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Lethal Turbidity Levels for Common Fish and Invertebrates in Auckland Streams

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Lethal turbidity levels for common freshwater fish and invertebrates in Auckland streams

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1. Executive Summary

- We examined the effects of acute (24 h) exposure to high turbidity levels on the survival of 6 species of aquatic invertebrate and 4 species of fish commonly encountered in Auckland region streams. These species were likely to be more sensitive to increases in turbidity than others. The invertebrates tested included the larvae of 2 caddisflies, 1 damselfly, 2 mayflies, and adult freshwater crayfish (koura). The fish tested were smelt, inanga, redfinned bully and banded kokopu.
- Individuals were placed in experimental cages and exposed to turbid waters ranging from 500 NTU up to 20,000 NTU. Turbid waters were all created from Auckland clays. The percent survival of animals was determined at each turbidity level and compared with that of control animals held in clear, conditioned tap water.
- There was no significant difference between the percentage survival of any of the aquatic insect larvae, crayfish, banded kokopu and redfinned bullies and their respective control groups at turbidities up to c. 20,000 NTU.
- As both inanga and smelt were affected by turbidities of less than 20,000 NTU, the median lethal turbidity level (LC50) over 24 hours was determined for both these species. For inanga it was 20,235 NTU, but for smelt it was 3,050 NTU.
- The time (in hours) for 50% survival (LT50) was also determined for both these species for a range of turbidity levels around the LC50. The 'best fit' curve to these data was produced and predicts the time in hours for 50% survival at any turbidity level between 15,000-30,000 NTU for inanga, and 2,000-6,000 NTU for smelt.
- We also exposed the common mayfly (*Deleatidium*) and smelt to 4 h of 1000 NTU every 2-3 days over a period of 2-3 weeks. These animals were kept in clear tap water between exposures to turbid water, and were allowed to feed between exposures. Survival was compared with that of control groups maintained in clear water. There was no significant difference in the percentage survival of the mayflies, or of the smelt between the control and turbidity exposed groups.
- The supposedly 'sensitive' invertebrate and fish taxa (excluding smelt) are tolerant of very high levels of turbidity (over 24 hours), and even repeated exposures to 1000 NTU had no adverse effects on their survival. Their absence from urbanised catchments and their relative scarcity in turbid rivers and streams is not caused by turbidity *per se*, but most likely reflects a combination of other environmental changes associated with high loadings of suspended solids. These will need to be determined in order to develop effective controls for sediment loadings in streams.
- In the meantime, the common smelt is clearly the most sensitive taxa to high turbidity levels in Auckland streams and the results from these tests provide guidelines for both its protection, as well as for predicting the effects of high turbidity events on its survival.

2. Introduction

Urban development generally involves land use changes that remove topsoils and increase the exposure of underlying clays to erosion by rainfall and runoff. Where control methods such as protective overlays, channelisation of surface water into settling ponds, or filtering measures are lacking, or are inadequate, large amounts of suspended solids can enter receiving waters. As a consequence, streams below some urban developments can, at times, experience very high levels of suspended solids for 1 –2 days following high rainfall events (pers. comm., J. Maxted).

Suspended solids produce two main ecological effects in streams that can affect fish and invertebrate communities; (a) increased turbidity of the stream water, and (b) increased siltation of stream beds. Knowledge of the main effects of suspended solids on the biota is needed to manage sediment concentrations in streams. Consequently a number of studies have recently addressed the effects of sublethal turbidity levels on native fish in New Zealand streams to identify the levels affecting them (Boubee et al. 1997; Rowe and Dean 1998; Rowe et al. 2000; Richardson et al. 2001; Rowe et al. 2002). In general, most species were little affected by sublethal turbidities. However migrant banded kokopu showed adverse responses to turbidities over 25 NTU (Nephelometric Turbidity Units). Their feeding was reduced, their avoidance reaction increased, and upstream migration rates in a small natural stream were all reduced. Field studies in New Zealand rivers indicated that turbidities over this level for more than 10% of the time during the whitebait migration season (August-December) could be expected to reduce the upstream migration of banded kokopu, resulting in reduced recruitment and a decline in adult populations. These studies have produced a better understanding of the effects of sublethal turbidities on native fish, but lethal turbidity levels were not determined.

High turbidity levels (i.e., > 100,000 NTU) will kill fish (Newcombe and MacDonald 1991), but such high levels rarely occur in nature or, where they do, rarely last long enough to pose a threat. However, there is wide variation in the lethal level among fish species (loc cit.), and the turbidity levels recorded in some Auckland streams after heavy rain can be relatively high (>10,000 NTU). Under such conditions, native fish could be killed. Accordingly, the ARC requested NIWA to determine the lethal turbidity levels that affect the common native fish in Auckland streams.

Even less is known about the tolerance of New Zealand freshwater invertebrates to high turbidity levels. There have, however, been a number of review studies documenting the effects of increased turbidity in streams on invertebrates (e.g., Lloyd et al. 1987; Newcombe and MacDonald 1991; Ryan 1991; Waters 1995; Wood and Armitage 1997; Death 2000). In general, these reviews concluded that high turbidity can reduce invertebrate abundance and diversity by: 1) smothering and abrading; 2) reducing their periphyton food supply or quality; and 3) reducing available interstitial habitat. Moreover, high turbidity also often results in sediment deposition, altering substrate composition and changing substrate suitability for some taxa (Wood and Armitage 1997). Sediment deposition creates conditions that are generally unsuitable for most New Zealand aquatic insects (Jowett et al. 1991; Death 2000; Harding et al. 2000), although burrowing taxa such as Icthybotus hudsoni and early instars of other taxa may be associated with fine substrates in depositional areas. Many of the streams in Auckland are relatively steep, and short, so the effects of sediment deposition may be secondary to any adverse acute effects of high turbidity events that can occur in these streams. However, as little is known about the effects of high turbidity on common invertebrates, little guidance can be given as to what an acceptable upper level of turbidity is to minimise loss of sensitive taxa.

We therefore investigated the short-term (<24 hour) effects of different turbidities on a range of different fish and invertebrate species to see whether they could be adversely affected. The absolute maximum turbidity level that was expected in ARC streams was less than 20,000 NTU, so this represented the highest level examined.

Our specific aims were to firstly determine which of the more common species of fish and invertebrate were affected by turbidity levels of 20,000 NTU, secondly to determine the LC50 or turbidity level resulting in 50% survival over 24 hours for these species, and thirdly to determine the exposure times resulting in 50% survival (LT50) for a range of turbidity levels. These data are needed by the ARC to estimate or predict the mortalities of the selected species given both the level and duration of a high turbidity event in an Auckland stream.

The survival rates of fish and invertebrates can be expected to vary with the frequency of exposure to relatively high turbidity, so we also determined whether repeated exposures (every 2-3 days) to a turbidity level of 1000 NTU for 4 hours per day would have any effect on the survival rates of the most sensitive fish and invertebrate. A 2-3 day periodicity is typical for rainfall events in the Auckland region, and the 4-hour duration was used to emulate the natural rise and fall of turbidity levels in streams following heavy rainfall events.

In this report, we present the results of the experiments to determine the effects of high turbidity levels on the common native fish and invertebrate species found in Auckland streams.

3. Sediment Characterisation

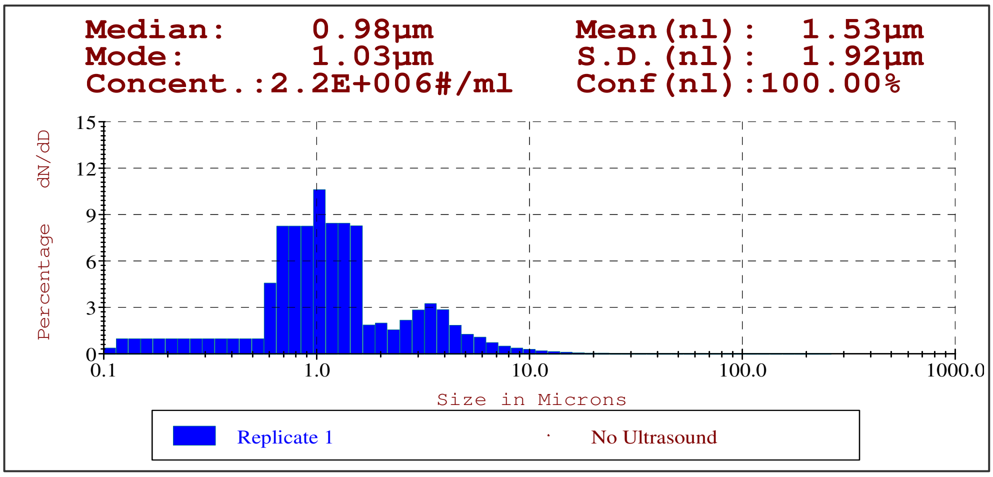
The ARC measures turbidity in streams in terms of NTU (Nephelometric Turbidity Units). NTU is a machine-specific measure, and depends on the type of light scattering sensor used. As a consequence, measures made by one machine can vary from those made by another. NTU levels are correlated with the amount of suspended sediment present but this can vary depending on variations in the characteristics of the sediment particles present (Lloyd et al. 1987). The mass concentration of suspended solids present in water (i.e., g m-3) provides a more objective measure of the sediment present, but it is more difficult and time consuming to measure. Consequently, NTU is the generally preferred measure of suspended sediment levels, especially as data loggers are available that can monitor NTU levels continuously. Moreover, the biases involved in such turbidity measurements with different machines will be insignificant in terms of the levels resulting in fish or invertebrate mortalities. Therefore, in order to provide data relevant to the monitoring of turbidity in streams by the ARC, we measured turbidity levels in the experiments with a HACH 2100P portable turbidimeter. This was calibrated before use with formazin standards.

