Relationships between farming intensity, water abstraction and brown trout and upland bully populations in the Manuherikia River catchment

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Executive Summary

1. The Clutha Fisheries Trust commissioned this investigation by the Department of Zoology, University of Otago, of the effects of agricultural land use and water abstraction on fish populations in the Manuherikia River catchment in Central Otago, New Zealand. This catchment is one of the driest in New Zealand.
2. In general, water quality and ecosystem health in the Manuherikia catchment are regarded as very good because current land use is still dominated by low-intensity farming. However, changes towards higher-intensity farming practices and further water abstraction may be expected to have negative impacts on stream health.
3. In autumn 2011, 36 stream sites spread through the Manuherikia catchment were electrofished. In total, 179 brown trout, 269 upland bullies, four perch, two rainbow trout, one longfin eel and zero galaxiids were caught. Brown trout were present at 15 sites and upland bullies at 11 sites. No fish were caught at 16 of the 36 sites sampled.
4. For each stream site included in this study, we derived two measures of land-use intensity. Our measure of % Farming Intensity was the percentage of the catchment area in the category 'high-producing exotic grassland'. Our measure of % Water Abstraction was estimated as the percentage of stream flow reduction from the *Dryland Scenario* (current land use, zero abstraction) to the *Current Scenario* (current land use, current abstraction) described in a published hydrological model of the Manuherikia catchment (Kienzle and Schmidt 2008). We also measured dissolved and total nutrient concentrations and fine sediment deposition at each site.
5. Both presence/absence and density of brown trout were negatively related to % Farming Intensity. Trout presence/absence at each site was also negatively related to % Water Abstraction. The negative relationship with intensive agriculture was particularly marked, and no trout were recorded where % Farming Intensity was greater than about 40 %. It is also notable that even at farming intensities below 40 %, trout were nevertheless likely to be absent when % Water Abstraction was higher than about 70 %.
6. By contrast, neither presence/absence nor density of upland bullies were related to % Farming Intensity or % Water Abstraction, implying that upland bullies can tolerate a wider range of upstream farming intensity or water abstraction than brown trout.
7. The in-stream physicochemical measure most strongly related to farming intensity was total nitrogen concentration (TN), and trout presence/absence and density showed negative relationships with TN. The distribution of upland bullies was also related to TN.
8. Based on our results it can be argued that to maintain healthy trout populations in the Manuherikia catchment, the proportion of highly intensively farmed land in any given sub-catchment should not exceed 40 %. Where % Farming Intensity is below 40 % there is also evidence for a critical threshold for % Water Abstraction of about 70 %. It can be further argued that total nitrogen concentrations in stream water should not exceed about 300 µg/L in the Manuherikia if trout populations are to be protected.
9. Given the generally good current water quality in the Manuherikia, it may be considered surprising that adverse responses by trout have become apparent at relatively low levels of farming intensity. The possibility that dryland rivers such as the Manuherikia are less resilient to intensive land-use practices than other rivers in the region deserves further research.

1 Background

The Clutha Fisheries Trust commissioned this investigation of the effects of agricultural land use and water abstraction on fish populations in the Manuherikia River catchment in Central Otago, New Zealand. The work was led by Katharina Lange (as part of her PhD research, supervised by Dr. Christoph Matthaei and Professor Colin Townsend), while Fish & Game and Clutha Fisheries staff carried out the electrofishing.

The knowledge gained from this study may help inform management decisions in the upcoming renegotiation of water leases across Central Otago in 2021.

2 Study catchment, scientific context and research objectives

The Manuherikia River catchment (Figure 1) is one of the driest in New Zealand, situated in the eastern rain shadow of the Southern Alps. The region has about 100 rain days (≥ 1 mm) per year and the climate within the catchment encompasses three distinct climate zones: the semi-arid zone with less than 480 mm (extending between Alexandra, Clyde and Omakau; Alexandra has the lowest average annual rainfall recorded in New Zealand at 335 mm), the sub-humid zone with 480 – 635 mm (north-east from Omakau to Blackstone Hill) and the humid zone of the headwaters (above Blackstone Hill, 400 – 2088 m above sea level) with more than 635 mm of rainfall per year (Rickard and Cossens 1973). Most of the catchment area is in the two driest categories.

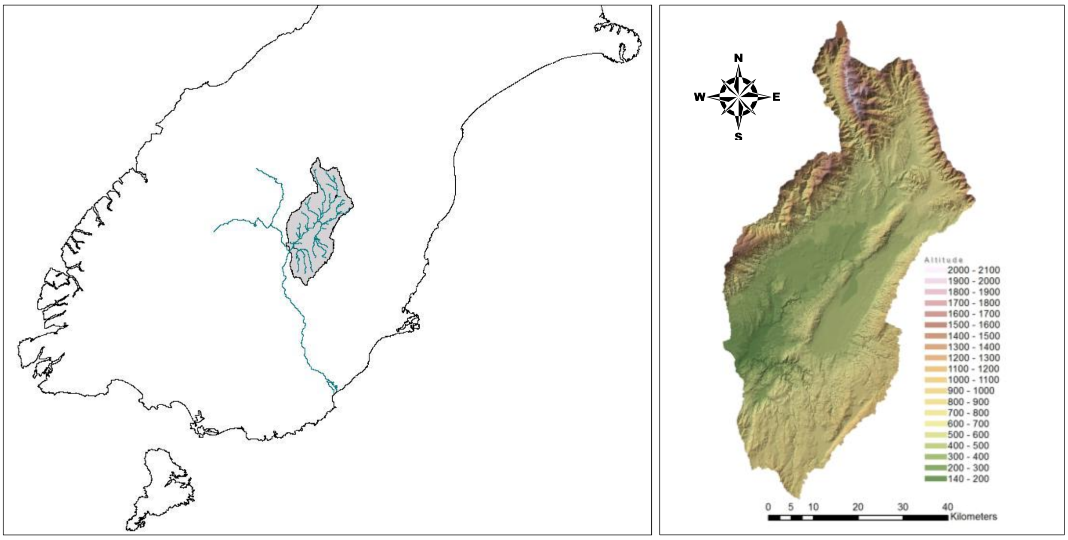

Figure 1. Left: Location of the catchment of the Manuherikia River, a tributary of the Clutha River. Right: Altitude in the catchment ranges from 2088 m a.s.l. at the top of the St Bathans range to 130 m a.s.l. at the confluence with the Clutha River in Alexandra.

In addition to the naturally dry hydrological regime in the Manuherikia River catchment, the high demand for irrigation water in the region puts even more pressure on water resources. The percentage reduction in stream flow associated with abstraction for irrigation was estimated by Kienzle and Schmidt (2008) and is illustrated in Figure 2 (for further details see Methods).

The natural vegetation in the catchment is dominated by tussock grasses but, since the arrival of European settlers, large areas have been developed into exotic grassland pastures. These currently support low-intensity sheep and beef farming in the upper catchment and higher-intensity farming with smaller farms and higher stocking rates in the middle and lower parts of the catchment

(Figure 2). In recent years, the national trend towards the expansion and intensification of dairy farming has also reached Central Otago. The first dairy farm (270 ha) in the Manuherikia Valley was registered in June 2008 and is situated alongside both riverbanks just upstream of the township of Omakau. Future pressure towards further land-use changes can be expected, including development of stone fruit orchards and/or viticulture.

In general, water quality and ecosystem health in the Manuherikia catchment are regarded as very good (Kitto 2011) because current land use is still dominated by low-intensity farming. However, changes towards higher-intensity farming practices are likely to alter the hydrological regime as water abstraction for irrigation increases. Inputs of nutrients, animal waste products and fine sediment from agricultural land are likely to increase as well (see e.g. Townsend et al. 2008, Magbanua et al. 2010, Wagenhoff et al. 2011). Such land-use changes have often been associated with a decline in stream health. Three major causes of degenerating stream health in New Zealand (determined using stream invertebrate and/or algal bioassessment metrics) have been identified in recent years, namely nutrient enrichment, increased fine sediment deposition (Matthaei et al. 2006, Niyogi et al. 2007, Townsend et al. 2008) and stream flow reduction (Matthaei et al. 2010). We refer to these factors as stressors because each exceeds its natural range of variation as a result of human activities and has consequences for stream biota (Townsend et al. 2008). In most ecosystems today, multiple stressors act simultaneously and the responses of stream ecosystems often follow complex patterns where the combined effects of multiple stressors can be greater (or smaller) than expected on the basis of the individual effects of each stressor involved.

