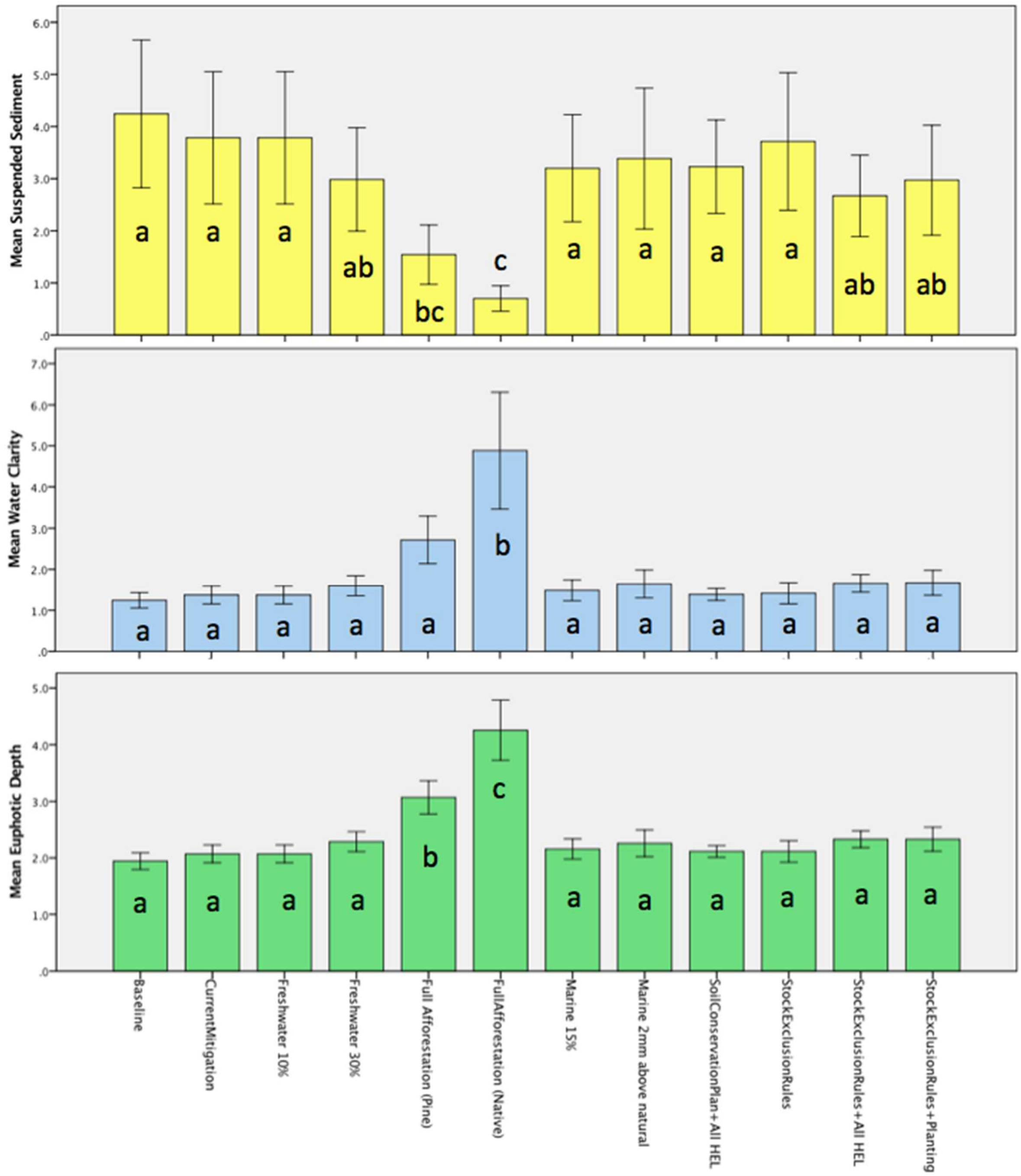

Figure 1. Suspended sediment concentration, water clarity and euphotic depth (means ± standard errors) across the 12 modelled mitigation scenarios (averaged across all 7 rivers for clarity and euphotic depth and, for sediment, across the 6 rivers for which data were available). Different letters (a, b, c) indicate mitigation scenarios that were significantly different from each other in the pair-wise post hoc test comparisons (see Table 1 for details). Shared letters indicate that the scenarios in question were not significantly different; for example, for euphotic depth only the full afforestation scenarios differed from the Baseline scenario, with Full Afforestation (Native) also being higher than Full Afforestation (Pine).

The ANOVA models for the three freshwater sediment attributes explained 70-90% of the total variation in the data (see Table 1), indicating that the statistical models fitted very well, and both fixed factors, mitigation scenario and river subcatchment, had strong effects on all three sediment attributes (Table 1). Consequently, the post hoc test rankings for the pair-wise comparisons are highly reliable for both factors.

Suspended sediment concentration (in g per m^3 of river water) was significantly lower under Full Afforestation with Native Forest (plus Wetland Restoration) than in all other scenarios except for the scenario with the second-lowest suspended sediment, Full Afforestation with Pine Forest (Fig. 1, Table 1), where sediment concentration was slightly higher but not by enough to be significantly different (Tukey post hoc test $P = 0.83$). Sediment concentration under Full Afforestation with Pine Forest was also significantly lower than in most other scenarios, apart from three: Stock Exclusion + All Highly Erodible Land Plans (the combination of Scenarios 2 & 3), Stock Exclusion Rules plus Riparian Planting, and Freshwater Node 30% (total annual sediment load in all seven river subcatchments reduced by 30%). In these three, sediment concentrations were somewhat higher than under Full Afforestation with Pine Forest but not by enough to be significantly different. Notably, none of the 10 scenarios that did not involve full afforestation (including Baseline and Current Mitigation) differed significantly from each other, indicating that suspended sediment concentration was similarly high in all of them (see Fig. 1). The only scenario among these that came close to being different from Baseline was Stock Exclusion + All Highly Erodible Land Plans (Tukey post hoc test $P = 0.066$). Compared to Current Mitigation, none of these scenarios came close to being different (Tukey post hoc test $P > 0.45$ for all pairwise comparisons).

Water clarity (in m) and euphotic depth (in m) both showed essentially the inverse response pattern to suspended sediment sediment concentration. Thus, water clarity was significantly higher under Full Afforestation with Native Forest (plus Wetland Restoration) than in all other scenarios (Fig. 1, Table 1). None of the other 11 scenarios (including Baseline and Current Mitigation) differed significantly from each other, indicating that water clarity was similarly low in all of them (Fig. 1). Just one of these scenarios showed a trend of being different from Baseline, that being Full Afforestation with Pine Forest (Tukey post hoc test $P = 0.18$). Compared to Current Mitigation, none of these scenarios came close to being different (Tukey post hoc test $P = 0.29$ for Full Afforestation with Pine Forest and $P = 1.00$ for all other pairwise comparisons).

