

The response and recovery of
benthic macroinvertebrates from water abstractions
along the Manuherikia River, New Zealand.

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science by thesis, Zoology
University of Otago, Dunedin New Zealand

2020

Abstract

Water abstraction for irrigation during seasonal low discharge periods alters the natural flow regime of a river. The response of macroinvertebrates to a significantly altered flow regime due to summer water abstraction for irrigation was assessed. Macroinvertebrate communities upstream and downstream of three major water abstraction points along the Manuherikia River were sampled during the irrigation season, and then immediately after and three weeks after water abstraction had ceased and a natural flow regime had been restored. The process of macroinvertebrate community recovery from water abstraction was assessed longitudinally along the river, and also spatially within each site by examining re-colonisation of re-wetted substrates along the edge of the stream channel. Benthic invertebrates were identified to the lowest possible taxonomic level to ensure a sensitive assessment of the impacts of water abstraction. Following the cessation of abstraction and the resumption of a natural higher-discharge flow regime, the densities of macroinvertebrates across all sites decreased, with the densities of macroinvertebrates being lowest downstream of the three water abstraction points. Densities remained the highest at the most upstream abstraction point and were relatively lower at the two most downstream abstraction points along the river. Recovery from water abstraction in the permanently wetted channel did not occur within the time-period of the study, though the densities at the most upstream site showed more resilience than the downstream sites along the river. The densities of univoltine taxa were relatively lower downstream of all takes relative to macroinvertebrate densities upstream of abstraction points. Immediately following the conclusion of the summer water abstraction season, the benthic invertebrate densities in newly wetted channel edges downstream of the water takes were relatively lower than channel edges upstream of the abstraction points, although three weeks later, macroinvertebrate densities were similar. However, the edge communities

downstream were dominated by multivoltine taxa rather than longer-lived univoltine taxa. The lag in the recovery of stream communities following the resumption of a natural discharge regime appears to be caused by the slower recovery of univoltine species with time-restricted reproductive seasons that are unable to numerically respond to the increase in available habitat. The information gained from this study will contribute to knowledge on the river ecosystems in New Zealand and elsewhere, and provide information for future river management in New Zealand.

Acknowledgement

I came to New Zealand from India last year for learning to be a better scientist. Today, I have learned a lot of skills and I grew as a human. Many people and resources were instrumental in this journey.

My supervisor, Prof. Gerry Closs has been kind, patient and the past year wouldn't have been this fulfilling without him. He has inspired me to continue on my dream to be a good scientist and professor. The University of Otago Master's scholarship for international students was a great help. Jason Augspurger helped me with the idea of this study. I learned a lot from his comments on my drafts. Ryan Easton is the friendliest and the most clever field help. I am so lucky he came from USA around the time of my thesis. Nicky McHugh kindly helped me with my water nutrient samples and made sure I was doing okay in the lab. Steffi Neupert from Germany has been so generous in reading my drafts quickly for feedback. Char char, my colleague, has been the sweetest friend and read my drafts in two days! Pierre, Hortense, Coline, and Claire, the interns from France in my lab turned sample processing into fun French lessons. Merci beaucoup! Oly and Joe helped me with the last fieldwork. From them I learned that fieldwork is supposed to be fun, not work. Kimmy, Pluto, and Jonah have been friendly in the department and there is never a boring moment if they're around. My friends back in India, Anubhuti, Jigmet, Deepika and Dziesetuono always made me feel loved and connected. Noam made this year a lot happier. My grandparents kept sending their blessings throughout the thesis. My parents are my pillars of strength.

Thank you all!

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Chapter 1. General introduction

1.1. Characteristics of the river

Seasonal variation in the discharge of permanent rivers is a feature of the natural flow regime (Poff, et al., 1997). The natural flow regime is the unaltered flow of a river, including the variation in discharge occurring seasonally due to the summer dry period marked by low discharge as the channel water recedes, and the winter wet season when higher discharge returns and channel banks are rewetted (James & Suren, 2009; Poff, et al., 1997). The natural low and high discharge periods of a river can be characterised by the five components of the natural flow regime - (i) the magnitude of discharge or the volume of water moving per unit time past a fixed location, (ii) the frequency of occurrence; the number of times the magnitude of discharge repeats in a given time, (iii) the duration of the discharge period, (iv) predictability of the discharge period, which defines how regularly it occurs in a specific time and, (v) rate of change of the discharge period, which defines whether the variability occurs gradually or spontaneously (Poff, et al., 1997). Variation in a permanent river also occurs in the physico-chemical conditions along the river length (Vannote, et al., 1980), with the size of the channel, magnitude of discharge, water quality and availability of the resource types, forming a longitudinal gradient of change and variation (Vannote, et al., 1980).

Seasonal variability in the discharge and longitudinal variation in the physico-chemical conditions of permanent rivers are essential to the aquatic fauna (Poff, et al., 1997). Aquatic species are adapted to (i) the critical pressures and opportunities created by the seasonal low and high discharge periods (Bunn & Arthington, 2002; Scarsbrook, 2002; Winterbourn, 1997) and (ii) the seasonal variation in the channel size (Hershkovitz & Gasith, 2013), and (iii) longitudinal variation in water quality and availability of the type of food (Vannote, et al., 1980). These adaptations may be manifested in the variation of life history strategies

(reproduction once or multiple times a year), flow velocity preferences and feeding habits (for example, filter-feeder, predator) (Bunn, 1988; Bunn & Arthington, 2002; Smith & Storey, 2018; Vannote, et al., 1980). Seasonal variability in discharge and longitudinal variation in physico-chemical parameters also regulates the population dynamics and diversity of the aquatic community (Garbe, Beevers, & Pender, 2016; Piniewski, et al., 2017; Sagar, 1986; Vannote, et al., 1980).

1.2. River water abstraction

The natural flow regime of a river is altered by water abstraction for irrigation (Bunn & Arthington, 2002; Dewson, James, & Death, 2007a). Of the total withdrawals from global freshwater resources, 70% is used to address the needs of irrigation for agriculture (FAO, 2016; Doll, Fiedler, & Zhang, 2009). Agricultural water abstraction is predictable and reduces the magnitude of discharge; it is often seasonal, driven by peak water requirements during dry seasons when water levels are naturally low, further reducing the magnitude of the naturally low discharge (Merciai, et al., 2017; Nelson & Lieberman, 2002; Wooster, Miller, & DeBano, 2016). Water abstraction increases both the frequency of occurrence and the duration of the low discharge conditions (Benejam, et al., 2010; Merciai, et al., 2017). It also increases the rate of change of the discharge conditions, such that instead of a gradual shift, water abstraction initiates a sudden and potentially more severe start to periods of low discharge (Merciai, et al., 2017; Wooster, Miller, & DeBano, 2016). The exacerbation of low discharge periods causes the loss of lateral connectivity to the riparian zone (Lake, 2003) and the reduction in flow velocity and depth, both of which are key determinants of habitat suitability for the biota in the river (Bunn & Arthington, 2002; Nelson & Lieberman, 2002).

Investigations into the response of fauna to water abstraction in permanent rivers have produced inconsistent results (Dewson, James, & Death, 2007a). Some studies report strong

negative responses of abundance, density and community structure of fish and invertebrates to the exacerbation of low discharge periods (Benejam, et al., 2010; González, Recuerda, & Elosegí, 2018; James & Suren, 2009; McIntosh, Benbow, & Burky, 2002; Merciai, et al., 2017; Phelan, et al., 2017; Salmaso et al., 2018), while other studies report only limited change in densities and community structure (Anderson, et al., 2015; Castella, et al., 1995; James & Suren, 2009). Specific aquatic taxa are benefitted by low magnitudes of discharge during dry periods such as, midges and algae while others such as trout, are negatively impacted (Aburaya & Callil, 2007; Montecino, et al., 2014; Xu, 2018). (Castella, Bickerton, Armitage, & Petts, 1995)

The inconsistency in the response of aquatic fauna to water abstraction likely arises from the variable context in which the altered flow regimes occur (Poff, et al., 1997; Vannote, et al., 1980). This inconsistency can be attributed to the various degrees of the magnitude of discharge, frequency of occurrence and duration of water withdrawal (Benejam, et al., 2010; Dewson, James, & Death, 2007a). It is common to find multiple water abstraction points and tributaries along a river that courses through areas of agricultural land use (Salmaso, et al., 2018). The response of fauna to water abstraction may vary due to longitudinal variation in various factors along the length of a river such as (i) water quality (Aazami, et al., 2015; Holst, Timm, & Kausch, 2002; Houser, et al., 2010; Scheibler & Debandi, 2008) and (ii) cumulative effect of agricultural land use and flow alteration, confounding interpretation of relationships between the water abstraction and the faunal response (Bunn & Arthington, 2002; Dickerson, et al., 2009; Lange, Townsend, & Gabrielsson, 2014; Lange, Townsend, & Matthaei, 2014; Wiley, Osborne, & Larimore, 1990).

Recovery of fauna in permanent rivers from water abstraction or unseasonal droughts depends on the variable magnitudes of discharge, frequency of occurrence and duration of the

low discharge periods, along with the spatial extent of abstraction (Fowler, 2004; Bêche, et al., 2009). The literature on the recovery of fauna from periods of low discharge in permanent rivers is dominated by studies on droughts which are climatic events acting on a whole landscape for an extended duration, unlike water abstraction which affects only certain reaches of the river system for a controlled duration of time (Dewson, James, & Death, 2007a; Lake, 2003). Studies of droughts of 1-5 years duration have reported that the recovery of fish abundance can occur within 1- 3 years post-drought (Adams & Warren Jr., 2011; Bêche, et al., 2009). Niemi, et al. (1990) suggested that the timing of low discharge periods relative to the spawning season of fish in rivers decides whether recovery takes one year or two. Recovery of invertebrates from droughts that are 1-4 years long can occur within 1 year of return of normal discharge in the rivers (Adams & Warren Jr, 2011; Boulton, 2003; Wood & Petts, 1994). In contrast, Miller, Wooster, & Li (2007) studied the effects on and recovery of invertebrates from a short duration seasonal water abstraction and found that, whilst recovery had not occurred one month after the return of high river discharge magnitudes, it had recovered before the next irrigation period began. There are few studies assessing recovery of invertebrates from water abstraction and fewer studies assessing patterns of recovery across a catchment when seasonal water abstraction ceases.

As high discharge periods return in permanent rivers, re-colonisation of rewetted river habitat by aquatic fauna occurs (Poff, et al., 1997; Ríos-Touma, Prat, & Encalada, 2012; Storey & Quinn, 2007). After rewetting of previously dry substrates, microbial activity is able to recover within a few days, allowing invertebrates and fish to re-colonise shortly after (Boyero & Bosch, 2004; Dodds, et al., 2004). The movement of river fauna by drifting, swimming and crawling longitudinally and laterally in a river, and their reproduction play a major role in the re-colonisation of previously disturbed river habitat (Brittain & Eikelan,

1988; Maazouzi, et al., 2017; Mackay, 1992; Ríos-Touma, Prat, & Encalada, 2012; Williams & Hynes, 1976). The increase in rewetted habitat is higher downstream of water abstraction (Dewson, James, & Death, 2007a) and the impact of water abstraction on fauna persists for some time following rewetting (Miller, Wooster, & Li, 2007), possibly due to the time taken for re-colonisation of previously dry habitat. (Dewson, James, & Death, 2007a)

Benthic invertebrates are reliable indicators of the impacts of water abstraction on river ecosystems, as they are sensitive to changes in the natural flow regime and water quality (Dewson, James, & Death, 2007a; Bunn & Arthington, 2002). Certain invertebrate taxa have different functional traits, such as life history strategies, feeding habits and flow preferences, which render them sensitive or tolerant to changes in the river ecosystem, such as flow regulation and the decline in water quality (Lancaster & Downes, 2013; McKie, et al., 2018; Miller, Wooster, & Li, 2007; White, et al., 2017). The response of various invertebrate community indices based on different functional traits has been used to assess the impacts of low discharge magnitudes on stream ecosystems (Collier & Winterbourn, 2000; Haegerbaeumer, et al., 2019; Feld, de Bello, & Dolédec, 2014; Walters, 2011). Given that the whole invertebrate community is an integral part of the aquatic food chain, reductions in invertebrate densities in response to water abstraction can impact fish and other wildlife (Weber, et al., 2007; Shearer, Stark, Hayes, & Young, 2003). The collection and assessment of invertebrate community structure, though intensive, is cost effective relative to other methods of environmental assessment, providing a time-integrated assessment of the impacts of water abstraction on lotic ecosystems (Stefanidis, Panagopoulos, & Mimikou, 2016).

1.3. Water allocation management in New Zealand

In New Zealand, the allocation of river water for irrigation is governed by the Resource Management Act 1991 (RMA), which was introduced to sustainably manage New Zealand's

natural resources, such as the rivers (New Zealand Government, 2020). The RMA states that the ecological values of the rivers provide for the social, economic, and cultural well-being of the New Zealand citizens (Section 5.2, RMA). A primary economic use of rivers is agricultural irrigation; over the last two decades, the area of irrigated farmland in New Zealand has increased by 94% (Stats NZ, 2017). The increase in irrigated area is reflected in the increase in New Zealand's Gross Domestic Product (Trading Economics, 2020), however these increases in irrigated area and intensive farming have also contributed to over-allocation of the nation's available river water (Ministry for the Environment & Stats NZ, 2019). To allocate river water for irrigation, landowners use Deemed Permits, which were issued under now obsolete mining legislation (OPUS, 2010); the RMA dictates that the Deemed Permits will expire on October 1, 2021 (Section 413.3, RMA). Before October 1, 2021, the landowners must apply for a Resource Consent from the relevant local authority or Regional Council. The Resource Consent includes acceptable details (to the local authority) of the amount of water to be abstracted and an assessment of its environmental effects (Section 88, RMA). The assessment of a landowner's application for a Resource Consent is based on the Regional Policy Statements and Regional Plans, which are prepared by the Regional Councils under the mandates of the RMA (Section 30.1 RMA) (Figure 1.1). The Regional Plans prescribe limits in the form of Minimum flows, on water use from rivers to account for protection of aquatic fauna (Section 61.2.iii), while providing for commercial use during summer abstraction period (Section 30.1.f). For instance, in the Lindis River catchment in Otago region of New Zealand, which has a Mean 7-day Annual Low Flow (MALF) of 1.86 m³/s, the minimum flow has been set at 0.55 m³/s and the allocation limit at 1.64 m³/s in 2019 (Edwards, 2019; Olsen, 2016).

