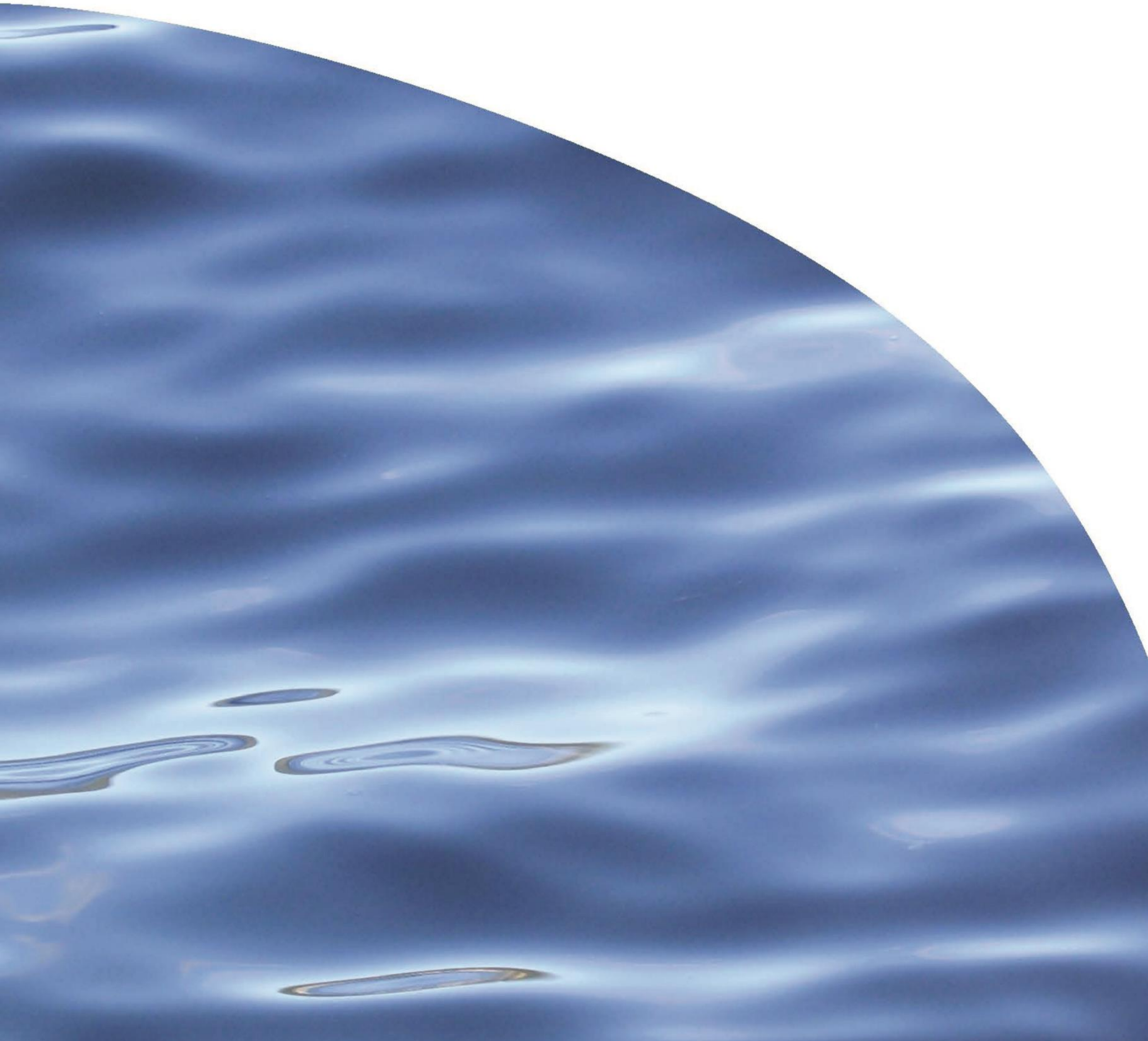
REPORT NO. 3574A

THE RELATIONSHIP BETWEEN INVERTEBRATE DRIFT AND FLOW IN THE MANUHERIKIA RIVER: REVISED ANALYSIS AND IMPLICATIONS FOR SETTING MINIMUM FLOW AND ALLOCATION LIMITS



THE RELATIONSHIP BETWEEN INVERTEBRATE DRIFT AND FLOW IN THE MANUHERIKIA RIVER: REVISED ANALYSIS AND IMPLICATIONS FOR SETTING MINIMUM FLOW AND ALLOCATION LIMITS

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1. INTRODUCTION

This report is in response to a request from Otago Fish and Game Council, supported by Otago Regional Council and Aukaha, for clarification of results and conclusions in Cawthron Report No. 3574 'The relationship between invertebrate drift and flow in the Manuherikia River' (Shearer & Hayes 2020). Clarification was sought on the following issues:

1. Context for the report results in terms of research on invertebrate drift/flow relationships in New Zealand and overseas;
2. Discussion on what implications arise if the MALF of the river is roughly 4 m^3/s and the median flows may be 10–12 m^3/s, based on existing flows, or potentially higher for naturalised flows, and;
3. Advice on interpretation of the results in decision-making on minimum flows and water allocation.

Further to the above issues, we carried out additional analysis of the Manuherikia drift versus flow data that has reversed our original conclusion in Shearer and Hayes (2020) that drift rate did not decline with flow reduction. We also revised the graphical presentation of the drift versus flow results with the aim of making the results clearer. We present these analyses first before addressing the above issues.

2. MANUHERIKIA INVERTEBRATE DRIFT VERSUS FLOW: REVISED ANALYSES

2.1. Methods

2.1.1. Data summary and standardisation

In our original analysis of the Manuherikia drift data we were aware that invertebrate benthic density appeared to increase from the first (December 2019) to second (January 2020) flow recession sampled for invertebrate drift, and over the sampling period in the second recession (Shearer & Hayes 2020) (Figure 1, Figure 2). However, due to time and cost constraints we did not test whether temporal differences in benthic density were statistically significant, and if they were, then standardise drift rate by benthic density. Drift concentration (no./m^3) and rate (no./s) can be influenced by benthic density; a higher benthic stock giving rise to more drifting invertebrates (Shearer et al. 2003; Weber et al. 2014). Ideally then, if benthic density varies significantly among drift sampling occasions, drift concentration or rate ought to be standardised by benthic density.

The revised analysis demonstrated that benthic invertebrate density did vary significantly between the two flow recessions, increasing from the first to second recession, so we standardised drift rate accordingly. This was done by multiplying the drift rates for the second (January) flow recession by the ratio of benthic density measured on 2 December 2019 (first flow recession) over benthic density estimated for each drift sampling occasion in the second recession. Benthic densities for each drift sampling occasion in the second recession were estimated from a regression of mean benthic densities estimated from benthic sampling on 15 and 21 January.