Euphotic depth was highest under Full Afforestation with Native Forest (plus Wetland Restoration), intermediate under Full Afforestation with Pine Forest, and lowest in the 10 other scenarios (Fig. 1, Table 1). Once again, none of the 10 scenarios that did not involve full afforestation (including Baseline and Current Mitigation) differed significantly from each other, indicating that euphotic depth was similarly low in all of them (Fig. 1). None of these scenarios came close to being significantly different from Baseline (Tukey post hoc test $P > 0.60$ for all pairwise comparisons) or from Current Mitigation (Tukey post hoc test $P > 0.95$ for all pairwise comparisons).

Table 1. Results of the 2-factor ANOVAs on the three freshwater sediment attributes. In addition to *P*-values for all findings, R^2-values indicate the proportion of the total variation in the data explained by each statistical model. For all significant overall effects, Tukey's HSD post hoc test rankings indicate which specific scenarios or river subcatchments differed significantly from each other. Further, effect sizes (ES) are provided for all significant findings (partial eta² values, range 0-1; effect size categories after Nakagawa and Cuthill, 2007: weak >0.10, moderate >0.30, strong >0.50; effects <0.10 are likely to be biologically unimportant). Note that for all scenarios only strong effects were observed.

Sediment Attribute	Mitigation Scenario	River Subcatchment
Suspended Sediment	<0.001 (ES 0.64)	<0.001 (ES 0.88)
(R^2 = 0.90)	Full Afforestation Native < all others (except for Full Afforestation Pine) Full Afforestation (Pine) < most others (except for Full Afforestation Native & 3 others – see Fig. 1)	Mangakahia > Wairua > others (see Fig. 2)
Water Clarity	<0.001 (ES 0.57)	<0.001 (ES 0.51)
(R^2 = 0.70)	Full Afforestation Native > all others	Kaipara > all others
Euphotic Depth	<0.001 (ES 0.81)	<0.001 (ES 0.73)
(R^2 = 0.87)	Full Afforestation Native > Full Afforestation Pine > all others	Kaipara > (Kaukapakapa = Kaihu = Hoteo) > (Wairua = Mangakahia); Kaipara > Manganui

Regarding overall differences between river subcatchments (averaged across all 12 mitigation scenarios), suspended sediment concentration was highest in the Mangakahia River, second-highest in the Wairua River, third-highest in the Hoteo, Kaihu and Kaukapakapa rivers, and lowest in the Kaipara River (Fig. 2, Table 1).

Water clarity and euphotic depth were both higher in the Kaipara River than in all other rivers (Fig. 2, Table 1). Moreover, euphotic depth was intermediate in the Hoteo, Kaihu, Kaukapakapa and Manganui rivers, and lowest in the Wairua and Mangakahia rivers.

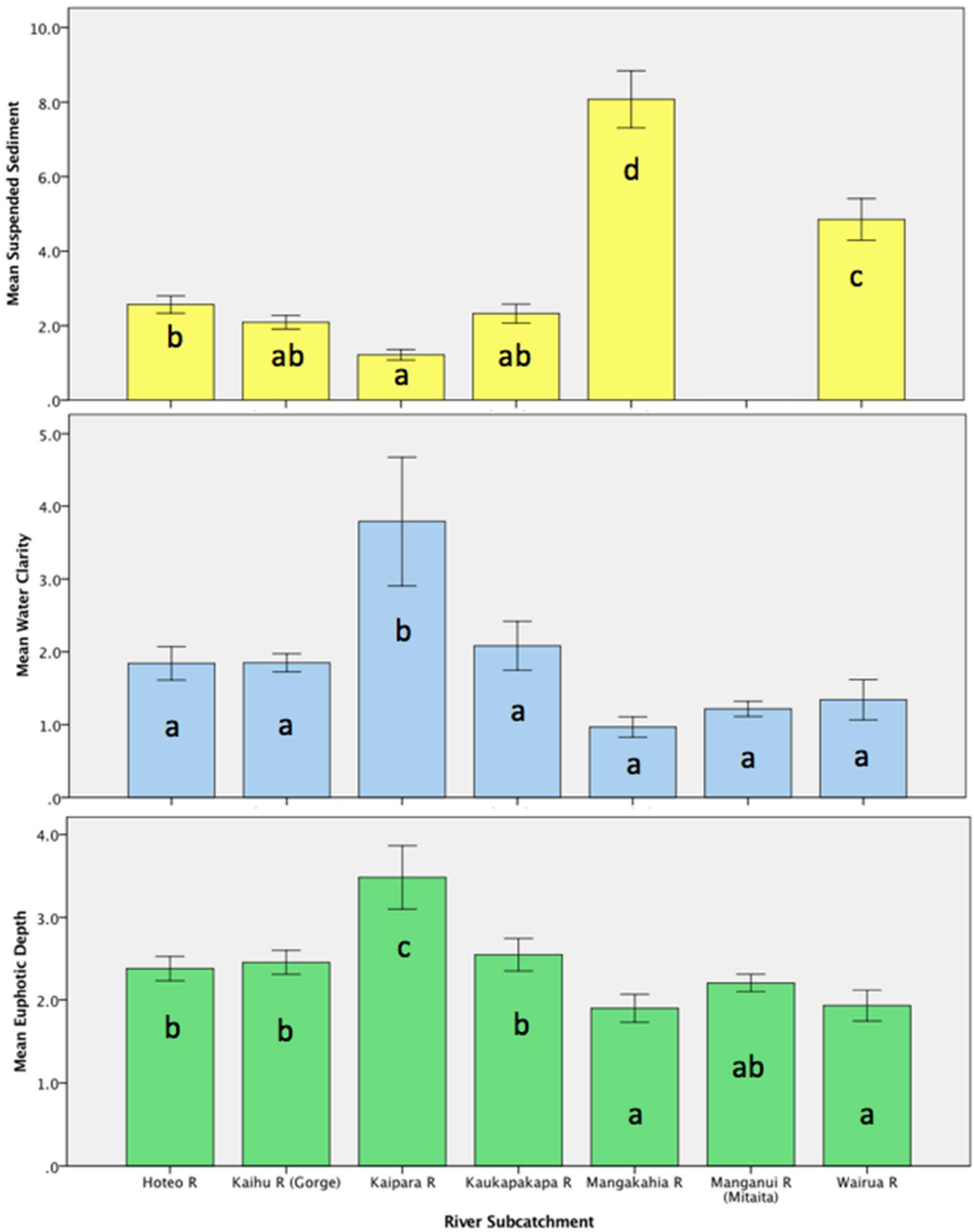

Figure 2. Suspended sediment concentration, water clarity and euphotic depth (means ± standard errors) across all subcatchments for which data were available (6 rivers for suspended sediment, 7 rivers for clarity and euphotic depth), averaged across all 12 mitigation scenarios. Different letters (a, b, c) indicate subcatchments that differed significantly from each other in the pair-wise post hoc test comparisons (see Table 1 for details). Shared letters indicate that the subcatchments in question were not significantly different; for example, for water clarity only the Kaipara River differed from the other six rivers.