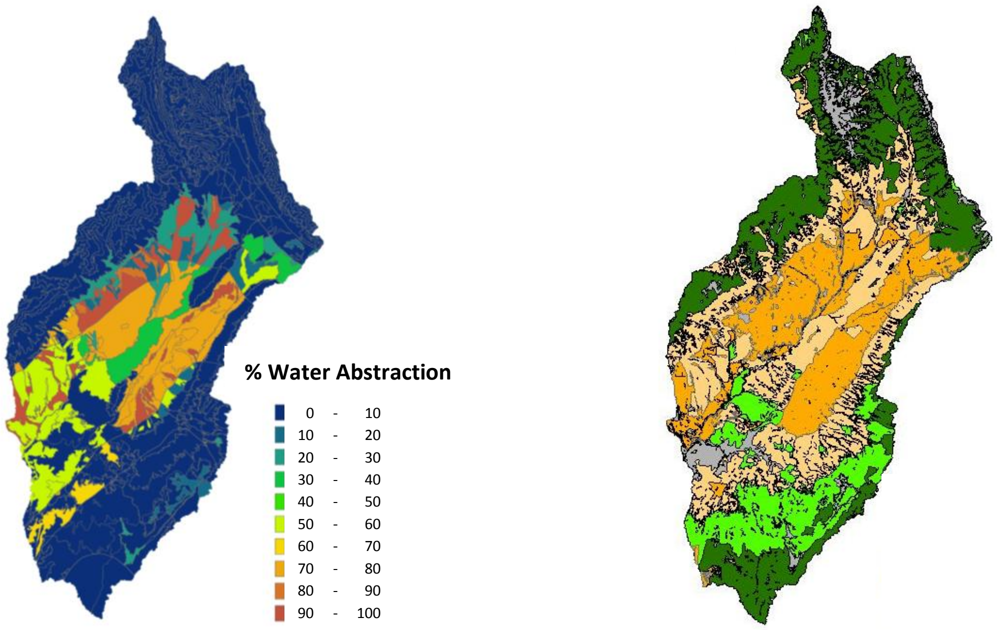

Figure 2. Left: Stream flow reduction (range 0 % (blue) to 100 % reduction (red)), as estimated by Kienzle and Schmidt (2008); Right: Land use types: tall tussock (dark green), depleted tussock (light green), low producing (light orange) and high producing (orange) exotic grassland (LCDB2, MfE).

The Manuherikia is the fourth most significant angling river for brown trout (*Salmo trutta*) in Otago (Otago Regional Council 2006). In a previous study in this catchment, exotic brown trout and native galaxiids (*Galaxias anomalus*) were reported to respond differently to human-induced changes in the hydrological regime (Leprieur et al. 2006). While galaxiids were able to persist in low-gradient stream sites with a high degree of upstream water abstraction, trout could not. In general, trout preferred faster flow velocities compared to galaxiids, as indicated by a negative correlation with the percentage of pool habitats at the studied sites. This previous study did not assess fine sediment deposition, something that may well be associated with negative effects on fish populations, through burial of fish eggs and larvae, gill clogging, impaired growth and a reduction in feeding efficiency (Collins et al. 2011).

So far, the combined effects of stream flow reduction (due to water abstraction for irrigation) and agricultural land-use intensification on fish populations have not been investigated in the Manuherikia River catchment. To address this shortcoming, the present study focused on the following questions:

(i) Are trout (and other fish) less likely to occur in streams with higher catchment land-use intensity and/or water abstraction intensity?

(ii) Is it possible to predict the presence/absence or density of trout (and other fish) based on catchment land-use intensity and water abstraction intensity?

(iii) Are trout presence and trout density related to the in-stream physicochemical variables (habitat characteristics) most strongly correlated to catchment land use?

3 Methods

3.1 Determination of catchment land-use intensity

Farming intensity in the Manuherikia sub-catchments

The River Environmental Classification (REC New Zealand; NIWA; open source database) was used to gain information on farming intensity in the Manuherikia River catchment and its sub-catchments (tributary catchments). Further, we acquired information on land cover types within the catchment from the Land Cover Database II (LCDB2; Ministry for the Environment, New Zealand; open source database) and then calculated the percentages of all land cover types for each sub-catchment. In the Manuherikia catchment, 44 % of total area was covered by tussock grasses, 24 % by low-producing and 25 % by high-producing exotic grassland (Figure 2). The LCDB2 land cover types were determined from satellite images acquired in summer 2001/02 with a spatial resolution of 15 m. Our measure of farming intensity was taken to be the percentage of the catchment area in the category 'high-producing exotic grassland', defined as "typically intensively managed exotic grasslands, rotationally grazed for wool, lamb, beef, dairy and deer production". Henceforth, this index is called % Farming Intensity. It ranged from 0 to 95% in the studied sub-catchments.

Water abstraction intensity in Manuherikia sub-catchments

NIWA scientists Jürgen Kienzle and Stefan Schmidt kindly provided us with data from their hydrological model of the Manuherikia catchment (Kienzle and Schmidt 2008). This enabled us to estimate the intensity of water abstraction for areas having similar hydrological properties (hydrological response units) within the catchment. Kienzle & Schmidt (2008) estimated stream flows using the ACRU model (Agricultural Catchments Research Unit; University of Natal, South Africa) under five different scenarios (Table 1).

Table 1. Characteristics of stream flow scenarios modeled by Kienzle & Schmidt (2008; abbreviation: irr. - irrigation).

Scenario	Natural	Dryland	Current	Improved	Optimal
Landcover	100 % tussock	current	current	current	current
Irrigated area	none	none	50% flood irr., 50% spray irr.	25% flood irr., 75% spray irr.	100% spray irr.

We chose to calculate stream flow reduction as the average of the difference in stream flow between the *Dryland Scenario* and the *Current Scenario* during the irrigation season (October – April) using the data for the years 2000-2004 (the most recent available period).

The index of water abstraction (henceforth called % Water Abstraction) was calculated for each hydrological response unit as follows:

First, we calculated the mean stream flow (Q) for each of the five irrigation seasons (1999/2000 to 2004/2005). The index was then calculated as the percentage of stream flow reduction from the *Dryland Scenario* to the *Current Scenario*:

% Water Abstraction = $(1- Q_{Current} / Q_{Dryland}) \times 100$

The index ranges from 0 (no water abstracted at all) to 100 (all water abstracted). The spatial distribution of water abstraction intensities in the Manuherikia catchment is shown in Figure 2.

3.2 Selection of study sites

The 36 stream sites surveyed in our study were chosen to provide as wide as possible spreads along the gradients of both farming intensity and water abstraction (Figure 3). The sites comprised 3rd, 4th and 5th order streams. Every stream site was associated with a discrete sub-catchment. All sites were unshaded (no riparian trees or shrubs) and situated within 1 km of a road.

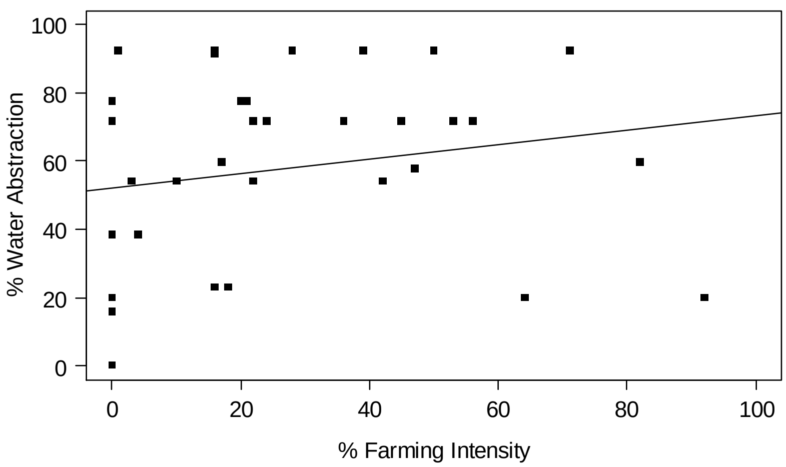

Figure 3. Distribution of study sites along the gradients of % Farming Intensity and % Water Abstraction. The two catchment-scale variables were not significantly correlated with each other (linear regression: FI = 0.18 WA + 0.15, adj. R^2 = 0.009, p = 0.26), allowing us to use them as independent predictor variables in subsequent analyses.

