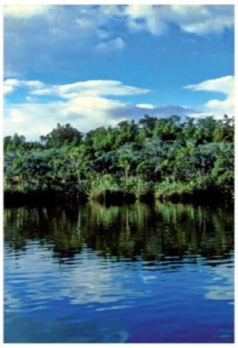
Effects of suspended sediment on freshwater fish

Envirolink Advice Grant: 1445-WCRC129



Landcare Research
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Effects of suspended sediment on freshwater fish

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Summary

Project and Client

- This report integrates new information on the effects of suspended sediment on fish with existing literature information to further develop guidance for determining acceptable suspended sediment concentrations in freshwater systems on the West Coast. The project was carried out for the West Coast Regional Council under Envirolink Grant 1445-WCRC129.

Objectives

- To provide additional information to develop guidance for determining acceptable suspended sediment concentrations in freshwater systems on the West Coast.

Methods

- Review of the published, peer-reviewed scientific literature and unpublished reports on the effects of sediment on fish and regulatory guidelines was undertaken. Also summarised here are the results of 96-h and 21-day laboratory trials of the effects of suspended sediment on four fish species conducted as part of an MBIE-funded research project.

Results

- Elevated suspended sediment concentrations may have direct or indirect effects on fish. Direct effects might be caused by the scouring and abrasive action of suspended particles, which damage gill tissues or reduce respiration by clogging gills, leading to susceptibility to infection or disease, reduced growth rate, or mortality. Younger fish, including sac fry, smolts and juveniles, are typically more sensitive than adults, for which direct lethal effects may not occur until extremely high concentrations occur that are uncommon in natural environments.
- Indirectly, fish may be affected by suspended sediments through decreases in water clarity, which can influence migration patterns, feeding success, and habitat quantity and quality, leading to decreased growth rates and changes in community structure and population size.
- Recent testing of four species – īnanga, kōaro, brown trout and eels – suggests that growth (length) of īnanga over 21 days may be affected at turbidity between 5 and 15 NTU, and between 15 and 50 NTU for kōaro. There was no apparent effect on weight of these species with turbidity levels up to 200 NTU. Similarly, no effect on growth (length) of brown trout was observed up to 200 NTU. There was a marked decrease in the mean weight gain for trout at all treatment levels, although this was not statistically significant. The low number of replicates (i.e. five fish) meant that the high variability between individuals affected the statistical analysis. Further testing with a greater number of individuals (to reduce variability) is required to determine whether this

decreased weight gain is significant. Eels were not affected by turbidity levels of up to 200 NTU.

Conclusions

- Determining the effects of suspended sediment on fish is challenging and there is limited information available on which to set robust guidelines for acceptable suspended sediment concentrations. Currently available data are difficult to compare, because of the different effects examined, different methods used to assess these effects and different methods used to determine suspended sediment concentrations (TSS mg/L or turbidity NTU).
- International guidelines for suspended sediment vary: in New Zealand ANZECC water quality guidelines of 4.6 and 5.6 NTU are based on visual clarity for upland and lowland streams;, in Canada guidelines based on effects on fish include a maximum increase of 8 NTU or 25 mg/L above background levels for short-term exposure (e.g. 24 h) and maximum average increase of 2 NTU or 5 mg/L for any long-term exposure; while in Europe suspended sediment concentrations should not exceed 25 mg/L for salmonid and cyprinid habitats.
- Our laboratory trials provided evidence for effects on the growth rate of fish at between 5 and 15 NTU. These results are broadly supportive of current limits used on the West Coast for determining acceptable sediment discharges.

Recommendations

- Further testing of effects on fish growth rate using a greater number of individuals and wider range of species would provide additional information to further delineate the suspended sediment concentrations at which effects are observed.
- Given the challenging nature of determining the effects of suspended sediment on fish, a range of testing strategies (e.g. in-stream studies, flume testing) are required to provide more definitive information on the effects and wider ecological impacts of suspended sediment on fish.

1 Introduction

Current research conducted through an MBIE-funded programme by the School of Biological Sciences at the University of Canterbury and Landcare Research is providing new information on the effects of fine suspended sediment on fish. This report integrates these new data with information from the existing literature to further develop guidance for determining acceptable turbidity levels for freshwater systems on the West Coast. The report focuses on the effects of suspended sediment and sediment only, as opposed to the effects of sediment with adsorbed contaminants. Some discussion on the effects associated with deposited sediment is provided. The project was carried out for the West Coast Regional Council under Envirolink Grant 1445-WCRC129.

2 Background

Owing to the ‘flashy’ nature of West Coast rivers, total suspended solids (TSS) can be present at naturally high levels in disturbed systems such as mining areas. The effects on freshwater ecosystems of fine sediment generated from mine or quarry sites are, however, inadequately understood, and thus it is not known what constitutes acceptable sediment limits. Some guidance for developing sediment limits for the West Coast to protect macroinvertebrates has been provided previously (Reid & Quinn 2011), but there remains a scarcity of data on sediment thresholds for the protection of fish species.

‘Fine sediment’ is defined as inorganic particles that range in size from 0.45 µm to 2 mm (Clapcott et al. 2011). Fine sediments of anthropogenic origin are recognised as major contaminants of aquatic ecosystems. Inputs of sediment can exert a diverse range of direct and indirect effects upon aquatic organisms and can result in significant changes to aquatic habitat and biota (e.g. Ryan 1991; Bilotta & Brazier 2008; Clapcott et al. 2011). These effects may result as much from entrained and adsorbed toxicants, pathogens and the *chemical constituency* of the mineral material in suspension as they do from the *physical effects* of abrasion, adherence, infilling and smothering. The sediment effects change from *suspended* sediment issues close to the source to effects associated with sediment *deposition* further downstream. The rate of deposition will depend on the physical characteristics of the sediment, and water velocity and turbulence.