Discussion

Which scenarios significantly affect the freshwater sediment attributes?

Only the two Full Afforestation scenarios resulted in significant improvements of the freshwater sediment attributes (i.e. reduced suspended sediment concentration and increased water clarity and euphotic depth) compared to the Baseline scenario (current land use with no mitigation practices) or the Current Mitigation scenario (current land use with likely proportion of mitigation practices implemented today). For suspended sediment concentration and euphotic depth, Full Afforestation with Pine Forest essentially performed as well as Full Afforestation with Native Forest (plus Wetland Restoration) in significantly reducing suspended sediment concentration and increasing euphotic depth compared to the Baseline or Current Mitigation scenarios. For water clarity, only Full Afforestation with Native Forest (plus Wetland Restoration) resulted in a significant increase of clarity compared to Baseline or Current Mitigation. Full Afforestation with Native Forest (plus Wetland Restoration) was included by Daigneault et al. (2017) in their modelling to estimate 'natural' erosion loads in the catchment and maximum attainable mitigation; therefore, this scenario is not a realistic mitigation goal. By contrast, Full Afforestation with Pine Forest was included in the modelling to estimate maximum attainable mitigation while maintaining a 'productive' land use, which is somewhat more realistic. The findings of the statistical analysis indicate that this scenario would probably be effective in improving at least two of the three freshwater sediment attributes, suspended sediment and euphotic depth, and that its overall performance would be not much below the maximum attainable mitigation (which would require considerably more effort without any potential future economic return). The implications of this first key result of the analysis for stream invertebrates and fish is discussed below.

The second key result is that none of the eight mitigation scenarios that did not involve full afforestation were able to achieve significant mean improvements in any of the three freshwater sediment attributes compared to the Current Mitigation or Baseline Scenarios at the scale of the entire Kaipara Harbour catchment. The only scenario of the eight that came close to being different from Baseline was Stock Exclusion + All Highly Erodible Land Plans (Tukey post hoc test $P = 0.066$). Compared to Current Mitigation, none of these eight scenarios came close to being different. The statistical models explained an unusually high percentage of the total variation in the sediment attribute data (70-90%) and all overall effects of the factor ‘mitigation scenario’ had strong effect sizes (0.57-0.81, maximum possible effect size 1.0; note that effect sizes >0.10 imply that the results are biologically relevant). Consequently, all findings are both statistically highly reliable and biologically relevant and indicate clearly that the strong overall patterns were driven only by the beneficial effects of the two afforestation scenarios. Based on our current understanding of the impacts of suspended sediment on New Zealand fish and invertebrate species (and keeping in mind as another caveat that data are lacking for significant areas of the catchment), this second key result essentially suggests that, unless the whole Kaipara Harbour catchment is fully afforested with pine forest or native bush, in-stream suspended sediment loads, water clarity or euphotic depth are unlikely to be improved to an extent that is relevant for stream invertebrate or fish communities at the scale of the entire catchment (discussed further below).

Regarding the potential reasons behind the observed response patterns, the results of the secondary analysis are of some help. The aim of that analysis was to determine if overall differences in the three sediment attributes occurred among the seven river subcatchments (when averaged across all 12 modelled mitigation scenarios). These differences are of secondary interest compared to the effects of the scenarios because they are at least partly due to regional differences such as subcatchment geology, topography, and annual rainfall. Nevertheless, the resulting information about the existing "background variation" in the three sediment attributes helps explain some of their responses (or lack thereof) to the different mitigation scenarios. Thus, for suspended sediment concentration, mean concentrations differed noticeably (by up to 37% compared to Baseline and up to 29% compared to Current Mitigation) across the 10 scenarios that did not involve fill afforestation (see Fig. 1). However, variation across the six subcatchment "replicates" available for this sediment attribute was relatively high, and this variation reduced the statistical power of the pair-wise comparisons between the 10 scenarios. In Fig. 2 the reason for this high variation between subcatchments becomes apparent: two of the subcatchments, the Mangakahia River and the Wairua River, had generally far higher sediment loads than the other four. Consequently, there is a chance that the mean suspended sediment loads under the three scenarios Stock Exclusion + All Highly Erodible Land Plans, Stock Exclusion Rules plus Riparian Planting, and Freshwater Node 30% (total annual sediment load in all seven freshwater river subcatchments reduced by 30%) (all three can be identified by the letters 'ab' in Fig. 1) might have also become significantly lower compared to the Baseline or Current Mitigation scenarios had the Study been conducted in say 20 river subcatchments (thus increasing statistical power and counterbalancing the high variation between subcatchments) instead of just six.

By contrast, for both water clarity and euphotic depth, the between-subcatchment-variation for all 10 scenarios that did not involve full afforestation is much smaller than for suspended sediment (see Fig. 1), and this is also reflected in the much smaller differences in clarity and euphotic depth across the seven subcatchments in Fig. 2. Therefore, this analysis was not hampered by potential issues related to variation, sample size and statistical power, and one would not expect the key result (that only the two full afforestation scenarios had significant effects on clarity or euphotic depth) to change had the study been conducted in a larger number of river subcatchments.

Implications for stream invertebrates and fish

Full Afforestation scenarios. As explained in the Background section, elevated concentrations of suspended fine sediment in streams and rivers and the related changes to visual clarity and euphotic depth can have a number of adverse ecological effects, including reduced foraging efficiency of fish and birds, increased drift rates of benthic invertebrates and reduced growth of periphyton and macrophytes on the river bed.

For ***suspended fine sediment***, Full Afforestation with Native Forest (plus Wetland Restoration) (this is the maximum theoretically attainable mitigation), would reduce mean concentrations from 4.95 g per m^3 of river water (Baseline) or 4.42 g (Current Mitigation) to 0.82 g (minus 84% compared to Baseline or minus 81% compared to Current Mitigation). For Full Afforestation with Pine Forest (1.80 g per m^3), the corresponding reductions would be 64% and 59% (all means taken from Fig. 1).