After standardisation by benthic density, the drift rates at each location were comparable within and between recessions but not between location, owing to water velocities and related volumes sampled being specific to each location. To average the trends between drift rate and flow among locations we further standardised drift rates, calculating the drift rate for each occasion at a location as a proportion of the total drift rate summed over all occasions for that location. Standardised drift rate for each occasion could then be averaged over all locations.[1]

2.1.2. Relationship between standardised drift rate and flow: Modelling

We used linear regression models to quantify the relationship between $\log_2$-transformed standardised drift rate and mean river flow at the time of sampling for the following size classes (1) invertebrates greater than 3 mm, and (2) greater than 6 mm.

2.2. Results and Discussion

2.2.1. Benthic density

Benthic invertebrate density differed significantly between the two flow recessions sampled for drift, and between the two benthic sampling occasions within the second flow recession (ANOVA $P = 0.005$). Benthic density increased between the first sampling occasion (2 December 2019, first recession) and second and third sampling occasions (15 and 21 January 2020, second recession) (Figure 1, Figure 2).

2.2.2. Drift rate versus flow relationship

Standardised drift rate for invertebrates > 3 mm and > 6 mm was significantly higher for the first flow recession than for the second recession ($P < 0.001$), but there was no significant trend over the second recession when flows were very low (Figure 3, Figure 4). Mean standardised drift rates of > 3 mm and > 6 mm invertebrates were 75% and 96% lower, respectively, during the second flow recession compared with the first recession.

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[1] Note that the description of the standardisation of drift rate in Shearer and Hayes (2020) differs from the standardisation in the present advice letter. Because drift rate was not standardised by benthic density in the original analysis standardisation was restricted to within recession, and trends in standardised drift density had to be examined within recession and not also across both recessions. Furthermore, the original description of drift rate standardisation on page 5 of Shearer and Hayes (2020) was worded incorrectly; it should have read: "Because the drift rates estimated for each sampling location were not comparable between sampling location and between recessions, we standardised the drift rates per recession, calculating for each recession the drift rate for each occasion at a location as a proportion of the total drift rate summed over all occasions for that location within the recession".

These revised results are qualitatively similar to those of the original results in that there are no significant trends in drift rate within each recession. However, the standardisation for benthic density in the revised analysis has allowed a large difference in drift rate between recessions to be revealed.

The revised conclusion that drift rate declined from about the MALF (~ 4 m^3/s) to low flows is consistent with previous studies undertaken by Cawthron on New Zealand rivers which have shown drift concentration and rate declining over lower mid-range flows to low flows (discussed in the next section).

Limitations with our results mean that we were unable to derive a predictive regression between drift rate and flow (and drift concentration and flow) based on several data points that would allow estimation of the percentage change in drift rate (or concentration) for a given percentage change in flow—to define the scale of effects of flow alteration on drift transport capacity. The limitations arose from the narrow range of flows sampled (missing mid-range flows between MALF and median flow) and very low water velocities over the low-flow range sampled. However, a sense of the magnitude of the reduction in drift rate over the MALF to low flow range can be obtained from a simple linear regression between mean standardised drift rate for the first and second flow recessions (i.e. a regression between two points representing the mean of sampled flows (m^3/s) and corresponding mean standardised drift rates for each flow recession). The equations of these regressions for > 3 mm and > 6 mm invertebrates, respectively, are: Std drift rate = 0.0009 x Flow – 0.0008; Std drift rate = 0. 0029 x Flow – 0.004. These regressions estimate that for a 1 m^3/s (25%) reduction in flow from the MALF (~ 4 m^3/s) drift rates for > 3 mm and > 6 mm invertebrates declined by 32% and 38%, respectively. These are large reductions. Mean water velocity is predicted to decline by only 16% for the same flow reduction[2]. This means that the reduction in drift rate with flow reduction is not entirely driven by water velocity. At least half of the reduction in drift rate must be due also to drift concentration declining.

We caution extrapolating the above regressions beyond the MALF because drift rate trended upward much less steeply between 3.072 m^3/s and 4.096 m^3/s (the two highest flows sampled—on the first flow recession) (Figure 3, Figure 4). The standard error bars in Figure 3 and Figure 4 indicate that drift rate did not differ significantly between these two highest flows sampled. However, if the trend continued at higher flows a regression based on more data would likely be significant.

Furthermore, the decline in drift rate with flow reduction below the MALF indicated by the above regressions may be overestimated because periphyton biomass and cover was higher during the second flow recession than the first. Proportionally fewer benthic invertebrates may drift when periphyton proliferates (Shearer et al. 2003). Ideally drift rates should be compared between flows with similar periphyton biomass and cover and similar

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[2] Water velocity estimates are from historical hydraulic modelling undertaken near Galloway for hydraulic-habitat modelling. Velocity was estimated with the flow / cross-sectional area method.

benthic invertebrate density and community composition to isolate the effect of flow from these other confounding variables. However, this is very difficult to achieve when sampling over natural flow recessions.

In summary, our revised analysis indicates that drift rate declined with flow reduction in the Manuherikia study reach from about the MALF (~ 4 m^3/s) to about 2 m^3/s. However, drift rate appeared to be insensitive to further flow reduction.