Measurements of suspended sediments are typically reported in either turbidity levels (Nephelometric Turbidity Units or NTU) or suspended sediment concentrations (mg/L). Turbidity is a water quality measure related to and often used as a surrogate for suspended sediments in monitoring programmes, but care must be taken in comparing results from studies reported in these different units as they are not necessarily translatable. Turbidity is a relative measure of the scattering of light caused by suspended particles in the water. Thus, a greater amount of suspended particles in the water results in higher measured turbidity levels. However, turbidity can also be influenced by suspended particles other than inorganic sediment (e.g. organic matter, algal cells). Thus it is possible to have high turbidity without high suspended sediments concentrations (Bilotta & Brazier 2008). Furthermore, turbidity is also influenced by the physical and optical properties of the suspended particles (e.g. particle size, shape, mineral composition) and the amount of dissolved colour (e.g. humic substances), which can vary widely between waterways and within a waterway over time (Davies-Colley & Smith 2001; Bilotta & Brazier 2008). In contrast, suspended sediment concentration is a direct measure of the mass of sediments suspended in a water sample.

Therefore, the relationship between turbidity and suspended sediment concentrations can be strong or highly variable (Davies-Colley et al. 1992; Culp et al. 2009). To be useful, turbidity measurements need to be calibrated with suspended sediment concentrations over a range of discharges to be used as a baseline, or on an individual waterway basis to examine local effects (Henley et al. 2000), or for a given study both measures may be reported.

3 Objective

- To provide additional information to develop guidance for determining acceptable suspended sediment concentrations in freshwater systems on the West Coast.

4 Effects of sediment on fish

Suspended and deposited sediments can impact fish directly through physical effects or indirectly through effects on water clarity or the habitat that fish rely on for feeding, cover, or reproduction. A number of reviews on the effects of sediment in aquatic systems have been undertaken in New Zealand (Ryan 1991; Crowe & Hay 2004; Reid & Quinn 2011). Here, we provide a brief overview from the literature of the effects of sediments on fish in streams, with a primary focus on suspended sediments and studies undertaken in New Zealand.

4.1 Suspended sediments – direct and indirect effects

Elevated levels of suspended sediments can impact fish by physically damaging tissues and organs or by decreasing light penetration and visual clarity in the water, which can cause a range of effects from behavioural changes to mortality. The severity of the impact may depend on several factors, including sediment concentration, duration or frequency of exposure, particle size and shape, associated pollutants, species, and life stage at time of exposure (Collins et al. 2011; Kemp et al. 2011).

Most direct effects are caused by the scouring and abrasive action of suspended particles, which damages gill tissues or reduces respiration by clogging gills, leading to decreased resistance to infection or disease, reduced growth, or mortality (Ryan 1991; Wood & Armitage 1997) (Table 1). Severe gill damage, gill thickening, and clogging tend to occur at relatively high levels of suspended sediments (i.e. >500 mg/L), but this level can differ between species and life stages, with minimal to no damage reported for some species at very high concentrations (e.g. arctic grayling; McLeay et al. 1987). However, longer exposure times to lower levels of suspended sediment (100 mg/L) can still cause moderate gill damage (Sutherland & Meyer 2007) (Table 1). Furthermore, small, angular sediment particles can be more damaging to gills than larger or rounded ones (e.g. Lake & Hinch 1999). The physiological stress caused by exposure to elevated concentrations of suspended sediments over time can make fish more susceptible to infection, parasitism and disease (e.g. fin rot; Herbert & Merkens 1961). Studies have shown consistent declines in growth rates (Table 1).

Table 1 Summary of the direct effects of suspended sediment (SS) on fish, reported in either turbidity or suspended sediment concentration. The SS measure (concentration or NTU – Nephelometric Turbidity Units) reflects the level at which significant effects were observed. Studies are ordered by increasing SS measure within effect type (e.g. gill damage, growth)

Taxon	*SS measure*	*Duration*	*Method*	*Effect*	*Country*	*Reference*
Gill damage						
Whitetail shiner	100–500 mg/L	21 d	Lab tank	Thickening of gill lamellae	USA	Sutherland & Meyer (2007)
Brown trout	810 mg/L	21 d	Lab tank	Gill thickening	England	Herbert & Merkens (1961)
Rainbow trout	4887 mg/L	64 d	Lab tank	Slight gill thickening	Canada	Goldes et al. (1988)
Redbreast tilapia	35 000 mg/L	1–48 h	Lab tank	Severely clogged gills (juveniles)	South Africa	Buermann et al. (1997)
Coho salmon	40 000 mg/L	4 d	Lab tank	Damage to gill filaments	Canada	Lake & Hinch (1999)
Redbreast tilapia	60 000 mg/L	1–48 h	Lab tank	Severely clogged gills (adults)	South Africa	Buermann et al. (1997)
Various species	104 000 mg/L	1 d	In-stream	Gill clogging	Bolivia	Swinkel et al. (2014)
Arctic grayling	250 000 mg/L	4 d	Lab tank	No gill damage	Canada	McLeay et al. (1987)
Growth						
Brook trout	10–40 NTU	12 h	Artificial channel	Reduced growth rate	USA	Sweka & Hartman (2001a)
Long steelheads	25 NTU	14–21 d	Lab channel	Reduced growth	USA	Sigler et al. (1984)
Arctic grayling	100 mg/L		Lab tank	Reduced growth	Canada	McLeay et al. (1984)
Spotfin chub	500 mg/L	21 d	Lab tank	Reduced growth rate	USA	Sutherland & Meyer (2007)
Disease						
Steelhead	2500 mg/L	11 d	Lab tank	Increased susceptibility to pathogen	USA	Redding et al. (1987)
Survival						
Coho salmon	100 mg/L	4 d	Lab tank	Increased mortality	Canada	Lake & Hinch (1999)
Smelt	3000 mg/L	24 h	Lab tank	LC50	New Zealand	Rowe et al. (2009)
Redbreast tilapia	21 000–24 000 mg/L	1–48 h	Lab tank	LC50 (juveniles)	South Africa	Buermann et al. (1997)
Redbreast tilapia	42 000–48 000 mg/L	1–48 h	Lab tank	LC50 (adults)	South Africa	Buermann et al. (1997)
Banded kōkopu	43 000 mg/L	24 h	Lab tank	Survival not affected	New Zealand	Rowe et al. (2009)
Īnanga	43 000 mg/L	24 h	Lab tank	Survival not affected	New Zealand	Rowe et al. (2009)
Various species	104 000 mg/L	1 d	In-stream	High % mortality	Bolivia	Swinkel et al. (2014)