3.3 In-stream physicochemistry

Deposited fine sediment

The amount of deposited fine sediment (particles ≤ 2 mm) was determined using three different methods. First, sediment cover was estimated visually as the average percentage of the streambed surface covered by fine sediment using a gridded viewing box (area 12 x 12 cm) at 10 random locations within the riffle. Second, where deposited fine sediment was present, its average depth was determined by pushing a metal ruler gently into the sediment until the underlying coarser substratum was reached. Third, the amount of re-suspendable inorganic fine sediment (SIS) within the stream bed was determined using the 'Quorer' technique (Clapcott et al. 2011). In contrast to estimating sediment cover on the bed surface, this allows quantification of deposited fine sediment trapped in the upper layers of the streambed. SIS samples were collected from five random locations in each riffle by sealing the Quorer, a sturdy PVC cylinder (inner diameter 24 cm, height 70 cm), tightly onto the streambed, taking five water depth measurements in it, then disturbing the substratum to a depth of about 5 cm with a metal rod for 30 s and collecting a 120-ml subsample of the slurry. Two water samples outside the Quorer were taken to correct for background turbidity. Back in the laboratory, sediment samples were measured, filtered, dried, weighed, ashed at 550°C and then weighed again to determine the mass of SIS per m^2, averaged for each site.

Concentration of dissolved and total nutrients

At each site, three filtered and three unfiltered water samples were collected, stored on ice in the dark in the field, and analysed for dissolved (nitrate, ammonium, dissolved reactive phosphorus) and total nutrients (total nitrogen, total phosphorus) using standard methods (APHA 1998) in the laboratory.

3.4 Fish presence/absence and density

Fish populations were assessed between 12 April and 31 May 2011 using a backpack electrofishing device. At each site, a 30-m stream reach was selected that was representative of the overall reach and included, where possible, a run-riffle-pool sequence. Stop nets were installed at the upstream and downstream ends and three passes were performed. All fish caught were identified and then released into the river. To determine the stream surface area sampled, average width was determined from 10 measurements of the wetted width at random locations and one measure of reach length. Fish densities were expressed as the numbers of fish (sum of all fish caught from the three passes) per 100 m^2. Analyses were performed based both on density and presence/absence.

3.5 Statistical analysis

Our data analysis comprised three steps. First, we investigated how presence and density of trout were related to the key catchment characteristics % Farming Intensity and % Water Abstraction using generalized linear models (GLMs). Second, we identified relationships between these catchment characteristics and in-stream physicochemical variables. Third, we selected the in-stream physicochemical variables most strongly related to % Farming Intensity and % Water Abstraction to find the best models describing the patterns in fish presence and density, again using generalized linear models (for details see Appendix 1). In general, we expected to find simple responses (gradual increases or declines) or unimodal responses (hump-shaped patterns, also called "subsidy-stress" responses) of fish presence or fish density to the stressors. We focused both on single-stressor effects and on interactive effects of multiple stressors.

Generation of hypotheses

We tested several competing hypotheses for the response of each fish population to the two catchment-scale predictor variables % Farming Intensity (FI) and % Water Abstraction (WA) by employing a set of generalized linear models and applying an information-theoretic model selection approach where the postulated hypotheses were simultaneously tested against the data (after Zuur et al. (2009) and Johnson and Omland (2004)).

The set of competing models included the null model (intercept only; ~ 1), the global model (intercept plus five predictor terms: the first-order terms % Farming Intensity (FI) and % Water Abstraction (WA), the quadratic terms FI^2 and WA^2 and the interaction FIxWA) and nested versions of the global model with one or more predictor terms removed (for more details see Appendix 2).

The generation of hypotheses for the in-stream physicochemical variables followed a similar procedure (Appendix 3). We applied binomial GLMs to the fish presence/absence data, and negative binomial GLMs for the fish densities dataset.

Fitting the models to the data

We only performed model selection for fish response variables where the fit of the global model was significantly better than the fit of the null model. If this condition was not met, we assumed that the fish response variable was not affected by our predictor variables.

To identify the model with the best fit to our data we ranked all models (global model, nested versions of global model and the null model) according to their AIC_c values (Akaike Information Criterion for small sample sizes; Burnham and Anderson 2004). The AIC_c is a relative measure of the goodness of fit of statistical models to a given data set and allows us to identify the “most parsimonious model” (the one that represents the best compromise between the model fit, which should be as good as possible, and the number of predictors in the model, which should be as low as possible).

The model that supported the data best (i.e. that had the lowest AIC_c value) was chosen for presentation in the Results below (‘best model’). All analyses were performed using the R software version 2.14 (R Development Core Team 2008).

4 Results

4.1 Summary of fish caught and site physicochemistry

In total, 179 brown trout (body length range: 47 – 250, median: 95 mm), 269 upland bullies (*Gobiomorphus breviceps*; body length range: 23 – 85, median: 52 mm), four perch (*Perca fluviatilis*), two rainbow trout (*Onchorynchus mykiss*) and one longfin eel (*Anguilla dieffenbachii*) were caught at the 36 sites. Galaxiids were caught at none of the sites. Analyses could only be performed on the first two species. Brown trout were present at 15 sites and upland bullies at 11 sites (Figure 4). The species occurred together at five sites. No fish were caught at 16 of the 36 sites sampled.

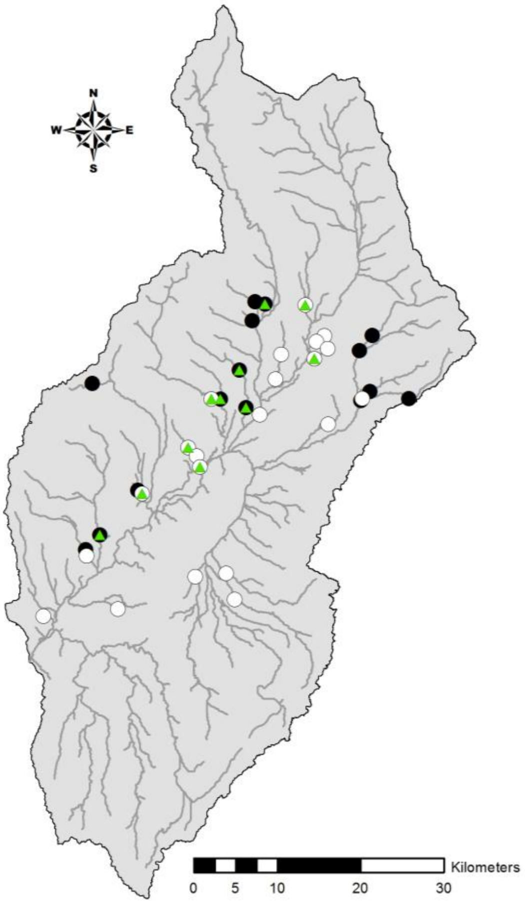

Figure 4. Surveyed stream sites in the Manuherikia River catchment where brown trout were present (black circles; 15 sites) or absent (open circles; 21 sites). Bullies were present at 11 of the 36 sites (green triangles) and occurred together with trout at five sites.

The physicochemical in-stream characteristics of the 36 sites covered a wide range of both dissolved nutrient concentrations and amounts of deposited fine sediment (Table 2).

Table 2. Summary statistics for nutrient concentrations, fine sediment measures and fish densities (TN = total nitrogen, TP = total phosphorus, DRP = dissolved reactive phosphorus, NO_3 = nitrate, NH_4 = ammonium, SIS = suspendable inorganic sediment) at the 36 sites

Variable	Minimum	Median	Maximum
TN (µg/L)	45.7	320.6	1336.3
TP (µg/L)	0.5	30.7	163.4
DRP (µg/L)	1.0	9.5	78.5
NO_3 (µg/L)	1.0	3.4	237.3
NH_4 (µg/L)	4.2	14.5	46.6
Fine sediment cover (%)	0.0	100.0	100.0
Fine sediment depth (mm)	0.0	15.7	470.0
Areal SIS (mg/m^2)	45.5	2476.7	14205.4
Trout density (Ind./100 m^2)	0	0	49
Bully density (Ind./100 m^2)	0	0	94

4.2 Patterns of brown trout in relation to catchment-scale predictors

The best model for brown trout presence/absence described a subsidy-stress (hump-shaped) response along the gradient of % Farming Intensity and a linear negative response to % Water Abstraction (Figure 5). This model predicted the presence/absence of trout with good accuracy (81 % of predictions were correct).