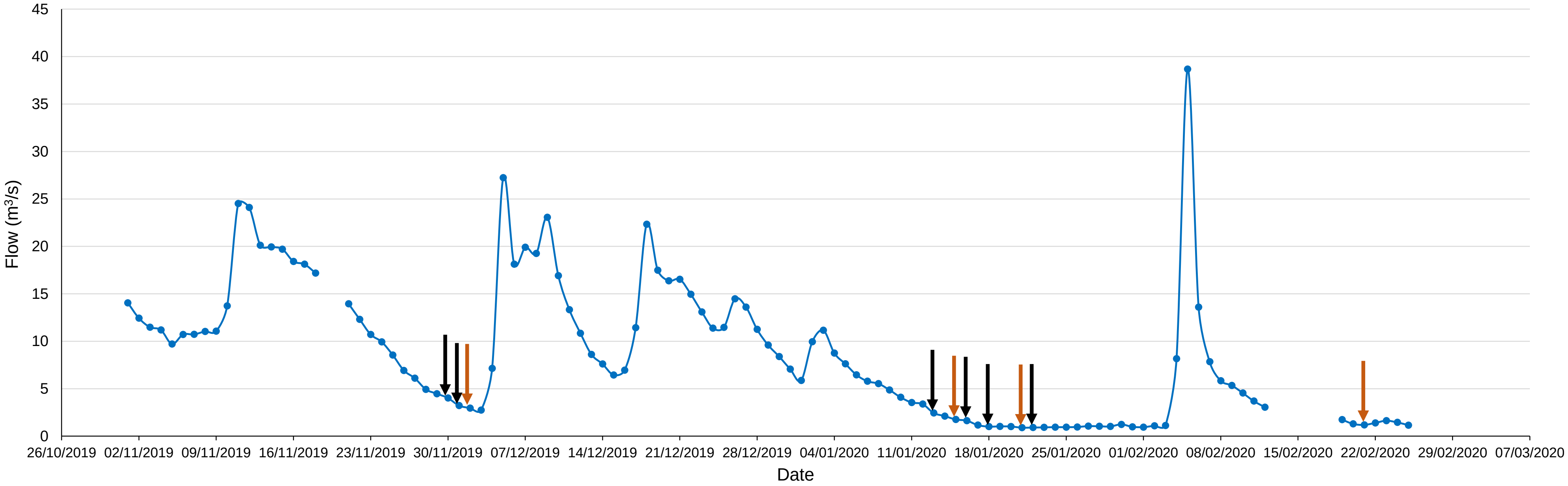

Figure 1. Hydrograph of mean daily flow in Manuherikia River in the Olrig Station invertebrate sampling reach from 1 November 2019 to 25 February 2020. Arrows indicate drifting invertebrate (black) and benthic invertebrate (orange) sampling occasions. Flow was estimated as the sum of flow in the Manuherikia above Chatto Creek (from the Manuherikia at Chatto Creek upstream flow recorder) and flow in Chatto Creek at confluence (from a flow recorder installed in Chatto Creek by Otago Regional Council for the Manuherikia project) (data and information supplied by Lu Xiaofeng, hydrologist, ORC). Drift samples were collected at 15 locations (3 locations on each of 5 cross-sections) in a reach of the Manuherikia River 1-2 km below Chatto Creek (by Olrig Station) on six sampling occasions (flows)—30 November 2019, 1 December 2019 and 13,16,18 and 22 January 2020. Mean flows during each drift sampling occasions were:4.096, 3.072, 2.341, 1.682, 1.010 and 0.977 m³/s.

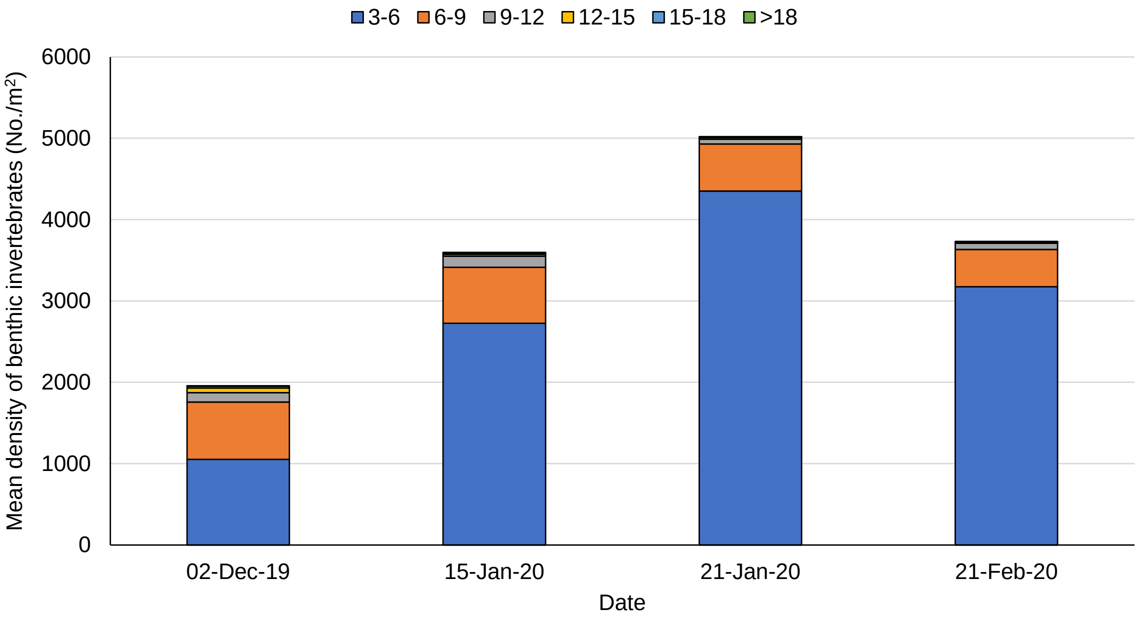

Figure 2. Mean benthic invertebrate densities (no./m²), by 3 mm size class, recorded from the in the Manuherikia River (Olrig Station reach). The first three sampling occasions were within the drift versus flow sampling period (Figure 1).

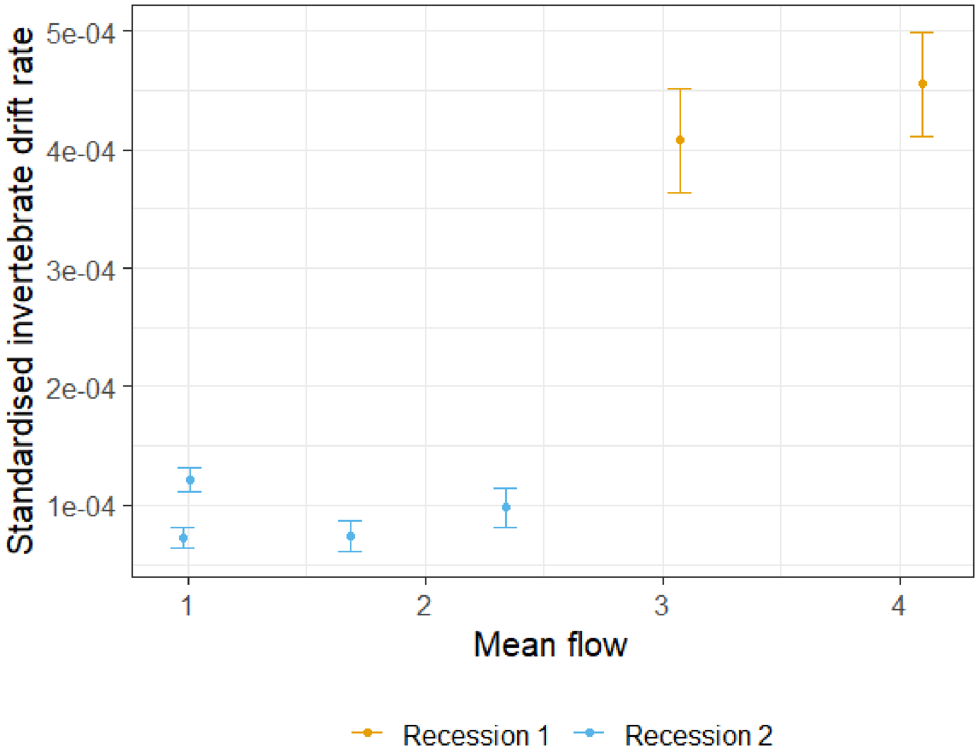

Figure 3. Standardised drift rate (± SE) versus mean daily flow (m^3/s) for aquatic invertebrates > 3 mm recorded for the Manuherikia River (Olrig Station reach). Drift rate was standardised to account for differences in benthic density over the sampling period, and for water velocities and related volumes sampled being specific to each location.