For example, significant reductions in growth rate in two minnow species exposed to suspended sediments have also been linked to impaired respiration (Sutherland & Meyer 2007). In many cases, suspended sediments directly influence fish by reducing overall rates of survival, causing declines in populations (Henley et al. 2000). Mortality can occur at concentrations ranging from 20 to 207 000 mg/L (reviewed by Newcombe & MacDonald 1991). Younger fish – including sac fry, smolts and juveniles – have been shown to be more sensitive than adults, for which direct lethal effects may not occur until extremely high concentrations that are uncommon in natural environments.

Indirectly, fish are affected by suspended sediments through decreases in water clarity (increased turbidity), which can alter movement or migration patterns, feeding success, and habitat quantity and quality. These effects can cause decreased growth rates and changes in community structure and population sizes (Kemp et al. 2011) (Table 2). Many fish avoid turbid waters by temporarily seeking refuge or moving to unimpacted stream reaches (Wood & Armitage 1997). Avoidance responses have been recorded at different turbidity levels, highlighting the sensitivity of different species to reduced water clarity (Table 2). For example, Richardson et al. (2001) showed that the upstream migration of banded kōkopu (*Galaxias fasciatus*) was reduced when turbidity exceeded 25 NTU, resulting in recruitment limitation. Elevated turbidity also tends to reduce feeding activity, rates and success by impairing the visual cues fish use to detect prey and by reducing the availability of food, for both benthic and drift-feeding fish (Newcombe & MacDonald 1991; Harvey & White 2007; Bilotta & Brazier 2008). Feeding rates vary over a wide range of turbidity for different species (Table 2), with declines in the distance at which fish react to, capture, or consume prey occurring at as low as 5–10 NTU. Further, declines in macroinvertebrate abundance, particularly sensitive or drifting taxa (e.g. mayflies), reduces preferred prey items and food supply for fish (Bilotta & Brazier 2008). Even when prey are abundant in turbid waters, reduced feeding efficiency of visual-feeding fish and greater energetic costs have been linked to lower growth rates (Sweka & Hartman 2001a; Kemp et al. 2011). Frequent or extended periods of high turbidity may also result in changes in fish distribution and community structure. This occurs when sensitive species are replaced with those more tolerant of the turbid conditions, increased sediment, and poorer habitat (Henley et al. 2000; Richardson & Jowett 2002).

In New Zealand, studies on the effects of suspended sediments on fish have focused on feeding, avoidance behaviour, migration and survival. The sensitivity of banded kōkopu has been highlighted with avoidance responses, reduced feeding rates, reduced in-stream occurrence, and limited upstream migration observed when turbidity exceeded 25 NTU in both laboratory and in-stream studies (Boubée et al. 1997; Rowe & Dean 1998; Rowe et al. 2000; Richardson et al. 2001) (Tables 1 & 2). Due to this sensitivity and their widespread distribution, banded kōkopu have been suggested as a useful benchmark species for the protection of fish in turbid waters in New Zealand (Rowe et al. 2002). In contrast, longfin eels, redfin bullies, and īnanga were more tolerant of elevated suspended sediments and did not exhibit avoidance responses or reductions in feeding rates until much higher turbidity levels, if at all (e.g. 420–1100 NTU; Tables 1 & 2) after short-term pulses of sediments in laboratory experiments (Boubée et al. 1997; Rowe & Dean 1998; Rowe et al. 2002). Lethal concentrations of suspended sediments have been established for common smelt (24-h LC50: 3000 mg/L; Rowe et al. 2009). In that study, survival of common smelt was reduced when suspended sediment concentrations were greater than 1000 mg/L, whereas concentrations up to 43 000 mg/L were not lethal to banded kōkopu or redfin bully. Futhermore, survival of smelt was not affected when they were repeatedly exposed (4 h, every 2–3 days) to high suspended sediment concentrations typical of flood events (800–1000 mg/L) over a 3-week period (Rowe et al. 2009).

Table 2 Summary of indirect effects of suspended sediment (SS) on fish reported in either turbidity or suspended sediment concentration. The SS measure (Nephelometric Turbidity Units, NTU) reflects the level at which significant effects were observed. Studies are ordered by increasing SS measure within effect type (e.g. feeding and foraging success, behaviour)