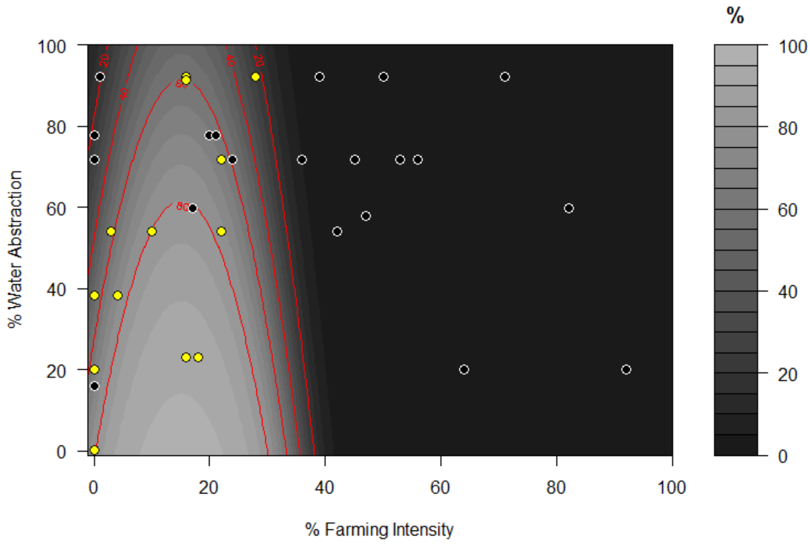

Figure 5. Brown trout presence (yellow circles) and absence (black circles with white surrounds) along the gradients of the catchment-scale predictors % Farming Intensity (FI) and % Water Abstraction (WA). The best model (trout presence ~ FI + FI^2 + WA) predicted the presence (light grey area: predicted probability: 100 %) and absence (black area: 0 %) of trout with an accuracy of 80.6 %. The decreasing probabilities of trout presence along both predictor gradients are shown using isopleths representing 20 % increments. (The Craig & Uhler's R^2-value of the fitted response shape was 0.59.) Note that trout were absent where % Farming Intensity was greater than about 40 % and that at lower farming intensities trout were nevertheless less likely to occur when % Water Abstraction was higher than about 70 %.

The best model to describe the pattern in trout density was a simple, negative response to the gradient of % Farming Intensity (Figure 6). Trout density was not related to % Water Abstraction.

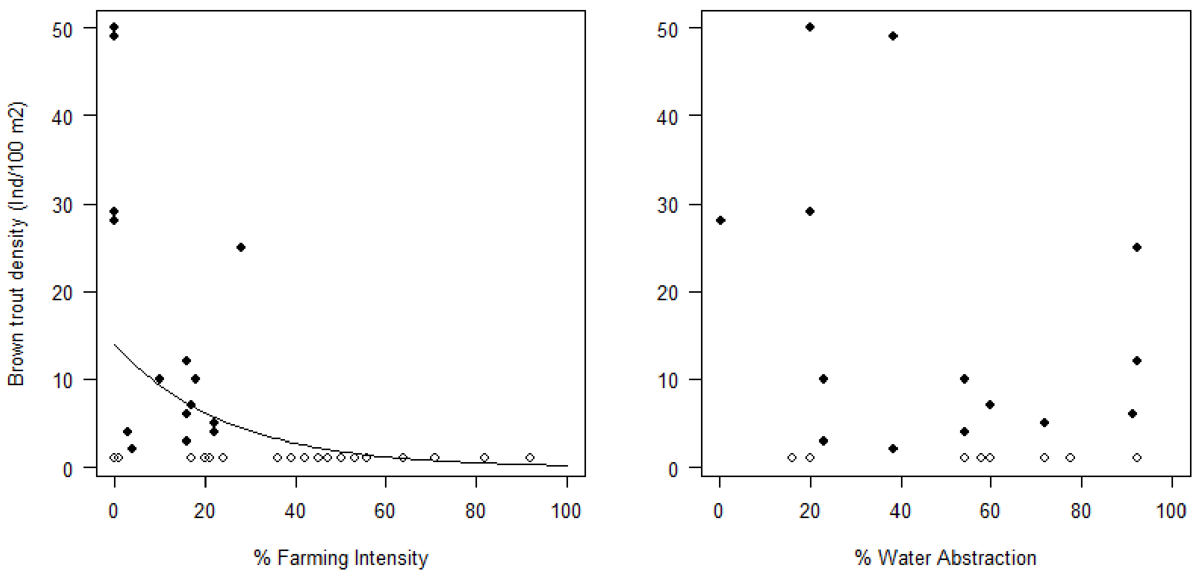

Figure 6. Left: The distribution of brown trout density (trout presence: black circles or absence: open circles) modeled along the gradient of % Farming Intensity. Right: The distribution of brown trout density shown along the gradient of % Water Abstraction. Note that % Farming Intensity was the only relevant catchment-scale predictor variable for trout density. The structure of the best model was: trout density ~ FI (Craig & Uhler's R^2 = 0.38).

4.3 Patterns of upland bullies in relation to catchment-scale predictors

Neither presence/absence nor density of upland bullies were related to % Farming Intensity or % Water Abstraction. In other words, in both cases the global model did not provide a significantly better fit than the null model (Figures 7 and 8).

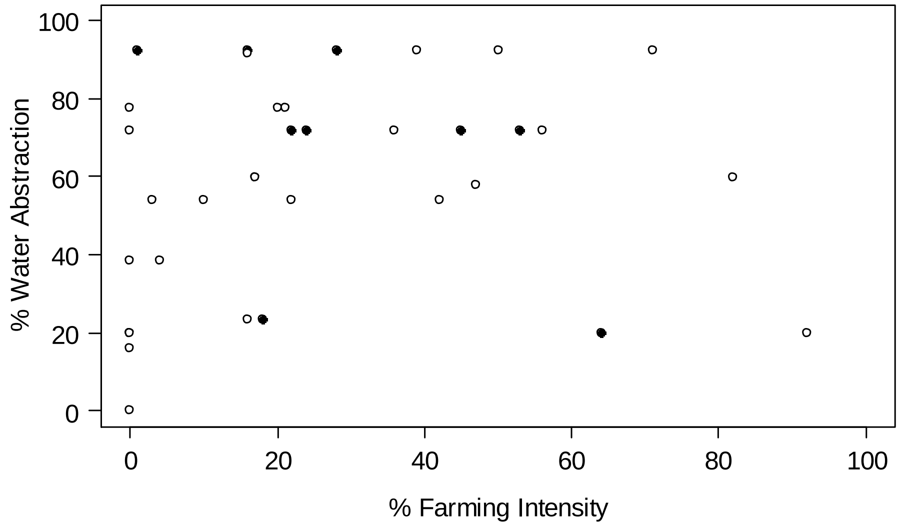

Figure 7. Upland bully presence (black circles) and absence (open circles) along the gradients of % Farming Intensity and % Water Abstraction.

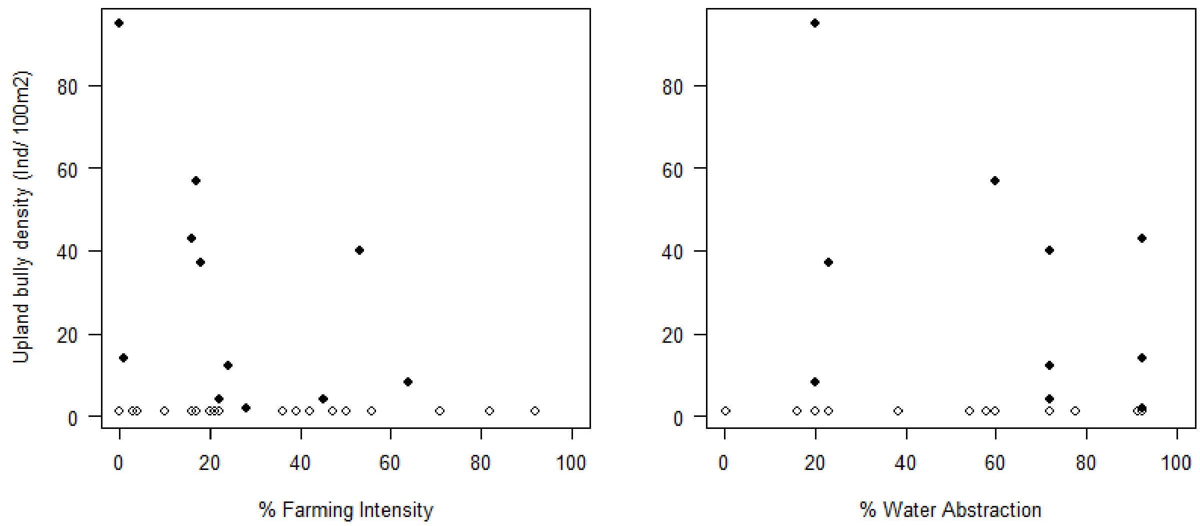

Figure 8. The distributions of bully densities (bully presence: black circles or absence: open circles) along the gradients of % Farming Intensity (left) and % Water Abstraction (right).