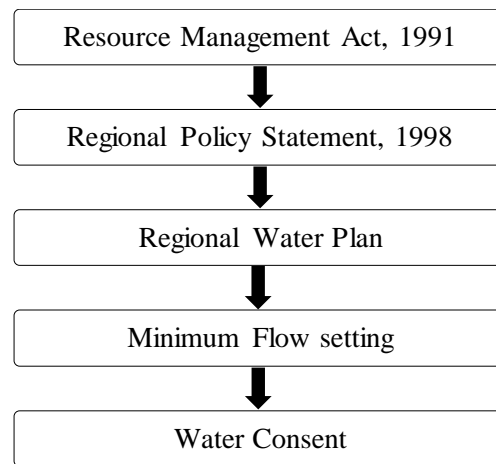


Figure 1.1. Summary of the statutory framework of the Resource Management Act relating to the issuing of water consents by the Regional Councils (New Zealand Government, 2020).

1.4. The Manuherikia River, New Zealand

To investigate the effects of water abstraction on aquatic invertebrates, the Manuherikia River, a part of the bigger Clutha River catchment, in Central Otago, New Zealand, was chosen as it presents a study model with abstraction from natural and altered flow regimes in relatively close proximity (Figure 1.2). The headwaters of the mainstem of the Manuherikia River and its tributary Dunstan Creek (catchment = 157 km²) originate in the Hawksdun Range and St. Bathans Range (Reid & Grant, 1980), with the snow accumulation from winter melting to provide the majority of the annual flow (Figure 1.2). However, the Manuherikia catchment (3033 km²) is relatively dry, receiving only 350-500 mm of annual rain. The main irrigation season (December to March) occurs during the natural summer low discharge periods (Olsen, Lu, & Ravenscroft, 2017; Poyck, et al., 2011). The river is dammed by the Falls Dam in its upper reaches for irrigation (Figure 1.2), altering the natural flow regime of the mainstem (Otago Regional Council, 2020). Currently, the river is subject to a minimum flow of 0.82 m³/s and an allocation limit of 3.20 m³/s (MALF = 3.20 m³/s), but these values are currently being renegotiated, as they allow over-allocation of the river through the 213 water takes for irrigation along its 64 km length (Olsen, Lu, & Ravenscroft, 2017). In her

study of the Manuherikia catchment, Lange, (2014) pointed out that at >21% water abstraction intensity, invertebrate community structures showed the strongest changes, with common taxa exhibiting relatively lower densities. The community structure of algae, which are a food source for invertebrates, showed the strongest changes at >41% water abstraction intensity. In light of that study, the three water abstraction points were chosen as the focus of this study - one on the tributary, Dunstan Creek, and two on the main stem of the Manuherikia River which abstract >50% discharge at their respective points of the river during the irrigation season (Figure 1.2).

Other anthropogenic factors that affect the invertebrates in the Manuherikia catchment have been identified. This includes a reduction in water quality in the lower reaches of the river, compared to the tributaries, a consequence of increasing intensity of agricultural land use and flow regulation in the lower Manuherikia catchment (Lange, Townsend, & Gabrielsson, 2014). The invasive diatom Didymo (*Didymosphenia geminata*) that changes habitat suitability for invertebrates, also thrives in the river (Kilroy, Larned, & Biggs, 2009; NIWA, 2014).

Manuherikia catchment has significant natural values (Kitto, 2011). It supports 11 native and game species of fish, including the endemic Alpine Galaxias (*Galaxias paucispondylus* - Manuherikia), the endemic Central Otago Roundhead Galaxias (*Galaxias anomalus*) (Allibone, et al., 2014), and the endangered Longfin Eel (*Anguilla dieffenbachii*) (Pike, Crook, & Gollock, 2019). Additionally, both brown (*Salmo trutta*) and rainbow (*Oncorhynchus mykiss*) trout contribute to a regionally significant recreational fishery (Shutt, 1990). Along with fishing, kayaking and swimming in the river are also popular sports among local residents and tourists.

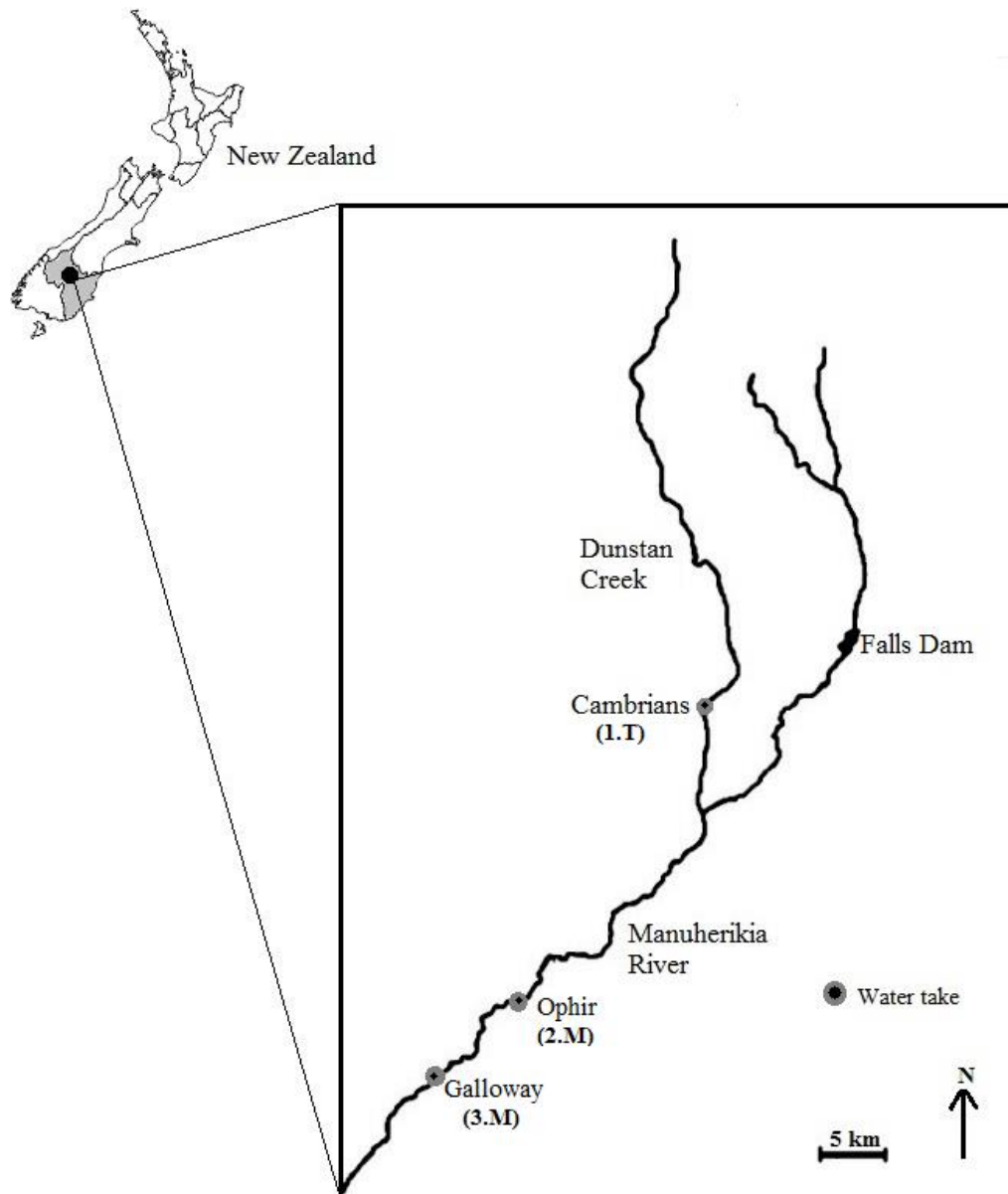


Figure 1.2. Three water abstraction points selected on the tributary Dunstan Creek and mainstem of Manuherikia River in Central Otago, New Zealand (Map adapted from Google Earth, 2019).

1.5. Thesis outline

The aim of my project is to quantify the response of benthic macro-invertebrates to the water abstraction in the Manuherikia catchment during the summer irrigation period and to investigate the recovery as the high discharge season resumes in winter after abstraction ceases, by using density and functional trait data. Upstream and downstream sampling sites of three major water abstraction points that abstract >50% of the discharge were selected

based on accessibility (Figure 1.2). For simplicity, the three abstraction points selected have been named 1, 2, and 3, and to describe their location, 'T' for tributary and 'M' for mainstem has been added to their labels. So, the water abstraction point at (i) Cambrians on the tributary Dunstan Creek (44°54'50.4"S, 169°45'31.7"E), an unregulated tributary is 1.T, and (ii) the next in the town of Ophir (45°08'03.1"S, 169°31'37.8"E) on the mainstem of the river, is 2.M, followed by (iii) the water diversion in the town of Galloway (45°11'16.3"S, 169°28'39.8"E), also on the mainstem, is 3.M (Figure 1.2). For better management of rivers, McIntosh, et al., (2016) had identified a gap in New Zealand studies on the variation in invertebrate response to water abstraction on a spatial gradient along a river. The arrangement of the abstraction points on the Manuherikia River allows the assessment of the impact of abstraction at each point and along a longitudinal gradient of increasing anthropogenic impact. Longitudinally, due to effect of flow regulation and declining water quality, it is expected that invertebrate assemblages would shift toward more tolerant taxa from the tributary Dunstan Creek to Galloway, near the mouth of the river, before it joins River Clutha. Hence, the response of invertebrates to water abstraction would be more pronounced in the tributary, followed by Ophir and then, Galloway (Figure 1.2). The rewetted channel was also sampled after abstraction ceased to assess the dynamics of recovery laterally across the stream channel as natural flows returned. (McIntosh, Death, Greenwood, & Paterson, 2016)

Chapter 2 explores the changes in the density and functional trait abundances of benthic macroinvertebrates during water abstraction and after abstraction ceases at each of the three water abstraction points in the permanently wet channel. Chapter 3 assesses the lateral recovery of invertebrate communities across the river channel after abstraction has ceased and natural flows return in winter. Lastly, Chapter 4 discusses the major findings and

implications. The findings of this study may contribute to the minimum flow setting process currently under review by the Otago Regional Council (Figure 1.1) by advancing understanding of the natural values and impacts of water abstraction and land use intensification on invertebrate aquatic fauna of the Manuherikia River. The project goal is to add to the limited number of empirical studies on the effects of water abstraction on benthic invertebrates and their recovery in New Zealand rivers and elsewhere, as understanding the impacts of water abstraction from rivers will advance the development of improved approaches to the management of rivers as a resource (Anderson, et al., 2019).

Chapter 2. The response and recovery of benthic macro-invertebrates from season-long water abstractions along the permanently wet channel of the Manuherikia River, New Zealand

2.1. Introduction

2.1.1. Response of benthic invertebrate communities to water abstraction

Benthic macroinvertebrate densities and community structure respond variably to water abstraction (Dewson, James, & Death, 2007a; James & Suren, 2009). Water abstraction from rivers alters the natural flow regime, which is essential to the functioning of natural benthic macroinvertebrate communities (Poff, et al., 1997). It reduces the magnitude of discharge, increases the frequency and the duration of low discharge periods, and increases the rate of the shift from high discharge to low discharge condition (and vice versa) (Benejam, et al., 2010; Merciai, et al., 2017; Nelson & Lieberman, 2002; Wooster, Miller, & DeBano, 2016). Benthic macroinvertebrate communities respond variably to the variable degrees of alteration of the natural flow regime due to water abstraction (Feld, de Bello, & Dolédec, 2014; McIntosh, Benbow, & Burky, 2002; Salmaso, et al., 2018; Scarsbrook, 2002; Walters, 2011; Winterbourn M., 1997).

In New Zealand, benthic invertebrates have been observed to respond variably to different patterns of river water abstraction (Dewson, James, & Death, 2007a; James & Suren, 2009; New Zealand Government, 2017). Severe and continuous reduction of >90% in the magnitude of discharge for a long duration of >1 year changed the community structure, with loss of a few sensitive taxa (Jowett & Biggs, 2006). Reduction in the magnitude of discharge by 25-98% by water abstraction even for a shorter duration of two months reduced invertebrate densities and induced changes in the community structure (James & Suren,

2009). Shorter periods of water abstraction, e.g. one month duration, caused concentration of invertebrates, leading to increased densities but little change in the community structure (Dewson & Death, 2007; Dewson, Death, & James, 2003; Dewson, James, & Death, 2007b; James & Suren, 2009). The variability in the response of invertebrates to water abstraction is evidently due to the variation in the impacts of the different components of altered natural flow regime, which may also vary along the river due to factors such as varying water quality, channel width, agricultural land-use and flow alteration due to a dam (Collier, et al., 2013; Lange, Townsend, & Matthaei, 2014). There are only limited studies that have assessed the impact of season long water abstraction in New Zealand rivers, and none that have examined how those impacts vary along the length of a river (McIntosh, et al., 2016).