Sediment of a type typically found in many Auckland streams was obtained by the ARC from a sediment retention pond adjacent to the Oteha Stream (NZMS 260, Map R10, Grid Ref. 642 950). It was sent to NIWA Hamilton, where it was mixed with natural tap water and aerated for 3 days to allow coarse particles to settle. Further sediment was added until the supernatant had a turbidity of approximately 20,000 NTU.

The type of particles creating turbid conditions in water can vary greatly in size, shape and density and such factors may be important in determining the effects of the turbidity on the biota. Therefore, a subsample of the suspended sediment solution was analysed by a Galai CIS-100 particle analyser to determine the physical characteristics of the suspended particles.

Two modes were apparent in the particle size distribution; one at 1 micron and a second at 3.5 microns (Fig. 1). Ultrasound treatment failed to influence this size structure indicating that the larger particles were not aggregations of the smaller ones. This bimodal distribution of diameters is characteristic of clays that comprise mainly plate–shaped particles with two main axes.

Figure 1. Size frequency distribution for the clay particles (relicate 1, without ultrasound).



Various measures of the shape of the particles were made and are compared with other sediments in Table 1. There was little difference in shape factor (a measure of the smoothness of particles - with 1 being round and smooth, and 0 elongate and rough), or aspect ratio (a measure of shape - where 1 is a square or round object, and 0 an elongate or line-shaped object shape) between the sediments. However, the ARC clays were generally smaller in mean diameter and the average feret diameter (the longest chord of an object) was four times greater and more variable than for the other types of sediment.

Table 1. Mean values (± SD) for median size, shape factor, aspect ratio and the average feret diameter for 5 different sediment North Island sediment types.

Sediment type/name	Median size (µm)	Shape Factor	Aspect ratio	Mean feret Diameter
ARC clay	0.98 (1.92)	0.76 (0.11)	0.61 (0.12)	26.1 (27.4)
Lake Waahi silt	0.94 (0.41)	0.74 (0.09)	0.57 (0.10)	4.5 (1.9)
Lake Coleridge (SI) sediment	1.34 (0.90)	0.77 (0.08)	0.60 (0.12)	5.6 (2.5)
Whatawhata mud	1.23 (1.16)	0.69 (0.16)	0.57 (0.10)	6.0 (----)
Waipa dirt	1.04 (0.60)	0.70 (0.15)	0.57 (0.11)	5.4 (3.9)

When mixed with freshwater, the ARC clay increased the acidity of the water, and reduced pH values from around 7 to 5.2-5.5. This acidity would probably irritate fish and invertebrate gills, and may compound the effects of high turbidity on the biota. To minimise this, the stock solution of turbid water was neutralised with Na2CO3. Titration was used to determine the amount of Na2CO3 to add to the stock solution to raise its pH close to 7. After the addition of Na2CO3 the pH of the stock solution was close to 7.1 and increased over the following 24 hours to around 7.5.

4. Effects Of Turbidity On Fish

4.1 Fish selection, collection and acclimation

The most common species of fish found in small Auckland streams are listed in Table 2. In general, the shortfinned eel and common bullies are more prevalent in turbid than in clear North Island, New Zealand rivers (Rowe et al. 2000) so were expected to be less sensitive to turbid conditions than other species. In contrast, banded kokopu, redfin bullies, smelt and inanga were all less common in turbid than in clear rivers so are likely to be more sensitive to the effects of turbid conditions (Rowe et al. 2000). Accordingly, these more sensitive species were selected for testing.

Table 2 Common native fish found in Auckland urban streams (occurrence data from Allibone et al. 2001)

Species	Common name	Site occurrence (%)	Rank abundance
Anguilla australis	Shortfin eel	73	1
Anguilla dieffenbachii	Longfin eel	42	2
Gobiomorphus cotidianus	Common bully	25	3
Galaxias maculatus	Inanga	23	4=
Galaxias fasciatus	Banded kokopu	23	4=
Gobiomorphus huttoni	Redfin bully	9	5
Retropinna retropinna	Smelt	2	6

All test fish were obtained from the wild. Juvenile banded kokopu were obtained from Hayes Stream (which drains into the Manukau Harbour), and inanga and smelt from the lower Waikato River. Redfin bullies are not abundant in Auckland streams and so were sourced from an east coast stream near Tauranga (NZMS U14 816 849). All fish were transported to the laboratory and placed in large (100 litre) tanks to which we added 10% salt water to minimise mortalities from the stress of capture and disease. The fish were acclimated to laboratory conditions for several days in these tanks at a constant temperature of 16°C, and a 12L:12D photoperiod. They were fed on Daphnia every 1-2 days before the experiments began.

4.2 Experimental methods

Exposure of fish to high turbidities requires large quantities of silt to be held in suspension for the duration of the test period (24 hours), and this requires continual mixing of the silt and water. As turbidity levels of around 20,000 NTU were required, and could not be maintained by aeration alone, a water circulation system was devised to continually mix the silt particles that steadily settled on the tank bottom back into surface waters. A tall (1.3 m high by 80 cm square) bin-type tank (wheelie bin) was used for this. Electric bilge pumps at the bottom of each bin continually re-circulated silt-laden water to the top and maintained the sediment in suspension (Fig. 2).

Plastic cages (200 mm high, 140 mm square) with 0.5 mm mesh sides were constructed to house the fish and invertebrates and were placed in a removable steel frame in the top half of the bin in such a way that the silt-laden water circulated freely around each cage as well as within it (Fig. 2). Four cages were positioned just under the water surface, with a further four below these and another four beneath these. Tests were made to ensure that; (a) turbidity levels in all cages were the same as those in the surrounding waters, (b) there was no difference in turbidity between the top and bottom cages, and (c) that the turbidity levels were maintained over 24 hours. Flows were adjusted so that the silt remained in suspension within the mesh cages and so that the fish and invertebrates were not exposed to high water velocities that could have injured or stressed them. Turbidity levels for testing were created by adding a known amount of the stock solution to freshwater. The bin was placed in a constant temperature and light room (16°C, 12L:12D) where any disturbance was minimal. The water was tested before, during and after each experiment to ensure that turbidity, dissolved oxygen levels, water temperatures and pH were all within the desired range. Tests of the apparatus without any sediment present indicated that there were no fish mortalities even after several days. There were no koura mortalities after 96 hours.

Figure 2. The bin used for maintaining high turbidities and the array of cages housing the animals.

4.2.1. Determination of 24 hour lethal turbidity levels (LC50)

Initial scoping tests were carried out to determine the range of turbidities over which mortalities could be expected within 24 hours. A minimum of 3 replicates was used for each species at each turbidity level. The nominal turbidity levels tested are shown in Table 3.

As some smelt and bullies died at turbidities over 5,000 and 10,000 NTU respectively, the silt was removed from a 20,000 NTU suspension by filtration and the elutriate tested to see whether any dissolved substances from the sediment could be affecting the fish and compounding the effects of turbidity. Fifty inanga were placed in a tank containing the filtered elutriate and kept overnight for 24 hours. Their survival rate was compared with that for a further fifty inanga in a control tank of conditioned tap water. No mortalities occurred in either tank.

Table 3. Nominal turbidity levels tested to determine the range within which some survival occurred within 24 hours for each species.

Turbidity (NTU)	Smelt	Inanga	Redfin bully	Banded kokopu
500	*			
1000	*			
3000	*			
5000	*	*	*	*
7000		*	*	*
10000	*	*		
15000	*	*	*	
20000		*	*	*
30000		*	*	*
40000			*	*

As both smelt and inanga were affected by turbidities less than 20,000 NTU, further experiments were conducted on both these species to determine their 24 hour median LC50 value (i.e., the turbidity level which results in 50% survival after 24 hours).

In a further series of tests, the survival rate over 24 hours was determined for smelt at nominal turbidities of 500, 1000, 2000, 3000, 5000, and 10000 NTU. For inanga, the nominal turbidity levels tested were 4000, 7000, 8000, 10000, 15000, 20000 and 30000 NTU. Sub-samples of fish for each species were set aside to determine their mean size. Three replicates of 7 fish were then tested at each turbidity level. The fish were placed in separate cages that were inserted into the test bins containing the turbid water. Turbidity, pH, temperature and oxygen level were measured at the start and end of each 24 hour test. Each tank was inspected at intervals of 1, 3, 12, and 21 hours after the start of each test, and any dead fish removed and measured. The number of fish remaining alive after 24 hours was then determined.

4.2.2. Determination of lethal times (LT50) for 50% survival

In addition, we determined the LT50 (i.e., the time at which 50% survival occurs) for a range of turbidity levels around the LC50 level for both smelt and inanga. This involved determining the cumulative survival rate of fish every 3 hours over a 24 hour period. Three (and occasionally 4) replicates of 7 fish were used at each turbidity level including the control. Fish were placed in 42 litre white PVC tanks in the constant temperature and fixed photoperiod room and acclimated for 24 hours. The turbidity of each tank (apart from the control) was then increased to produce nominal turbidities, for smelt, of 10 (control), 1000, 2000, 2500, 3000, 4000, 5000 and 6000 and 7000 NTU. Inanga were tested at nominal turbidity levels of 0 (control), 10000, 12000, 14000, 16000 and 18000 NTU. Aeration was used in these tanks to ensure that the sediment stayed in suspension and that the water was well oxygenated. Turbidity levels as well as pH, dissolved oxygen and temperature were recorded at the start and end of each test as well as after 12 and 21 hours. All tanks were inspected every 3 hours and any dead fish removed and measured.