Suspended fine sediment data from New Zealand rivers sampled along gradients of different catchment land use intensities are surprisingly scarce. One of the few existing such data sets was collected by the Otago Regional Council from 10 tributaries of the Pomahaka River, a sixth-order river in South Otago (13-14 collections during one year). These data are included in Chapter 2 of the PhD thesis by J. Ramezani (2014), who was supervised by C. Matthaei and G. Closs. In that study, suspended sediment concentration was significantly positively correlated (R^2 = 0.42) with the prevalence of dairy farming in the tributary catchments (0-79% of the catchment area; sheep/beef farming was the other main land use). Both Full Afforestation scenarios would reduce mean suspended sediment concentrations in the seven Kaipara Harbour subcatchments below the lowest values observed in the Pomahaka River study, which occurred in tributaries dominated by sheep/beef farming (see Fig. 2.2 in Ramezani 2014, copied below). Because these low-sediment Pomahaka tributaries generally possessed both healthy stream invertebrate and stream fish faunas and these ecological measures of stream health decreased significantly as dairy farming became more prevalent (see Fig. 2.3 in Ramezani 2014 for invertebrate results, copied below; also Ramezani et al., 2016), it would be reasonable to predict that stream invertebrate and fish communities in the Kaipara Harbour subcatchments would become significantly healthier if one of the Full Afforestation scenarios was implemented. Note that Auckland Council may have collected suspended sediment data as part of their sediment monitoring; if so a similar analysis may be possible using these data.

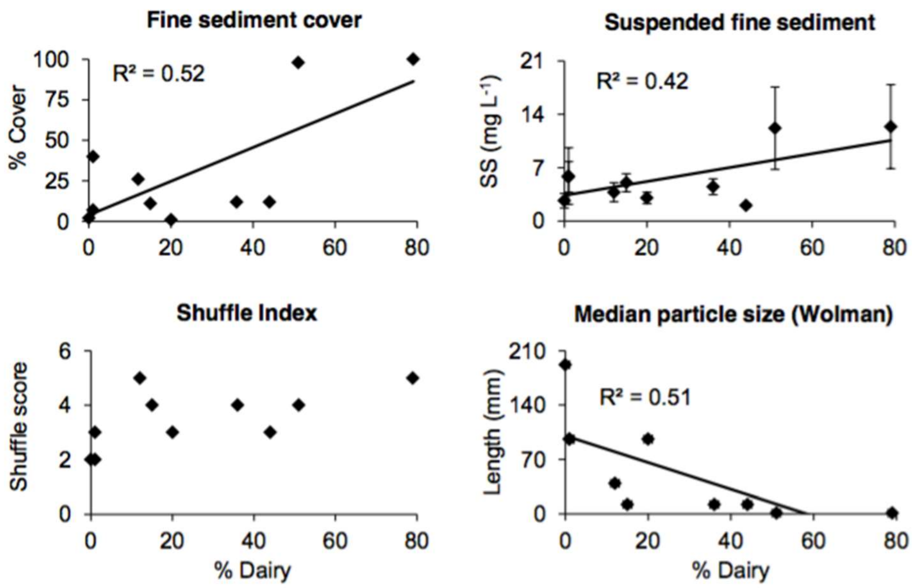

Figure 2.2 from Ramezani (2014): Levels of suspended and deposited fine sediment and median streambed particle size (based on Wolman pebble counts) in relation to the prevalence of dairy farming (in % of the catchment area) for the ten Pomahaka River tributaries (stream order 3-6). For suspended fine sediment, data points are means and standard errors of 13-14 collections during one year in each stream. The other three variables were determined once in each tributary. Regression lines are shown for all significant relationships.

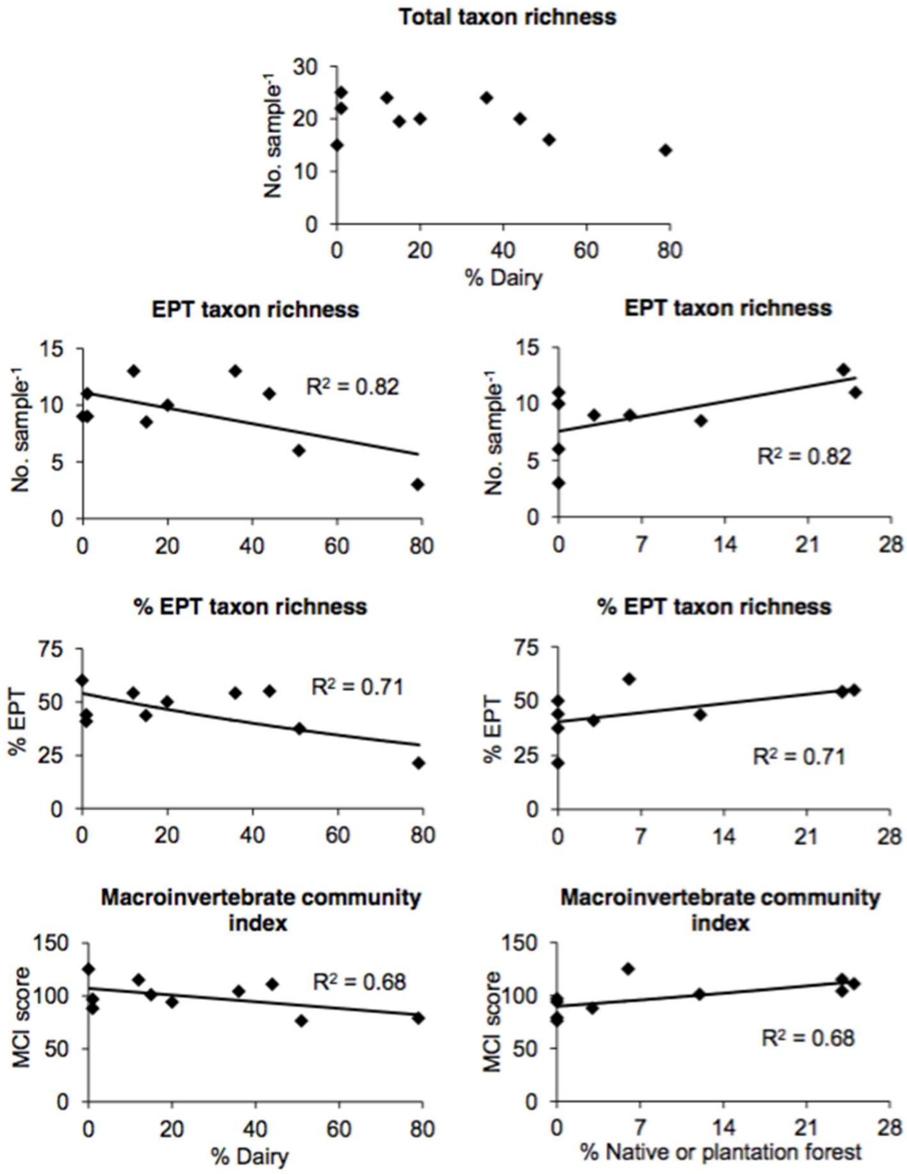

Figure 2.3 from Ramezani (2014): Invertebrate community metrics in relation to land use intensity expressed as (on the left) the prevalence of dairy farming (in % of the catchment area) or (on the right) the prevalence of native or exotic forest (in % of the catchment area) for the ten Pomahaka River tributaries. All invertebrate variables were determined once in each tributary. Regression lines are shown for all significant relationships. R^2-values for EPT metrics and MCI are for multiple regressions with both land-use predictor variables.