2.1.2. Recovery of benthic invertebrate communities

The recovery of benthic macroinvertebrate density and community structure following a period of water abstraction also depends on the degree of alteration to the natural flow regime (Miller, Wooster, & Li, 2007). When the period of abstraction is relatively short, e.g. of one month duration, communities that had been previously concentrated into reduced areas of habitat may then re-attain near-normal densities with the onset of pre-abstraction discharge (Dewson, James, & Death, 2007a). Given that continuous long periods (potentially many years) of high reduction in the magnitudes of discharge can result in greatly altered macroinvertebrate communities, the recovery of invertebrate densities and community structure may be extended, potentially taking 2 to 4 years in some New Zealand streams (Jowett & Biggs, 2006). In New Zealand, there are a limited number of studies on the recovery of invertebrates from low discharge periods caused by river water abstraction during the summer irrigation period. There is no study comparing the recovery from water abstraction along the length of a river in New Zealand.

2.1.3. Chapter objectives

The first aim of this chapter is to quantify the response and recovery of benthic invertebrate densities and community structure from water abstraction over the summer irrigation season resulting in >50% reduction in the magnitude of discharge at each of three water abstraction points along the length of the Manuherikia River; one on the tributary 1.T and two on the mainstem, 2.M, and 3.M (Figure 2.1). The second aim is to compare the response and recovery at each of the three water abstraction points, given the increasing anthropogenic impacts with distance along the river. Invertebrates of the sites of the tributary abstraction point, 1.T, were expected to be more sensitive to water abstraction than sites on the mainstem – 2.M, followed by 3.M – that are more disturbed by agricultural inputs and regulation of flow by Falls Dam than the tributary water abstraction point (Figure 2.1). Hence, a longitudinal pattern of a reduced response of benthic macroinvertebrates to water abstraction was expected along the Manuherikia River.

It was hypothesised that in response to the reduction in the magnitude of discharge due to the seasonal water abstraction during the natural low discharge, (i) the densities of benthic macroinvertebrates downstream of water abstraction would reduce, (ii) the densities of taxa that reproduce once a year (univoltine) would be lower downstream than the densities of taxa that reproduce multiple times a year (multivoltine) contributing to the change in community structure and, (iii) the community structure of invertebrates at the upstream and downstream sites would also change due to the flow velocity preference and feeding strategies of invertebrates. With respect to the recovery after the seasonal water abstraction ceases, (iv) at each water abstraction point, the univoltine taxa densities are expected to be less resilient to water abstraction than multivoltine taxa densities.

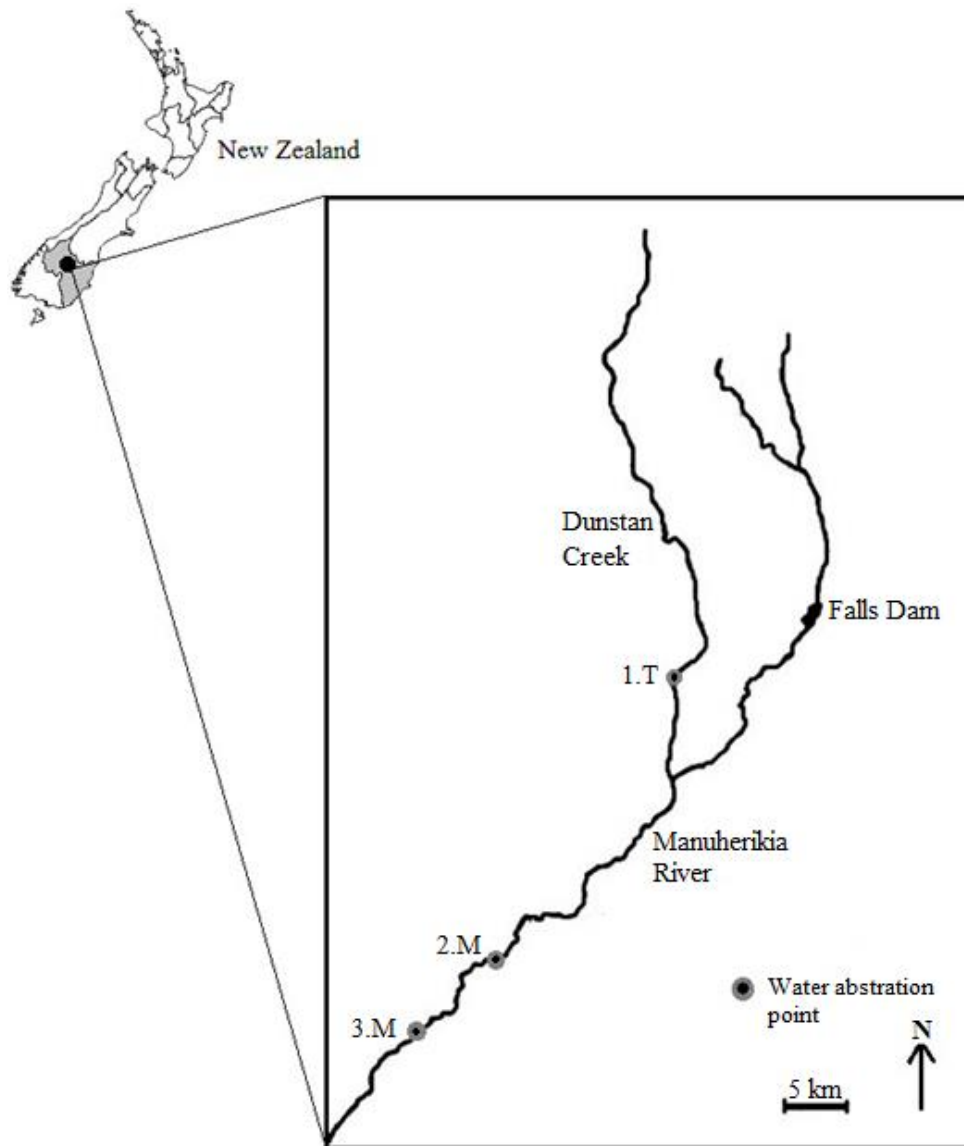


Figure 2.1. Three water abstraction points selected for the study lie along the length of the Manuherikia River in Central Otago, New Zealand. Water abstraction point 1.T lies on the tributary of the Manuherikia River and has the discharge conditions closest to a natural flow regime. 2.M lies on the mainstem in an agriculture intensive landscape and below the Falls Dam that regulates the flow of the river, followed by the water abstraction point 3.M, also on the mainstem of the river.

2.2. Methods

2.2.1. Study design

To study the invertebrate response to and recovery from water abstraction, benthic invertebrates and physico-chemical parameters were assessed upstream and downstream of three major water abstraction points located along the river during and post seasonal water

abstraction. The tributary water abstraction point, 1.T represents a suitable system to study the impacts of water abstraction on invertebrate communities, given the absence of any water abstraction upstream of this point, whereas the two water abstraction points on the mainstem, 2.M, and 3.M, are impacted by the upstream water abstraction, dam regulation and extensive areas of agriculture. 1.T is a small weir, which slightly dams the tributary flow before water is directed into an irrigation water race (Figure 2.2). To assess longitudinal macroinvertebrate density and community structure gradients upstream (U) and downstream (D) of 1.T, multiple upstream - U2, U1 - and downstream - D1, D2 and D3 - sites accessible about 1.T were sampled (Figure 2.4). Between sites D2 and D3, there are four small tributary inflows, all of which were most likely seasonal, draining the local farmland in winter months (NZ Topo Map, 2020). Thus, the only significant alteration to the flow regime downstream of 1.T is the water abstraction.



Figure 2.2. A panorama of the water abstraction weir, 1.T clicked during the abstraction and the seasonal low discharge period in March, 2019. Downstream of 1.T, behind the green boxed gauge, the dry tributary bed can be seen while >50% of the discharge runs into the concrete irrigation water race.

The water abstraction point 2.M, an underground pipeline lies in an inaccessible gorge on the mainstem of the Manuherikia River. The nearest Upstream - U (4.74km) and downstream - D (7.26km) sites accessible to the 2.M abstraction were sampled (Figure 2.4). Along the gorge, between sampling sites U and D, there are numerous small ephemeral or intermittent tributaries (NZ Topo Map, 2020). However, there is no agriculture in the gorge, and the discharge into the river along the gorge over summer is minimal. The water abstraction point

3.M is an annually constructed diversion on the mainstem of the Manuherikia River (Figure 2.3). The upstream- U, and downstream- D sites accessible directly adjacent to 3.M were sampled (Figure 2.4). The downstream sampling site D was just upstream of the location where the Galloway diversion discharged back into the Manuherikia River.



Figure 2.3. Aerial view of the water abstraction point 3.M, temporary Galloway diversion during water abstraction and seasonal low discharge period, 2019 occasion - DA. The direction of flow is away from the reader. Most water flows into the irrigation water race and <50% of the discharge flows into the main river channel.

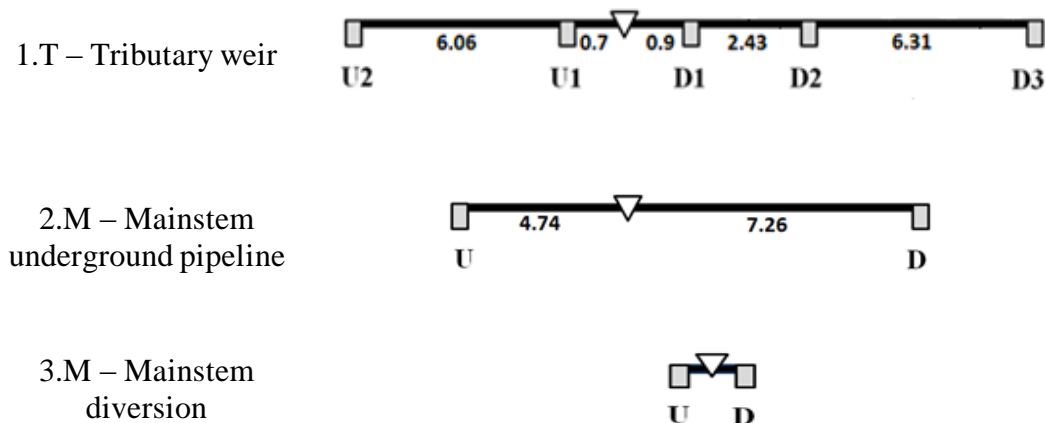
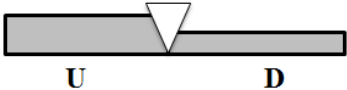
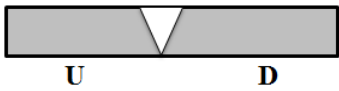
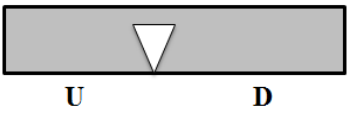


Figure 2.4. Overviews of sampling setup for 3 water abstraction points and their up- and downstream sampling sites. Triangles show water abstraction points for 1.T, 2.M and 3.M. Rectangles show upstream (U) and downstream (D) sampling sites which each consists of a 300m reach within which 5 random riffles were chosen for sampling. Black values between sampling sites show the distances (in km) Note: Distances in the diagram between sampling sites are not to scale.

The water abstraction points were sampled three times in 2019; once, in March about four months into the irrigation period, which is seasonally the period of lowest discharge, and once each in May and June, after abstraction ceased and higher seasonal discharge down the river resumed (Table 2.1). Sampling during the abstraction season, referred to as DA for short, was conducted on March 6th, 7th and 20th during the irrigation season, when 50 to 70% of the water was being abstracted at the abstraction points (Otago Regional Council, 2019). The second sampling period was carried out on May 6th-8th soon after the irrigation season ended, immediately post water abstraction, referred to as IPA for short; followed by the third and final sampling period from June 1st-3rd, three weeks post abstraction and is referred to as 3PA for short (Table 2.1).

Table 2.1. Overview of the occasions of sampling. Grey areas show the relative magnitude of discharge. White triangles show the position of the same water abstraction point at different time points of sampling. U indicates upstream and D indicates downstream of the water abstraction point.

Sampling occasion	Month	Season	Seasonal Discharge	Relative magnitude of discharge at the same water abstraction point
DA -During abstraction	March	Summer	Low	
IPA -Immediate post abstraction	May	Autumn	High	
3PA -Three week post abstraction	June	Winter	High	

2.2.3. Field sampling

To quantify the response and recovery from seasonal water abstraction in the Manuherikia River, quantitative benthic invertebrate Surber samples of 0.1m² benthic area, 500µm mesh size were collected for 1 minute each and preserved in 70% ethanol (Protocol C3 by Stark et

al., 2002). Each site consisted of a 300 m centreline reach, in which five randomly chosen riffle habitats were sampled between 0800 to 1600 hours at each occasion. Hence, in the document, a site means the 300m reach used for sampling upstream or downstream of the water abstraction points, 1.T, 2.M, and 3.M. Macro-invertebrates are invertebrates larger than 500 μm and have been found to give sufficient information for the assessment of environmental impacts, such as water abstraction (Stark, et al., 2002). On the occasions, IPA and 3PA, due to the health and safety issues arising from high flows sampling from centreline in the mainstem sites of 2.M and 3.M water abstraction points were slightly off-centre but not from the recently wetted edges.