4.4 Relationships of in-stream variables to catchment-scale predictors

As in previous studies investigating the effects of land-use intensity on New Zealand streams and rivers (Wagenhoff et al. 2011, Bierschenk et al. in press), we decided to choose one nutrient and one sediment variable that were most closely related to our land-use intensity gradients to determine the relationships of fish presence and density to in-stream physicochemistry. Our choice was between five in-stream variables for dissolved nutrients (total nitrogen, TN; and total phosphorus, TP; dissolved reactive phosphorus, DRP; nitrate NO_3; ammonium, NH_4) and three for deposited fine sediment (percentage streambed cover, FS %; depth of streambed cover, FS mm; and areal re-suspendable inorganic sediment, SIS) (Table 3).

Table 3. R^2-values and p-values for simple linear regressions of % Farming Intensity (FI, square-root transformed) and % Water Abstraction (WA) against the studied in-stream variables. The largest R^2-values within the four nutrient variables and within the three sediment variables are printed in bold. In-stream variables were log(x) (*) or log(x+1) (+) transformed prior to analysis. For abbreviations of variable names see text.

In-stream variable		% FI		% WA	
		R^2	p	R^2	p
TN	*	**0.42**	< 0.01	0.05	0.19
TP	+	0.25	< 0.01	0.08	0.08
DRP	*	0.24	0.01	0.06	0.14
NO_3	*	0.00	0.88	0.00	0.86
NH_4	*	0.14	0.03	0.11	0.04
FS %	*	0.09	0.08	0.00	0.94
FS mm	*	0.18	0.01	0.01	0.64
SIS	*	**0.23**	< 0.01	0.02	0.44

The in-stream variables TN and areal SIS, respectively, explained the highest proportions of the variation in % Farming Intensity and were therefore selected for our further analyses. Note that none of these in-stream variables were strongly related to % Water Abstraction, which is an advantage for our analysis (because it simplifies interpretation) and parallels our finding that % Farming Intensity and % Water Abstraction were also not significantly related to each other.

4.5 Patterns of brown trout in relation to in-stream variables

For this analysis, the in-stream variables TN and SIS and the catchment-scale predictor % Water Abstraction were chosen as potential predictors of trout presence/absence and trout density. These were selected because previous experimental work has shown that augmented nutrients, fine sediment and water abstraction are influential multiple stressors in streams (Matthaei et al. 2010).

The best model for trout presence/absence indicated a negative relationship with TN (Figure 9), but neither SIS nor % Water Abstraction was related to trout presence/absence.

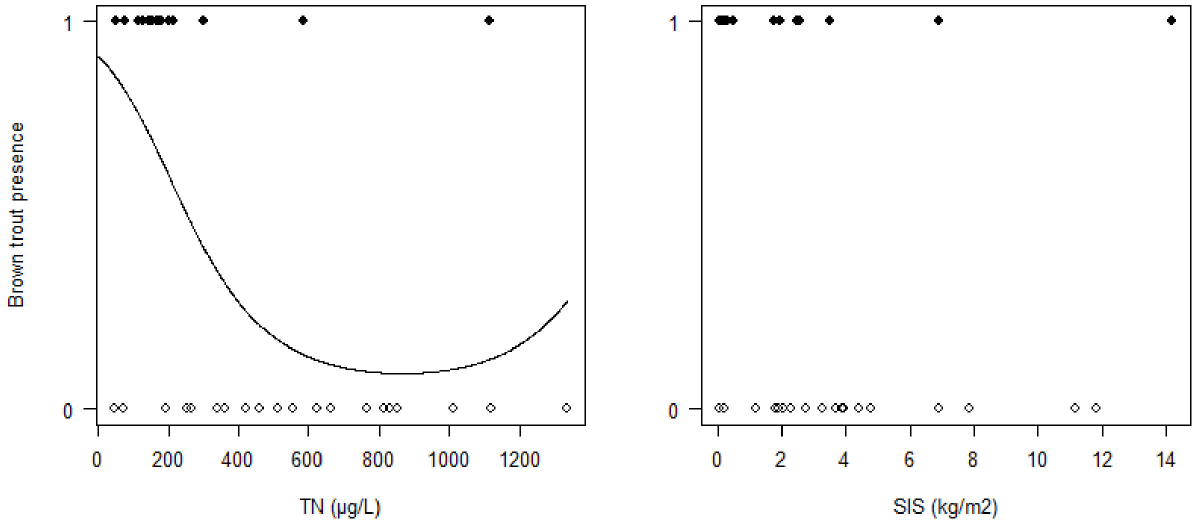

Figure 9 Trout presence (black circles) or absence (open circles) along the gradients of total nitrogen (TN, left) and areal re-suspendable inorganic sediment (SIS, right). Note that TN was the only relevant in-stream predictor variable for trout presence. The best model (trout presence ~ TN + TN^2) predicted the presence and absence of trout with an accuracy of 83.3 % (R^2 = 0.38).

For trout density, by contrast, the best model included both % Water Abstraction and TN. Trout density declined steeply along the gradient of TN concentrations, and more gradually along the gradient of % Water Abstraction (Figures 10). There was no relationship with SIS.

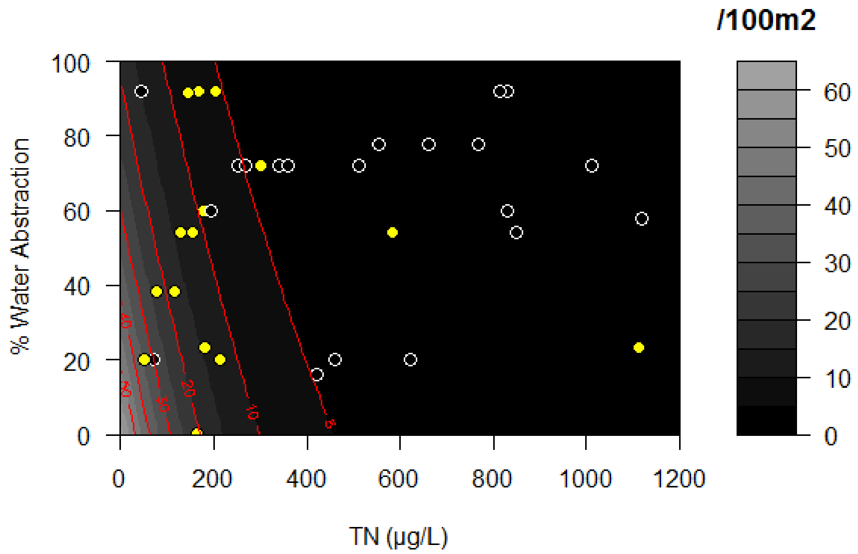

Figure 10. The distribution of trout density modeled along the gradients of TN and % Water Abstraction. Shades of grey range from the highest expected densities (light grey areas) to no trout expected (black areas); yellow circles = trout caught, black circles with white surrounds: no trout caught. The structure of the best model was trout density ~ TN + TN^2 + WA (Craig & Uhler's R^2 = 0.53). Trout were generally absent from locations where TN exceeded about 300 µg/L while, for a given concentration of TN, lower trout densities were associated with higher % Water Abstraction values.

4.6 Patterns of upland bully in relation to in-stream variables

The best model predicting the probability of the presence/absence of upland bullies was characterized by a subsidy-stress response to TN, while neither SIS nor % Water Abstraction were included (Figure 11). The best model for upland bully density was a simple negative relationship with TN (Figure 12).