The only two existing experimental studies that exposed stream invertebrates and fish to suspended sediment measured in g per water volume (rather than solely in Nephelometric Turbidity units, NTUs), Boubée et al. (1997, a NZ study on juvenile native fish) and Shaw & Richardson (2001, a Canadian study of stream invertebrates and rainbow trout), used far higher sediment concentrations (100-1200 g or 704 g, respectively, per m^3 of water) than those in the present study (range 0.82-4.95 g per m^3) or the stream survey by Ramezani (2014; range ca. 2-20 g per m^3). Therefore, the findings of these two manipulative experiments are not discussed any further here.

For ***water clarity***, Full Afforestation with Native Forest is predicted to increase mean clarity in the Kaipara Harbour freshwater tributaries from 1.24 m (Baseline) or 1.37 m (Current Mitigation) to 4.89 m (plus 3.65 m [294%] compared to Baseline, and plus 3.52 m [257%] compared to Current Mitigation). For Full Afforestation with Pine Forest (mean clarity 2.71 m), the corresponding increases would be 1.47 m (119%) and 1.34 m (98%; all means taken from Fig. 1). No specific research is available to determine whether an increase in water clarity by these margins from those baseline clarities represents a biologically relevant improvement for visually feeding stream fish (such as salmonids) or for sediment-sensitive benthic stream invertebrates. Moreover, it is worth noting that native NZ fish such as galaxiids are at least partly nocturnal and also use lateral lines to locate their prey, therefore achieving improvements in visual clarity may not be essential for all freshwater fish species in the Kaipara catchment.

In one of the few available related studies on stream fish, a stream-scale manipulative experiment on competing brown trout and brook trout in Michigan, USA (Fausch and White, 1981) found that the preferred feeding positions of these two visually hunting fish species were strongly influenced by the current velocity measured within 60 cm upstream of the fishes' snouts. This finding suggests that, at least for salmonids, the mean Baseline water clarity of 1.24 m in the Kaipara freshwater tributaries may already be sufficient to allow efficient visual hunting of aquatic or terrestrial invertebrates drifting downstream towards the fish. Thus, while the water clarity increases that would be achievable with the two Full Afforestation scenarios are certainly impressive when expressed in absolute or relative terms, they may not offer any substantial ecological advantage to salmonids in the Kaipara freshwater tributaries because, on average, their visual hunting abilities were not strongly impaired to begin with. Nevertheless, this situation may be different within certain Kaipara subcatchments where Baseline water clarity is unusually low – please see the related discussion below.

For ***euphotic depth***, Full Afforestation with Native Forest is predicted to increase mean euphotic depth in the Kaipara Harbour freshwater tributaries from 1.94 m (Baseline) or 2.07 m (Current Mitigation) to 4.26 m (plus 2.32 m [120%] compared to Baseline, and plus 2.19 m [106%] compared to Current Mitigation). For Full Afforestation with Pine Forest (mean euphotic depth 3.07 m), the corresponding increases would be 1.13 m (58%) and 1.00 m (48%; all means taken from Fig. 1). Similar to the results for water clarity discussed above, these considerable increases in euphotic depth may be less ecologically relevant than one might first assume. 'Euphotic depth' is typically defined as the distance of water through which light travels and becomes attenuated to 1% of the surface light intensity. This distance defines the 'euphotic zone' in which there is sufficient light for photosynthesis and periphyton and macrophytes may be sustained in benthic stream or lakeshore communities. Given that mean euphotic depth in the Kaipara Harbour freshwater tributaries is already almost 2 m in the Baseline scenario, benthic plant communities in these running-water ecosystems are unlikely to be strongly light-limited even without any mitigation measures, apart from in the very deepest river sections (e.g. pools with water depths of 2-4 m).

Having said this, the strong increases in mean euphotic depth predicted for the two Full Afforestation scenarios may translate to higher light levels reaching most riverbed habitats, which is likely to result in somewhat increased primary production, with potentially positive flow-on effects for higher trophic levels (e.g. grazing invertebrates and, indirectly, predators feeding on the grazers) due to the increased autochthonous (locally produced) energy available for the entire stream food web. On the other hand, both Full Afforestation scenarios would increase stream shading by tall riparian vegetation, thus reducing in-stream light levels and potentially counterbalancing or outweighing (depending on factors such as stream width or bank slope) the positive effects of reduced suspended sediment concentrations on in-stream euphotic depth. Finally, one should note that higher net light levels reaching streambed communities, if they do indeed occur, might also increase the likelihood of 'excessive' algal growth leading to algal blooms if they are combined with fairly high nutrient concentrations. However, one would expect the Full Afforestation scenarios to also strongly reduce nutrient inputs into the Kaipara subcatchments; therefore, increased algal blooms should not be an issue in practice.

All other mitigation scenarios. As explained above, in the current statistical analysis none of the eight mitigation scenarios that did not involve full afforestation were able to achieve significant improvements in the mean values of any of the three freshwater sediment attributes compared to the Current Mitigation or Baseline scenarios at the scale of the entire Kaipara Harbour catchment. For suspended sediment, there remains a possibility that this conclusion might be partly due to high variation between subcatchments in the data and the fairly small number of river subcatchments (only six) included in the study. For water clarity and euphotic depth, this potential limitation is unlikely to apply. On balance, therefore, our current understanding (and keeping in mind that data are lacking for significant areas of the catchment) suggests that, for achieving the goal of improving river water quality for stream fish and invertebrates in the ***entire*** Kaipara Harbour catchment via improving the freshwater attributes suspended sediment concentration, water clarity, and euphotic depth, only the two full afforestation scenarios would provide a realistic chance of success.

On a more positive note, however, some trends in the data suggest that certain non-afforestation mitigation measures may be successful at least in some of the Kaipara Harbour subcatchments, as already discussed by Daigneault et al. (2017), if not across the entire catchment. These subcatchment-specific trends should be interpreted with some caution because they cannot be underpinned by any statistical analysis (as there is only a single data point per subcatchment – see Fig. 18 in Daigneault et al. 2017), but they are still worth considering in this narrative. For example, the scenario Stock Exclusion + All Highly Erodible Land Plans is expected to reduce suspended sediment concentrations compared to Baseline by 51% in the Wairua, 41% in the Mangakahia, 32% in the Kaukapakapa and 28% in the Kaipara (see Table A.5.2 in Appendix 5 of Daigneault et al. 2017). Moreover, this scenario is expected to increase water clarity compared to Baseline by about 0.5 metres in 4 of the 7 subcatchments (Kaipara, Kaukapakapa, Manganui, Wairua; see Table A.5.3 in Appendix 5), and also euphotic depth by the same amount in 3 of the 7 subcatchments (Kaipara, Kaukapakapa, Wairua; see Table A.5.4 in Appendix 5). As Daigneault et al. (2017) point out, for the Kaipara and Kaukapakapa subcatchments (which both show decent improvements in all three freshwater sediment attributes), this could be due to the fact that both subcatchments comprise a variety of pastoral land uses with relatively high erosion rates that could benefit from implementing a range of mitigation practices. By contrast, other Kaipara subcatchments already have relatively high proportions of forest plantations or native bush; thus, they produced minimal erosion and/or had limited mitigation potential and did not experience the same increases in water clarity and euphotic depth.