Habitat changes due to water abstraction translate into changes in physico-chemical parameters (Caruso, 2002). Discharge in cubic metres per second - m^3/s was accounted from flow gauge records of ORC installed for monitoring purposes along the Manuherikia River (Otago Regional Council, 2019). Before every Surber sample, velocity (at 0.4 times depth from the bed), wetted width and depth were measured at that point. Velocity of flow was measured in metre/second (m/s) using an electromagnetic flow metre (Marsh-McBirney Model 2000, Frederick, Maryland). On the occasions IPA and 3PA, the increased discharge and water velocities prevented measurement of total wetted widths at the mainstem sites of 2.M and 3.M water abstraction points, also at 1.T sites in the third occasion 3PA. It must be noted that velocities, wet widths and depths measured at the riffle reach selected for sampling are not true measures for the river course. They give more information on the standardisation of sampling.

At every Surber sample location in a site, temperature, dissolved oxygen and electrical conductivity were measured with the YSI Professional Plus instrument (Professional Series - Instrument 6050000, YSI Incorporated, Yellow Springs, Ohio, USA). pH was measured by using the Hanna pH meter (No.- HI98128 pHep, Hanna Instruments, Woonsocket, Rhode

Island); and turbidity by using the Hach turbidimeter (Cat. No 2100Q01, Hach World Company Headquarters PO Box 389 Loveland, CO 80539, USA). At every Surber sample location in a site, water samples were collected for nutrient analysis through the Skalar San plus Automated Wet Chemistry Analyzer - Continuous Flow Analyzer (Skalar Analytical B.V. Tinststraat 12 4823 AA Breda, The Netherlands) to measure the total nitrogen, total phosphorus, dissolved ammonia, dissolved nitrates/nitrites and dissolved reactive phosphorus. To assess substrate composition, the longest axis of 75 randomly selected substrate particles were measured at each site once on the DA occasion.

2.2.4. Laboratory processing

Benthic macro-invertebrates collected in Surber samples were identified to the genus level where possible using the New Zealand invertebrate identification keys (Winterbourn, Gregson, & Dolphin, 2006). Samples were poured through 1cm and 500µm sieves to separate debris. Total counts of all samples were made in sorting trays under the dissection microscope (Stark et al., 2002). The larvae of Family Chironomidae were placed in different Petri dishes based on gross assessments of morphology, including anal appendages, antenna, eyes, length of head, body segments, etc. Whole specimens were then digested in 10% potassium hydroxide (KOH) for 5 minutes at 100°C. Then under a dissecting microscope, the head was removed from the body and placed with ventral side up on a labelled slide. A semi-permanent mount with glycerol was sealed with nail polish, and these slides were viewed under a compound microscope at 400 times magnification for identification (see Figure 2.5) (Drayson, Cranston, & Krosch, 2015; Richardi et al., 2013).

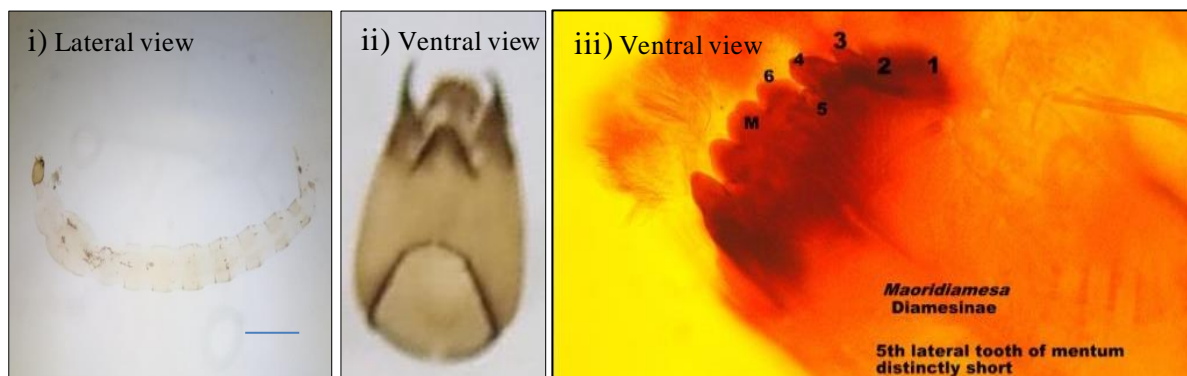


Figure 2.5. i) A Chironomidae larva after digestion in a 10%KOH solution under ii) The partially digested head of the specimen is placed ventrally on a slide iii) Mouthparts of the specimen in the semi-permanent glycerol mount are used for identification.

2.2.5. Data analysis

Discharge and wet width at the point of Surber sampling were compared visually in bar plots. A principal component analysis was used to summarise variation in water quality with respect to water abstractions and to visualise the longitudinal pattern of the river physico-chemical variables measured. To assess the response of benthic macroinvertebrate densities and community structure to water abstraction, (i) bar plots of benthic invertebrate density (number of individuals per 0.1m² of Surber sample), (ii) taxa number, and (iii) Non-metric Multi-Dimensional Scaling or NMDS (Bray-Curtis distance) after log transformation data plots were used.

The differences in the density of macroinvertebrates upstream and downstream of the water abstraction points, 1.T, 2.M, and 3.M individually were tested for significance for each occasion by using the Kruskal-Wallis test and post hoc Dunn's test. The difference between upstream and downstream sites was considered ecologically significant if the P-value ≤ 0.10 . The significance level alpha was changed from 0.05 to 0.10, as it helps to avoid type II errors (Keough & Quinn, 2002). To test the significance of differences between upstream and downstream of sites, there were nine cases to test - three cases for water abstraction point 1.T,

at each of the occasions DA, IPA and 3PA, and similarly three cases each for water abstraction points 2.M and 3.M. To test whether the centroids in NMDS plot were significant, PERMANOVA (Permutational Analysis of Variance) and ANOSIM (Analysis of Similarity) were conducted (Anderson, 2017).

To further assess the response of community structure to water abstraction, changes in specific invertebrate groups based on the taxa-specific preferences for flow velocity and the feeding strategies were analysed using (i) Lotic Index for Flow Evaluation New Zealand or LIFENZ (Greenwood, et al., 2016), and (ii) relative abundances of shredders, scrapers, deposit-feeders, filter-feeders, predators, and algal-piercers (NIWA, 2016). LIFENZ is proposed as a variant of the UK based LIFE index to construct a New Zealand specific index for comparing river ecosystems based on the invertebrate preferences for flow velocities and discharge (Greenwood, et al., 2016).

To visualise the differences in the response and recovery from water abstraction based on life history traits, the taxa that contribute to the differences in community structure due to water abstraction were identified using the Similarity Percent or the SIMPER analysis (Whitfield-Cargile, et al., 2015). The first ten taxa contributing to the dissimilarity in the SIMPER results were categorised based on their life history traits: multivoltine or univoltine. Bar plots of total densities of the taxa from upstream and downstream sites were used to visualise patterns. PAST or Paleontological Statistics, software version 3 (Hammer, Harper, D.A.T., & Ryan, 2001) was used for analyses (Whitfield-Cargile, Cohen, Suchodolski, Chaffin, McQueen, & Arnold, 2015)

2.3. Results

2.3.1. Habitat parameters

On the during abstraction occasion or DA, the 1.T water abstraction point at the tributary caused a 68.8% reduction in the magnitude of discharge, 2.M abstraction point at the main stem caused a reduction of 50% and 3.M, also on the mainstem, caused a reduction of 65.5% (Figure 2.6). At the conclusion of the irrigation season, there was an expected increase in natural magnitudes of discharge seen immediately and three weeks post-abstraction – IPA and 3PA; but, the downstream sites of all the three water abstraction points saw a relatively higher increase in magnitudes of discharge than upstream sites (Figure 2.6). The magnitudes of discharge at the mainstem sites of 2.M and 3.M were understandably higher at any given occasion than the tributary sites of 1.T.

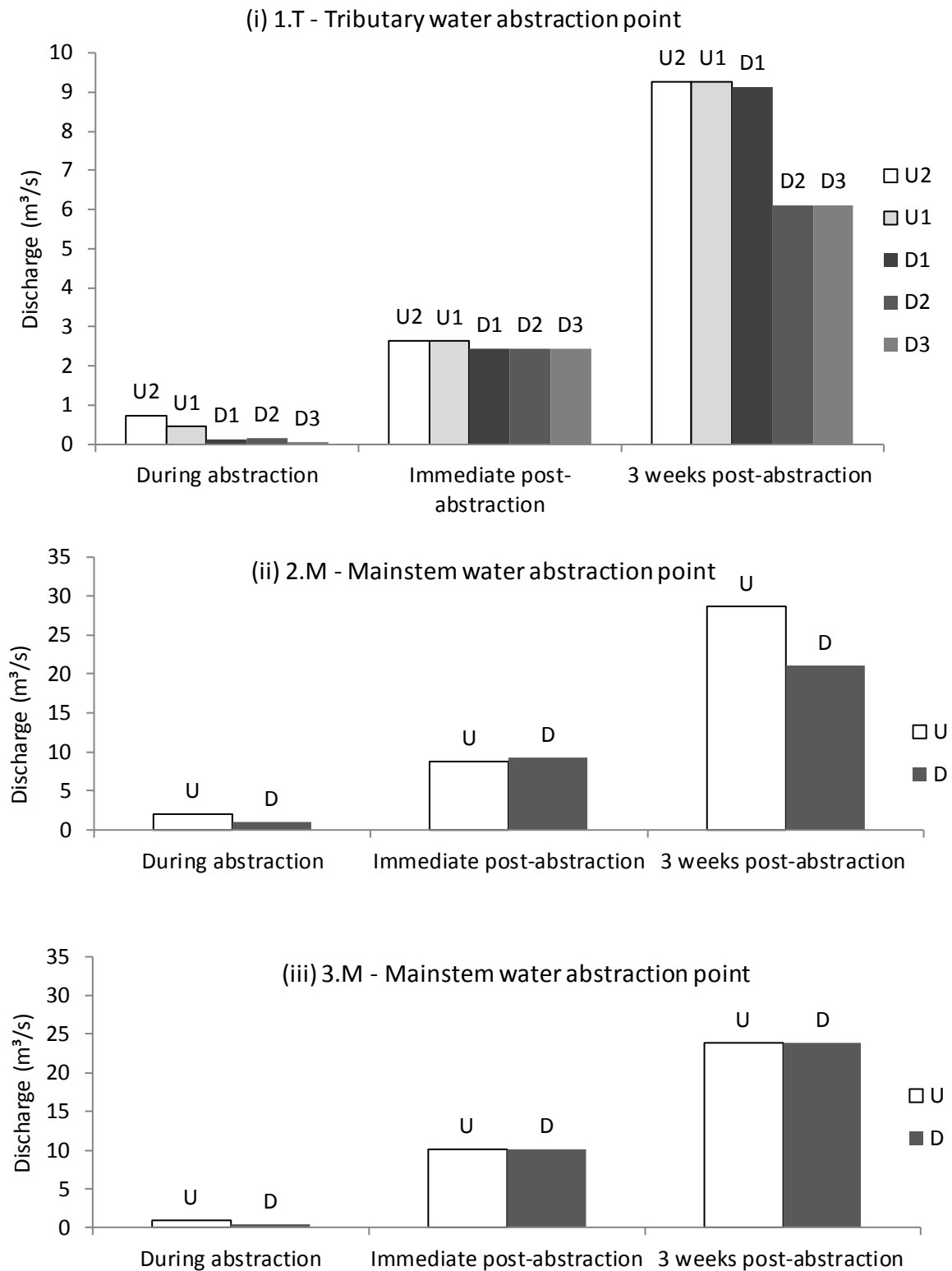


Figure 2.6. The accounted magnitude of discharge at the upstream (U) and downstream (D) sites depicted by colours in the legends of the three water abstraction points (i) 1.T, (ii) 2.M, and (iii) 3.M at the three occasions of study, during abstraction and seasonal low discharge period, and immediate and three weeks post abstraction occasions during seasonal high discharge period. Tributary abstraction point 1.T had five sampling sites; U2-most upstream from 1.T, U1- upstream site closest to 1.T, D1- first downstream site closest to 1.T followed by D2 and D3 further downstream. Mainstem abstraction points, 2.M and 3.M have the upstream site, U and the downstream site, D about them.

The principal component analysis of physico-chemical parameters showed that the water quality did not vary due to water abstraction at upstream and downstream sites but varied along the river from 1.T tributary sites to 2.M mainstem sites, followed by 3.M mainstem sites (Appendix Figure A.1, Table A.2). Velocities and depths of Surber samples did not differ due to water abstraction. The velocities and depths were similar along the length of the river. In the DA occasion, wet widths did not show significant differences due to water abstraction. The increase in wet widths on occasion IPA from that on DA occasion of downstream sites of 1.T was higher than the increase in the wet widths of upstream sites of 1.T. Wet widths of mainstem sites of 2.m and 3.M could not be compared with post-abstraction occasions, IPA and 3PA, as they were not measured.

2.3.2. Macroinvertebrate density

The mean benthic invertebrate densities of water abstraction point 1.T and mainstem sites (of 2.M and 3.M) decreased over the course of the study (Figure 2.7). On the during abstraction occasion or DA, the mean total benthic macro-invertebrate densities at downstream of the tributary abstraction point 1.T were higher or similar to upstream sites. The downstream site, D1 of 1.T had higher density than the upstream site U1 and the downstream sites D2 and D3 (Table 2.2, 2.3). The decrease in density in the next occasion IPA is higher downstream of the 1.T abstraction point than upstream, more so in 3PA. At the 3PA occasion, the mean densities at downstream sites of 1.T, D2 and D3 were significantly lower than upstream site U1 (Table 2.3). The densities of benthic invertebrates downstream of the mainstem abstraction points, 2.M and 3.M were generally less than those upstream at all three sampling seasons. The seasonal decrease in densities was generally more pronounced downstream of the abstraction points than upstream, more so in the three weeks post abstraction or the 3PA occasion, similar to the pattern seen with sites of 1.T (Figure 2.7). At the 3PA occasion, the mainstem

downstream sites of 2.M and 3.M had significantly lower densities than that of the respective upstream sites (Table 2.2).