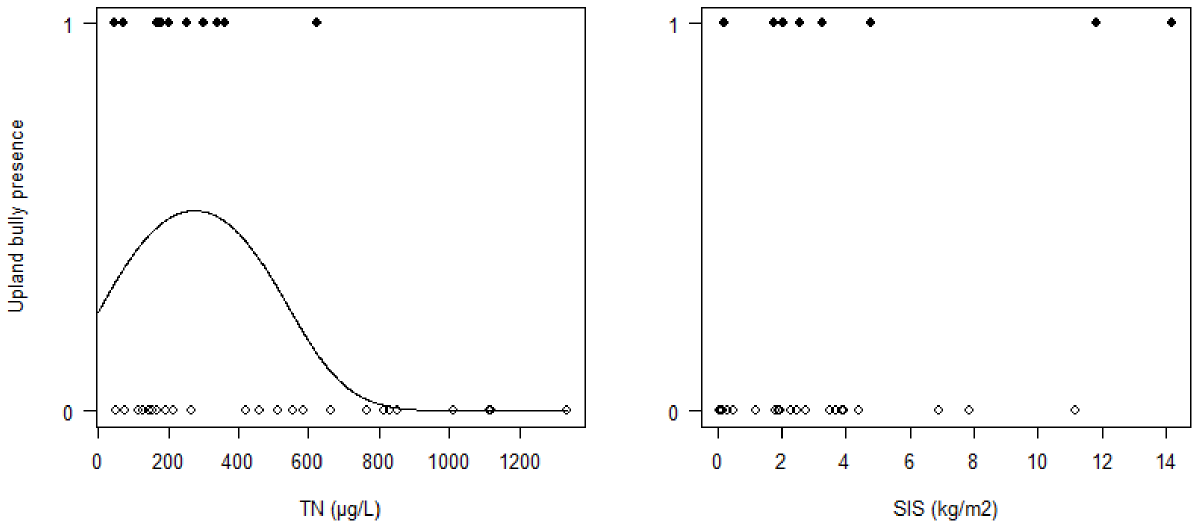

Figure 11. Upland bully presence (black circles) or absence (open circles) along the gradients of total nitrogen (TN, left) and areal re-suspendable inorganic sediment (SIS, right). Note that TN was the only relevant in-stream predictor variable for bully presence. The best model (bully presence ~ TN + TN^2) predicted the presence and absence of bullies with an accuracy of 63.8 % (R^2 = 0.30).

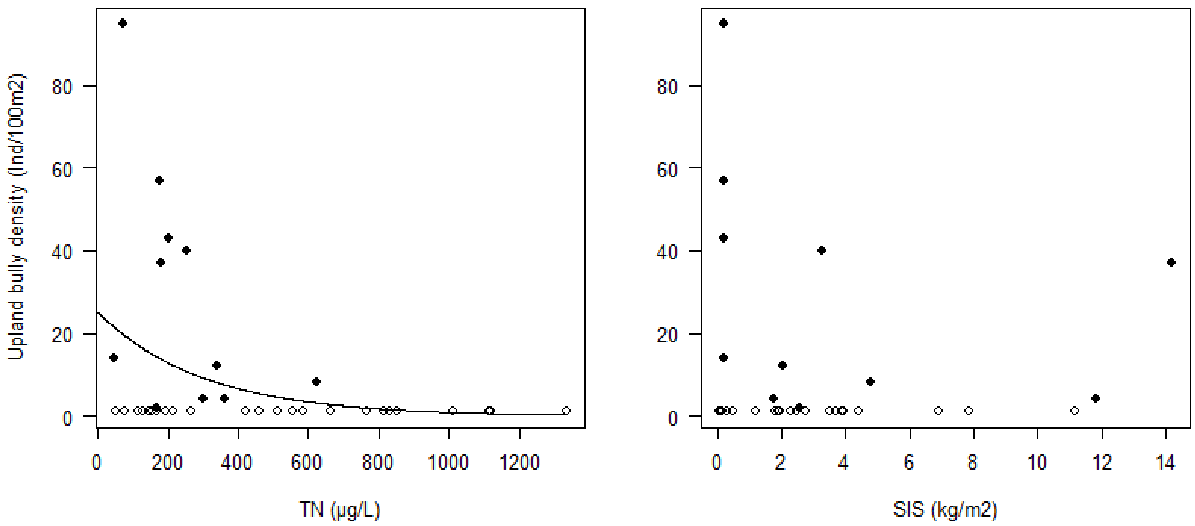

Figure 12. Upland bully density (bully presence: black circles or absence: open circles) along the gradients of total nitrogen (TN, left) and areal re-suspendable inorganic sediment (SIS, right). Note that TN was the only relevant in-stream predictor variable for bully density. The best model (bully density ~ TN) predicted the density of bullies with an R^2 of 0.38.

5 Discussion

Presence and density of brown trout in relation to farming intensity and water abstraction

In this study conducted in Autumn 2011 at 36 stream sites in the Manuherikia River catchment, both presence/absence and density of brown trout were negatively related to the percentage of the catchment area above each stream site devoted to intensively managed exotic grassland. Trout presence/absence at each site was also negatively related to our index of the percentage of stream water abstracted upstream for irrigation. The negative relationship with intensive agriculture was particularly marked, and no trout were recorded where % Farming Intensity was greater than about 40 %. It is also notable that even at lower farming intensities, trout were nevertheless likely to be absent when % Water Abstraction was higher than about 70 %. Trout were present at 15 of the sites sampled, located in the upper Ida Burn catchment, in the Dunstan Creek catchment and in the lower Manuherikia River catchment.

By contrast, neither presence/absence nor density of upland bullies were related to farming intensity or water abstraction, implying that upland bullies can tolerate a wider range of upstream farming intensity or water abstraction than brown trout. Brown trout and upland bullies were the only species caught in sufficient numbers to be included in our analysis.

Our chosen model selection approach was conservative because we used the AIC_c, a model selection criterion suitable for relatively small data sets such as ours (Burnham and Anderson 2004). Descriptive surveys such as ours are generally less effective at providing tidy relationships than experimental studies where the factors of interest can be carefully manipulated. Nevertheless, our best models explained a gratifyingly substantial proportion of variation in the data and the patterns can be considered quite robust. However, it should be noted that other environmental factors that we did not include in our analysis may also influence fish populations.

As % Farming Intensity increased from low levels to about 20 %, the best model indicated a slightly increased probability for trout to be present. Above this level there was a steep decline in probability of trout presence with complete absence above about 40 %. If this aspect of the pattern is real, it provides an interesting extension of a similar phenomenon, known as a subsidy-stress response, seen for benthic invertebrates in other streams and rivers (Townsend et al. 2008, Wagenhoff et al. 2011). A modest amount of high intensity farming may be associated with a nutrient subsidy that increases the productivity of stream algae and grazing invertebrates that form part of the diet of brown trout.

The best model for trout presence/absence included not only a subsidy-stress response to farming intensity but also a negative response to water abstraction intensity. This model explained 59 % of the variation in the data (R^2 of 0.59), allowing trout presence/absence to be predicted correctly in 81 % of cases. Had we considered only farming intensity or water abstraction as a single predictor variable, our models would have been less accurate with an R^2 of 0.53 for farming intensity (72 % correct) and 0.09 (67 % correct) for water abstraction intensity. These numbers indicate that, even though multiple stressors are at work in the Manuherikia catchment, farming intensity was the most important single stressor in our study. Further, the best model for trout presence/absence did not include an interaction term. This means that while water abstraction intensity contributed some additional stress to the more important impact of farming intensity on trout, the two stressors acted independently to create a simple additive response (rather than a complex synergistic response).

Relationships of brown trout with in-stream physicochemical variables

Total nitrogen at a site was the in-stream measure most strongly related to farming intensity upstream. Areal suspended inorganic sediment, a measure of deposited fine sediment on the streambed, was also significantly related to farming intensity. Nevertheless, in the best models for both trout presence/absence and density, total nitrogen was consistently chosen over deposited sediment. Total nitrogen was also the only in-stream factor affecting the distribution of upland bullies. None of the in-stream variables was highly significantly related to % Water Abstraction.

Trout presence and density both declined steeply along the gradient of total nitrogen concentration and trout density also declined (albeit more gradually) as water abstraction intensity increased (when modeled together with total nitrogen and SIS). The highest trout densities were achieved at sites with very low concentrations of total nitrogen combined with low water abstraction intensity. The best model for trout density did not include an interaction term, which means that both stressors were important but acted independently to create a simple additive response.

Management implications

Our research indicates that brown trout populations in the Manuherikia River catchment are affected both by farming intensity and water abstraction upstream. It can be argued, therefore, that these two catchment-scale measures of land-use intensity should be taken into account when making management decisions about land use and water abstraction and their consequences for brown trout populations in this river.

More specifically, it appears that to maintain healthy trout populations in the Manuherikia catchment, the proportion of highly intensively farmed land in any given sub-catchment should not exceed 40 %. Where % Farming Intensity is below 40 % there is also evidence for a critical threshold for % Water Abstraction of about 70 %. It can be further argued that total nitrogen concentrations in the stream water should not exceed about 300 µg/L in the Manuherikia if trout populations are to be protected.