Taxon	*SS measure*	*Duration*	*Method*	*Effect*	*Country*	*Reference*
Feeding & foraging success						
Sable fish	5–10 NTU	70 min	Lab tank	Reduced prey consumption	USA	De Robertis et al. (2003)
Rosyside dace	10–30 NTU	40 min	Lab tank	Decreased reactive distance	USA	Hazelton & Grossman (2009)
Yellowfin shiners	10–30 NTU	40 min	Lab tank	Decreased reactive distance	USA	Hazelton & Grossman (2009)
Brook trout	10–40 NTU	12 h	Artificial channel	Decreased reactive distance	USA	Sweka & Hartman (2001b)
Brook trout	10–40 NTU	12 h	Lab tank	Reduced capture success	USA	Sweta & Hartman (2001b)
Rainbow trout	15–30 NTU	1 h	Artificial channel	Reduced reactive distance by 20–55%	USA	Barrett et al. (1992)
Banded kōkopu	20 NTU	2 h	Lab tank	Reduced feeding rate	New Zealand	Rowe & Dean (1998)
Redfin bully	40–640 NTU	2 h	Lab tank	Reduced feeding rate	New Zealand	Rowe & Dean (1998)
Cutthroat trout	100 NTU	18–24 h	Lab tank	70% reduction in drift feeding success	USA	Harvey & White (2007)
Coho salmon	100 NTU	18–24 h	Lab tank	70% reduction in drift feeding success	USA	Harvey & White (2007)
Common bully	160 NTU	2 h	Lab tank	Reduced feeding rate	New Zealand	Rowe & Dean (1998)
Īnanga	160 NTU	1 h	Lab tank	No significant effect on feeding rate	New Zealand	Rowe et al. (2002)
Smelt	160 NTU	1 h	Lab tank	No significant effect on feeding rate	New Zealand	Rowe et al. (2002)
Rainbow trout	160 NTU	30 min	Lab tank	No significant effect on feeding rate	New Zealand	Rowe et al. (2003)
Coho salmon	200 NTU	18–24 h	Lab tank	Almost 0% success in benthic feeding	USA	Harvey & White (2007)
Īnanga	640 NTU	2 h	Lab tank	Reduced feeding rate	New Zealand	Rowe & Dean (1998)
Smelt	640 NTU	2 h	Lab tank	Reduced feeding rate	New Zealand	Rowe & Dean (1998)

Steelhead	2000–3000 mg/L	7 days	Lab tank	Reduced feeding activity	USA	Redding et al. (1987)
Behavioural						
Brook trout	5–10 NTU	70 min	Lab tank	Disrupted predator-prey interactions	USA	De Robertis et al. (2003)
Steelhead and coho salmon	11–51 NTU	14–21 days	Lab tank	Avoidance	USA	Sigler et al. (1984)
Banded kōkopu	17–25 NTU	20 min	Lab tank	Avoidance response (50%)	New Zealand	Boubée et al. (1997)
Coho salmon	20 NTU			Reduced predator-prey interactions	USA	Berg & Northcote (1985)
Banded kōkopu	>25 NTU	100 s	In-stream	Reduced upstream migration	New Zealand	Richardson et al. (2001)
Kōaro	70 NTU	20 min	Lab tank	Avoidance response (50%)	New Zealand	Boubée et al. (1997)
Coho salmon	370 NTU		Lab tank	Disrupted predator-prey interactions	USA	Gregory & Northcote (1993)
Īnanga	420 NTU	20 min	Lab tank	Avoidance response (50%)	New Zealand	Boubée et al. (1997)
Redfin bully	1110 NTU	20 min	Lab tank	No avoidance	New Zealand	Boubée et al. (1997)
Longfin eel	1110 NTU	20 min	Lab tank	No avoidance	New Zealand	Boubée et al. (1997)
Shortfin eel	1100 NTU	20 min	Lab tank	No avoidance	New Zealand	Boubée et al. (1997)
Coho salmon	88 mg/L	30 min	Lab tank	Avoidance	USA	Bisson & Bilby (1982)
Banded kōkopu	120 mg/L	5 months	In-stream	Reduced occurrence during migration	New Zealand	Rowe et al. 2000

Finally, in-stream studies have shown that community structure changed and native fish diversity and abundance were reduced with increased sediment loads. For example, Rowe et al. (2000) found that the mean occurrence of banded kōkopu was reduced by 89.5% in turbid rivers (defined as those where suspended sediment concentrations exceeded 120 mg/L for over 20% of the time) and other diadromous fish species were also less common. Similarly, Richardson and Jowett (2002) found that fish abundance and diversity reduced as sediment load increased among streams, with up to nine fish species in streams with low sediment loads and only two species in streams with high sediment loads (up to 830 mg/L). The need for a better understanding of the mechanisms driving species-specific responses of fish to elevated sediments in New Zealand streams and rivers has been suggested (Rowe et al. 2009).

4.2 Deposited sediments

Suspended sediment is ultimately deposited at some point in the system, and this can also result in negative impacts. The effects of deposited sediments on fish have been shown to be mostly related to habitat degradation and loss – mainly through declines in the quantity and quality of spawning areas, and reduced food supply. High or continuous levels of sedimentation on streambeds can lead to alterations in fish presence and community structure, reduced reproductive success, and increased rates of mortality, particularly of eggs and larvae (Wood & Armitage 1997; Kemp et al. 2011). By infilling interstitial spaces, covering substrata, or burying woody debris, deposited sediments can reduce habitat complexity and cover for fish and significantly alter available habitat (Henley et al. 2000). Fish eggs and sac fry are especially sensitive to deposited sediments, which can smother or bury eggs and decrease oxygen supply by reducing water velocity and flow through substrata, resulting in reduced egg hatching, increased mortality of eggs, and entrapment of emerging fry (e.g. Servizi & Martens 1991; Greig et al. 2007). A decrease in the availability of suitable spawning and rearing areas reduces spawning activity and can supress reproductive potential and success (e.g. Turnpenny & Williams 1980). Furthermore, deposited sediments have been shown to hinder development of eggs, fry, and larvae and disrupt developmental progress (e.g. age at smolting for salmonids; Suttle et al. 2004). Reductions in habitat quantity and quality and cover also affect juveniles and adults, particularly those that prefer cobbled beds with large interstitial spaces for refuge (Collins et al. 2011; McEwan & Joy 2013). Prey availability and quality for fish can also decrease because of the adverse effects of sedimentation on benthic macroinvertebrates (e.g. significantly reduced abundances, increase in burrowing taxa; Wood & Armitage 1997; Suttle et al. 2004; Burdon et al. 2013). This reduction in food supply, combined with reduced feeding efficiency, can lower growth rates over time (Collins et al. 2011). Finally, as sedimentation increases, fish may relocate temporarily causing short-term declines in population sizes or may lead to more permanent changes in community composition over time (e.g. Jowett & Boustead 2001). For example, high levels of sediment deposition in streams reduced the distinction between riffles, pools, and runs resulting in declines in abundance of riffle-dwelling benthic invertebrates (Berkman & Rabeni 1987).