An increase of euphotic depth by 0.5 m would allow benthic periphyton (where streambed substrata are suitable) and/or macrophyte communities to increase primary production in deep river waters, with potentially positive flow-on effects on higher trophic levels such as invertebrates or fish. However, as discussed in the previous section, this advantage would probably become relevant mainly in the very deepest sections of the seven rivers (because even at Baseline euphotic depth is already 1.5-2.6 m – see Table 15 in Appendix 5). On the other hand, while no specific research is available to determine whether an increase in water clarity by 0.5 m (starting from a Baseline clarity of 0.8-2.1 m) represents a biologically relevant improvement for visually feeding stream fish or for sediment-sensitive benthic stream invertebrates, this seems at least possible for visually feeding fish in certain subcatchments, especially for the Wairua and Manganui rivers where Baseline clarity was quite low at less than 1 m (please see the related discussion above which refers to the experiment on salmonids by Fausch and White, 1981). Consequently, on balance, as also concluded by Daigneault et al. (2017), the scenario Stock Exclusion + All Highly Erodible Land Plans has the potential to yield beneficial outcomes for the running-water ecosystems in certain Kaipara Harbour subcatchments. These could be prioritized for mitigation efforts based on the Daigneault et al. (2017), the present report and the remaining components of the Study.

Implications for human contact recreation

It is crucial to note that the decision as to which mitigation scenario (or combination of scenarios) should be further explored for the Kaipara Harbour in the future should be made based on a number of criteria, not just on these three freshwater sediment attributes, and not just based on expected effects (or lack thereof) on stream invertebrates or fish.

For example, the findings for visual clarity in several of the modelled scenarios that did not involve full afforestation have encouraging implications for human contact recreation, which is affected (in terms of both safety and aesthetics) by visual clarity in rivers (West et al., 2016). The ANZECC (2000) guidelines recommend that visual clarity should be greater than 1.6 m for contact recreation. In the Kaipara Harbour catchment, mean water clarity in the modelled Baseline scenario (1.24 m) and the Current Mitigation scenario (1.37 m) are both below that threshold, indicating that the current mean visual clarity is too low for the river to be generally suitable for contact recreation.

However, in four of the 10 modelled non-afforestation mitigation scenarios, mean visual clarity would increase to values at or above the 1.6 m guideline for contact recreation. These are Freshwater Node 30% (1.60 m), Marine 2 mm above 'natural' AASR (1.64 m), Stock Exclusion + All Highly Erodible Land Plans (1.66 m), and Stock Exclusion Rules plus Riparian Planting (1.67 m). These increases in visual clarity may be a benefit for those people living in the Kaipara catchment who would enjoy swimming in these rivers.

Future research needs

As a final general point, it should be noted that ecological effects of suspended fine sediment in streams and rivers have been much less extensively researched than those of deposited fine sediment (see reviews by Clapcott et al., 2011; Jones et al., 2012; Kemp et al., 2011; Ryan, 1991; Waters, 1995; Wood and Armitage, 1997). The impacts of deposited fine sediment on stream ecosystems are known to be far-reaching and include a number of well-documented negative effects on stream invertebrates, fish and ecosystem processes. The most commonly inferred mechanism driving the responses of benthic stream invertebrates to deposited fine sediment is a change in habitat (Clapcott et al., 2011), whereas fish are affected via impacts on both habitat and food supply (Kemp et al., 2011). Therefore, it would ultimately be desirable to link catchment sediment loads to in-stream levels of not just suspended fine sediment but also deposited fine sediment. However, this is a challenge for future research.

A complicating factor in this context is that the quantitative relationship between suspended fine sediment concentrations and deposited fine sediment levels in a given stream or river may not be straightforward. For example, two studies of New Zealand streams in dairy catchments (Matthaei et al., 2006; Ramezani et al., 2014) found that the amount of deposited fine sediment (determined as percentage sediment cover in the former study and as Suspendable Inorganic Matter (SIS) using the Quorer method in the latter) can increase considerably over one month even during relatively stable flow periods without bed-moving floods, presumably due to small but frequent surface runoff from farmland and/or bank erosion.

What can already be done in the Kaipara Harbour Catchment?

Regarding deposited fine sediment levels in streams and rivers in the Kaipara Harbour Catchment, Clapcott et al. (2011) used boosted regression tree models to predict the relative proportion of fine sediment cover in every stream reach in New Zealand (see Appendix 6.3 in Clapcott et al. for model details). They predicted both contemporary (Fig 4-24, p. 78 in Clapcott et al.) and "reference" (in the absence of human land-use impacts) in-stream sediment cover (Fig 4-25, p. 79 in Clapcott et al.). According to these predictive models, contemporary fine sediment cover in the Kaipara Harbour Catchment varies mainly between 60-100%, whereas reference sediment cover would be considerably lower at between 20-50%. Given this difference, the very high contemporary deposited fine sediment levels should be at least partly reversible, with expected positive effects on stream communities, making reducing in-stream deposited fine sediment a worthwhile longer-term goal to aim for. The regular (at least annual) collection of quantitative deposited fine sediment, stream invertebrate and fish data from the same sites at a suite of long-term monitoring sites located throughout the catchment (ideally spanning the widest currently available range of sediment cover values) would provide the necessary data base for being able to detect any longer-term improvements in ecological stream health related to changes in in-stream sediment levels due to mitigation measures implemented in the catchment.

Additional information following MfE Sediment Workshop, 2 November 2017

A recent NIWA-led research project (Depree et al. 2017) contains a review of suspended fine sediment effects on stream invertebrates. Notably, almost all suspended sediment values in the published literature reviewed in this context (see Table 5.2 on p. 80-81 of Depree et al. 2017) are considerably higher than the suspended sediment concentrations predicted for the seven individual river subcatchments. Furthermore, the "30% effect thresholds" for water clarity developed by Depree et al. (2017; see Table 5-5 and Fig 5-6, p. 94-95) based on their literature review are well below 1.0 m for most of the studied invertebrate metrics. In the Kaipara Study modelling, mean predicted water clarify is above 1 m even for the Baseline scenario, suggesting little or no adverse effects of suspended sediment on stream invertebrate communities. However, given that the Kaipara Harbour Catchment is far from pristine, one would expect to see at least some detrimental impacts on stream invertebrates due to elevated suspended sediment concentrations based on the thresholds developed by Depree et al. (2017). The difference between modelled and experimental/survey-based data casts some doubt on the modelled absolute (but not necessarily the relative) values of suspended sediment concentrations and water clarity.