Given that current water quality in the Manuherikia catchment can generally be regarded as very good (Kitto 2011), because land use is still dominated by low-intensity farming, it may be considered surprising that adverse responses by trout have become apparent at relatively low levels of farming intensity (i.e. above about 40 % of the catchment devoted to high-producing exotic grassland defined as “typically intensively managed exotic grasslands, rotationally grazed for wool, lamb, beef, dairy and deer production”). It is possible that dryland rivers such as the Manuherikia are less resilient to intensive land-use practices than other rivers in the region, but comparative research will be necessary to test this hypothesis. Changes towards higher-intensity farming practices and further water abstraction can be expected to exacerbate a situation that already gives cause for concern for brown trout populations in the Manuherikia River.

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7 Appendix

Appendix 1. Summary of the best models for fish presence/absence and density with the catchment-scale and in-stream predictors (see Appendix 2 and 3 for AIC_c values). Accuracy can only be determined for presence/absence models.

Fish	Best Model	Craig & Uhler's R^2	Accuracy (% Correct)
~ catchment variables			
Trout presence/absence	~ FI + FI^2 + WA	0.59	80.6
Trout density	~ FI	0.38	
Bully presence/absence	~ 1	NA	NA
Bully density	~ 1	NA	
~ in-stream variables			
Trout presence/absence	~ TN + TN^2	0.38	83.3
Trout density	~ TN + TN^2 + WA	0.59	
Bully presence/absence	~ TN + TN^2	0.30	63.8
Bully density	~ TN	0.38	

Appendix 2. Performance of the different predictive models (AIC_c and delta AIC_c) for trout presence/absence, trout density, bully presence/absence and bully density (*best model = lowest AIC_c in bold print) at the 36 studied sites in the Manuherika River catchment for the catchment-scale variables % Farming Intensity (FI) and % Water Abstraction (WA). Delta AIC_c values were calculated as the difference in AIC_c from the best model (lower delta AIC_c value indicate a better fit of the model).

Predictor terms	**Trout presence**		**Trout density**		**Bully presence**		**Bully density**	
	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc
~ FI	42.6	5.38	**204.0**	**0.00**	48.7	2.24	225.0	0.26
~ FI + FI^2	37.5	0.29	205.5	1.50	48.4	1.96	227.0	2.20
~ WA	50.5	13.29	215.4	11.37	48.2	1.72	226.4	1.61
~ WA + WA^2	52.8	15.59	215.0	10.99	50.3	3.83	228.7	3.94
~ FI + WA	44.3	7.03	205.6	1.56	50.5	4.10	227.3	2.56
~ FI + WA + FIxWA	46.8	9.54	207.4	3.39	51.9	5.45	230.0	5.26
~ FI + FI^2 + WA *	**37.2**	**0.00**	208.1	4.04	50.9	4.50	228.7	3.94
~ FI + WA + WA^2	46.8	9.56	205.0	1.01	52.8	6.36	230.0	5.27
~ FI + FI^2 + WA + WA^2	39.5	2.27	207.8	3.75	52.9	6.43	231.3	6.52
~ FI + FI^2 + WA + FIxWA	39.2	1.98	210.0	5.97	51.0	4.53	231.6	6.81
~ FI + WA + WA^2 + FIxWA	49.5	12.24	207.6	3.57	54.1	7.67	232.9	8.16
~ FI + FI^2 + WA + WA^2 + FIxWA	42.1	4.81	210.5	6.47	52.1	5.62	234.4	9.60
~ 1	51.0	13.78	219.3	15.29	**46.4**	**0.00**	**224.8**	**0.00**

Appendix 3. Performance of the different predictive models (AIC_c and delta AIC_c) for trout presence/absence, trout density, bully presence/absence and bully density (*best model = lowest AIC_c in bold print) at the 36 studied sites in the Manuherika River catchment for the in-stream variables total nitrogen (TN), re-suspendable inorganic sediment (SIS) and % Water Abstraction (WA). Delta AIC_c values were calculated as the difference in AIC_c from the best model (lower delta AIC_c value indicate a better fit of the model).

Predictor terms	Trout presence		Trout density		Bully presence		Bully density	
	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc
~ 1	51.0	7.51	219.3	19.78	46.4	4.12	224.8	14.50
~ WA	50.5	7.03	215.4	15.85	48.2	5.85	226.4	16.11
~ WA + WA^2	52.8	9.32	215.0	15.48	50.3	7.95	228.7	18.43
~ TN	43.7	0.15	203.0	3.47	42.3	0.02	**210.3**	**0.00**
~ WA + TN	44.7	1.20	201.2	1.63	42.9	0.55	212.8	2.51
~ WA + WA^2 + TN	47.2	3.74	201.7	2.14	45.2	2.88	215.4	5.19
~ TN + TN^2	**43.5**	**0.00**	200.5	0.98	**42.3**	**0.00**	211.3	1.08
~ WA + TN + TN^2	44.6	1.10	**199.5**	**0.00**	43.1	0.83	214.0	3.78
~ WA + WA^2 + TN + TN^2	47.3	3.77	200.9	1.41	45.3	2.97	216.9	6.66
~ SIS	51.7	8.15	221.2	21.71	48.4	6.12	227.5	17.29
~ WA + SIS	50.9	7.36	216.4	16.85	50.2	7.89	229.0	18.77
~ WA + WA^2 + SIS	53.3	9.77	215.4	15.83	52.4	10.13	231.1	20.89
~ TN + SIS	45.6	2.10	205.5	5.99	43.6	1.32	212.8	2.53
~ WA + TN + SIS	46.5	2.96	203.5	3.94	43.7	1.43	215.4	5.18
~ WA + WA^2 + TN + SIS	49.2	5.67	203.9	4.41	46.2	3.90	218.3	8.05
~ TN + TN^2 + SIS	46.0	2.48	203.1	3.54	44.7	2.35	214.0	3.77
~ WA + TN + TN^2 + SIS	47.1	3.61	202.4	2.89	45.3	3.04	216.9	6.67
~ WA + WA^2 + TN + TN^2 + SIS	50.0	6.47	204.0	4.47	47.7	5.41	220.0	9.76
~ SIS + SIS^2	49.0	5.48	222.9	23.34	46.8	4.44	217.2	6.90
~ WA + SIS + SIS^2	50.2	6.69	218.8	19.29	46.5	4.19	219.9	9.60
~ WA + WA^2 + SIS + SIS^2	52.8	9.29	217.6	18.12	49.0	6.66	222.5	12.29
~ TN + SIS + SIS^2	47.7	4.22	207.7	8.18	45.9	3.59	213.3	3.03
~ WA + TN + SIS + SIS^2	49.1	5.55	205.2	5.67	45.5	3.15	216.2	5.93
~ WA + WA^2 + TN + SIS + SIS^2	51.9	8.44	206.2	6.65	48.1	5.80	219.3	9.02
~ TN + TN^2 + SIS + SIS^2	48.6	5.12	204.3	4.73	46.7	4.34	215.9	5.65
~ WA + TN + TN^2 + SIS + SIS^2	50.0	6.50	203.1	3.57	46.5	4.15	219.0	8.75
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2	53.1	9.57	205.2	5.69	48.9	6.55	222.3	12.04
~ WA + TN + WAxTN	44.8	1.30	203.8	4.31	42.8	0.52	215.5	5.21
~ WA + WA^2 + TN + WAxTN	47.5	3.95	204.5	5.02	45.3	3.02	218.3	8.08
~ WA + TN + TN^2 + WAxTN	45.1	1.63	202.4	2.89	43.8	1.52	216.7	6.46
~ WA + WA^2 + TN + TN^2 + WAxTN	48.0	4.46	204.0	4.49	46.5	4.22	219.8	9.56
~ WA + TN + SIS + WAxTN	46.8	3.32	206.3	6.81	44.0	1.72	218.3	8.07
~ WA + WA^2 + TN + SIS + WAxTN	49.7	6.15	207.0	7.50	46.8	4.46	221.4	11.15
~ WA + TN + TN^2 + SIS + WAxTN	47.9	4.44	205.5	5.99	46.1	3.84	219.8	9.53
~ WA + WA^2 + TN + TN^2 + SIS + WAxTN	51.0	7.46	207.3	7.78	49.1	6.77	223.1	12.85
~ WA + TN + SIS + SIS^2 + WAxTN	49.5	5.98	208.2	8.70	45.7	3.37	219.2	8.95
~ WA + WA^2 + TN + SIS + SIS^2 + WAxTN	52.5	9.02	209.5	9.94	48.5	6.24	222.5	12.27
~ WA + TN + TN^2 + SIS + SIS^2 + WAxTN	51.0	7.53	206.4	6.90	47.3	4.94	222.0	11.77
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxTN	54.3	10.79	208.8	9.28	50.3	8.02	225.6	15.33
~ WA + SIS + WAxSIS	49.5	5.96	216.2	16.67	51.0	8.65	227.3	17.02
~ WA + WA^2 + SIS + WAxSIS	52.0	8.51	215.8	16.28	53.5	11.22	230.2	19.91
~ WA + TN + SIS + WAxSIS	47.4	3.91	205.2	5.67	45.7	3.36	216.7	6.42
~ WA + WA^2 + TN + SIS + WAxSIS	50.3	6.81	205.9	6.35	48.4	6.13	219.8	9.51
~ WA + TN + TN^2 + SIS + WAxSIS	48.5	5.01	204.5	4.94	47.3	4.97	218.4	8.15
~ WA + WA^2 + TN + TN^2 + SIS + WAxSIS	51.6	8.08	206.2	6.65	50.0	7.67	221.6	11.35
~ WA + SIS + SIS^2 + WAxSIS	51.3	7.78	219.0	19.51	49.0	6.66	222.5	12.27
~ WA + WA^2 + SIS + SIS^2 + WAxSIS	54.1	10.59	218.7	19.22	51.6	9.33	225.3	15.06
~ WA + TN + SIS + SIS^2 + WAxSIS	50.3	6.75	206.6	7.07	48.0	5.64	218.7	8.45
~ WA + $WA^2$2 + TN + SIS + SIS^2 + WAxSIS	53.4	9.86	207.8	8.26	50.9	8.56	222.0	11.73