In New Zealand, the effects of deposited sediments on fish are usually reported in studies related to habitat suitability, species-specific habitat use or small-scale distribution of native species (e.g. Jowett & Boustead 2001; Akbaripasand et al. 2011; McEwan & Joy 2013). Few quantitative relationships between deposited sediment and fish populations have been established in New Zealand. A summary of studies reporting these relationships is provided by Clapcott et al. (2011).

4.3 Effect of suspended sediment on fish – recent testing

As part of a related MBIE research project (CRLE1202 – Minerals Sector Environment Framework), the effects of suspended sediment on feeding rate and growth were assessed under laboratory conditions.

4.3.1 Feeding rate trials

Feeding rate trials were undertaken using a 6-m-long (280 mm deep, 250 mm wide) flume located at the Natural Resource Engineering facilities at Lincoln University. Five cages of approximately 1 m in length were created along the length of the flume using steel mesh as partitions. An electric pump was used to continuously recirculate approximately 780 L of low salinity water at a flow rate of ~0.1 m/s. Eels (*Anguilla* spp.), brown trout (*Salmo trutto*) and kōaro (*Galaxias brevipinnis*) were collected in the field and transported to the laboratory in bubbled containers. In the laboratory, fish were placed in 30-L holding tanks with a low-concentration saline solution for a minimum of 1 day prior to the transfer to the flume. Fish were placed in individual cages with a large cobble (>15-cm-long axis) and to acclimatise, with feeding, to the flume conditions for 2 days prior to commencement of experiments. Fish were not fed for 24 h prior to being included in an experiment.

The planned experiment was to assess feeding rate by using video camera footage to determine the time to consumption of, and distance travelled by, food items (dried blood worm) that float on the surface of the water at five suspended sediment concentrations (0, 5, 15, 50, and 200 NTU). However, initial trials found that eels and kōaro do not take food from the surface under these conditions, and thus this is not a useful system to test feeding rate effects associated with suspended sediment for these species. While brown trout did take food from the surface, insufficient numbers of trout meant that full testing did not occur.

4.3.2 Fish-growth laboratory trials

Methods

To assess the effects of suspended sediment on fish growth and condition, 96-h and 21-day trials with four species (īnanga (*Galaxias* spp.), brown trout, eels, and kōaro) were conducted at the University of Canterbury. Fish were collected in the field and transported to the laboratory in bubbled containers. In the laboratory, fish were treated in a low-concentration saline solution for a minimum of 3 days prior to the experiment. Preliminary experiments showed fish were subject to fungal infection when stressed and the best treatment was treating with salt. For the experiment, individual fish were placed in a 30-L tank equipped with a pump and a large cobble (>15-cm-long axis). All species tested use cover in the wild and fish were less agitated when cobble cover was provided. Experiments were run in a temperature-controlled room at 15ºC, with a 12-h day–night cycle. We used five replicates of each of five turbidity treatments (0, 5, 15, 50 and 200 NTU). All tanks were cleaned every day to remove waste products and reduce biofilm growth. Fish were fed daily on frozen or dried bloodworms. At the beginning and end of each experiment the body length and wet weight of all fish were measured. Wet weights were measured by placing live fish in a plastic bag with a pre-weighed amount of water, and body length (snout to fin ray) was measured using a fish board. On at least two occasions during each experiment, turbidity (NTU) and total suspended solids (TSS) were measured in randomly selected tanks. Turbidity was created in each experiment by adding fine ceramic clay. Preliminary trials indicated this clay was non-toxic and remained in suspension for several days in tanks with pumps circulating the water. The daily cleaning included re-suspending any deposited clays.

Experiments were run for 96 h to determine any *acute toxicity* effects, and then continued for a total of 21 days in order to measure any loss of condition or *chronic* effects.

Results

Only one fish died during the four 96-h and 21-day trials. The standard 96-h trials were designed to test any short-term toxicity due to suspended sediment. However, as no treatments of any of the four species showed mortality over this time, all trials were continued for a further 17 days.

Over the 21 days, īnanga showed a significant decline in body length as turbidity increased (Figure 1). At 0 and 5 NTU fish increased in body length, but at 15 NTU fish did not increase body length. In contrast, no change in body weight was detected regardless of NTU. Brown trout showed no change in length in all treatments including the control. We expected to see some trout growth over 21 days, so this may have been due to the fish not being provided with enough daily food to show growth. While statistically there was no decrease in trout weight – due to the large variance between individuals, the markedly lower mean weight gain at all treatments other than the control is suggestive of a negative impact occurring. Further testing with a greater number of individuals is required to validate this observation. For kōaro, there was a smaller increase in body length at 50 NTU than at lower turbidity levels, although no effect on weight was apparent. Eels showed no change in weight or body length over 21 days for all turbidity levels. As eels are long-lived, our 21-day trials may not have been long enough to detect growth in these fish (data not shown).