4.2.3. Effects of repeat exposures to turbidity

A repeat exposure experiment was carried out on smelt, as this species proved to be the most sensitive to turbidity. Five smelt were placed in each of 6 PVC tanks (50 cm x 40 cm x 30 cm high) and the fish in 3 of these tanks exposed to turbid water (nominal level of 1000 NTU) for 4 hours every 2-3 days for a period of three weeks (10 exposures). Fish in the remaining 3 tanks served as controls. After each exposure, the water was changed in both control and experimental tanks and the fish were fed on whiteworms. Turbidity level, oxygen saturation, water temperature and pH were recorded in all tanks at the start and finish of each test. Dead fish were recorded in all tanks (control and experimental) after each exposure to high turbidity, and the following morning. The cumulative survival resulting from repeated exposure to a turbidity of 1000 NTU was then determined.

Summary of critical limits determined	
LC_{50}	Median **L**ethal **C**oncentration of suspended clay in water (expressed as NTU turbidity) resulting in 50% survival of fish (smelt or inanga) within 24 hours
LT_{50}	**L**ethal **T**ime (h) at which a 50% survival of fish (smelt or inanga) occurs for a given turbidity level.
$CSFE_{1000}$	**C**umulative **S**urvival rate (%) of smelt from **F**requent **E**xposure (i.e., once every 2 days for 4 hours per day over 3 weeks) to a turbidity of 1000 NTU.

4.3 Data analysis

The mean size of fish tested was determined for each of the tests and differences determined by ANOVA. We also compared the mean sizes of fish that died with that for the fish that lived to determine whether survival from high turbidity was influenced by fish size.

The measured turbidity levels at the start and end of each trial were averaged to produce a mean NTU level. This was then compared with the nominal level and was used in all further analyses. We used ANCOVA (on the log x+1 mean survival rates) of fish to determine whether survival rates varied with turbidity levels. Where a significant relationship occurred, the median lethal turbidity levels over a period of 24 hours (LC50) was determined using the ToxCalcTN (version 5.0) analysis package produced by Tidepool Scientific Software (1994). This uses the USEPA approved statistical methods for analysis of toxicity data. The overall 24 hour survival rates from the LT50 tests on smelt and inanga (see below) were added to this data set to further strengthen it. As the data were non-normal, hypothesis testing was carried out using the non-parametric, Bonferroni adjusted t-test, and the median lethal values (LC50) were calculated using the 'trimmed' Spearman-Kaber method.

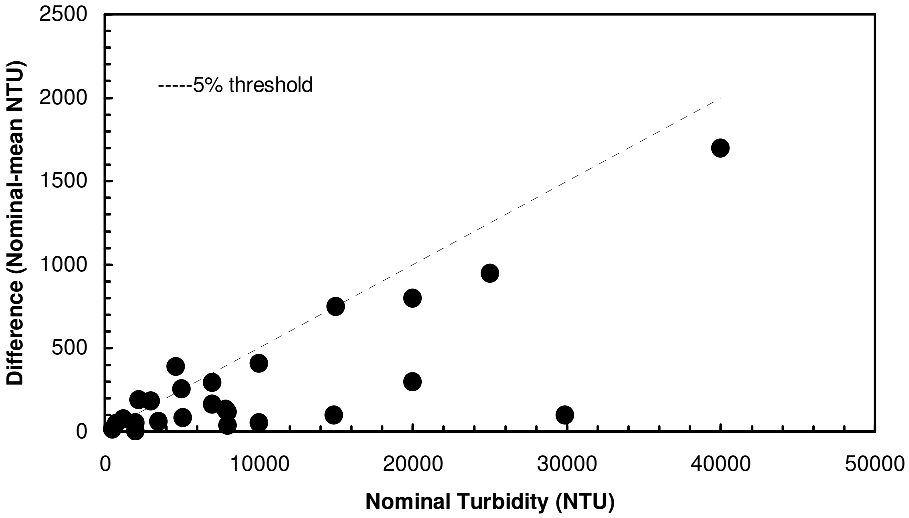
The 3 hourly cumulative survival rates were plotted for each of the LT50 tests and the time at which 50% survival occurred was determined for each of the mean turbidity levels from each test and plotted against mean turbidity level. The LT50 curve was then determined by the line which produced the 'best fit' (i.e., highest R2 value for an exponential curve) to these data.

The mean survival rates for smelt exposed to 1000 NTU for 4 hours at 2-3 day intervals over a period of 3 weeks were calculated and compared with that for the control fish using one-way ANOVA.

4.4 Results

Mean turbidity levels for the tests were generally within 5% of the nominal values irrespective of the level used (Fig. 3). However, as the mean of the measured values provides a more accurate measure of the turbid conditions in each tank, this was used in further data analysis.

Figure 3. Differences between the mean and the nominal turbidity levels for each nominal level. Points above the 5% threshold line indicate that the actual turbidity level was more than 5% above or below the nominal value.



Survival rates of fish were, at times, sensitive to fish size for all species except for smelt (Table 4). A significant difference in size was apparent (at the $P < 0.05$ level) in 34% of all tests and in these the dead fish were all smaller than the live ones. Overall, the dead fish were smaller than the live fish for 78% of all comparisons. These data suggest that smaller fish may be more vulnerable to the effects of turbidity than larger fish. Although more data are needed to confirm this, caution is clearly needed in interpreting results where there is a difference in the mean size of test fish, especially where fish are smaller and so could be more vulnerable to high turbidity levels.

There were no significant differences in the mean sizes of smelt, redfinned bullies and banded kokopu used in the tests (Table 5). However, there was a significant difference in size for inanga. In particular, one group of inanga tested at the nominal turbidity of 10,000 NTU was comprised of smaller fish, whereas inanga tested at 30,000 NTU were generally larger (Table 5). Removal of the data for these two tests resulted in no significant difference in mean size for inanga among the remaining tests. Therefore, the results from these two tests were inspected to see whether the smaller and larger size of fish could have biased results and produced lower and higher survival rates, respectively.

Table 4. Effects of fish size on mortalities caused by turbid conditions in tanks (* significant at $P \leq 0.05$, ** significant at $P \leq 0.01$)

Species (NTU level)		**Mean length (mm)**		**ANOVA**
	N	**Alive**	**Dead**	***P***
Smelt (10)	50	63.1	61.3	0.507
Smelt (500)	7	56.7	61.8	0.214
Inanga (7,000)	21	55.5	48.5	0.010 **
Inanga (7,000)	21	49.3	43.0	0.196
Inanga (8,000)	7	59.7	52.4	0.072
Inanga (30,000)	7	52.0	59.3	0.483
Redfin bully (7,000)	21	42.3	31.3	0.011 **
Redfin bully (30,000)	7	54.2	47.0	0.454
Banded kokopu (15,000)	7	43.2	39.5	0.032 *

4.4.1 Turbidity levels resulting in 50% survival over 24 hours (LC50)

The mean 24 h survival rates for both redfin bully and banded kokopu were generally close to 100% irrespective of turbidity levels up to approximately 40,000 NTU (Fig. 4). An exception was provided by the low survival of redfin bully at 14,250 NTU (Fig. 4). There was no obvious reason why survival was low at this level and not at higher turbidities. It is possible that the fish for this particular test were stressed in some way.

Although mean survival rates for smelt and inanga were 100% at turbidities of less than 1,000 NTU they declined with increasing turbidity and were 0% at turbidities of 15,000 and 30,000 NTU, respectively (Fig. 5). High turbidity levels (up to 40,000 NTU) therefore affected both smelt and inanga, but not banded kokopu and redfin bullies.

Table 5. Differences in the mean lengths (± SE) of groups of fish used in the turbidity tests.

Nominal turbidity (NTU)	Mean lengths (mm)			
	Smelt	Inanga	Redfin bully	Banded kokopu
0	61.5 (1.4)	51.3 (2.2)	42.8 (2.5)	40.8 (0.5)
500	60.6 (1.8)	-	-	-
1,000	70.4 (4.2)	-	-	-
2,000	64.3 (3.5)	-	-	-
3,000	64.4 (2.3)	-	-	-
4,000	-	-	-	-
5,000	60.9 (4.9)	-	-	-
7,000	-	48.4 (1.3)	46.3 (3.1)	-
8,000	-	47.7 (1.3)	-	-
10,000	60.4 (2.1)	46.7(1.6), 52.4 (1.5)	40.6 (1.1)	-
15,000	-	-	41.8 (2.2)	42.1(0.9)
20,000	-	49.7 (1.3)	46.1 (3.3)	39.1 (0.5), 40.3 (0.7)
30,000	-	55.0 (3.3)	52.1 (3.9)	40.4 (1.0)
40,000	-	-	48.0 (2.5)	40.6 (0.4)
P value (ANOVA)	0.274	< 0.001	0.197	0.110

Analysis of covariance indicated statistically significant interactions between species and turbidity (P = 0.004), and turbidity significantly affected the survival of both species (P = 0.001 and 0.005 respectively). Tukey post hoc multiple comparisons tests indicated that survival rates for smelt were lower than for both redfin bullies and banded kokopu (P < 0.05), but were no different to those for inanga (P = 0.795).

The scatter of mean survival rates for smelt and inanga over the range of turbidities tested (Fig. 5) produced an envelope within which the LC50 could be expected to lie for the various turbidity levels. Visual inspection of these data suggests an LC50 of around 3,000 NTU for smelt, and 20,000 NTU for inanga.