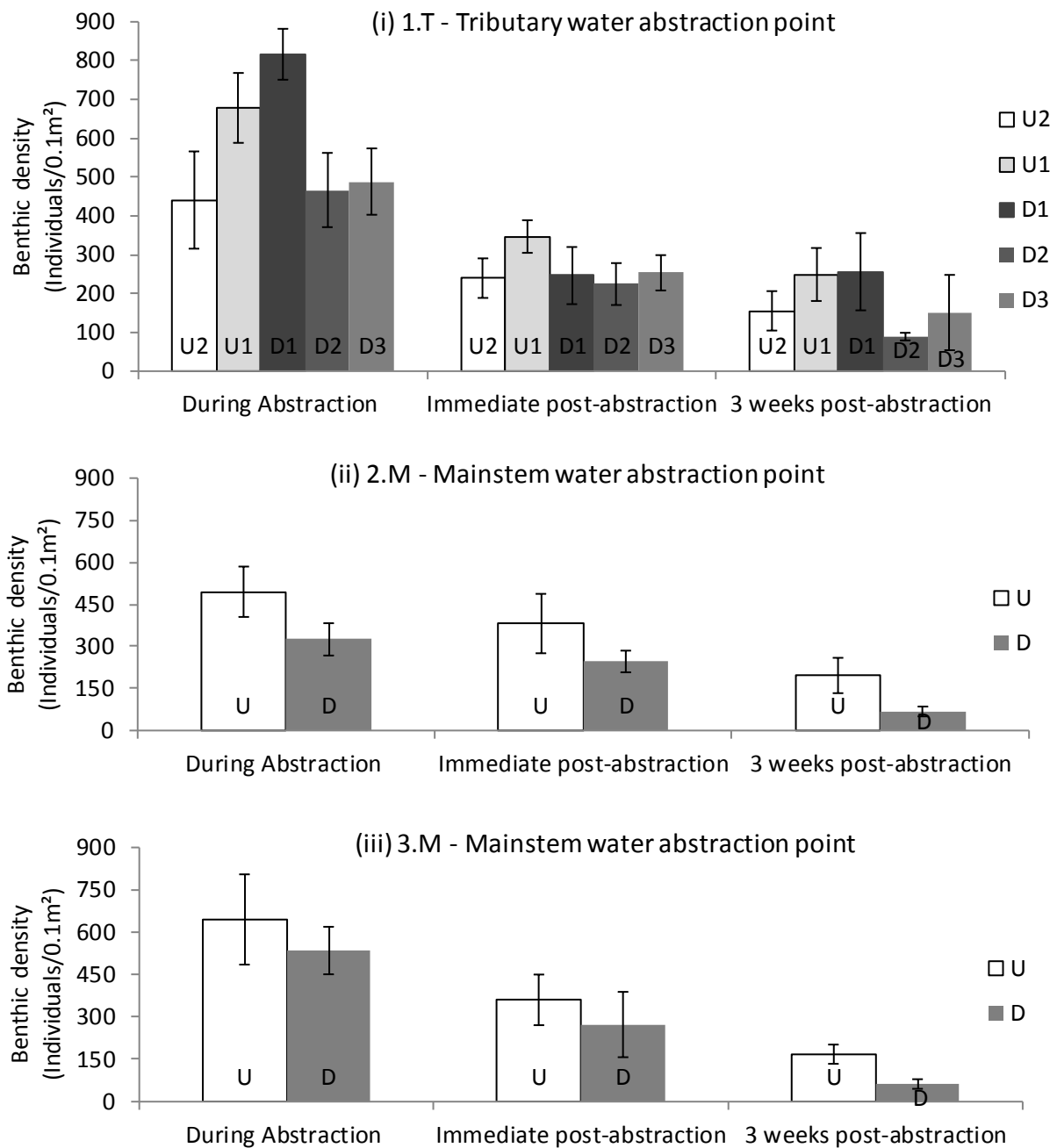


Figure 2.7. Mean total densities with standard error bars (N=5) of sampling sites of the three water abstraction points, (i) 1.T on the tributary, and (ii) 2.M and (iii) 3.M both on the mainstem of the river; at the three occasions- during abstraction occasion which coincides with the seasonal low discharge period, and immediate and three weeks post abstraction period which coincide with seasonal high discharge periods. Tributary abstraction point 1.T had five sampling sites; U2-most upstream from 1.T, U1- upstream site closest to 1.T, D1-first downstream site closest to 1.T followed by D2 and D3 further downstream. Mainstem abstraction points, 2.M and 3.M have the upstream site, U and the downstream site, D about them. The sites are depicted by colour in the legend.

Table 2.2. Results of Kruskal-Wallis tests that tested the significance of the difference between total densities of upstream and downstream sites (number of Surber samples per site = 5) of the three water abstraction points studied at the three occasions of sampling. Tributary 1.T has U2, U1, D1, D2 and D3 sites and mainstem 2.M and 3.M have U and D sites. H stands for the H statistic obtained in the Kruskal-Wallis test, P for p-values of the result and η^2 represents the calculated eta-squared estimate of effect size. Statistically significant values are in bold. In the case there was significant differences were found at Dunstan weir sites, post-hoc test results are shown in Table 2.3.

Abstraction Point	1.T			2.M			3.M		
Study occasion	H	P	η^2	H	P	η^2	H	P	η^2
During Abstraction	9.47	0.05	0.27	1.84	0.17	0.11	0.53	0.46	-0.06
Immediate post-abstraction	4.58	0.33	0.03	0.53	0.46	-0.06	0.54	0.46	-0.06
Three weeks post-abstraction	7.84	0.10	0.19	4.81	0.03	0.48	4.81	0.03	0.48

Table 2.3. Result of Dunn's post hoc test to pinpoint the total densities at sites of tributary water abstraction point 1.T which were significantly different from others at the DA occasion below the diagonal and at the 3PA occasion above the diagonal in italics.

Sites	U2	U1	D1	D2	D3
U2		<i>0.34</i>	<i>0.67</i>	<i>0.30</i>	<i>0.16</i>
U1	0.13		<i>0.61</i>	0.05	0.02
D1	0.02	0.37		<i>0.14</i>	<i>0.06</i>
D2	0.97	0.14	0.02		<i>0.70</i>
D3	0.90	0.17	0.02	0.93	

2.3.3. Macroinvertebrate community structure

2.3.3.1. Taxa number and overall community structure

A total of 42 invertebrate taxa were identified across the study. There were no distinct changes in taxa numbers seen due to abstraction points across any season (Figure 2.8). At Dunstan weir during abstraction, both upstream sites U2 and U1 had slightly higher taxa numbers than downstream sites D1, D2 and D3. A slight reduction in taxa numbers was seen along the Manuhirikia River – higher at 1.T sites and lower towards 2.M and 3.M sites.

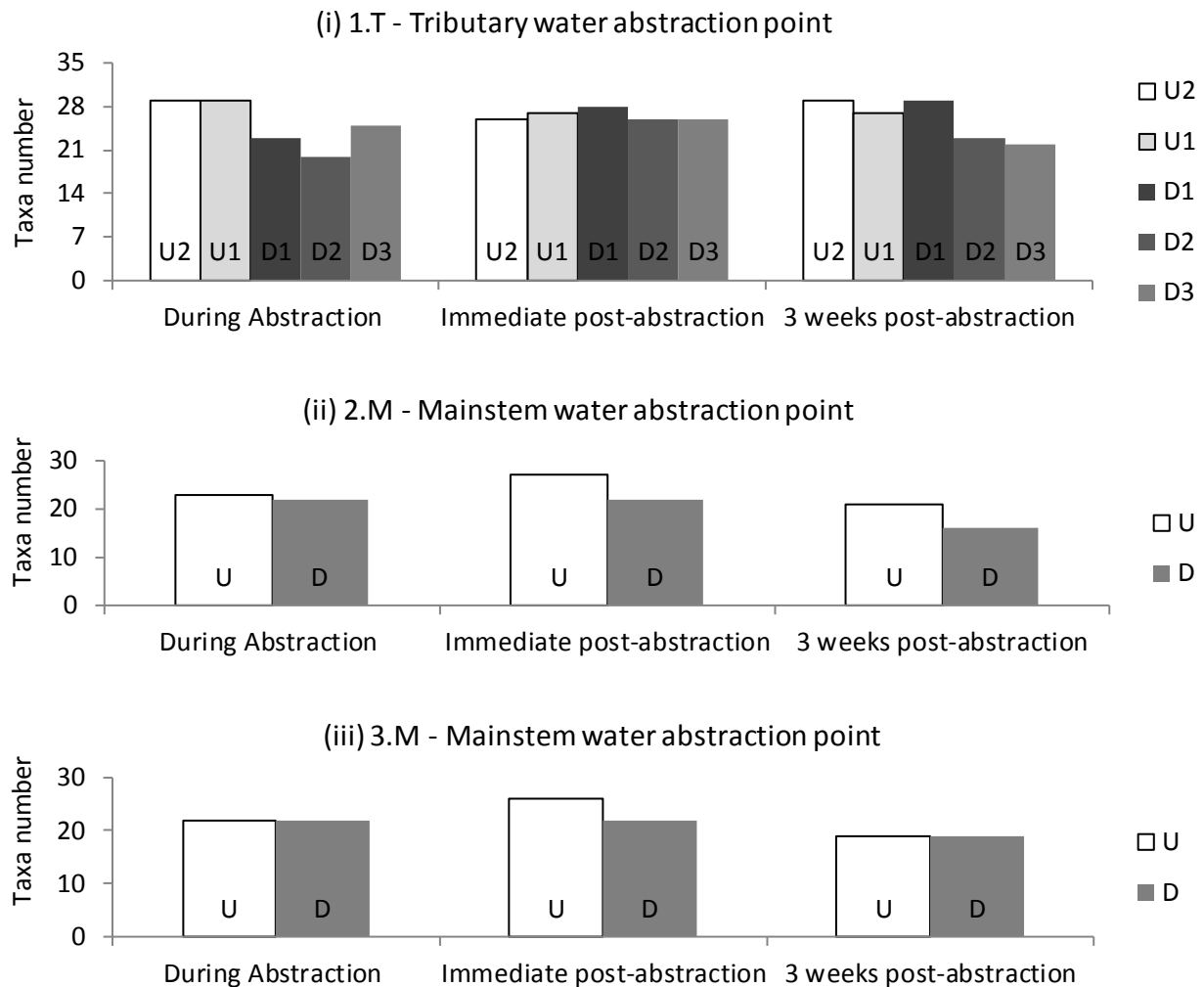


Figure 2.8. The bar graphs depicts the total number of the taxa identified in each site of the three water abstraction points, (i) 1.T on the tributary, and (ii) 2.M and (iii) 3.M both on the mainstem of the river over the three occasions of study - during abstraction which coincides with the seasonal low discharge period, and immediate and three weeks post abstraction which coincide with the seasonal high discharge periods. Tributary abstraction point 1.T had five sampling sites; U2-most upstream from 1.T, U1- upstream site closest to 1.T, D1- first downstream site closest to 1.T followed by D2 and D3 further downstream. Mainstem abstraction points, 2.M and 3.M have the upstream site, U and the downstream site, D about them. The sites are depicted by colour in the legend.

The Non-metric Multi-Dimensional Scaling (NMDS) plots of the 42 invertebrate taxa densities at the sites of the water abstraction points 1.T, 2.M and 3.M illustrated a weak difference between upstream and downstream sites community structure (Figure 2.9). The slight difference between the upstream and downstream sites of all three water abstraction points is the largest three weeks post-abstraction - 3PA during the seasonal high discharge

period. However, the seasonal changes in community were greater than community differences up and downstream of the abstraction points (Figure 2.9). The stress values of the NMDS plots are ecologically applicable (between 0.17 and 0.24) and all the plots capture >75% variation in the data (Figure 2.9). The PERMANOVA ($F \geq 3$, $P\text{-value} < 0.05$, for the three abstraction points) and ANOSIM results ($R > 0.29$, $P\text{-value} < 0.05$ for the three water abstraction points) showed that the distance between the centroids (sites – U/D) of each of the plots (Figure 2.9) constructed via NMDS analysis are of statistical significance.