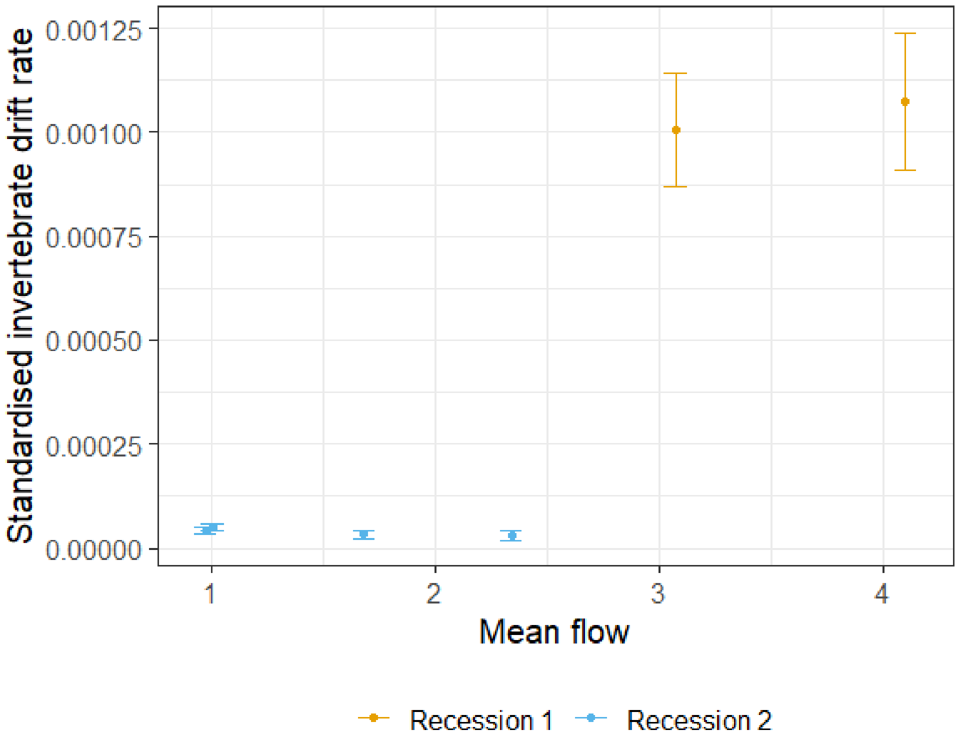

Figure 4. Standardised drift rate (± SE) versus mean daily flow (m^3/s) for aquatic invertebrates > 6 mm recorded for the Manuherikia River (Olrig Station reach). Drift rate was standardised to account for differences in benthic density over the sampling period, and for water velocities and related volumes sampled being specific to each location.

3. CONTEXT OF MANUHERIKIA DRIFT VS FLOW RESULTS IN RESPECT OF OTHER SUCH RESEARCH IN NEW ZEALAND AND OVERSEAS

3.1. Aim and rationale of the Manuherikia River drift versus flow study

The primary aim of the Manuherikia River drift versus flow study was to obtain empirical evidence for whether aquatic invertebrate drift concentration and/or rate declines with flow reduction in the Manuherikia River to help inform decision making on the effects of flow allocation and minimum flow management scenarios for the river on drift transport capacity. Invertebrate drift is an ecosystem process that is relevant for the dispersal of benthic invertebrates and for providing a food resource for drift feeding fishes, such as introduced trout and native galaxiids. The fine fraction of drift, seston, which comprises macro- and micro-invertebrates, algae and detritus, also provides food for filter-feeding macroinvertebrates (such as net-spinning caddis flies, *Aoteapsyche* sp.), kakahi (freshwater mussels) and juvenile lampreys (ammocoetes) but was not retained by our drift samplers. Nevertheless, the fine fraction of drift ought also to be influenced by the flow-related processes affecting the coarse fractions of drift.

The benthic invertebrate stock of variable flow rivers is continually changing as a result of floods resetting the stock to lower biomass, followed by biomass accrual and community change during the following flow recessions. Drift concentrations and rates will vary in response, i.e. drift concentrations should increase in response to increasing benthic density and biomass. It is important not to conflate this natural variation in benthic-drift dynamics with the influence of flow, and flow alteration, on drift. In the context of drift, an allocation/abstraction regime should be thought of as a state change effect on drift arising from whatever benthic stock is present at the time.

The context for obtaining local empirical data on drift versus flow from the Manuherikia was that while evidence exists for drift concentration and rate declining with flow reduction, from first principles particle transport theory and empirical studies in New Zealand and elsewhere, the empirical evidence is rather sparse and equivocal—some studies confirming the expected pattern, others not.

3.2. The challenge of isolating passive, flow related, drift from active drift

As mentioned in the Manuherikia drift versus flow report, benthic aquatic invertebrates enter the water column and drift via passive or active mechanisms (Shearer & Hayes 2020). Passive drift occurs when invertebrates are accidentally entrained into the water column by near-bed shear stress (related to water velocity and turbulence). It is a challenging task to obtain empirical evidence for passive drift responding to flow because it can be obscured by active drift. Invertebrates enter the drift actively (i.e. volitionally) for various reasons, including to find more suitable habitat, escape predators, and emerge (to complete their lifecycles). Particle transport theory and process-based transport modelling predicts that the concentration and flux of suspended particles (including invertebrates) should decline with flow reduction. However, random variation in active drift can obscure this expected pattern, as can flow-induced active drift—which can occur at very low flows when invertebrates actively drift to escape desiccation and find more suitable faster flowing habitat.

Flow variation, especially floods, adds to the challenge of detecting the response of passive drift to flow reduction. Ideally flows would be stable for a month or more before drift sampling, to allow benthic invertebrates to colonise the river channel, and then flow artificially reduced in steps to provide drift samples over a flow range relevant for assessing effects of flow allocation (e.g. over the mid- to low-flow range; median to below MALF). However, flows are rarely able to be controlled to this degree, so the next best study design is to sample drift over a natural flow recession. Even then our experience with New Zealand rivers is that sampling over a natural flow recession is often interrupted by flooding, requiring sampling to be staggered over two flow recessions and the results from the different flow recessions stitched together. Furthermore, it is very difficult to time the onset of drift sampling to begin on sufficiently high, falling, but clear, mid-range flows to cover the upper end of the flow range potentially affected by primary allocation.