Results of the ToxcalcTN analysis are shown in Table 6. There was a significant effect of turbidity level on the survival rates of both inanga and smelt (Bonferroni adjusted t-test, P < 0.001). The LC50 for inanga ranged from 20,235-20,771 NTU depending on the extent of trim used in the analysis. This is close to that expected from visual inspection of the data. The LC50 for smelt ranged from 2,951-3,050 NTU, again close to that expected.

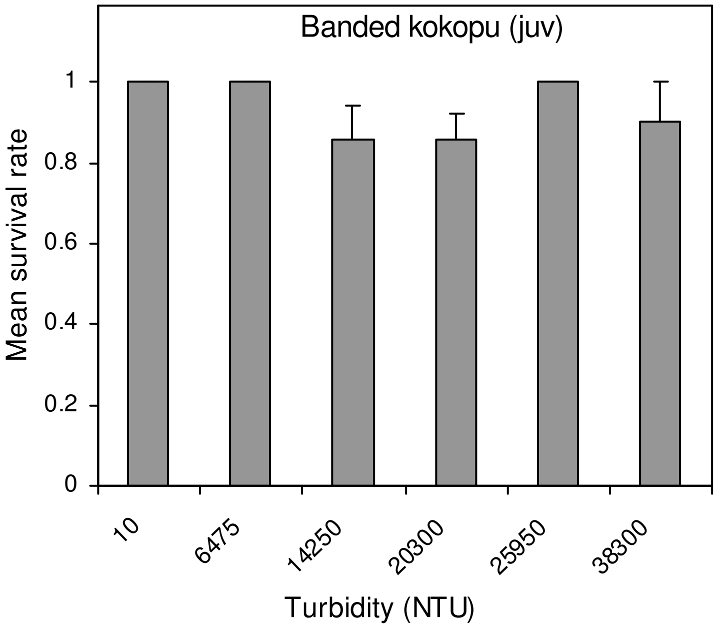
Table 6. Median lethal turbidity levels (LC_{50}) for smelt and inanga to suspensions of clay that can be expected to occur in Auckland region streams.

Species	Trim level used	LC_{50} (NTU)	Confidence levels for the LC_{50}	
			-95%	+95%
Smelt	20%	2,951	2,579	3,378
Smelt	Auto (8.8%)	3,050	2,761	3,371
Inanga	20%	20,771	19,042	22,656
Inanga	Auto (11.8%)	20,235	18,590	22,028

4.4.2 Lethal times for 50% survival (LT50) over the range of turbidity levels resulting in survival of smelt and inanga

The results of tests to determine the LT50, or time at which 50% survival would occur, for a range of turbidity levels are shown in Fig. 6 for smelt and Fig. 8 for inanga. The dashed line represents the 50% mean survival level and the interception of this line with the survival curve for each turbidity level was used to develop the LT50 curve for each species. The LT50 for each of these tests, together with the median LC50 value (from section 3.4.1), which represents the LT50 at 24 hours, are plotted in Fig. 7 for smelt and Fig. 9 for inanga. The solid line is the 'best-fit' to these data by an exponential curve. R2 values of 0.89 for inanga and 0.83 for smelt indicate a reasonable fit despite the large variation encountered.

Figure 4. Mean survival rates over 24 h for redfin bully and juvenile banded kokopu at turbidity levels ranging up to c. 40,000 NTU. Error bars indicate one standard error. Means are for 3 replicates, except for banded kokopu at 20,300 NTU (9 replicates), and for redfin bullies at 6835 and 10410 NTU (6 replicates each).



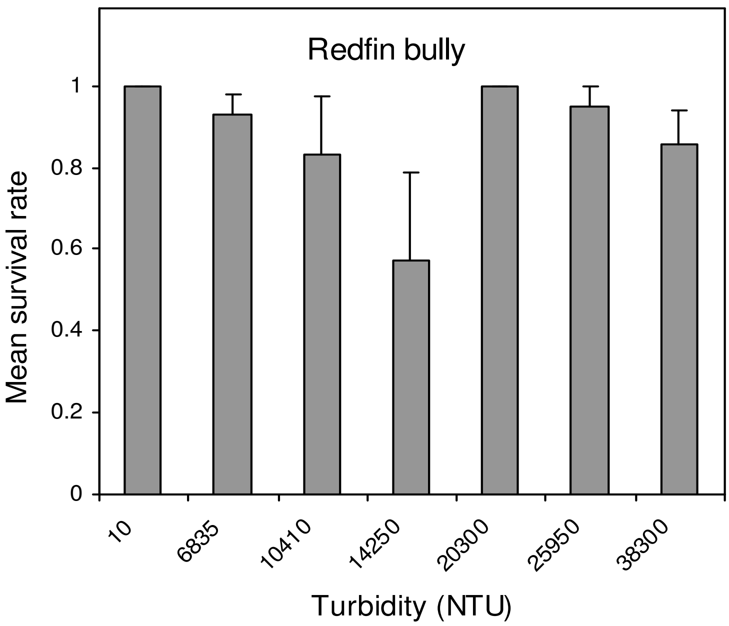


Figure 5. Mean survival rates (± 1 SE) over 24 h for smelt and inanga at turbidity levels ranging up to c. 15,000 and 30,000 NTU, respectively. Data from the LT_{50} tests were combined with those from the LC_{50} tests for both species. Solid lines enclose the data points and illustrate the variability among the different groups of fish within a species, as well as the greater variability for inanga compared with smelt.

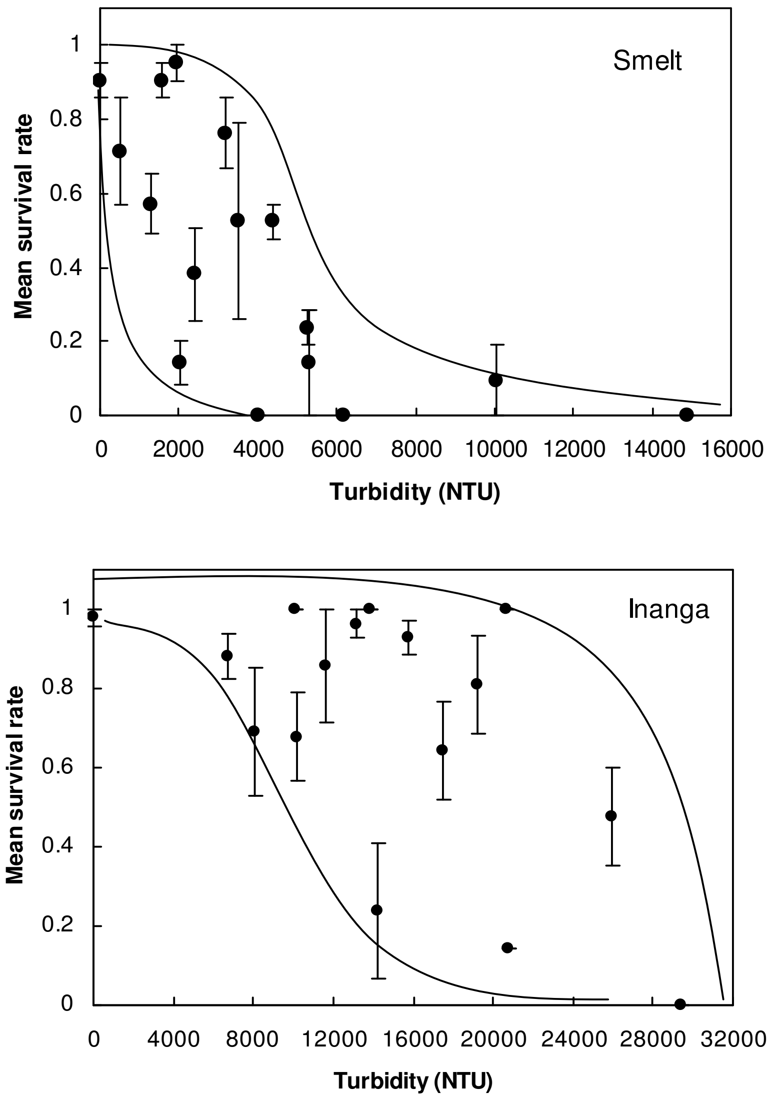


Figure 6. Cumulative survival rates with time for smelt at different turbidity levels

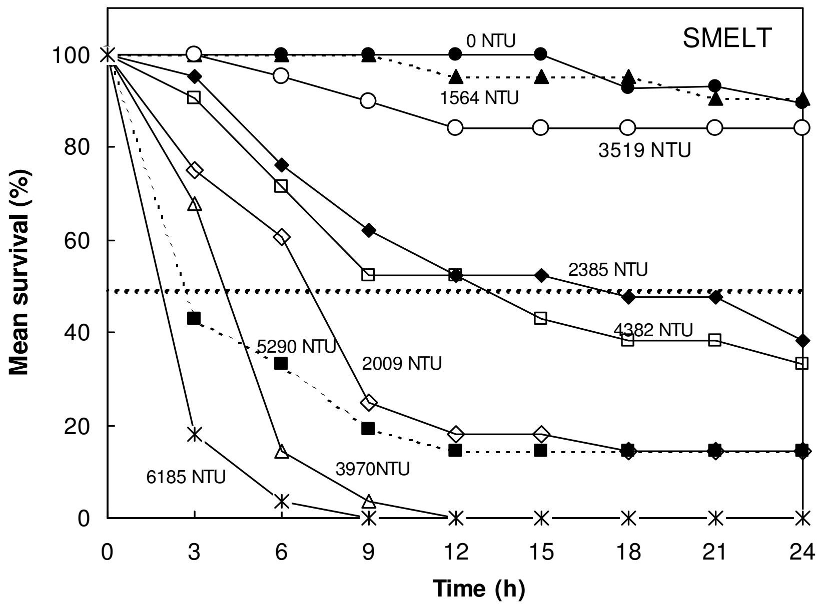


Figure 7. LT_{50} curve for smelt at turbidity levels ranging up to 7,000 NTU. The arrow indicates that the LT_{50} at this turbidity level would have exceeded 24 hours. The dotted lines enclosing the data points (i.e., 100% confidence limits) reflect the variation in LT_{50} values that could be expected for a given turbidity level.