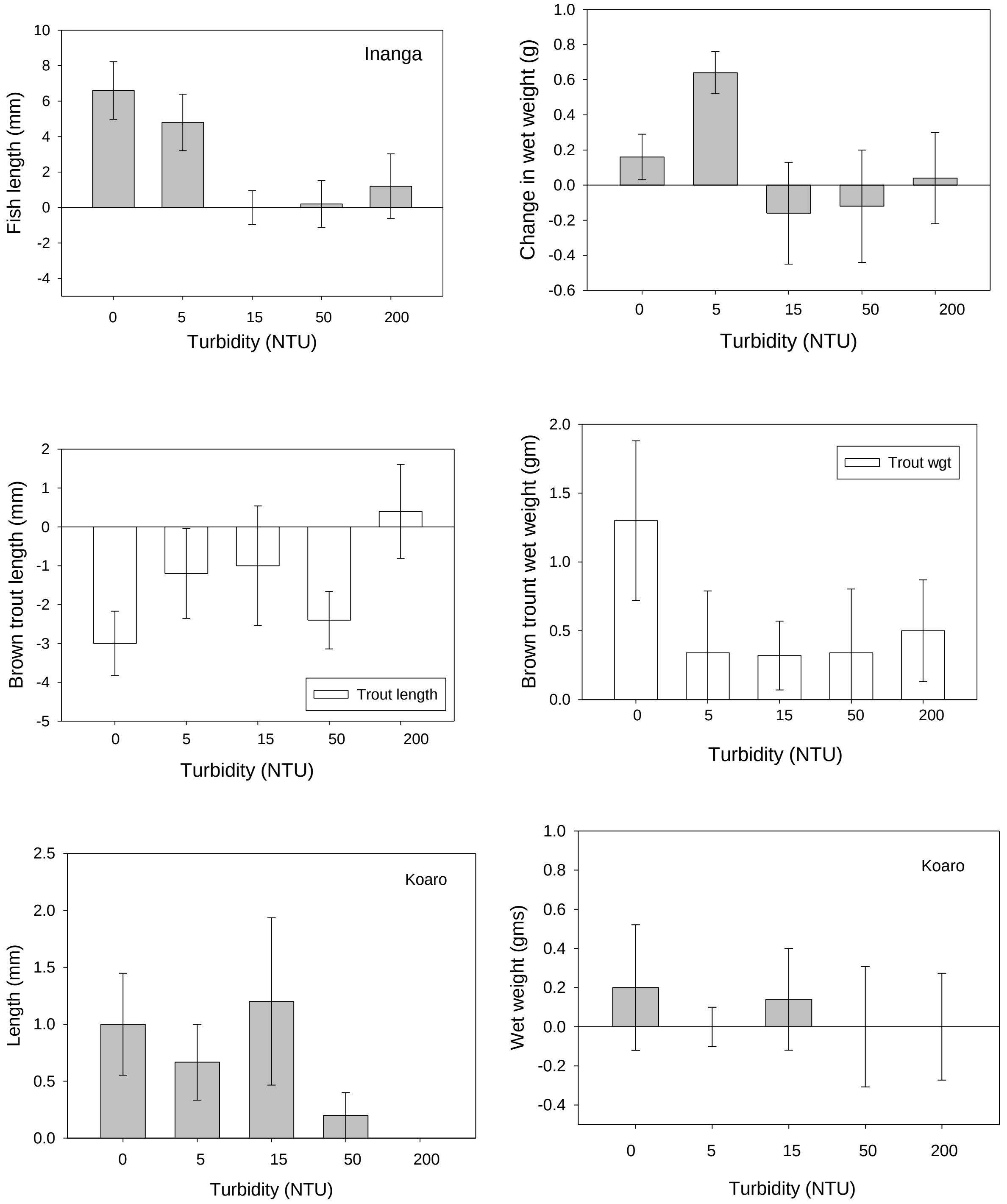

Figure 1 Mean length change (± 1 SE) (first column) and weight (second column) in īnanga, brown trout and kōaro over 21 days at different suspended sediment concentrations.

5 Regulatory approaches to mitigating the biological effects of sediment inputs

5.1 Regulatory context

Water quality or sediment guidelines (or criteria) have been established by various government agencies responsible for managing fresh water for the protection of aquatic biota. Internationally, guidelines have been derived using a variety of different approaches and are either numerical, narrative (e.g. ‘free of colour’) or related to undesirable biological effects (e.g. ‘no adverse effects’; Berry et al. 2003). Defining guidelines is a challenge, in view of the diversity of environments in which they are expected to be applied, the range of conditions experienced in these environments (e.g. drought to flood), and variation in species responses to sediments (Bilotta & Brazier 2008). National or federal guidelines tend to be set at a broad level and then be used as a basis for state, provincial, or regional guidelines that may aim for greater or lesser protection depending on differences in environment, land use, management needs or priorities.

5.2 Suspended sediment guidelines

Most international guidelines use turbidity or total suspended solids as a measure of suspended sediments and give an absolute value (e.g. not greater than 25 mg/L) or are stated in the form of exceedance over a background level (e.g. maximum increase of 8 NTU above background) (Table 3).

In the United States, many states have set their own numeric or narrative (or both) guidelines, but there is little consistency among these (see US EPA (2006) Appendix D for guidelines listed by state) (Berry et al. 2003). Comparisons of guidelines can be difficult, particularly when written as an exceedance above background levels, as often, what constitutes ‘background’ is not well defined. In the European Union (EU), guidelines for suspended sediment concentrations are minimal; however, a guideline value for the EU Freshwater Fish Directive was established to support and protect salmonids and cyprinids (Table 3). In British Columbia (Canada), the scientific rationale for water quality guidelines related to suspended sediments and turbidity are provided by Caux et al. (1997). In the case of suspended sediments, the guideline values are based on changes in concentration that result in an increase of 1 in a severity-of-ill-effects score – determined from a severity-of-ill-effects model – for the most sensitive taxonomic group of organisms, which are salmonids in British Columbia (Caux et al. 1997). In many cases, the scientific basis or biological justification supporting the guideline value is not given.