3.3. Limitations of drift sampling in the Manuherikia

Our drift sampling data set from the Manuherikia River was compromised by interruption by floods and, in hindsight, late timing of the onset of drift sampling on the first of the two flow recessions over which sampling was staggered. We had anticipated that spring was the best time to sample drift over a flow recession in the Manuherikia, after the channel has been colonised by invertebrates over winter and before abstraction reduces the channel width and benthic invertebrate stock. We had intended to time spring drift sampling to coincide with a natural flow recession steepened and prolonged by the onset of abstraction. However, variable flows over the spring of 2019 made us cautious to commence sampling prematurely. In hindsight, this coupled with uncertainty over the median flow statistic, resulted in us starting drift sampling too late (and hence at too low a flow) in November 2019 (see Shearer & Hayes 2020, Figure 1). As it turned out the estimated flow during the first drift sampling occasion was 4.096 m^3/s, which was close to the MALF. Once committed to that flow recession, our plan to sample drift over at least 5 progressively lower flows was derailed by a flood of about 26 m^3/s beginning 4 days after the onset of sampling.

In addition, our drift data set was further compromised by low water velocities over the low flow range sampled during the second flow recession, lower than the calibration range of the drift sampler current meters. This resulted in us being unable to accurately estimate water velocities through the drift sampler current meters, which meant we could not estimate drift concentration. Fortunately, we were able to calculate standardised drift rates for the two flow recessions sampled because drift was sampled in the same locations on each sampling occasion, meaning that rates estimated at each location retained relativity between occasions. In our original report (Shearer & Hayes 2020) this relativity was confined within recessions because we did not also standardise drift for benthic density, which varied between recessions. Hence, we were unable to stitch the data sets from the two recessions together because the standardised drift rates were comparable only within, not between, recessions. Our subsequent revised analysis, done for the present report, standardised drift rate for temporal variation in benthic density thereby overcoming this limitation. Stitching the results for the two recessions together has allowed us to identify the expected relationship of drift rate declining with flow reduction.

3.4. Numerical, process-based drift transport modelling—establishing a theoretical basis for passive invertebrate drift versus flow relationships

Hayes et al. (2018a) numerically modelled the theoretical relationship between drift concentration and flow, based on sediment particle transport theory, and tested the predictions against an empirical drift concentration versus flow data set collected over two natural flow recessions from the Mataura River. Their study was motivated from the recognition that there are few empirical studies on the response of aquatic invertebrate drift to flow reduction, and the available evidence for invertebrate drift concentration or rate declining with flow reduction was equivocal, The process-based, numerical model confirmed that aquatic invertebrate drift concentration should decline with flow reduction and the predictions matched the pattern of decline in total drift concentration with flow reduction observed in the Mataura study reach. The fit of the model to the drift concentration versus flow relationships for specific taxa and size classes varied from excellent to poor. Hayes et al.'s (2018a) study provides a solid theoretical modelling foundation for mechanistically understanding why we should expect that passive aquatic invertebrate drift concentration, and rate (or flux)[3], should decline with flow reduction. This evidence from first principles assists in interpreting sparse and equivocal empirical evidence for drift versus flow relationships.

3.5. Empirical evidence for invertebrate drift versus flow relationships

3.5.1. New Zealand research

Cawthron has obtained empirical evidence on the relationship between drift concentration and/or rate from six New Zealand rivers. In addition to the Manuherikia these include the: Lindis, Aparima, Oreti, Mataura and Upper Clutha (listed in ascending order in respect of flow) (Hayes et al. 2016, 2018a, 2018b, 2019, 2020; Gabrielsson 2018). We found significant declines in drift concentration with flow reduction in 4 of the 5 rivers: for invertebrates > 3 mm in the Lindis, Aparima and Mataura rivers (Figure 5) and for invertebrates > 6 mm in the Oreti, Aparima and Mataura rivers (Figure 6; Figure 7).

The forms of the significant relationships between drift concentration and flow are obscured by the log scale in Figure 5. Figure 6 plots the relationships on an untransformed scale, revealing that drift concentration declines according to curvilinear power functions, with the slope of decline decreasing with flow reduction.

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[3] Recall from Shearer and Hayes (2020) that "drift rate (no./s) is the product of drift concentration (no./m^3), water velocity (m/s) and cross-sectional area (m^2) sampled, the latter being the area of the drift sampler—which is a constant", and "Even if drift concentration was constant (i.e. did not decline) with flow reduction, drift rate ought to decline simply because average water velocity declines…".

This is best illustrated by the Mataura > 3 mm and > 6 mm, Oreti > 6 mm (Figure 6) and Aparima > 3 mm and > 6 mm (Figure 7) plots.

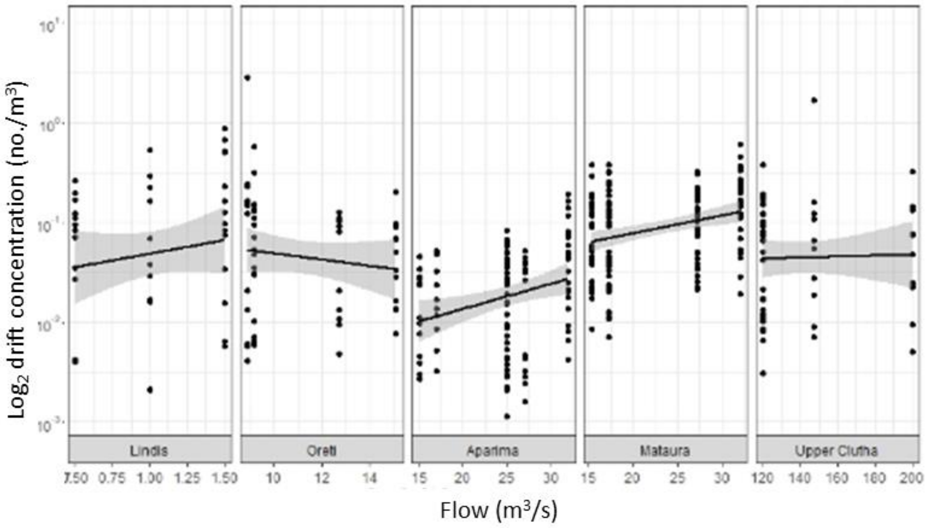

Figure 5. Log$_2$ drift concentration versus flow relationships for > 3 mm aquatic invertebrates for three New Zealand rivers.