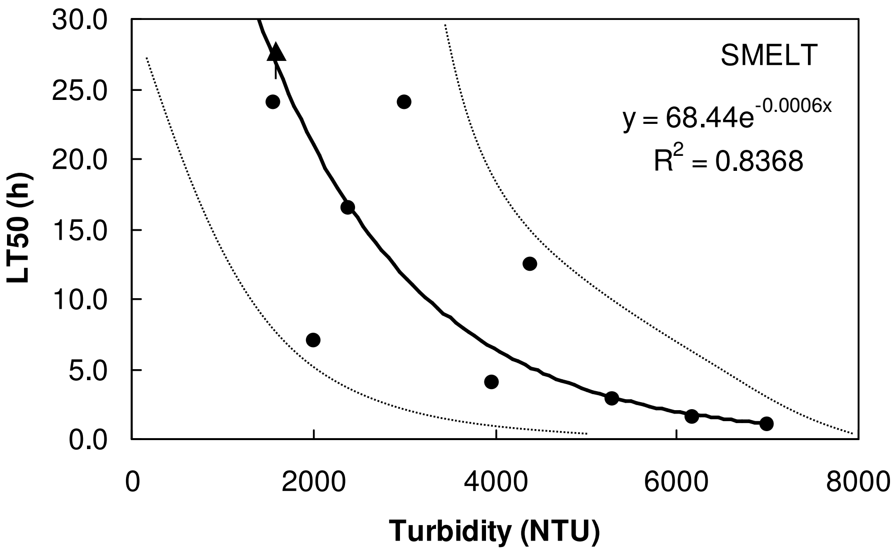


Figure 8. Cumulative survival rates with time for inanga at different turbidity levels

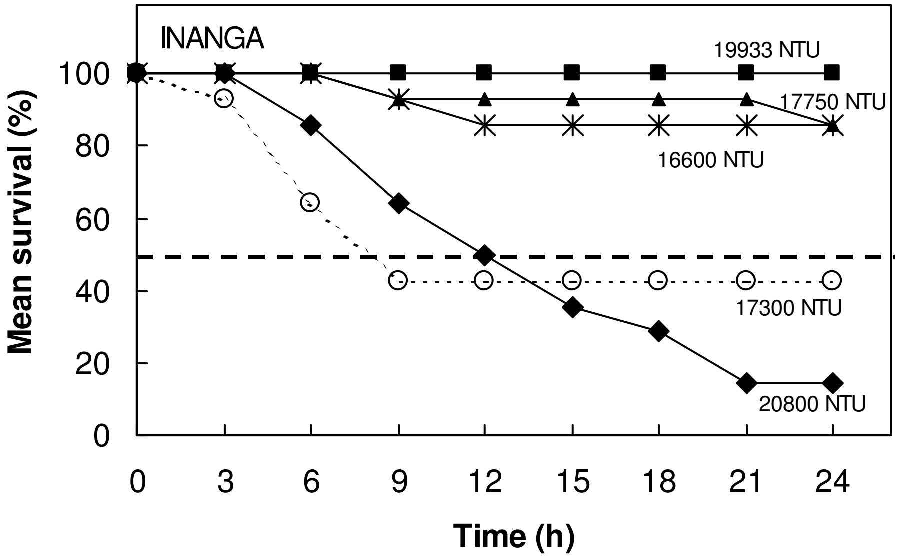
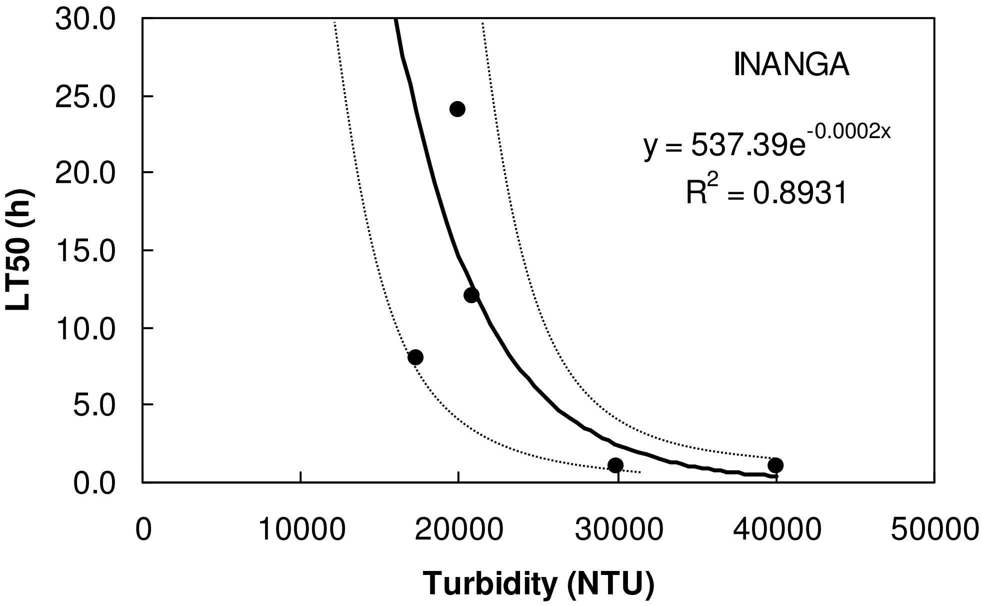


Figure 9. LT_{50} curve for inanga at turbidity levels ranging up to 40,000 NTU. The dotted lines enclosing the data points (i.e., 100% confidence limits) reflect the variation in LT_{50} values that could be expected for a given turbidity level.



4.4.3 Results of repeat exposure to 1000 NTU

Smelt were exposed to a 4 hour period in turbid water (nominal value of 1000 NTU) every 2-3 days over a period of 22 days between 24th May and 14th June (i.e., ten separate exposures). Actual turbidity levels declined over the four hour period from levels of 950-1000 NTU at the start to 850-750 NTU at the end. Dissolved oxygen concentrations remained high throughout at 91-115% saturation, and pH ranged from 6.3-8.1, except on 6th June when it was as low as 4.7. This low value was probably caused by a lack of buffer in the tank water on this occasion. Fortunately it had no observable effect on the smelt.

There were no mortalities of smelt in any of the 3 replicate tanks that were repeatedly exposed to high turbidity levels or in the control tanks. The smelt were observed feeding readily on whiteworms after each exposure and appeared healthy and in good condition after the 22 day period of repeat exposures.

4.5 Discussion

Turbidity levels over 20,000 NTU and as high as 40,000 NTU had no detectable effect on the survival rates of juvenile banded kokopu or adult redfin bullies. This is despite the fact that these two species are the least abundant native fish in turbid North Island rivers (Rowe et al. 2000), and that the movement and feeding of banded kokopu was reduced by turbidity levels over 25 NTU (Boubee et al. 1997; Rowe and Dean 1998, Richardson et al. 2001). It is clear that the behavioural responses of these fish to sublethal turbidities are not to avoid mortality but to facilitate some other aspect of their ecology or life history (e.g., feeding or navigation). It can be concluded that high levels of turbidity (up to 40,000 NTU) do not directly affect the survival of either redfin bullies or banded kokopu. However, this should not be taken to mean that they are unaffected by high levels of suspended solids in natural streams. Impacts from siltation have not been addressed and remain a possibility, especially as Jowett and Boustead (2001) showed that deposited sediments (produced by a high suspended sediment load) reduced the abundance of Upland bullies in artificial stream channels.

The survival of both smelt and inanga was reduced at high levels of turbidity, more so for smelt than for inanga. However, both species exhibited high variability in their survival rates at a given turbidity level. Mortality caused by high turbidity is likely to be size-dependent for these fish, but fish size was not responsible for the variation in our tests. Individual fish differences related to sex, maturation status, parasite loading, or physiological status could all be responsible.

Turbidity levels exceeding 1000 NTU are rare in Auckland rivers and streams, unless large slips or blow-outs of sediment ponds occur. As the survival of inanga was only marginally reduced at turbidities exceeding 5000 NTU, and as its LC50 was 20,235 NTU, it is exceedingly unlikely that inanga will be adversely affected by high turbidities in these streams. However, the survival of smelt was significantly reduced at turbidity levels as low as 2000 NTU, so this species could be adversely affected. Indeed, the scarcity of smelt compared with inanga in Auckland urban streams (Table 2) is likely to reflect their greater sensitivity to high turbidity levels produced during flood flows. However, a number of other environmental factors, including differences in fish behaviour and recruitment, may also explain this difference.