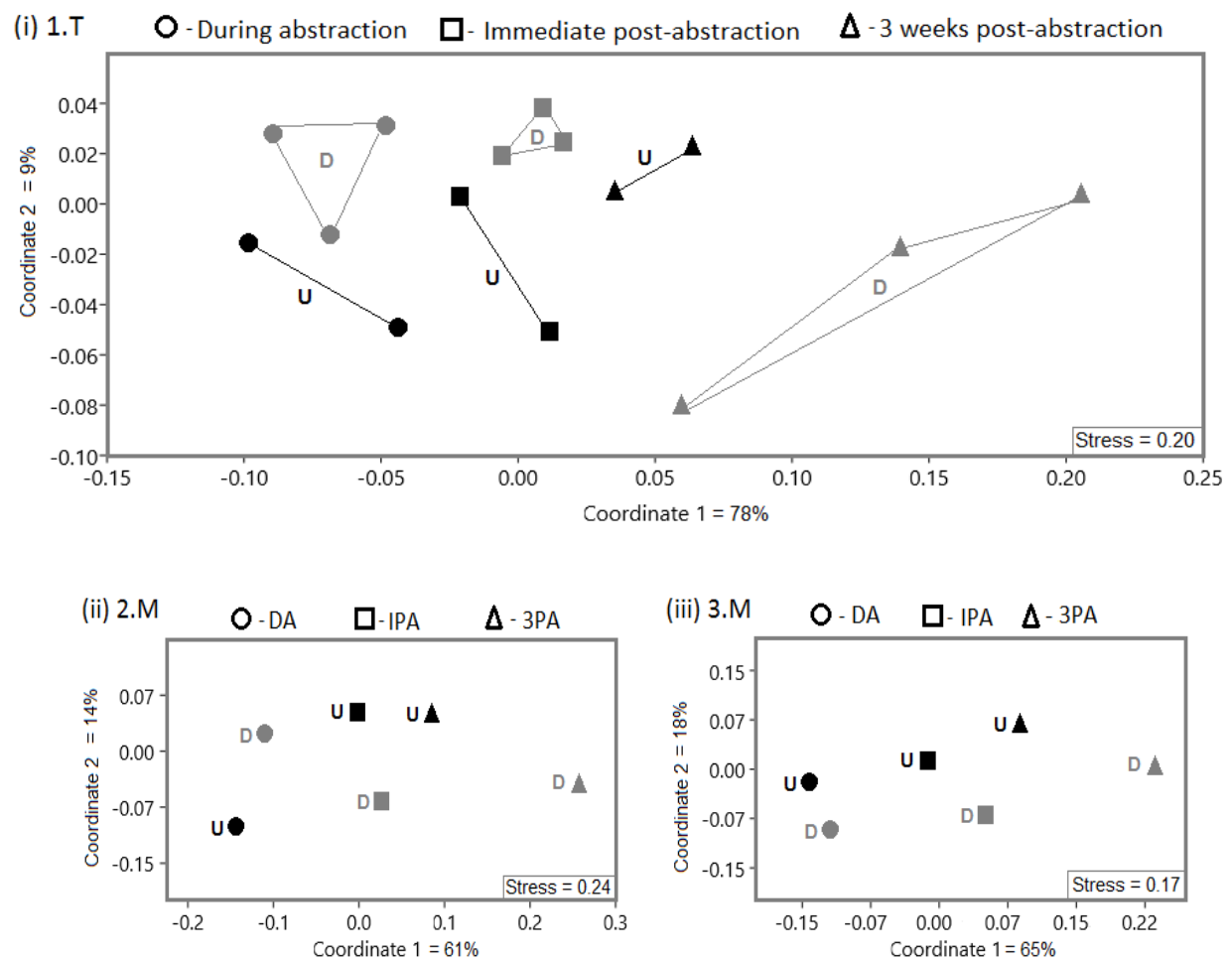


Figure 2.9. Non-metric multi-dimensional plot of mean taxa densities at the sites of water abstraction points (i) on the tributary 1.T and the mainstem, (ii) 2.M and (iii) 3.M. The centroid shape depicts the occasion of study as shown in legend on top: ○ – During abstraction or DA and seasonal low discharge period, □ – immediate post-abstraction or IPA during seasonal high discharge period, and finally △ – three weeks post abstraction or 3PA also during the seasonal high discharge period. The black centroid colour depicts that the site was upstream (U) and grey centroid colour depicts that the site was downstream (D) and are also labelled next to the centroid. The stress of each of the ordination plots is given at the right bottom and the variation captured by each coordinate is given in percent.

2.3.3.2 Functional groups based on flow preference, feeding strategies, and life history

The mean values of the Lotic Invertebrate Index for Flow Evaluation or LIFENZ, which is sensitive to flow velocity preference, did not vary greatly between the up and downstream sites of the water abstraction points, 1.T, 2.M, and 3.M. Mean LIFENZ values of all sites at all occasions were distributed across a narrow range from 7.27 to 8.19. The relative composition of benthic macro-invertebrate feeding groups - scraper, predator, filter-feeder, shredder, deposit-feeder, and algal piercer groups – did not differ between the up and downstream sites of any of the water abstraction points (Appendix Table A.1).

The SIMPER analysis helped identify taxa that contributed to 95% of the dissimilarity in the datasets of each the three water abstraction points, 1.T on the tributary, 2.M and 3.M on the mainstem. A total dissimilarity of >65% was recorded between sites and occasions at 1.T, 2M and 3.M through the SIMPER analysis (Table 2.4). The taxa were grouped based on their life history as univoltine and multivoltine as in Table 2.4 and used to plot the bar graphs in Figure 2.10 (Boothroyd, 1999; Hogg, Willmann-Huerner, & Stevens, 2002; Monson & Emberson, 2003; NIWA, 2016; Steedman & Anderson, 1985; Winterbourn & Harding, 1993; Winterbourn, 2004; Wissinger, Greig, & McIntosh, 2009).

Table 2.4. List of invertebrate taxa contributing to 95% dissimilarity in the sites of each water abstraction points 1.T, 2.M and 3.M. Life history traits groups them as Univoltine – U or multivoltine – M. X denotes that the taxon does not contribute to the 95% dissimilarity of that water abstraction point (Boothroyd, 1999; Hogg, Willmann-Huerner, & Stevens, 2002; Monson & Emberson, 2003; NIWA, 2016; Steedman & Anderson, 1985; Winterbourn & Harding, 1993; Winterbourn, 2004; Wissinger, Greig, & McIntosh, 2009).

Order	Taxon	Life history	1.T	2.T	3.T
Ephemeroptera	<i>Deleatidium</i>	M			
Trichoptera	<i>Pycnocentroides</i>	U			
	<i>Pycnocentria</i>	U			
	<i>Oecetis</i>	U		X	X
	<i>Olinga</i>	U		X	X
	<i>Aoteapsyche</i>	U			
	Ecnomidae	U	X		
Diptera	<i>Austrosimulium</i>	M			
	Tanytarsini	M	X	X	
	<i>Eukiefferiella</i>	M			
Coleoptera	<i>Hydora</i>	U			
Megaloptera	<i>Archicauliodes</i>	U	X		
Oligochaeta	Oligochaeta	M			

The univoltine taxa densities downstream of 1.T water abstraction point on the tributary were less than half the density of multivoltine taxa at DA (Figure 2.10). A similar, less pronounced pattern at DA occasion was seen at 2.M and 3.M downstream sites. At downstream sites of 2.M and 3.M, the pattern of decreasing univoltine taxa densities became more accentuated in the third occasion, 3PA, than at 1.T downstream sites at 3PA. The densities at both upstream and downstream sites declined with ascending season and study occasion (as also seen in Figure 2.7), from DA, IPA to 3PA. The decrease in multivoltine taxa densities downstream of water abstraction point 1.T was more severe than at mainstem downstream sites (Figure 2.10).

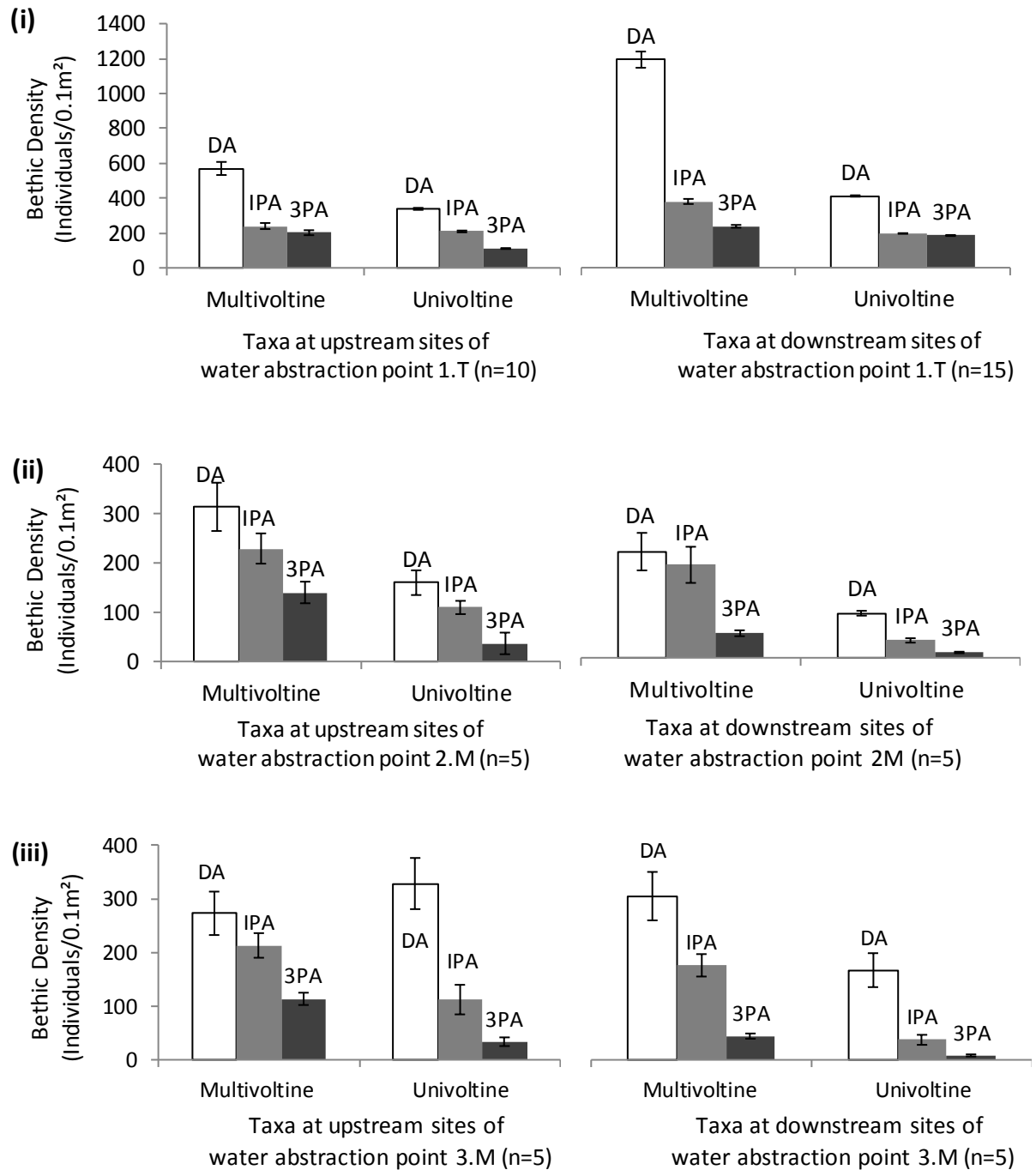


Figure 2.10. Total mean with standard error bars densities of 10 benthic macro-invertebrate taxa that contributed to 95% dissimilarity in SIMPER analysis have been grouped based on their life histories as univoltine or multivoltine. The bar plots are of the upstream and downstream sites (in legend) of the three water abstraction points (i) 1.T, (ii) 2.M, and (iii) 3.M at the three occasions of study: DA – during abstraction period and seasonal low discharge period, IPA and 3PA – immediate and 3 weeks post abstraction during seasonal high discharge periods depicted by colour (see Table 2.4)

2.4. Discussion

2.4.1. Response of benthic invertebrate communities

The first aim of this chapter was to quantify the response of benthic invertebrate densities to summer season-long water abstraction that caused >50% reduction in the magnitude of channel discharge at three water abstraction points, and secondly, to compare this response along the length of the Manuherikia River (Figure 2.1). The during abstraction (DA) sampling date was about four months after the start of the irrigation season and coincided with a seasonal low discharge period. On the DA occasion, the macroinvertebrate densities downstream of the water abstraction point on the tributary 1.T had responded by increasing higher in density than the densities upstream. In contrast, the macroinvertebrate densities downstream of the mainstem water abstraction points, 2.M and 3.M were generally lower than the densities upstream. Hence, the hypothesis that the densities of benthic macroinvertebrates downstream of water abstraction would decrease held for mainstem sites but not for the tributary site. It was expected that there would be a longitudinal pattern of reduced response of benthic macroinvertebrates to water abstraction along the Manuherikia River, but the results indicated that this was not the case.

Other studies of streams in New Zealand after one month of discharge reduction have reported results similar to the results in the tributary of this study (Dewson & Death, 2007; Dewson, Death, & James, 2003; Dewson, James, & Death, 2007b). However, the results of this study suggest that along the river, in the mainstem, benthic invertebrates not only respond to water abstraction by concentrating in the reduced river channel but have lower densities downstream than densities upstream of water abstraction. The pattern of mainstem sites in this study is similar to the reduction in densities reported after two months of experimental 25% reduction in magnitude of river discharge reported by James & Suren

(2009). McIntosh, Benbow, & Burky (2002) also reported a reduction in densities during the abstraction of >90% natural discharge for four months in a Hawaii stream.

The other part of the aim of this was to quantify the response of benthic invertebrate community structure and compare it along the river. The overall benthic invertebrate community structure changed slightly due to water abstraction at DA. This difference is attributed to differences in univoltine and multivoltine taxa densities. At downstream sites of 1.T, multivoltine taxa densities were more than twice the density of univoltine taxa. This pattern was similar along the river but less pronounced at the downstream sites of 2.M and 3.M water abstraction points at the mainstem. Water abstraction changes benthic community structure downstream of abstraction as the univoltine taxa are not able to resist decrease in densities as well as the multivoltine taxa. So, the results support the hypothesis that the densities of taxa that reproduce once a year (univoltine) would be lower than densities of taxa that reproduce multiple times a year (multivoltine) contributing to the change in community structure for all the abstraction points studied along the river. The study of water abstraction in the Adda River, Italy by Salmaso, et al. (2018) has reported similar results, that 3 months of low discharge period reduced the univoltine invertebrate densities as compared to multivoltine densities.