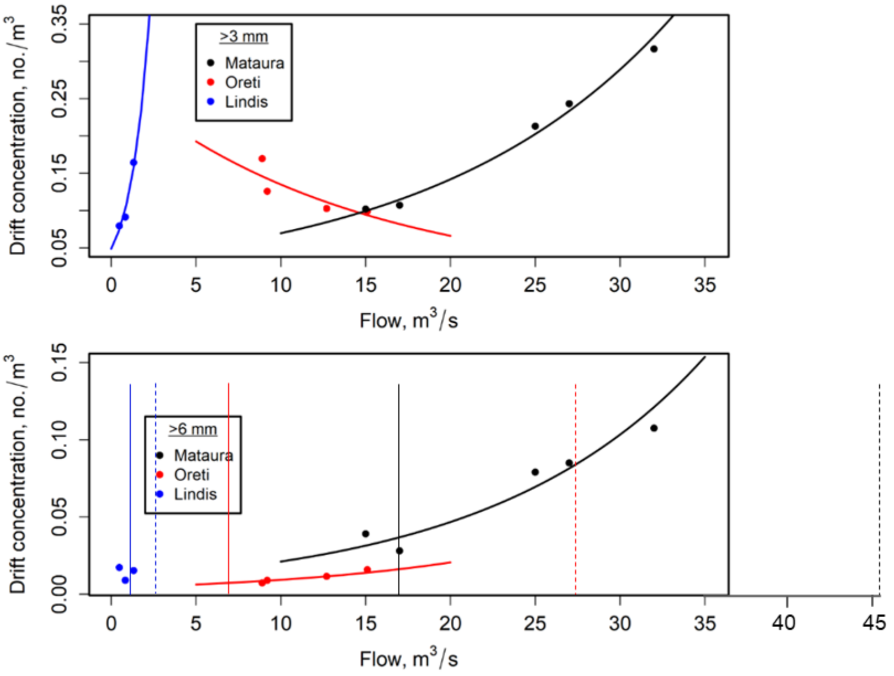

Figure 6. Drift concentration versus flow relationships for > 3 mm and > 6 mm aquatic invertebrates for the Mataura, Oreti and Lindis rivers. Solid vertical lines represent 7-d MALFs and dashed lines median flows.

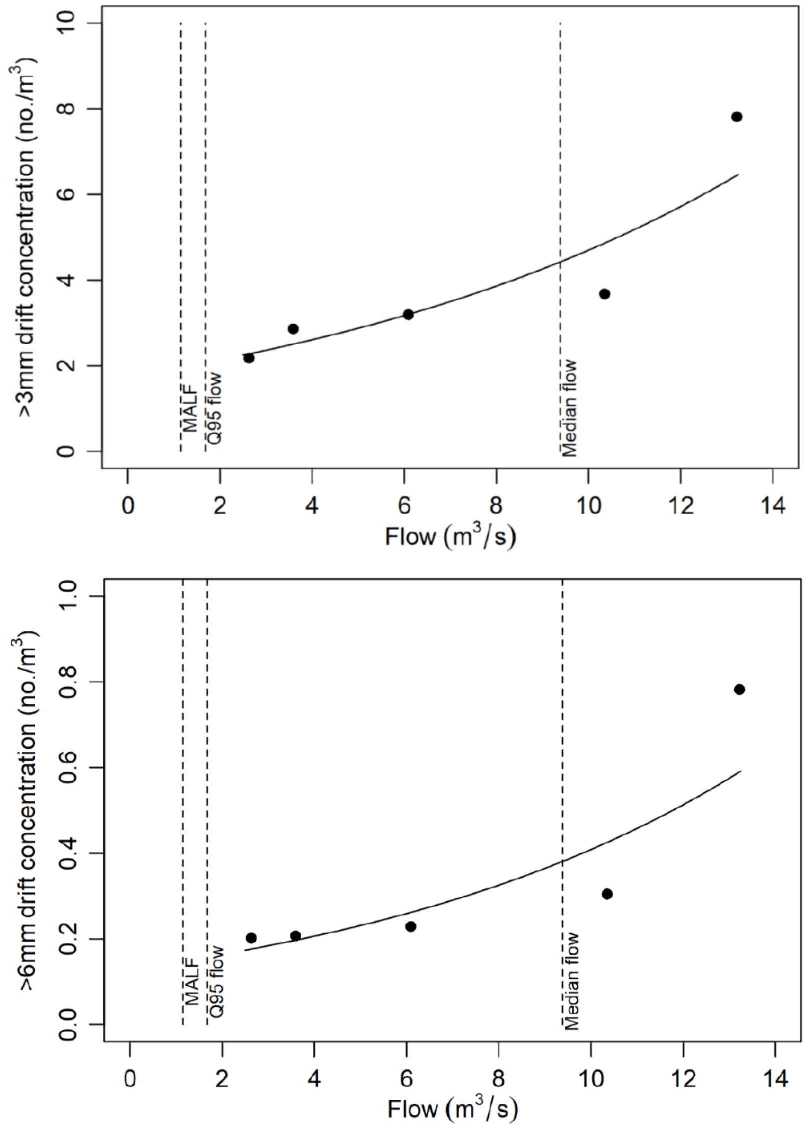

Figure 7. Relationship between drift concentration (all taxa) and flow for invertebrates > 3 mm (top panel) and > 6 mm (bottom panel) for the Aparima River. 7-d MALF, Q95 and median flow estimated over 2010–2019 are shown as dashed and dotted vertical lines.

We failed to find significant relationships between drift concentration, or rate, and flow in only the Upper Clutha River. The Upper Clutha River experiences substantial daily and weekly flow variation due to hydropeaking for hydro-electric power generation. The highly fluctuating flows result in regular dewatering of the channel margins during the low flow phase of the fluctuating cycle and high water velocities in the permanently wetted channel during the high flow phase of the cycle. Furthermore, the permanently wetted bed of the Upper Clutha River is thickly overlain with didymo. The benthic invertebrate community may be conditioned by the regular flow fluctuations to resist entrainment at higher flows and didymo may add to such insensitivity to flow variation by providing shelter from near-bed shear stress.

The water velocities at the drift sampling locations on the Manuherikia during the January 2020 flow recession were the lowest that we have encountered in our drift versus flow research on New Zealand rivers. We have sampled at lower flows, in the Lindis River, but the low-flow mean velocities in the Lindis are about 10–30% higher for the same flows (e.g. 1–2 m^3/s) in the Manuherikia.

Dewson et al. (2007a) studied invertebrate responses to short-term flow reduction in three small (< 1 m^3/s) North Island streams by using weirs to divert flow and monitoring the response of the benthos and drift for one month (discharge reduced by 89–98%). They found that the propensity of invertebrates to drift (drift density [or concentration] / benthic density) increased immediately following flow drawdown but thereafter it declined to control levels in two streams and kept increasing in the other. Benthic density increased in the streams following flow drawdown, apparently a result of invertebrates concentrating in the reduced wetted channels. Dewson et al. (2007a) do not report drift rates but total rate (flux) of drift must have declined in the two streams in which drift propensity returned to control levels after flow drawdown because discharge reduced by about 90% (mean velocity declined by 50–57%); the rationale being that drift propensity is based on drift concentration, and drift rate for a stream (flux) is the product of drift concentration and flow.

3.5.2. Synthesis of New Zealand research on drift versus flow relationships with overseas research

The New Zealand studies that have provided theoretical and empirical evidence for invertebrate drift declining with flow reduction, consistent with passive drift, is supported by some overseas studies (Harvey et al. 2006; Sotiropoulos et al. 2006; Hauer et al. 2012; Kennedy et al. 2014; Naman et al. 2017a). Kennedy et al. (2014) provide convincing evidence for drift concentration declining with flow reduction due to passive entrainment which, in common with Hayes et al.'s (2018a) numerical modelling study on the Mataura River, is strengthened by sediment transport theory—although in their case sediment transport theory informed the construction of statistical models. They reported positive drift concentration versus flow relationships for the majority of invertebrate taxa in the Colorado River below Glen Canyon Dam, including Chironomidae, *Gammarus* and the New Zealand mud snail, *Potamopyrgus* spp.