Variations in the sensitivity of fish species to high levels of suspended solids in rivers are believed to be related mainly to differences in feeding behaviour and reproductive requirements (Berkman and Rabeni 1987). Species whose feeding depends on visual cues and whose eggs require silt-free substrates are likely to be more affected than species not dependent on vision and whose eggs are not sensitive to siltation. In this respect, smelt are mainly visual feeders and scatter eggs over sandy substrates on stream beds where they are susceptible to smothering by silt. These life history traits indicate that smelt would be vulnerable to high suspended solids concentrations in streams. In comparison, inanga deposit their eggs in and on vegetation on the flooded margins of streams where siltation is less of an issue. Therefore, they will be less vulnerable than smelt.

Smelt have a reputation as a more easily stressed fish than inanga. The physiological basis for this is unknown, however, high turbidity levels increased the oxygen consumption of redbreast tilapia because of mechanical damage caused to their gills (du Preeze et al. 1996). Smelt may experience a similar problem. The mechanism for stress aside, smelt populations in turbid streams can be expected to be much more vulnerable to the effects of suspended sediment than inanga because they are more easily stressed and succumb to a lower turbidity level, and because their eggs are more vulnerable to siltation.

It is apparent that an increase in either the frequency of exposure, or in the duration of exposure to a given turbidity level can affect fish (Newcombe and McDonald 1991). However, knowledge of the critical frequencies and exposure periods is only now being developed. Shaw & Richardson (2001) found that an increase in the duration of sediment pulses from 1 to 6 hours significantly reduced the growth rate of rainbow trout fingerlings. However, repeat exposure of smelt to a turbidity of 1000 NTU for 4 hours every 2-3 days had no discernable effect on their survival. Although the critical frequency of exposure and duration of turbidity for smelt remains unknown, an exposure of 1000 NTU for 4 hours every 2-3 days is well above the upper limit for natural flood conditions in most Auckland streams (Wilcock & Stroud 2000). Therefore, typical turbidity conditions experienced in these urban streams are unlikely to affect the smelt. However, it should be noted that turbid conditions in the wild may be accompanied by both reduced pH and oxygen levels which, combined with high turbidity, may result in synergistic effects on fish survival.

These results deal with the direct effects of turbidity on fish and not the indirect effects of increased siltation on substrates providing habitat for fish or their food supply. It is apparent that although turbidity can directly affect some native fish species (e.g., banded kokopu and smelt) through sublethal and lethal effects, respectively, indirect effects of siltation on stream ecosystem functioning may be more important in the long term and affect other species such as redfin bullies and inanga.

5. Effects of Turbidity on Invertebrates

5.1 Choice of invertebrate species

The invertebrate fauna of many urban streams in Auckland City is dominated by relatively few tolerant taxa such as amphipods, snails, midges and worms (e.g., Sides and Bennett 1998; Suren et al. 1998; Suren 2000). Very few of the more sensitive invertebrates such as mayflies or caddisflies are found, and stoneflies are generally absent from urban streams. This species-poor fauna is typical of Auckland urban streams, and reflects the high degree of habitat modification and the generally low water quality in many streams. In contrast to urban streams, non-urban streams in the Auckland Region often support high densities of more sensitive invertebrates such as mayflies and caddisflies. There are a multitude of factors associated with catchment development that may lead to a loss of sensitive invertebrate taxa. Sediment is one of these and when washed into streams it may lead to a loss of sensitive taxa, with a shift in the fauna to one dominated by more tolerant species.

In this study, invertebrates were selected that are characteristically found in non-urban catchments, as we wanted to assess the sensitivity of these taxa to suspended sediments. A high sensitivity of these animals to suspended sediment may explain their absence from urban streams. Discussions between Mike Scarsbrook (NIWA) and John Maxted (ARC), and a review of the literature of the effects of landuse changes and turbidity on invertebrates (e.g., Quinn et al. 1992; Harding et al. 2000), identified five insect taxa that were either common on soft substrates in Auckland streams, or taxa known to be adversely affected by high turbidities. These were two caddisflies (Polyplectropus and Triplectides), the damsel fly (Xanthocnemis), and two mayflies (Zephlebia and Deleatidium). Zephlebia is relatively common in non-urbanised, soft bottomed streams in the Auckland Region and Deleatidium, although less common in Auckland streams, was included because it is ubiquitous and known to be sensitive to sediment. We also selected a crustacean, the freshwater crayfish (Paranephrops) for the study as these animals are less mobile than fish, and so may prove vulnerable to suspended solids.

These animals all have different morphologies. The two mayflies are characterised by thin gills on each side of their abdomen, while the damselfly has long, flat, tail-like gills on the end of its body. The caddisfly Triplectides has abdominal gills as well, but these tubular gills are protected within a case, usually made of plant material such as hollowed out sticks. The other caddisfly, Polyplectropus, has no gills, but relies on small apertures along its abdomen for gas exchange. The freshwater crayfish Paranephrops relies on gas exchange through a series of tufted filamentous gills that arise at the point of attachment of each of the thoracic legs. These are protected by the carapace. Crayfish also have mechanisms to minimise the damage to their gills by suspended sediments. As such, we expect that these animals would have different tolerances to suspended sediments, reflecting differences in how the gills were exposed to fine, potentially abrasive or clogging sediment.

Invertebrates for the experiments were obtained from a number of small streams in the Hamilton region. Samples of Xanthocnemis were collected from a small stream flowing through pasture south-west of Hamilton. These animals were collected from dense growths of macrophytes, usually Ceratophyllum and Elodea, using a kick net. Samples of other invertebrates were collected from small streams flowing through the Whatawhata Hill Country Research Station. Polyplectropus were collected using a kick net, sampling the stream margins amongst riparian vegetation and detrital debris in the channel. Deleatidium and Zephlebia were collected by electric-fishing small sections of selected streams, and collecting all animals in a downstream net. Paranephrops were collected from streams in the Whatawhata Hill Country Research Station by electric-fishing.

All invertebrates were kept in small plastic containers on ice until returned to the NIWA Hamilton laboratory. Here they were separated into individual plastic containers and kept in a constant temperature room (16°C, photoperiod 12L:12D) for 1-2 days before the experiments began.

5.2 Experimental methods

5.2.1 Establishment of a lethal concentration

For the experiments, selected numbers of invertebrates were placed into plastic cages (200 mm high, 140 mm square) with 0.5 mm mesh sides (Fig. 10). Ten individual Triplectides, Zephlebia and Deleatidium, and 7 Xanthocnemis were placed into separate cages. Larval Polyplectropus were placed individually into smaller cages (cylinders 5 cm diameter, 10 cm long, 0.5 mm mesh at both ends) as these individuals displayed strong antagonistic behaviour to each other. Small pieces of Ceratophyllum were placed in each cage containing the Xanthocnemis, and leaf litter was placed in the cages containing Triplectides to give these animals something to cling onto. We used 3 replicate cages for all animals except Polylectropus, where we used 6 replicate cages (Table 7) containing individual animals, because these animals attack each other. Separate trials were also done for Paranephrops, where we placed one individual into each of 12 large plastic containers (Table 7).

Figure 10. One of the test cages used to house the invertebrates in when assessing their sensitivity to turbidity. Individual *Xanthocnemis* nymphs are seen in the containers, along with some *Ceratophyllum* for shelter.

Each cage was placed in a removable steel frame, which was then placed into large "wheelie-bins" containing water of a specified turbidity level (see Section 3.2). One cage containing each of Triplectides, Zephlebia, Deleatidium and Xanthocnemis were positioned just under the water surface, with a further set of these in the middle layer, and the final set of cages at the bottom layer of the steel frame. A control bin with no added sediment was used to assess survival as a result of experimental handling of all invertebrates (Table 7). We tested the 24 h lethal exposure of three levels of turbidity for the aquatic insects: 0, 4000 NTU, 12000 NTU and 18300 NTU (Table 7). One-way ANOVA was used to ascertain whether there was any significant effect of sediment concentration on invertebrate survivability over the 24 h period.

Table 7. Summary of experimentals showing the number of individuals and replicates used to assess the effects of suspended sediment on 6 invertebrate taxa. Also shown are the turbidity levels tested.

Invertebrate species	Animals per cage (N)	Replicates per Trial (N)	Turbidity levels tested (mean NTU)
Deleatidium	10	3	0, 4000, 12000, 18300
Polyplectropus	1	6	0, 4000, 12000, 18300
Triplectides	10	3	0, 4000, 12000, 18300
Xanthocnemis	7	3	0, 4000, 12000, 18300
Zephlebia	10	3	0, 4000, 12000, 18300
Paranephrops	1	12	0, 21300

The cages were left in the turbid test water for 24 h, after which time they were removed from the bins and placed into clear water to rinse the sediment away. Each cage was then opened and the number of invertebrates still living was recorded. On a few occasions (in both control and experimental conditions), some invertebrates (< 5 %) were trapped between the mesh sides and the plastic containers and had died there. These were not included in our assessments of survival related to turbidity level. In other cages, not all invertebrates were present at the end of the trial, as some had managed to 'escape' through small holes in the cages. Again, the number of individuals that escaped was small, so was not included in our estimates of survival.

5.2.2 Effects of repeat exposure to 1000 NTU

Following the above experiment, we quantified the effect of repeated exposure to a lower turbidity level, as would more typically occur in Auckland streams. We tested the sensitivity of Deleatidium to a repeat exposure of 1000 NTU (nominal level). For this experiment, we collected mayflies from the Whatawhata Hill Country Research Station, and placed 20 into the same plastic cages described above. These cages were then placed into the large plastic wheelie bins containing clear tap water. We used six replicate cages that were left in clean tap water as controls, while another five replicates were used to assess the impact of repeated exposure to 1000 NTU over a long time period. After the first day in the clear water, five experimental cages were placed into the turbid solution for four hours, before being removed, washed and replaced into the clear tap water. The survival of invertebrates was assessed before replacing the cages back into the clear tap water. Survival in the control cages was also assessed at this time. This experiment was run for 14 days, during which time invertebrates were allowed to feed on natural periphyton covering ceramic tiles. These tiles were removed prior to placing the cages into the sediment solution, to avoid contamination, and were replaced when the cages were replaced back into the clean tap water.