A recent national-scale study led by NIWA (Hicks et al. 2016) found no relationship between catchment sediment loads and in-stream deposited fine sediment.

By contrast, an even more recent, targeted spatial survey conducted by Cawthron scientists (presented in Depree et al. 2017, p. 44-45) yielded more encouraging results. This study did find a fairly strong, non-linear relationship ($R^2 = 0.45$) between catchment sediment yield and in-stream deposited sediment determined as SIS (but not as % cover bankside) at 16 stream/river sites chosen to represent wide gradients of sediment yield and stream power and where long-term suspended sediment data were available. Consequently, it might be possible after all to link catchment sediment loads to in-stream levels of deposited fine sediment - but clearly more research is needed on this topic.

Further boosted regression tree modelling by J. Clapcott and colleagues (see Depree et al. 2017, p. 30-34 and Appendix N) used a model trained with data from 2,022 reference sites to predict reference state for all stream segments of the digital river network. This new model predicted a national median sediment cover of 13% and that 75% of stream segments have <30% sediment cover in reference state, while the remaining 25% of stream segments have >30% sediment cover. According to J. Clapcott (pers. comm.), this reference-site based modelling is the most reliable existing estimate of natural sediment covers for NZ streams and rivers. Fig. 3 (see next page) shows an enlargement of Fig. 2.8 in Depree et al. (2017) that focuses on the Kaipara Harbour Catchment.

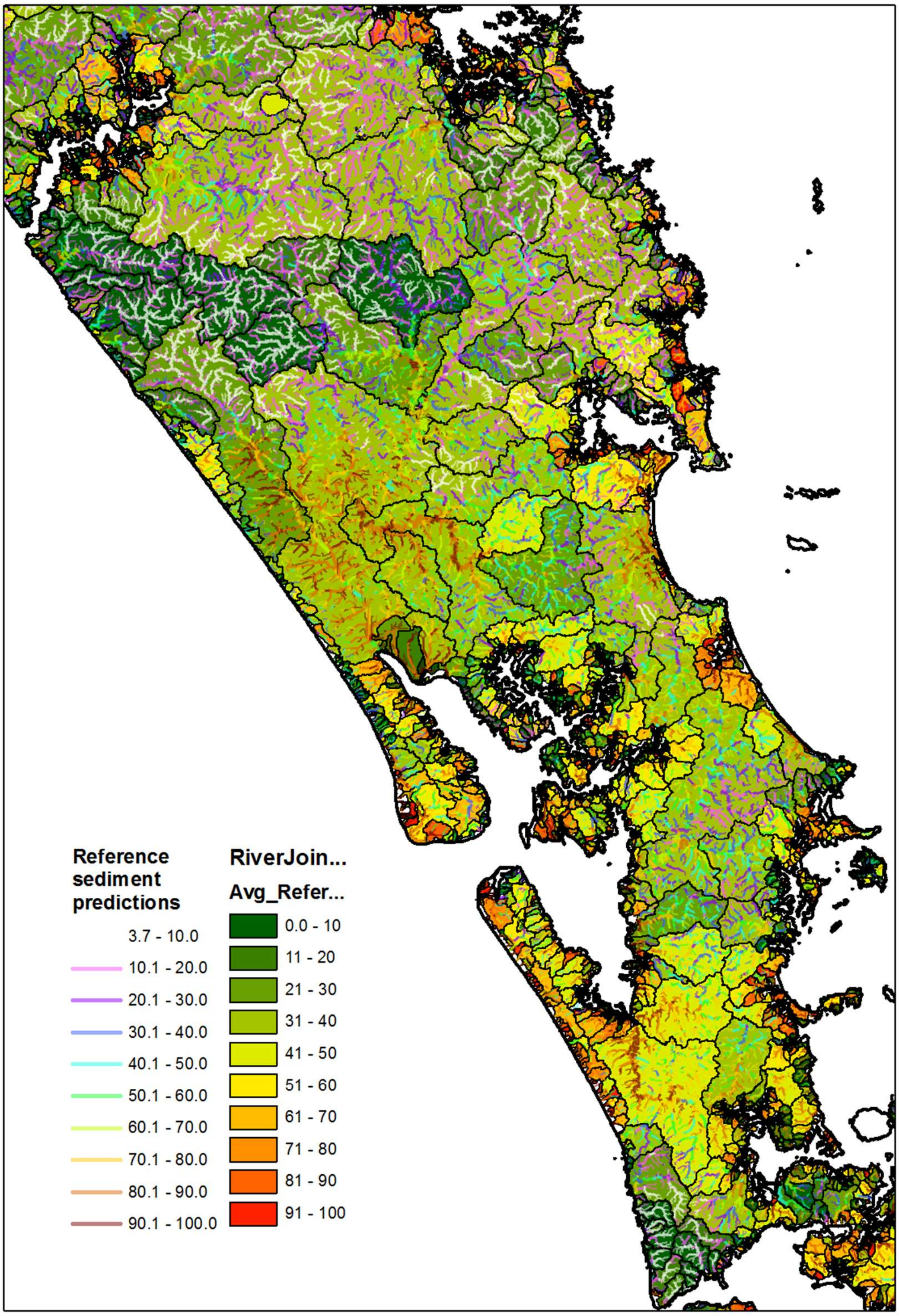

Figure 3. Predicted reference sediment cover (% Fines) for the Kaipara Harbour catchment from the Boosted Regression Tree 'REF' model (based on 2,022 reference sites) from Depree et al. (2017). The coloured areas (labelled 'RiverJoin Avg_Refer') show the per-subcatchment average of all reaches in a given subcatchment, and the coloured lines (labelled 'Reference sediment predictions') show individual reaches within each subcatchment. Enlargement reproduced with permission (E. Goodwin & J. Clapcott, Cawthron Institute).

The most recent boosted regression tree modelling in Depree et al. (2017) essentially confirms the predictions of the earlier modelling in Clapcott et al. (2011) for the Kaipara Harbour catchment: reference sediment cover ranges widely (from <10% to >90%) but mostly varies between 10-60% cover of fines across the different subcatchments (see the % cover averages of all reaches in each subcatchment in Fig. 1).

To accurately estimate instream deposited fine sediment cover at a given site, Depree et al. (2017, p. 70; amended by J. Clapcott, pers. comm) recommend that data should be collected monthly for at least two years. This amount of information is required to account for the temporal variation in sediment cover and the likely experimental error of visual estimates. (By contrast, SIS would require up to 6 years of quarterly measurements to accurately estimate mean values, a far greater effort.) To minimise the extra effort for Council staff, this sediment cover monitoring could be conducted together with the monthly periphyton data collection.

References

ANZECC (2000) Australia and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council. Agriculture and Resource Management Council of Australia and New Zealand http://www. mfe.govt.nz/fresh-water/tools-and-guidelines/anzecc-2000-guidelines.