In a study of upland streams in the United States., average drift concentrations and transport rates decreased by ~92 and ~82%, respectively, as summer discharge decreased by ~88% over a two-month period (Sotiropoulos et al. 2006). Other studies have reported opposite responses between drift concentration and flow, i.e. concentration increasing with flow reduction (Dewson et al. 2007b; Naman et al. 2017a). Many of those studies have focussed on short-term (< 1 week) impacts of sudden decreases in flow due to water abstraction or hydropeaking associated with power generation (Minshall & Winger 1968; Gore 1977; Corrarino & Brusven 1983; Poff & Ward 1991; James et al. 2009). Such changes are likely to drive active drift in response to reduction in wetted width and habitat suitability. In a longer (~8 week), summer, study of the effects of water abstraction, Wooster et al. (2016) also reported total community drift concentration increasing with flow reduction. However, in their situation drift communities had changed over the period in response to low-flow drawdown by abstraction, becoming dominated by microcrustaceans. These examples highlight the importance of context and isolating confounding variables when interpreting drift concentration (and rate) versus flow responses.

Naman et al. (2017b) examined drift versus flow relationships in the context of channel architecture and species traits (e.g. mobility, body size, and dislodgement susceptibility). They found that these factors mediated the effects of flow on bulk drift abundance and taxa-specific per capita drift rates (the rate of emigration from the benthos). In complementary experiments, they reduced and increased flows in small stream mesocosms (15 cm wide channels; 0.25–0.3 m^3/s) with contrasting cross-sectional channel profiles: concave channels, where habitat area contracted and expanded with altered flow but velocity remained relatively constant; and flat channels (with vertical sides), which maintained constant habitat area but experienced greater changes in velocity. Per capita drift rates for the most mobile taxa increased about 10% under flow reduction (75%), indicating a behavioural response, whereas drift of other taxa declined. Per capita drift increased for all taxa following elevated flow but by the largest magnitude in taxa with body shapes that experience more drag, suggesting passive dislodgement.

The contrasting responses of invertebrate drift to flow change reported in the literature has caused confusion over whether, or how, drift concentration (and rate) is related to flow. Taxa least likely to show decreasing drift concentration with decreasing flow are those with strong attachment traits and high-water velocity requirements, e.g., filter-feeders. These may actively drift at lower flows as habitat quality deteriorates e.g., simulid (black fly) larva (Statzner et al. 1988; Poff & Ward 1991; Kennedy et al. 2014). Taxa most likely to decrease in the drift as flow declines are mobile collector-gatherer-browser-scrapers which are susceptible to passive entrainment and are most common in the drift (Keup 1988; Rader 1997; Kennedy et al. 2014).

If drift-prone taxa dominate the community then, assuming passive drift and no change in the benthic community, total background drift concentration ought to decrease with flow reduction. Exceptions to this rule appear to be more common in small streams where behavioural drift may dominate over passive drift (Naman et al. 2016, 2017a). In small streams, and by inference in larger streams/rivers at very low flow, active drift of the mobile, more drift prone, taxa may increase resulting in drift concentration, and possibly drift rate, increasing—especially when benthic invertebrates are concentrated at high density. This response is indicative of ecological stress.

4. IMPLICATIONS FOR INTERPRETATION OF THE MANUHERIKIA RESULTS IF THE MALF IS 4 M^3/S AND MEDIAN FLOWS MAY BE 10-12 M^3/S, BASED ON EXISTING FLOWS, OR POTENTIALLY HIGHER FOR NATURALISED FLOWS

In respect of assessing the effects of flow management scenarios, drift versus flow relationships are most relevant for assessing effects of the primary allocation block. As stated in Shearer and Hayes (2020):

> Once a regression relationship between flow and drift concentration, or flow and drift flux, is established, it can be used to estimate the percentage reduction in instantaneous drift food supply that a flow allocation rate represents, relative to the drift concentration or flux sustained by a reference flow in the absence of allocation (i.e. for X percentage flow reduction, caused by an allocation being taken, drift concentration or flux (rate) declines by Y percent).

Ideally then, a drift versus flow data set should span a good proportion of flows affected by the primary allocation block (i.e. from above a minimum flow through lower mid-range flows towards the median flow). In the absence of a minimum flow, the MALF and median flows provide marker posts for choosing the range of flows to sample for drift, the aim being to begin sampling on a flow recession at least halfway between the MALF and median flow, when water has cleared following a flood, and continue sampling down to at least the MALF, and preferably lower.

At the time of drift sampling on the Manuherikia, flow statistics, especially those for naturalised flows, were uncertain. We have since been advised that the status quo and naturalised 7-d MALF at Manuherikia Campground recorder is 0.8 m^3/s and 4 (± 0.5) m^3/s, respectively[4]. Status quo and naturalised median flows are 11.1 m^3/s and 15 m^3/s. In comparison, the flows sampled for drift in the Manuherikia ranged from 0.977 m^3/s to 4.096 m^3/s (Shearer & Hayes 2020: figure 4).

Figure 6 and Figure 7 show that drift concentrations decline most steeply from lower mid-range flows down to about the MALF. This means it is much more difficult to detect a decline in drift concentration, or rate, when the sampled flow range does not include the lower mid-range (between the median flow and MALF) and is restricted to the low flow range. This was a shortcoming of the Manuherikia drift data set; it does not inform that part of the flow range affected by allocation above the MALF and over which drift rate might be expected to decline most steeply with flow reduction. Most of the flow range sampled for drift was well below the MALF where the influence of

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[4] Flow statistics estimated by R. Henderson (NIWA) from 2014–2019 data.

passive drift is weak and can be obscured by day-to-day variation in drift concentration. Moreover, the very low velocities over the low flow range in the study reach are likely to have encouraged active drift, thereby further obscuring passive drift.

5. INTERPRETATION OF THE MANUHERIKIA DRIFT VERSUS FLOW RESULTS IN DECISION-MAKING ON MINIMUM FLOWS AND WATER ALLOCATION

Our revised analysis confirms that drift rate appears to decline with flow reduction from about the MALF to 2.3 m^3/s in the lower Manuherikia River. This is due to water velocity and drift concentration declining with flow reduction. Moreover, the decline in drift rate with flow reduction from the MALF is relatively steep; the percentage reduction in drift rate being 32-38% for a 25% reduction in flow. Hence around the MALF, abstraction is likely to have a large adverse effect on drift transport capacity. Our results indicate drift rate is insensitive to flow reduction below 2.3 m^3/s, suggesting that these very low flows have little capacity to transport drift. Unfortunately, we do not have data to inform how drift responds to flow reduction above 4.1 m^3/s. However, given the large reduction in drift rate from the MALF to 1.5 m^3/s (mean of second recession flows sampled), and the synthesis of results from drift sampling on other New Zealand rivers, it is likely that drift rate in the Manuherikia River will be sensitive to abstraction at higher flows affected by primary allocation.