Invertebrates in the experimental cages were exposed to the 1000 NTU solution on days 1, 2, 5, 7, 9, and 12, and their survival checked before and after each exposure. Survival was compared with that of the control. The experiment was concluded after 14 days. The pH, turbidity, temperature and dissolved oxygen in each tank was measured on each sampling day to see whether any of these parameters changed over time.

For each trial, we calculated the percentage survival of Deleatidium in both the control and experimental cages. A repeated measures ANOVA was used to ascertain whether there was any difference in the survival rates over time between the exposed and control groups. Linear regression was also used to ascertain whether there was any time dependent effect on survival.

5.3 Results

5.3.1 Establishment of a lethal concentration

There were no significant differences in the survival of any of the five insect taxa in the control or turbid water after a 24 h period, even for the most turbid solution (18,300 NTU; Fig. 11). Mean survival rates in all trials ranged from a low of 88 % for Zephlebia to 95 % for Xanthocnemis. There was little pattern in the survival of the different taxa in each of the different test solutions. Surprisingly, the 24 h survival of Deleatidium, Polyplectropus, and Xanthocnemis in the clear-water control solution was always lower than in the most turbid solution (18,300 NTU) (Fig. 11). This difference was not significant, but the consistency of the pattern suggests that these invertebrates were less stressed in the highly turbid water than in clear water.

Paranephrops also displayed no reduction in survival in turbid water (21,300 NTU) over a 24 h period; indeed we found only a 91% survival in the controls compared to a 100 % survival in the most turbid test solution.

Based on these results, it is evident that there are little, if any adverse effects of short-term (24 h) acute exposure to even very high turbidities for the six invertebrate taxa selected for this study.

5.3.2 Effects of repeat exposure to 1000 NTU

Water quality parameters remained relatively constant between the control and 1000 NTU solutions over the 14-day period. Turbidity in the control solution was always low (c. 1 NTU), and the average turbidity of the test solution was 1052 NTU. The pH of the control solution (pH = 7.49) was slightly lower than that of the test solution (pH = 7.61), but this small difference was not considered to be physiologically significant.

Overall, survival of Deleatidium nymphs was high for both the control and experimental groups, with over 80 % of the nymphs surviving repeat exposures to a turbidity of c. 1000 NTU over the 14-day period. There was no significant difference in the survival of mayflies between either the control or experimental groups after 14-days ($P > 0.05$), and although there was a slightly lower survival of individuals in the experimental groups exposed to 1000 NTU from 5 days onward (Fig. 12), the difference was not significant ($P > 0.05$).

There was, however, a significant decrease in the survival of mayfly nymphs in both the control and experimental groups over the 14-day period ($F = 13.5$, $P < 0.001$, $r2 = 0.54$). This difference suggests that holding these animals over the 14-day period had a slightly negative effect on their survival, but this was unrelated to periodic exposure to turbidity.

Figure 11. Summary bar graph of the mean survival of selected invertebrate taxa exposed for 24 h to various turbidities (the means are for 3 replicates per species, except for *Polyplectropus* where 6 replicates were used, and the error bars are 1 standard error).

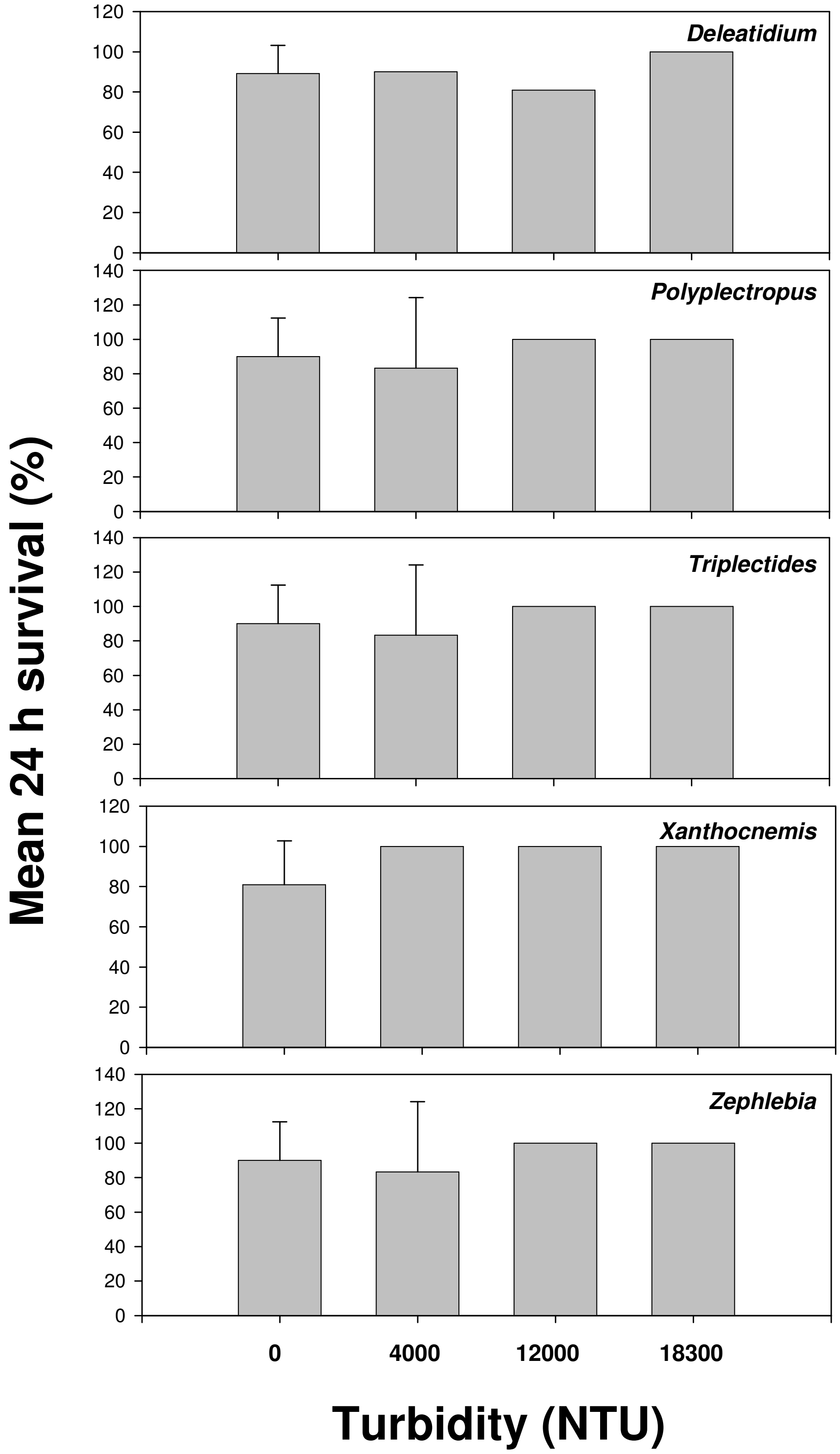
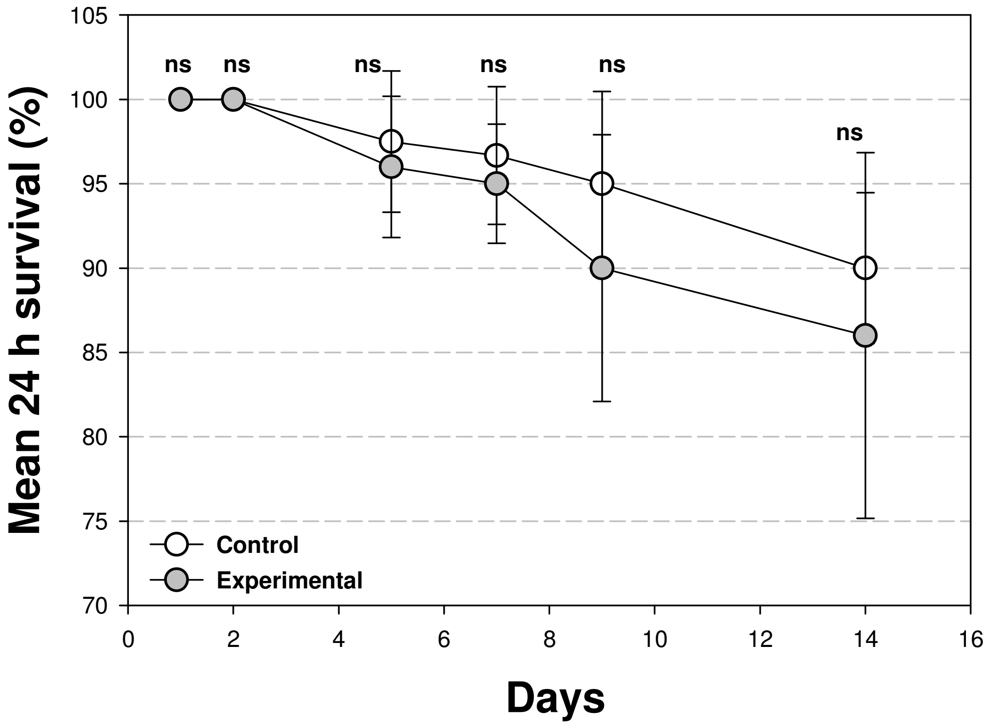


Figure 12. Plot of the mean (± 1 SE) survival of 20 *Deleatidium* nymphs to repeated 4 h exposures of 1000 NTU over a 14-day period ($x \pm 1$ sd, $n = 6$ for control, 5 for experimental cages). Although there was a decrease in the survival of nymphs after 5 days, there was no significant difference (ns, $P < 0.05$) between control and turbidity-exposed groups after 6 exposures over 14 days.