Appendix 3. continued

Predictor terms	Trout presence		Trout density		Bully presence		Bully density	
	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc	AICc	ΔAICc
~ WA + TN + TN^2 + SIS + SIS^2 + WAxSIS	51.2	7.69	204.7	5.19	49.2	6.87	221.5	11.24
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxSIS	54.5	10.97	206.9	7.38	51.9	9.58	224.9	14.69
~ WA + TN + SIS + WAxTN + WAxSIS	48.9	5.40	208.1	8.57	46.8	4.44	219.6	9.29
~ WA + WA^2 + TN + SIS + WAxTN + WAxSIS	51.9	8.44	209.1	9.55	49.7	7.42	222.8	12.59
~ WA + TN + TN^2 + SIS + WAxTN + WAxSIS	50.3	6.79	207.8	8.23	49.0	6.74	221.7	11.48
~ WA + WA^2 + TN + TN^2 + SIS + WAxTN + WAxSIS	53.6	10.06	209.8	10.23	52.2	9.92	225.2	14.94
~ WA + TN + SIS + SIS^2 + WAxTN + WAxSIS	52.0	8.48	209.5	9.95	48.8	6.47	222.0	11.78
~ WA + WA^2 + TN + SIS + SIS^2 + WAxTN + WAxSIS	55.3	11.76	211.0	11.51	51.9	9.57	225.6	15.31
~ WA + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxSIS	53.6	10.05	208.1	8.59	50.6	8.27	225.0	14.78
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxSIS	57.1	13.57	210.7	11.13	53.9	11.60	228.8	18.54
~ TN + SIS + WAxTN	46.5	2.98	207.3	7.73	46.0	3.67	215.3	5.08
~ WA + TN + SIS + WAxTN	47.4	3.85	204.9	5.40	46.3	4.04	218.1	7.88
~ WA + WA^2 + TN + SIS + WAxTN	50.2	6.72	205.4	5.86	49.0	6.69	221.2	10.91
~ TN + TN^2 + SIS + WAxTN	45.7	2.16	203.5	4.00	47.3	4.97	216.7	6.40
~ WA + TN + TN^2 + SIS + WAxTN	47.1	3.59	202.8	3.28	48.2	5.87	219.7	9.49
~ WA + WA^2 + TN + TN^2 + SIS + WAxTN	50.2	6.69	204.4	4.90	50.8	8.44	223.1	12.82
~ TN + SIS + SIS^2 + WAxTN	49.0	5.48	209.6	10.05	48.4	6.07	216.2	5.93
~ WA + TN + SIS + SIS^2 + WAxTN	50.2	6.74	206.6	7.07	48.3	5.97	219.3	9.03
~ WA + WA^2 + TN + SIS + SIS^2 + WAxTN	53.3	9.81	207.6	8.12	51.1	8.81	222.6	12.36
~ TN + TN^2 + SIS + SIS^2 + WAxTN	48.6	5.05	204.7	5.13	49.5	7.16	219.0	8.72
~ WA + TN + TN^2 + SIS + SIS^2 + WAxTN	50.1	6.55	203.1	3.61	49.6	7.24	222.3	12.05
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxTN	53.4	9.88	205.3	5.80	52.2	9.88	225.9	15.62
~ WA + TN + SIS + WAxTN + WAxTN	46.0	2.53	208.0	8.45	46.6	4.34	221.2	10.98
~ WA + WA^2 + TN + SIS + WAxTN + WAxTN	49.0	5.53	208.7	9.16	49.6	7.29	224.5	14.24
~ WA + TN + TN^2 + SIS + WAxTN + WAxTN	47.0	3.49	206.1	6.61	48.9	6.62	222.8	12.58
~ WA + WA^2 + TN + TN^2 + SIS + WAxTN + WAxTN	50.2	6.66	208.0	8.48	52.1	9.80	226.4	16.17
~ WA + TN + SIS + SIS^2 + WAxTN + WAxTN	49.1	5.55	209.8	10.30	48.6	6.26	222.5	12.28
~ WA + WA^2 + TN + SIS + SIS^2 + WAxTN + WAxTN	52.3	8.79	211.2	11.63	51.7	9.38	226.1	15.86
~ WA + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxTN	50.3	6.78	206.7	7.19	50.4	8.08	225.6	15.34
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxTN	53.7	10.21	209.2	9.68	53.8	11.45	229.5	19.20
~ WA + TN + SIS + WAxSIS + WAxTN	48.7	5.22	207.6	8.09	48.6	6.25	219.7	9.44
~ WA + WA^2 + TN + SIS + WAxSIS + WAxTN	51.8	8.32	208.4	8.87	51.5	9.22	223.0	12.73
~ WA + TN + TN^2 + SIS + WAxSIS + WAxTN	48.7	5.16	205.9	6.40	50.4	8.07	221.7	11.48
~ WA + WA^2 + TN + TN^2 + SIS + WAxSIS + WAxTN	52.0	8.49	207.8	8.27	53.3	11.00	225.1	14.88
~ WA + TN + SIS + SIS^2 + WAxSIS + WAxTN	51.5	7.98	209.2	9.67	51.0	8.72	221.9	11.68
~ WA + WA^2 + TN + SIS + SIS^2 + WAxSIS + WAxTN	54.8	11.31	210.6	11.06	54.2	11.85	225.4	15.13
~ WA + TN + TN^2 + SIS + SIS^2 + WAxSIS + WAxTN	50.6	7.05	206.2	6.69	52.5	10.20	225.0	14.79
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxSIS + WAxTN	54.1	10.63	208.6	9.09	55.5	13.17	228.7	18.44
~ WA + TN + SIS + WAxTN + WAxSIS + WAxTN	48.8	5.25	210.8	11.25	49.7	7.36	222.8	12.52
~ WA + WA^2 + TN + SIS + WAxTN + WAxSIS + WAxTN	52.0	8.50	211.9	12.35	52.9	10.56	226.2	15.97
~ WA + TN + TN^2 + SIS + WAxTN + WAxSIS + WAxTN	49.9	6.39	209.5	9.98	52.2	9.86	225.3	15.06
~ WA + WA^2 + TN + TN^2 + SIS + WAxTN + WAxSIS + WAxTN	53.4	9.87	211.7	12.15	55.6	13.31	229.0	18.75
~ WA + TN + SIS + SIS^2 + WAxTN + WAxSIS + WAxTN	52.1	8.58	212.4	12.88	51.9	9.59	225.5	15.27
~ WA + WA^2 + TN + SIS + SIS^2 + WAxTN + WAxSIS + WAxTN	55.6	12.09	214.2	14.64	55.3	12.96	229.2	18.97
~ WA + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxSIS + WAxTN	53.1	9.61	210.0	10.44	54.0	11.66	228.9	18.63
~ WA + WA^2 + TN + TN^2 + SIS + SIS^2 + WAxTN + WAxSIS + WAxTN	56.9	13.38	212.7	13.22	57.6	15.31	232.9	22.63