The invertebrate community structure based on the assessment of traits related to functional feeding groups or specific flow preferences of different taxa did not change due to water abstraction at any of the three water abstraction points along the Manuherikia River. The hypothesis that community structure as assessed by invertebrate flow velocity preferences and feeding strategies would change in response to water abstraction was therefore not supported in this study. Feld, de Bello, & Dolédec (2014) and Walters (2011) also did not find any consistent functional trait responses to the reduced flow in 65 streams in Germany, Netherlands and Poland, and in forest streams of Connecticut, USA, respectively.

Adaptability to highly variable flow regimes is a characteristic of invertebrates of the lotic systems (Scarsbrook, 2002; Winterbourn, 1997); which may be responsible for the resistance of functional community structure to water abstraction with respect to flow preference and feeding strategies, observed in my study.

2.4.2. Recovery of benthic invertebrate communities

The second aim of this chapter was to quantify the recovery of benthic invertebrate densities from the summer water abstractions that causes >50% reduction in magnitude of channel discharge at three water abstraction points, and to compare the recovery along the length of the Manuherikia River. The recovery of benthic invertebrates was studied in the last two occasions of study after abstraction was ceased and winter high discharge period had resumed – immediate post-abstraction (IPA) and three weeks post-abstraction (3PA). The benthic macroinvertebrate densities of the downstream sites of the three water abstraction points studied did not fully recover to the upstream densities within the time period of this study. The difference in the benthic invertebrate densities between upstream and downstream sites of the mainstem water abstraction points, 2.M and 3.M, had not recovered at IPA, and had become greater by 3PA. The lack of recovery at downstream sites of the tributary water abstraction point 1.T also became more apparent at 3PA.

Abstraction in the Manuherikia Catchment ceases with the onset of winter as seasonal high discharge returns. The continuous increase in discharge that occurred as the study progressed resulted in an increase in the area of wetted channel, with the greatest increase in area occurring downstream of the abstraction points into which benthic invertebrates could disperse. Given the relatively short duration of this study, the primary sources of colonists for this wetted habitat would either come from the area of channel that remained wet through the irrigation season, or from further upstream (Brittain & Eikelan, 1988; Mackay, 1992). The overall seasonal drop in the benthic invertebrate density likely reflects the increases in wetted

area across all sites, with the marked decrease in density downstream of takes reflecting the greater area of formerly dry habitat now available for colonisation. These results are similar to those reported by Miller, Wooster, & Li (2007) in a USA River, where the recovery of densities from two months of reduction in discharge and >90% reduction in discharge had not occurred one month after the return of seasonal high discharge period.

The other part of the second aim of this chapter is to quantify the recovery of community structure from summer season long water abstraction. The community structure also did not recover within the time period of this study. The NMDS plots showed that the overall community structures differed the most during the third occasion, 3PA. The densities of the univoltine taxa *Pycnocentroides*, *Pycnocentria*, *Aoteapsyche*, *Oecetis*, *Olinga*, *Ecnomidae*, *Archicauliodes*, and *Hydora* were less resilient than the densities of the multivoltine taxa *Deleatidium*, *Eukiefferiella*, *Austrosimulium*, and *Tanytarsini* against the season long water abstraction in the Manuherikia River. The increasing discharge accentuates the decrease in densities further from which the community structure is unable to recover to upstream community structure at least till three weeks post abstraction in June. These results are similar to those reported by Miller, Wooster, & Li (2007) in a USA River - the recovery of community structure from >90% reduction in discharge for two months did not occur at least till one month after the return of seasonal high discharge period- but, the change in community structure they reported was in feeding groups unlike life history groups in this study. It was noted that along the river the resilience of community structure declined. The downstream sites of 1.T showed a lower difference in univoltine/multivoltine taxa densities than downstream sites of 2.M and 3.M on the 3PA sampling date.

Furthermore, New Zealand literature on the population and life histories of the univoltine taxa, *Pycnocentroides*, *Pycnocentria*, *Oecetis*, *Olinga*, *Ecnomidae*, and *Hydora* suggest that the adults emerge in the summer and lay eggs in autumn (Hogg, Willmann-Huerner, &

Stevens, 2002; Monson & Emberson, 2003; Wissinger, Greig, & McIntosh, 2009). Therefore, the univoltine invertebrate adults must have laid eggs in the autumn of 2019, which coincided with the IPA occasion of the study, but the results showed that their densities had not recovered on 3PA. The next reproduction period of these taxa would have been after the next irrigation season, suggesting that recovery from water abstraction of the benthic invertebrate densities would not be contributed to by the univoltine taxa and that these univoltine taxa have very low resilience to the impacts of the water abstraction during summer irrigation period (Walters, 2011).

2.5. Conclusion

The findings of this study suggest that the benthic invertebrate densities and community structure are affected by four-month long water abstraction that causes a reduction in discharge of >50%, with greater changes in the more impacted downstream reaches of the Manuherikia River than in the relatively pristine Dunstan Creek tributary. The recovery of densities and community structure had not occurred three weeks post water abstraction ceased and seasonal high discharge periods had returned in June. The univoltine taxa appear to be weakly resilient against the impact of water abstraction.

Chapter 3. Effect of the season-long water abstraction on the re-colonisation of rewetted channel edges and the recovery of benthic macroinvertebrates at the Dunstan Creek, Central Otago, New Zealand.

3.1. Introduction

3.1.1. Re-colonisation of rewetted channel edges

Benthic invertebrates can re-colonise rewetted edges of permanent rivers as the high discharge periods return following the seasonal low discharge periods (Hose, Walter, & Brooks, 2007; Poff, et al., 1997; Storey & Quinn, 2007). Drying, as part of the natural flow regime of a permanent river, occurs as the river channel recedes laterally towards the base discharge in the channel during the low discharge periods - increasing the area of the dry channel (Gasim, et al., 2013; Poff, et al., 1997). Invertebrates on the drying channel edges either move into the permanent river channel or die out as the river recedes laterally (Gasim, et al., 2013; Lake, 2003; Poff, et al., 1997). Then, when the higher discharge periods return, the dry areas are rewetted and can be re-colonised (Gasim, et al., 2013; Poff, et al., 1997). Benthic aquatic invertebrates are both resistant and resilient to seasonal variation in the channel width (Hershkovitz & Gasith, 2013), and the re-colonised river channel edges often have higher taxonomic richness than the permanently wetted channel (Hose, Walter, & Brooks, 2007; Principe & Corigliano, 2006).

The movement of benthic invertebrates drives the patterns of re-colonisation at the rewetted edges of permanent rivers (Mackay, 1992; Shearer, Stark, Hayes, & Young, 2003). The movement of benthic invertebrates within a river channel occurs as they move from the benthos, and drift laterally and along the river - for reasons such as foraging, defence against predators, dispersal and accidental dislodgement (Brittain & Eikelan, 1988; Mackay, 1992).

Re-colonisation also occurs due to the crawling movement of benthic invertebrates and the eggs laid by adults at the edges (Lancaster, Downes, & Dwyer, 2020). The location and rate of deposition of the drifting and crawling invertebrates, and the laying of eggs by the adults depends on their habitat preferences – typically related to the availability of food, substrate type and flow velocity (Boyero & Bosch, 2004; Jowett, et al., 1991; Mackay, 1992; Principe & Corigliano, 2006). For instance, predatory invertebrates could be expected to be the last to re-colonise as they require prey to persist (Mackay, 1992). Simulated drought studies show that invertebrate drift is responsible for 41-80% of the total abundance of benthic invertebrates in newly re-colonised river habitat (Mackay, 1992; Williams & Hynes, 1976). Other drought and spate studies of rivers suggest that, as long as there was a permanent lentic refuge, invertebrate re-colonisation of the rewetted channel area may take 6 to 30 days to recover to densities and taxa richness seen in the permanently wet river habitat (Fowler, 2004; Matthaei, et al., 1996; Vorste, Malard, & Datry, 2016). However, our knowledge of the patterns of invertebrate re-colonisation at the rewetted edge habitat of permanent rivers is mostly based on studies of re-colonisation following spate and drought disturbances rather than anthropogenic impacts, such as water abstraction (Chadd, et al., 2017; Death, 2011; Lake, 2003; Mackay, 1992; Sagar, 1983).

3.1.2. Water abstraction may affect re-colonisation of rewetted channel edges

Impacts of river water abstraction on the physical habitat would affect the invertebrate re-colonisation of the rewetted channel edges (Poff, et al., 1997; Ríos-Touma, Prat, & Encalada, 2012; Storey & Quinn, 2007). Water abstraction can increase the area of dry channel edges that would otherwise be dewatered naturally during the seasonal low discharge period. This results in the loss of lateral connectivity to the riparian zone, which correlates with the patterns of invertebrate assemblages (Chadd, et al., 2017; Lake, 2003; Shilla & Shilla, 2012). When seasonal higher discharge periods return following the end of water abstraction season,

more rewetted area for re-colonisation is available downstream of the water abstraction than upstream (Hershkovitz & Gasith, 2013). In the previous chapter, there was greater increase in discharge downstream of the water abstraction points than upstream during the seasonal high discharge period, as seen in the last two occasions of the study, post-abstraction. Furthermore, within the study period, the full recovery of downstream benthic invertebrate communities had not occurred relative to upstream of the three water abstraction points in the Manuherikia River. Re-colonisation of the recently wetted channel edges- that occurs during the high discharge periods coinciding with post-abstraction occasions- will depend on the benthic invertebrate densities impacted by the water abstraction in the preceding irrigation season, given that they provide the source populations for re-colonisation (Mackay, 1992; Shearer, Stark, Hayes, & Young, 2003). There is a dearth of studies on re-colonisation of rewetted permanent channel edges by benthic macroinvertebrates after season long periods of water abstraction, with no studies in New Zealand or elsewhere.

3.1.3. Chapter objectives

The aim of this chapter is to quantify the benthic invertebrate re-colonisation of the rewetted edge habitat following the cessation of water abstraction in the Manuherikia River. In the previous chapter, the recovery of benthic macroinvertebrate densities and community structure with respect to the life history traits had not occurred three weeks after cessation of water abstraction in the permanently wetted channel. Hence, it is expected that the invertebrate densities and community structure along the re-colonised rewetted channel edges downstream of water abstraction would differ from upstream on the two occasions of high seasonal discharge - immediate and three weeks post-abstraction (IPA and 3PA). It is hypothesised that (i) densities of re-colonised rewetted channel edges downstream of water abstraction at IPA and 3PA occasions would be lower than upstream, and (ii) the densities of univoltine taxa would be lower downstream contributing to differences in community

structure. The findings of this study will contribute to the understanding of macroinvertebrate community recovery after water abstraction has ceased and seasonal high discharge resumes, providing information on community recovery on a fine spatial scale. It will address a significant gap in the knowledge of the recovery of benthic invertebrates from the impacts of water abstraction in New Zealand.

3.2. Methods

3.2.1. Study design

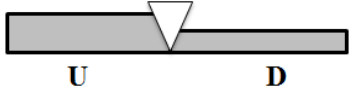
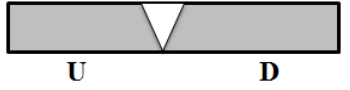
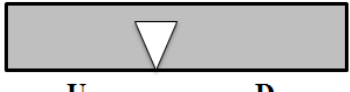
This investigation of the re-colonisation of recently wetted substrates by benthic macroinvertebrates after the seasonal cessation of water abstraction, builds on the work assessing during and after impacts of water abstraction described in Chapter 2. The work described in this chapter uses the same sites and sampling methodologies for benthic macroinvertebrates and habitat measurements. Key differences between this and the preceding work are summarised in the following paragraphs.

Riffle Surber samples from edges were collected on the two seasonal high discharge occasions - immediate post-abstraction (IPA) and three weeks post-abstraction (3PA) (Table 3.1). . The same invertebrate data from centreline sites of tributary water abstraction points 1.T used in the previous chapter in DA, IPA, and 3PA occasions was used to compare with data collected from the edge sampling (Figure 3.1) (see Section 2.2.1).

Only upstream and downstream sites of the Dunstan Creek tributary water abstraction point, 1.T, and not of the mainstem 2.M and 3.M were used for this part of the study, given (i) the smaller size of this stream allowed for safe sampling of the centreline of the stream during high seasonal discharges in the IPA, and 3PA occasions and, (ii) the absence of disturbance

from a dam regulating river flow and other anthropogenic impacts that could confound interpretation of responses in the invertebrate assemblage.

Table 3.1. Overview of the occasions of sampling. Grey areas show the relative magnitude of discharge. White triangles show the position of the same water abstraction point at different time points of sampling. U indicates upstream and D indicates downstream of the water abstraction point.