5.4 Discussion

The results of this study showed that there was no evidence of a direct lethal effect from a 24 h exposure to high turbidities on selected invertebrate taxa. These taxa were chosen a priori as being "sensitive" to landuse changes, and are commonly absent from streams flowing through modified catchments where turbidity is high (Quinn and Cooper 1997; Quinn et al. 1997; Suren 2000; Harding et al. 2000). The suspended sediment concentrations that we exposed the test invertebrates to were extremely high (up to over 18,000 NTU), and at the extreme upper limit of what would be found in even the most turbid conditions for urban streams. Lack of lethal effects of even such high turbidity implies that infrequent periods of high turbidity are unlikely to adversely affect the survival of even the most sensitive stream invertebrates.

We also detected no significant difference in survival of the common mayfly Deleatidium when repeatedly exposed to a 1000 NTU solution over a 14-day period. These animals were given adequate uncontaminated food during this period, and they appeared to suffer few adverse effects from the short term (4 h) exposures to turbidity. Lack of any observable lethal effect to repeat exposures suggests that the absence of sensitive taxa from urban streams is not due to any direct effect of the animal's inability to tolerate acute turbid conditions.

Although we did not detect any direct lethal effects on invertebrates from short-term, or repeated exposures to solutions with high turbidities, it is highly likely that significant long-term effects of highly turbid waters on invertebrate communities will occur in natural streams. High turbidities increase invertebrate drift rates (Suren 1998) and reduce the density of bottom dwelling invertebrates (Wagener and LaPierre 1985; Ryan 1991; Quinn et al. 1992). Suspended sediment also settles on the substrate, clogging spaces between stones and reducing the available habitat for invertebrates (Suren and Jowett 2001). Deposited sediments also contaminate periphyton layers on stones, reducing their food value and attractiveness to invertebrates (Ryder 1989; Broekuizen et al. 200l). Invertebrate densities are reduced in places where suspended sediment has settled, and the fauna is dominated by taxa tolerant of silted conditions (e.g., Lester et al. 1994; Death 2000; Suren and Jowett 2001). Taxa such as the ones tested in this study will be absent from such areas as some of them (e.g., mayflies, caddisflies) have shown strong negative responses to both suspended and deposited sediment in streams.

A number of studies have examined the ecology of urban streams in the Auckland region (e.g., Williamson et al. 1994; Anon 1995; Macaskill et al. 1995; Wilding 1996; Sides and Bennett 1998; Allibone et al. 2001). The report by Sides and Bennett (1998) is the largest and most comprehensive study, whereby a systematic large-scale survey of 61 sites on 44 streams in central and west Auckland, and on the North Shore was conducted. Streams in non-urban catchments were characterized by at least 4 caddisfly genera, 3 mayfly genera, and 1 stonefly genera, all of which are regarded as being 'sensitive' to catchment development. In contrast, more tolerant invertebrates such as midges, worms, the snail Physa, and the damselfly Xanthocnemis generally characterized the urban streams examined in the Sides and Bennett study. These latter taxa have been identified elsewhere as common components of urban streams throughout the country (Suren 2000; Suren et al. 1998).

There are many differences in the physical structure of urban and non-urban streams (Suren 2000). For instance, the non-urban streams studied by Sides and Bennett (1998) were generally longer, had greater catchment areas, were higher and had their samples collected at a greater distance from the sea than the urban streams. The non-urban streams also had a relatively high percentage of unmodified catchment, and were surrounded mostly by native vegetation. They had high dissolved oxygen concentrations, and were often characterized by riffles flowing over a bouldery substrate. The urban streams, in contrast, often had highly modified stream channels, consisting of concrete channels or reinforced banks. Overhanging riparian vegetation was also relatively rare in these streams, and spot water temperatures quite high. Algae and /or macrophyte biomass was also high in some of the streams.

As a consequence, the absence of sensitive insect taxa from these urban streams may reflect differences in the physical habitat conditions, and the inability of sensitive taxa to survive in the highly modified habitats characteristic of urban streams. Thus, the occurrence of highly turbid waters in these streams is only one of many different environmental pressures faced by the biota. There is, however, a decline in the density of sensitive insect taxa from streams that are in the process of becoming urbanized, despite the fact that the overall habitat conditions of these streams is relatively natural (e.g., Suren 1999). Such a decline may reflect the sedimentation associated with the construction and urbanization phase of small catchments (Williamson 1993; Snelder and Trueman 1995; Suren 2000). Our results suggest that this reduction is not a result of direct lethal effects of turbidity, but more a result of emigration by invertebrates from areas of high turbidity. Once suspended sediments settle, they create unsuitable instream habitat within the streambed (Suren and Jowett 2001) and lower the nutritional value of food such as periphyton on cobbles (Ryder 1989; Broekhuizen et al. 2001). It is these more subtle effects on habitat quality that are thought to reduce invertebrates in urbanized streams.

6 Conclusions

Exposure of the aquatic larval stage of 2 caddisflies, a damselfly and 2 mayfly species to high turbidity levels (up to c. 20,000 NTU) had no effect on their 24 hour survival. Similarly, the freshwater crayfish, adult redfin bullies and juvenile banded kokopu were not affected by turbidities of c. 20,000 NTU. As the highest turbidity levels recorded in Auckland streams are well below 20,000 NTU, it can be concluded that these species will not be directly affected by the high turbidities associated with flood flows. This is not to say that other environmental effects caused by the presence of high levels of suspended solids in streams will not affect them. We found that the Auckland clay used for these tests reduced the pH of water to levels (5.2-5.5) which may stress some biota, and there are the numerous indirect and longer-term effects of settled clay particles on stream ecosystems to consider. These issues aside, we concluded that when concentrations of Auckland area clay particles in water produce turbidities of c. 20,000 NTU or less, the short-term (24 h) survival of these species will not be affected.

This is in contrast to the results obtained for inanga and smelt. The survival of both these species was reduced by turbidity levels below 20,000 NTU. The survival of inanga was reduced by turbidity levels ranging from 7,000 NTU upwards. Its LC50 was close to 20,000 NTU and turbidities over 30,000 NTU resulted in 0% survival over 24 hours. Even so, this species survival is unlikely to be greatly affected by the turbidity levels occurring naturally in Auckland streams.

Smelt were an order of magnitude more sensitive than inanga. Their survival was reduced at turbidity levels ranging from 700 NTU upward. Their LC50 was close to 3,000 NTU and turbidities over 10,000 NTU resulted in 0% survival over 24 hours. Despite the limitations of the LT50 curve for this species, it provides a guide to the time for 50% survival to occur at a given NTU level. However, turbidities of 2,000 NTU would need to persist for more than several days to reduce smelt survival by 50%. These data indicate that smelt survival could well be affected in streams when sediment holding ponds are breached and unusually high turbidities occur for relatively short periods. As other factors, such as low pH and low oxygen levels, can be expected to occur on such occasions, actual smelt mortalities may be much higher.

Repeat exposure of smelt to turbidities of 1000 NTU for 4 hours every 2-3 days over a period of 20 days did not affect their survival. These data establish a ‘safe’ baseline for repeat exposures. However, the effects of 2000 NTU for 4 hours every 2-3 days, or of an increase in the duration of exposure from 4 to 8 hours remain unknown.

With the exception of smelt, this study has largely eliminated water column turbidity as a major stressor of fish and invertebrates in Auckland streams. This means that impacts of suspended solids on the biota are mediated primarily through changes in benthic habitats and /or stream production.

7 Recommendations

- Use of the LT_{50} curve for smelt is constrained by the high variability in survival rates encountered for this species and the resultant wide spread of data points. Further testing could be be carried out over the critical range of turbidity levels for this species to strengthen the LT_{50}-turbidity level relationship.
- Tests were undertaken using an Auckland based clay collected from a restricted locality to avoid any variability in the results from different types of clay. It would now be useful to undertake some testing on smelt with a clay from a different part of the city to ensure similar results occur. This will enable a more general application of the results.
- Preliminary data indicated an effect of fish size on susceptibility to high levels of turbidity. Smaller fish were more vulnerable to turbidity than larger fish. This is unlikely to be an issue for species other than smelt. However, juvenile smelt were not tested and may prove to be more vulnerable than the adults used in this study.
- The repeat exposure at 1000 NTU established a useful baseline for smelt and the mayfly *Deleatidium*. However, some smelt mortalities occurred at 2000 NTU. If turbidities of this magnitude occur in some Auckland streams, repeat exposures to this level should be tested. The 4 hour exposure may also be low relative to the duration of turbid conditions in some Auckland streams.
- The remaining fish and invertebrate species were not sensitive to high levels of turbidity *per se*, but are likely to be affected by other environmental changes associated with high suspended solids loadings in streams. Such environmental effects will need to be identified in order to develop controls on solids loadings. As they could include water quality changes (reduced pH and oxygen levels), effects of siltation on invertebrate and fish habitats, and changes in invertebrate and fish food supplies, an initial scoping study is required to identify which of these processes is likely to be more critical and therefore worth investigating further.

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