Ausseil, O. (2013) Recommended biological and water quality limits for streams and rivers managed for contact recreation. Amenity and Stock Drinking Water in the Wellington Region. Report Prepared for Greater Wellington Regional Council. Aquanet, Palmerston North. http://www.gw.govt.nz/assets/Plans–Publications/Regional-Plan-Review/FINAL-REPORT-biological-and-water-quality-limits-for-contact-recreation-stock-watering-and-amenity-values-June-2013.PDF.

Basher L. (2017) Kaipara Harbour Sediment Mitigation Study – Mitigation Cost and Effectiveness. Landcare Research Analysis, January 2017.

Bond, N.R., Downes, B.J. (2003) The independent and interactive effects of fine sediment and flow on benthic invertebrate communities characteristic of small upland streams. Freshwater Biology, 48: 455–465.

Boubée, J., Dean, T.L., West, D.W., Barrier, R.F.G. (1997) Avoidance of suspended sediment by the juvenile migratory stage of six New Zealand freshwater fish species. N.Z. Journal of Marine & Freshwater Research, 31: 61–69.

Burdon, F. J., McIntosh, A. R., Harding, J. S. (2013) Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams. Ecological Applications, 23: 1036–1047.

Clapcott, J.E., Young, R.G., Harding, J.S., Matthaei, C.D., Quinn, J.M., Death, R.G. (2011) Sediment assessment methods: protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values. Cawthron Institute, Nelson, New Zealand.

Conroy, E., Turner, J.N., Rymszewicz, A., Bruen, M., O'Sullivan, J.J., Lawler, D.M., Lally, H., Kelly-Quinn, M. (2016) Evaluating the relationship between biotic and sediment metrics using mesocosms and field studies. Science of the Total Environment, 568: 1092–1101.

Daigneault, A., Dymond, J., Basher, L. (2017) Kaipara Harbour sediment mitigation study: Catchment economic modelling. Report prepared by Landcare Research for Northland Regional Council and Auckland Council, June 2017.

Davies-Colley, R.J., Ballantine, D.J., Elliott, S. H., Swales, A., Hughes, A.O., Gall, M.P. (2014) Light attenuation – a more effective basis for the management of fine suspended sediment than mass concentration? Water Science and Technology, 69: 1867–1874.

Davies-Colley, R.J., Smith, D.G. (2001) Turbidity, suspended sediment, and water clarity: a review. Journal of the American Water Resources Association, 5: 1085–1101.

Depree, C., Clapcott, J., Booker, D., Franklin, P., Hickey, C., Matheson, F., Shelley, J., Unwin, M., Goodwin, E., Mackman, J., Rabel, H. & Wagenhoff, A. (2017) Development of ecosystem health thresholds for suspended and deposited sediment in New Zealand rivers and streams. NIWA client report no. 2017076HN; prepared for Ministry for the Environment, June 2017.

Dymond, J. (2016) Kaipara Harbour Sediment Mitigation Study – Sediment loads in the Kaipara Harbour Catchment and Translation to Freshwater Sediment Attributes. Landcare Research Contract Report LC2413, November 2016.

Dymond J.R., Davies-Colley R.J., Hughes A.O., Matthaei C.D. (2017) Predicting improved optical water quality in rivers resulting from soil conservation actions on land. Science of the Total Environment, 603-604: 584–592.

Fausch, K.D., White, R.J. (1981) Competition between brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) for positions in a Michigan stream. Canadian Journal of Fisheries and Aquatic Sciences, 38: 1220-1227.

Green, M., Swales, A., Reeve, G. (2017) Kaipara Harbour Sediment Mitigation Study: Methods for Evaluating Harbour Sediment Attributes. Streamlined Report Report NRC1601–2 Prepared for Northland Regional Council and Auckland Regional Council, March 2017.

Hicks, D.M., Greenwood, M., Clapcott, J., Davies-Colley, R., Dymond, J., Hughes, A., Shankar, U. & Walter, K. (2017) Sediment Attributes Stage 1. NIWA Client Report No. CHC2016-058; prepared for Ministry for the Environment, June 2016.

Jones, J.I., Murphy, J.F., Collins, A.L., Sear, D.A., Naden, P.S., Armitage, P.D. (2012) The impact of fine sediment on macro-invertebrates. River Research and Applications, 28: 1055–1071.

Julian, J.P., Davies-Colley, R.J., Gallegos, C.L., Tran, T.V. (2013) Optical water quality of inland waters: a landscape perspective. Annals of the Association of American Geographers, 103: 309–318.

Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I. (2011) The impacts of fine sediment on riverine fish. Hydrological Processes, 25: 1800–1821.

Larsen, S., Ormerod, S.J. (2010) Low-level effects of inert sediments on temperate stream invertebrates. Freshwater Biology, 55: 476–486.

Matthaei, C.D., Weller, F., Kelly, D.W., Townsend C.R. (2006) Impacts of fine sediment addition to tussock, pasture, dairy and deer streams in New Zealand. Freshwater Biology, 51: 2154–2172.

Nakagawa, S., Cuthill, I.C. (2007) Effect size, confidence interval and statistical significance: a practical guide for biologists. Biological Reviews, 82: 591–605.

Newcombe, C.P., MacDonald, D.D. (1991) Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management, 11: 72–82.

Ramezani, J. (2014) Intensive land use effects on fish communities and their invertebrate prey in Otago, New Zealand. PhD thesis, University of Otago.

Ramezani, J., Rennebeck, L., Closs, G.P., Matthaei, C.D. (2014) Effects of fine sediment addition and removal on stream invertebrates and fish: a reach-scale experiment. Freshwater Biology, 59: 2584–2604.

Ramezani, J., Akbaripasand, A., Closs, G.P., Matthaei, C.D. (2016) In-stream physicochemistry, invertebrate and fish community health across a gradient of dairy farming prevalence in a New Zealand river catchment. Limnologica, 61: 14–28.

Rowe, D.K., Dean, T.L. (1998) Effects of turbidity on the feeding ability of the juvenile migrant stage of six New Zealand freshwater fish species. New Zealand Journal of Marine and Freshwater Research, 32: 21–29.

Ryan, P.A. (1991) Environmental effects of sediment on New Zealand streams: a review. New Zealand Journal of Marine and Freshwater Research, 25: 207–221.

Shaw, E.A., Richardson, J.S. (2001). Direct and indirect effects of sediment pulse duration on stream invertebrate assemblages and rainbow trout (*Oncorhynchus mykiss*) growth and survival. Canadian Journal of Fisheries and Aquatic Sciences, 58: 2213–2221.

Waters, T.F. (1995) Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7. American Fisheries Society, Bethesda, MD.

West, A.O., Nolan, J.M., Scott, J.T. (2016) Optical water quality and human perceptions of rivers: an ethnohydrology study. Ecosystem Health and Sustainability, 2:1–11.

Wood, P.J., Armitage P.D. (1997) Biological effects of fine sediment in the lotic environment. Environmental Management, 21: 203–217.