In New Zealand, narrative guidelines provided by the Resource Management Act 1991 (i.e. ‘no conspicuous change in colour or clarity’), together with numeric guidelines for turbidity and visual clarity, measured as black disc, are most commonly used as guidelines for measuring limits for suspended sediments. For many rivers, the concentration of suspended sediments is positively related to turbidity, and both turbidity and sediment concentration are negatively related to visual clarity in the water (e.g. Davies-Colley & Close 1990).

Table 3 Summary of water quality guidelines related to suspended sediment levels in Australia, New Zealand, Canada, the European Union, and the United States, produced by, or for, government environmental agencies.

Country (Region)	*Standard*		*Reference*
	Upland rivers (>150 – <1500 m altitude)	**Lowland rivers (<150 m altitude)**	
New Zealand	4.1 NTU (0.6 m visual clarity)	5.6 NTU (0.8 m visual clarity)	ANZECC (2000)
Australia (south-east)	2–25 NTU	6–50 NTU	ANZECC (2000)
Australia (south-west)	10–20 NTU	10–20 NTU	ANZECC (2000)
Australia (tropical)	2–15 NTU	2–15 NTU	ANZECC (2000)
Australia (south-central)	1–50 NTU	1–50 NTU	ANZECC (2000)
Canada	Clear flow: maximum increase of 8 NTU or 25 mg/L above background levels for short-term exposure (e.g. 24 h). Maximum average increase of 2 NTU or 5 mg/L for any long-term exposure (e.g. 24 h – 30 days).		CCME (2007)
	High flow: maximum increase of 8 NTU or 25 mg/L above background levels at any time when background levels are between 8 and 80 NTU or 25 and 250 mg/L, respectively. Should not increase more than 10% of background levels when background is >80 NTU or ≥250 mg/L		CCME (2007)
European Union	25 mg/L should not be exceeded, with the exception of floods or droughts, for both salmonids and cyprinids		European Parliament and Council - Freshwater Fish Directive (2006/44/EC)
United States	Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life		US EPA (2007)

Most guidelines set by regional councils are based on the Australian and New Zealand Environment Conservation Council (ANZECC 2000) and Ministry for the Environment (1994) water quality guidelines and are stated as an absolute value, a range of acceptable values or a maximum percent change in turbidity or visual clarity depending on site conditions, waterbody type, group, or water management subzone (Tables 3 & 4). The rationale for selection of guideline values, if stated in regional plans or as part of monitoring programmes, includes derivation from national or other standards and guidelines, or are based on research or expert opinion, although details are not necessarily provided. A few councils are currently developing guidelines specific to suspended solids and sediments (e.g. Waikato, Taranaki). Specific guidelines have been recommended to protect brown trout and fisheries values in the Manawatu-Wanganui region (Hay et al. 2006) and macroinvertebrates in West Coast rivers (Quinn et al. 1992; Reid & Quinn 2011). For the Manawatu-Wanganui Region, turbidity and visual clarity guidelines apply to fisheries identified as: (1) outstanding or regionally significant (0.5 NTU and 5 m); (2) other significant fisheries (0.7 NTU and 3.75 m); and (3) spawning streams (0.7 NTU and 3.75 m). These guidelines were developed using foraging model predictions and should maintain reaction distances of drift-feeding trout at acceptable levels with increases in turbidity (Hay et al. 2006). Guidelines recommended for protecting macroinvertebrate abundance and species richness are a maximum average increase in turbidity of less than 5 NTU (or <5 g/m^3 TSS) and less than 20 NTU, respectively, in gravel-bed rivers on the West Coast (Quinn et al. 1992; Reid & Quinn 2011).

Table 4 Summary of water quality guidelines related to suspended sediment levels used by regional councils in New Zealand. Guidelines are used for purposes of monitoring ecosystem health, protecting aquatic life, or managing aquatic ecosystems. Note: Links to sources below are provided in the references and are listed by council name.

Council	*Guideline variable (unit)*	*Standard (Reference)*	*Source*
Northland	Visual clarity (m)	20–40%reduction in clarity depending on site conditions	Regional Water and Soil Plan for Northland
Waikato	Turbidity (NTU)	<2 (excellent), 2–5 (satisfactory), >5 (unsatisfactory)	River water quality monitoring programme
Taranaki	Visual clarity	≥1.6 m (MFE 1994)	State of the environment monitoring report
Horizons	Visual clarity (m)	≥1.6–3.4 m or max 20–30% reduction in clarity depending on water management subzone, in Proposed One Plan	
Greater Wellington	Visual clarity (m)	≥ 1.6 m (MFE 1994)	Rivers State of the Environment report
Tasman	Turbidity (NTU); Visual clarity (m)	5.6 NTU; ,<1.6 (unsatisfactory) to >5 m (excellent) (ANZECC 2000; Tasman District Council 2009)	State of the Environment report
Nelson	Turbidity (NTU); Visual clarity (m)	≤1–5 NTU (Class A–D); not less than 6–0.6 m (Class A–D)	Nelson Resource Management Plan
Marlborough	Turbidity (NTU)	4.1–5.6 NTU (Upland–lowland; ANZECC 2000)	River water quality monitoring
West Coast	Turbidity (NTU); Visual clarity (m)	5.6 NTU; 0.8 m (ANZECC 2000)	State of the Environment technical report
Environment Canterbury	Visual clarity (m)	Max 20–35% reduction depending on river or watercourse type	Canterbury Natural Resources Regional Plan
Otago	Turbidity (NTU)	3–5 NTU depending on receiving water group (applied as 5-year, 80th percentiles, when flow are at or below median flow)	The Regional Plan: Water for Otago (the Water Plan)
Environment Southland	Visual clarity (m)	No change – >3.0 m depending on waterbody type	Regional Water Plan
	Visual clarity (m)	0.8 m (ANZECC 2000)	State of the Environment report