The low drift transport capacity, and periphyton proliferation, at flows below 2.3 m^3/s observed during our study (Shearer & Hayes 2020) are indicative of ecological stress.

The further that minimum flow options depart downward from the MALF to about 2 m^3/s, and the higher the primary allocation rate, the more drift transport capacity will be adversely affected in the lower Manuherikia River.

6. REFERENCES

Corrarino CA, Brusven MA 1983. The effects of reduced stream discharge on insect drift and stranding of near shore insects. Freshwater Invertebrate Biology 2: 88-98.

Dewson ZS, James ABW, Death RG 2007a. Invertebrate responses to short-term water abstraction in small New Zealand streams. Freshwater Biology 52: 357-369.

Dewson ZS, James ABW, Death RG 2007b. A review of the consequences of decreased flow for instream habitat and macroinvertebrates. Journal of the North American Benthological Society 26(3): 401-415.

Gabrielsson RM 2018. Evidence presented to the Environment Court on fishery values and effects of flow on instream habitat, fish passage, invertebrate food production and drift and trout survival in the Lindis River. In relation to an Appeal on Otago Regional Council's Plan Change 5A and the Lindis Catchment Group consent application. ENV-2016-CHC-61 & ENV-2018-CHC-155.

Gore JA 1977. Reservoir manipulations and benthic macroinvertebrates in a prairie river. Hydrobiologia 55: 113-123.

Harvey BC, Nakamoto RJ, White JL 2006. Reduced streamflow lowers dry-season growth of rainbow trout in a small stream. Transactions of the American Fisheries Society 135: 998-1005.

Hauer C, Unfer G, Graf W, Leitner P, Zeiringer B, Habersack H 2012. Hydro-morphologically related variance in benthic drift and its importance for numerical habitat modelling. Hydrobiologia 683: 83-108.

Hayes JW, Goodwin E, Shearer KA, Hay J, Kelly L 2016. Can WUA correctly predict the flow requirements of drift-feeding trout? Comparison with a drift-net rate of energy intake model incorporating drift-flow processes. Transactions of the American Fisheries Society 145: 589–609.

Hayes J, Goodwin EO, Shearer KA, Hicks DM 2018a. Relationship between background invertebrate drift concentration and flow over natural flow recession, and prediction with a drift transport model. Canadian Journal of Fisheries and Aquatic Sciences 76(6): 871-885.

Hayes J, Goodwin E, Hay J, Shearer K, Gabrielsson R, Hicks M, Willsman A, Hoyle J, Walsh J 2018b. Ecological flow regime assessment for the upper Clutha River / Mata-au: complementing hydraulic-habitat modelling with drift-feeding trout net energy intake modelling. Prepared for Otago Regional Council. Cawthron Report No. 3105. 118 p. plus appendices.

Hayes J, Goodwin E, Shearer K, Hay J, Hicks M, Willsman A, Bind J, Haddadchi A, Walsh J, Measures R 2019. Ecological flow regime assessment for the Oreti River at Wallacetown: Complementing hydraulic-habitat modelling with drift-feeding trout net energy intake modelling. Prepared for Environment Southland and Envirolink. Cawthron Report No. 2948. 70 p. plus appendices.

Hayes J, Goodwin E, Shearer K, Bind J, Hoyle J, Stecca G, Measures R, Haddadchi A, Walsh, J, Willsman A 2020. Ecological flow regime assessment for the Aparima River at Anderson's Beach: Complementing hydraulic-habitat modelling with drift-feeding trout net energy intake modelling. Prepared for Environment Southland. Cawthron Report No. 3457. 129 p. plus appendices.

James ABW, Dewson ZS, Death RG 2009. The influence of flow reduction on macroinvertebrate drift density and distance in three New Zealand streams. Journal of the North American Benthological Society 28: 220–232.

Kennedy TA, Yackulic CB, Cross WT, Grams PE, Yard MD, Copp AJ 2013. The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river. Freshwater Biology 59: 557-572.

Keup LE 1988. Invertebrate fish food resources of lotic environments. Prepared for U.S. Fish and Wildlife Service. Instream Flow Information Paper 24, Biological Report 88(13).

Minshall GM, Winger PV 1968. The effect of reduction in stream flow on invertebrate drift. Ecology 49: 580-582.

Naman SM, Rosenfeld JS, Richardson JS 2016. Causes and consequences of invertebrate drift in running waters: from individuals to populations and trophic fluxes. Canadian Journal of Fisheries and Aquatic Sciences 78: 1292-1305.

Naman SM, Rosenfeld JS, Third LC, Richardson JS 2017a. Habitat-specific production of aquatic and terrestrial invertebrate drift in small forest streams: implications for drift-feeding fish. Canadian Journal of Fisheries and Aquatic Sciences 74: 1208-1217.

Naman SM, Rosenfeld JS, Richardson JS, Way JL 2017b. Species traits and channel architecture mediate flow disturbance impacts on invertebrate drift. Freshwater Biology 62: 340-355.

Poff NL, Ward JV 1991. Drift responses of benthic invertebrates to experimental streamflow variation in a hydrologically stable stream. Canadian Journal of Fisheries and Aquatic Sciences 48: 1926-1936.

Rader RB 1997. A functional classification of the drift: traits that influence invertebrate availability to salmonids. Canadian Journal of Fisheries and Aquatic Sciences 54: 1211-1234.

Shearer K, Hayes J 2020. The relationship between invertebrate drift and flow in the Manuherikia River. Prepared for Otago Regional Council, Aukaha, and Otago Fish & Game. Cawthron Report No. 3574. 14 p. plus appendix.

Shearer KA, Stark JD, Hayes JW, Young RG 2003. Relationships between drifting and benthic invertebrates in three New Zealand rivers: implications for drift-feeding fish. New Zealand Journal of Marine and Freshwater Research 37: 809-820.

Sotiropoulos JC, Nislow KH, Ross MR 2006. Brook trout, *Salvelinus fontinalis*, microhabitat selection and diet under low summer stream flows. Fisheries. Management and Ecology 13: 149–155.

Statzner B, Gore JA, Resh VH 1988. Hydraulic stream ecology: observed patterns and potential applications. Journal of the North American Benthological Society 7: 307-360.

Weber N, Bouwes N, Jordan CE 2014. Estimation of salmonid habitat growth potential through measurements of invertebrate food abundance and temperature. Canadian Journal of Fisheries and Aquatic Sciences 71: 1158-1170.

Wooster D, Miller SW, DeBano SJ 2016. Impact of season-long water abstraction on invertebrate drift composition and concentration. Hydrobiologia 772: 15-30.