5.3 Deposited sediment

International guidelines for deposited sediments are usually based on streambed measures (substrate composition, embeddedness, % fines), owing to the importance of substrata for habitat availability, particularly for key life stages of various aquatic biota (e.g. salmonid redds). For example, guidelines in British Columbia were established to minimise the potential negative effects on salmonid survival rates (egg-to-fry) associated with sediment deposition on substrata (Caux et al. 1997). In parts of the United States and Canada, guidelines most commonly use percent sediment as a measure of deposited sediments (Table 5), although comparison or interpretation of guideline values is challenging because the definition of sediment varies between states and provinces (e.g. size range: < 0.85 mm to <6.4 mm). Guidelines in some states are related to a specific time period (e.g. 5 mm for hard-bottomed streams during the 24 h following a heavy rainstorm event; Berry et al. 2003).

Table 5 Selected deposited sediment guidelines expressed in a similar way to recent New Zealand guidelines. Note: a number of guidelines based on different streambed measures for other Canadian provinces and US states are not shown here (see M. Rowe et al. 2003; Sutherland et al. 2008; Culp et al. 2009).

Country (State, province, region)	*Criteria*	*Guideline (target)*
New Zealand	Sediment cover (%)	<20% or within 10% cover of reference
	Substrate size (%)	<20% or within 10% cover of reference
New Zealand (Environment Canterbury)	Sediment cover (%)	10–40% depending on water quality management unit
New Zealand (Horizons)	Sediment cover (%)	15–25% depending on water management subzone
Canada (British Columbia)	% fine sediment in redds (by mass)	≤10% (<2 mm)
Canada (New Brunswick)	% sediment (Wolman + visual estimate)	≤7.2% (<2 mm) ≤9.3% (<6.35 mm)
	% sediment in riffles (by mass)	≤3% (<2 mm)
USA (Alaska)	% fine sediment	≤5% above reference or
	(0.1–4.0 mm by mass)	≤30% absolute
USA (Arizona)	% sediment in riffles (Wolman)	≤35%
USA (Idaho)	% fine sediment in riffles (by mass)	≤10 % (<0.85 mm)
USA (Montana)	% fine sediment in riffles (by mass)	≤30% (<6.35 mm)
USA (Oregon)	% fine sediment in riffles (by mass)	<20%

Guidelines for assessing the effects of deposited sediments based on measures of sediment cover, substrate size, and suspendible sediment have recently been developed for New Zealand hard-bottom streams, using an evidence-based approach (Clapcott et al. 2011) (Table 5). These numerical guidelines are specific to the protection of biodiversity, fish habitat, and amenity values. Both Canterbury and Horizons regional councils provide numerical guidelines for deposited sediments as a range of maximum percent cover of riverbed in regional planning depending on water quality management units or management subzones (Table 5). The Environment Canterbury guidelines were based on data collected at

144 sites since 1999 (Hayward et al. 2009 in Clapcott et al. 2011). Horizons also state that a specific narrative or numerical guidelines are applicable for all streams with trout spawning values (from 1 May to 30 September), in relation to resource consent applications and state-of-environment monitoring, respectively.

5.4 Guidelines for acceptable suspended sediment concentrations for the West Coast

Currently, consent conditions on the West Coast for smaller mines allow for an increase in 10 NTU between the upstream and downstream samples after a mixing zone (J. Adams, WCRC, pers. comm.). The mixing zone is to be the lesser of 12 times the width of the water body, or 200 m. For larger mines that have constant testing, a running median concentration has been set of 25 NTU over 30 days with a 90th percentile maximum concentration. Consent conditions will vary depending on the receiving system (J. Adams, WCRC, pers. comm.).

Reid and Quinn (2011) recommended (on the basis of Quinn et al. (1992)) limiting the average increase in TSS to 5 mg/L or turbidity to <5 NTU to protect macroinvertebrate abundance, and to <20 NTU to protect macroinvertebrate diversity in West Coast gravel-bed rivers.

The results obtained from recent testing are broadly supportive of the current guidelines used on the West Coast, with effects on fish growth indicated to occur between 5 and 15 NTU, depending on species. Further testing, e.g. with a greater number of fish, is required to provide more precise results.

6 Conclusions

There is limited information on which to set robust guideline values for acceptable suspended sediment concentrations. Currently available data are difficult to compare, because of the different effects examined, the different methods used to assess these effects, and the different methods used to determine suspended sediment concentrations (TSS mg/L or turbidity NTU).

Similarly, international guidelines for suspended sediment vary – with a maximum increase of 8 NTU or 25 mg/L above background levels allowed for short-term exposure (e.g. 24 h) and maximum average increase of 2 NTU or 5 mg/L for any long-term exposure in Canada; while in Europe suspended sediment concentrations are not to exceed 25 mg/L. The ANZECC water quality guidelines are 4.6 and 5.6 NTU for upland and lowland streams in New Zealand based on visual clarity, while up to 50 NTU may be acceptable in some lowland rivers in Australia.

The testing undertaken currently has highlighted the challenging nature of determining the effects of suspended sediment on fish, but has provided some evidence for effects on the growth rate of fish at levels between 5 and 15 NTU. These findings are broadly supportive of the suspended sediment guidelines currently used on the West Coast.

7 Recommendations

- Further testing of effects on fish growth rate using a greater number of individuals and wider range of species would provide additional information to further delineate the suspended sediment concentrations at which effects are observed.
- Given the challenging nature of determining the effects of suspended sediment on fish, a range of testing strategies (e.g. in-stream studies, flume testing) are required to provide more definitive information on the effects and wider ecological impacts of suspended sediment on fish.

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