Sampling occasion	Month	Season	Seasonal Discharge	Relative magnitude of discharge at the same water abstraction point
DA -During abstraction	March	Summer	Low	
IPA -Immediate post abstraction	May	Winter	High	
3PA -Three week post abstraction	June	Winter	High	

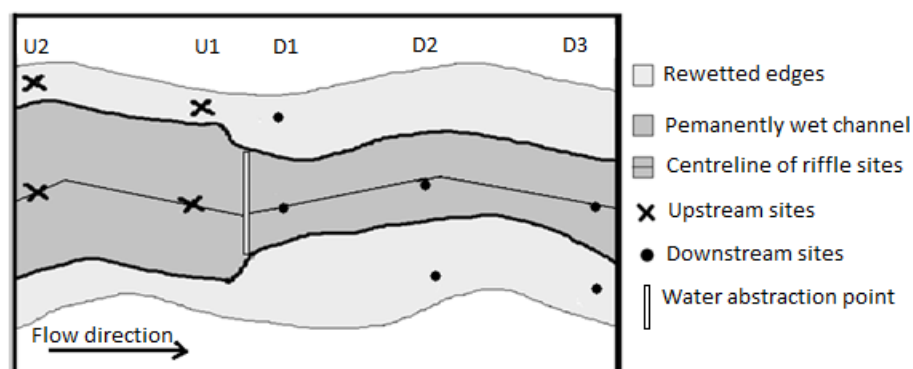


Figure 3.1. Study design of tributary water abstraction point, 1.T. The rewetted edges and centreline of the stream were used to collect Surber samples from upstream sites, U1 and U2 (crosses), and downstream sites, D1, D2 and D3 (dots), of the water abstraction point 1.T (vertical white bar). In DA, low discharge periods are a result of season and water abstraction at downstream sites. The rewetted edges are a result of returning seasonal high discharge period and cessation of water abstraction and were sampled in the Immediate and three week post-abstraction sampling dates.

Five riffles within the 300m reach along each edge site of the water abstraction point 1.T, were Surber sampled for one minute with physical parameters - depth and velocity at the point of sampling measured (see section 2.2.3). The lateral length of the rewetted edge, used to collect Surber samples in IPA and 3PA, was calculated as half of the difference between wet widths measured in DA and IPA. In fact, this edge was clearly demarcated by blooms of the pest algae *Didymo*, which had not colonised the rewetted edges at the time of sampling. The Surber samples were processed, identified and counted using the methodology described in Chapter 2 (see section 2.2.4).

3.2.2. Data analysis

To compare benthic macroinvertebrates upstream (U) and downstream (D) of the water abstraction point, 1.T along the centreline and edges, total density of invertebrates was calculated (mean number of individuals per 0.1m² area of the Surber sample). The significance of differences due to water abstraction and between centre and edge samples was tested using a Kruskal-Wallis test. The significance level alpha was changed to 0.10 as it helps to avoid type II errors (Keough & Quinn, 2002). Where the Kruskal-Wallis test was significant ($P\text{-value} \leq 0.10$), a post hoc Dunn's test was used. Taxa number and NMDS (Non-metric Multi-Dimensional Scaling) of total taxa densities using a Bray-Curtis distance were used to summarise and visualize the overall benthic macroinvertebrate community structure. The significance of distances between centroids of NMDS plots was tested using ANOSIM (Analysis of Similarity) and PERMANOVA (Permutational Analysis of Variance). To locate and explore the dissimilarities in the dataset, SIMPER analysis (Similarity Percentage) was used; and the first ten taxa contributing to the dissimilarity between up/downstream sites of the edge/centreline, and between occasions of the study were used to compare densities of univoltine and multivoltine taxa.

3.3. Results

3.3.1. Habitat parameters

Within edge and centreline sites, the depth and velocity of flow of respective upstream (U1 and U2) and downstream sites (D1, D2 and D3) of 1.T were not significantly different from each other. All upstream and downstream edge sites had significantly lower depth and velocity of flow at the point of Surber sampling in IPA and 3PA occasions than all upstream and downstream centreline sites of Dunstan Creek. The PCA plot of physico-chemical parameters shows that the water quality of upstream and downstream sites of 1.T varied strongly due to season but water abstraction had limited impact (Appendix Figure A.2).

3.3.2. Macroinvertebrate density

Over the study period, from during abstraction (DA) to immediately post-abstraction (IPA), followed by the three weeks post-abstraction (3PA), the mean benthic macroinvertebrate densities declined (Figure 3.2). On the DA occasion, the centreline site immediately downstream of the abstraction point, i.e. D1 of 1.T had significantly higher density than the other upstream and downstream centreline sites (Table 3.2 and 3.3); on the IPA occasion, the decrease in benthic density of the downstream centreline site D1 from the DA occasion was the highest among all centreline sites. On the IPA occasion, the density of edge site D1 was significantly lower than the other upstream and downstream edge sites, while the other downstream edge sites had similar densities to upstream sites (Figure 3.2(ii), Table 3.3, 3.4). On the 3PA occasion, the edge downstream sites had similar densities to the edge upstream sites (Table 3.2), but the centreline downstream site D2 had lower density than centreline upstream sites.

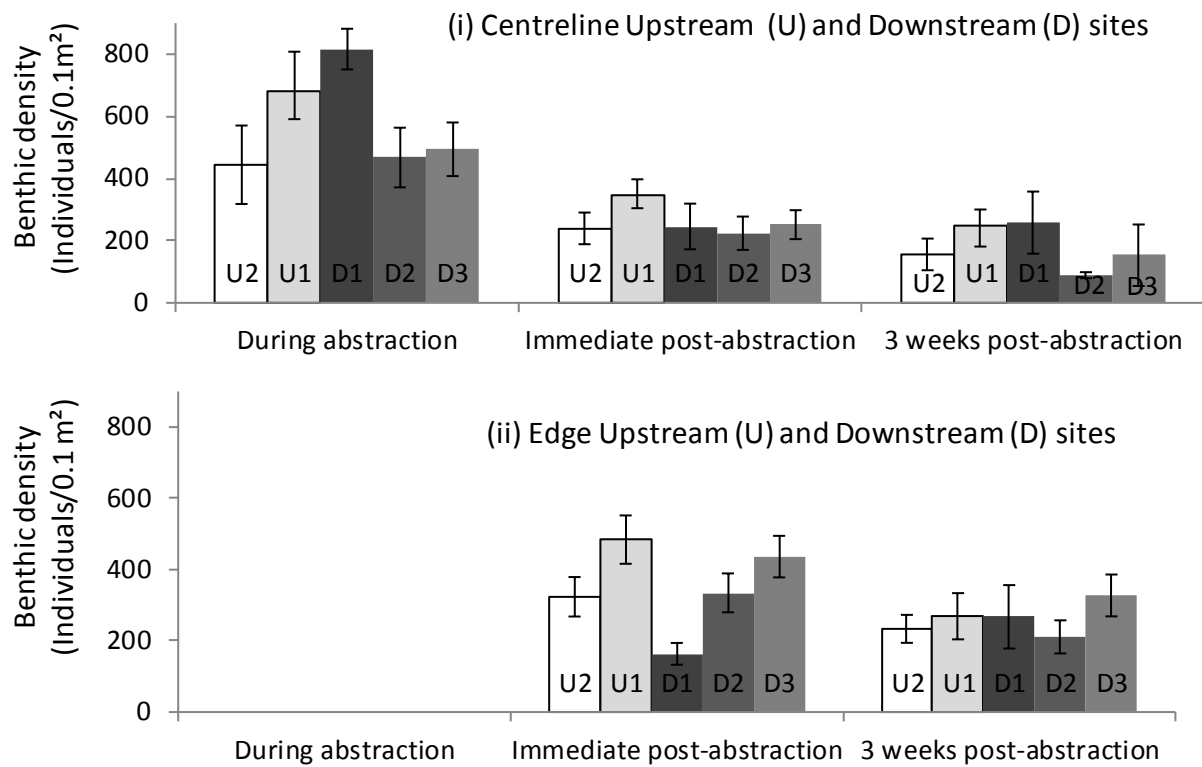


Figure 3.2. Mean benthic invertebrate density with error bars (N = 5) at upstream and downstream sites of respective (i) centreline and (ii) edge habitat at the water abstraction point 1.T on the tributary at three occasions of study, during abstraction period and seasonal low discharge period, immediate and three weeks post abstraction period which coincide with seasonal high discharge periods. Tributary abstraction point had five sampling sites, depicted by colour and labelled; U2-most upstream from 1.T, U1- upstream site closest to 1.T, D1- first downstream site closest to 1.T followed by D2 and D3 further downstream

Table 3.2. Kruskal-Wallis test results to test the difference between the upstream and downstream mean benthic macroinvertebrate densities (individuals per 0.1m²) at edge and centreline habitats of 1.T water abstraction point sites at the three occasions - during abstraction period and seasonal low discharge period - DA, immediate and three weeks post abstraction period which coincide with seasonal high discharge periods - IPA and 3PA. Where significant differences were found (in bold), the post hoc test is summarised in Tables 3.3 and 3.4.

Study occasion	Centreline			Edge		
	H	P	η^2	H	P	η^2
During abstraction	9.47	0.05	0.27	-	-	-
Immediate post-abstraction	4.58	0.33	0.03	11.67	0.01	0.38
3 weeks post-abstraction	7.84	0.10	0.19	1.83	0.76	-0.10

Table 3.3. Result of Dunn’s post hoc test to pinpoint the total densities at sites of tributary water abstraction point 1.T which were significantly different from others at the DA occasion below the diagonal and at the 3PA occasion above the diagonal in italics.

Centrelines Sites	U2	U1	D1	D2	D3
U2		<i>0.34</i>	<i>0.67</i>	<i>0.30</i>	<i>0.16</i>
U1	0.13		<i>0.61</i>	0.05	0.02
D1	0.02	0.37		<i>0.14</i>	<i>0.06</i>
D2	0.97	0.14	0.02		<i>0.70</i>
D3	0.90	0.17	0.02	0.93	

Table 3.4. Dunn’s post-hoc P-values for significant invertebrate density differences in edge sites upstream and downstream of water in May, during the “after abstraction ceased” occasion. D1 had significantly lower (P-values in bold) density than all other edge sites.

Edge sites	U2	U1	D2	D3
D1	0.07	<0.05	0.06	<0.05

3.3.3. Macroinvertebrate community structure

3.3.3.1. Taxa number and overall community structure

Forty taxa were identified from the Dunstan Creek tributary over the course of the study. The taxa number varied little between upstream and downstream sites of the water abstraction point and at edge and centrelines habitat on the three sampled dates - during abstraction (DA) and seasonal low discharge period followed by immediate and three weeks post abstraction (IPA and 3PA) (Figure 3.3).

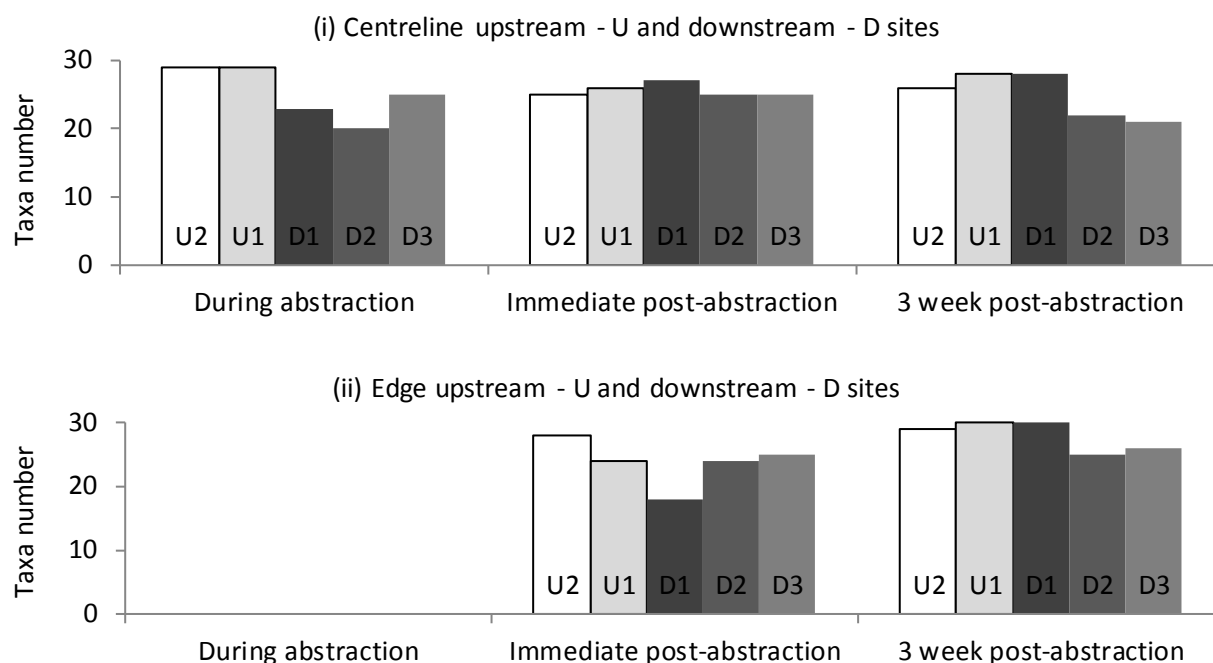


Figure 3.3. The bar graph depicts number of the taxa identified at upstream (U) and downstream (D) sites of the respective **(i)** centreline and **(ii)** edge habitat of the water abstraction point 1.T on the tributary at three occasions - during abstraction and seasonal low discharge period, immediate and three weeks post abstraction and seasonal high discharge periods.

The NMDS analysis of community structure showed that the small difference between the community structure of centreline sites upstream and downstream of the water abstraction point increased slightly with each sampling date (Figure 3.4). However, there was strong overlap between the edge upstream and downstream sites on the three weeks post-abstraction occasion. The distances between the centroids (sites) of the NMDS plot were of statistical significance as seen from the ANOSIM ($R = 0.3$, $P\text{-value} < 0.05$) and PERMANOVA results ($F = 2.92$, $P\text{-value} < 0.05$).

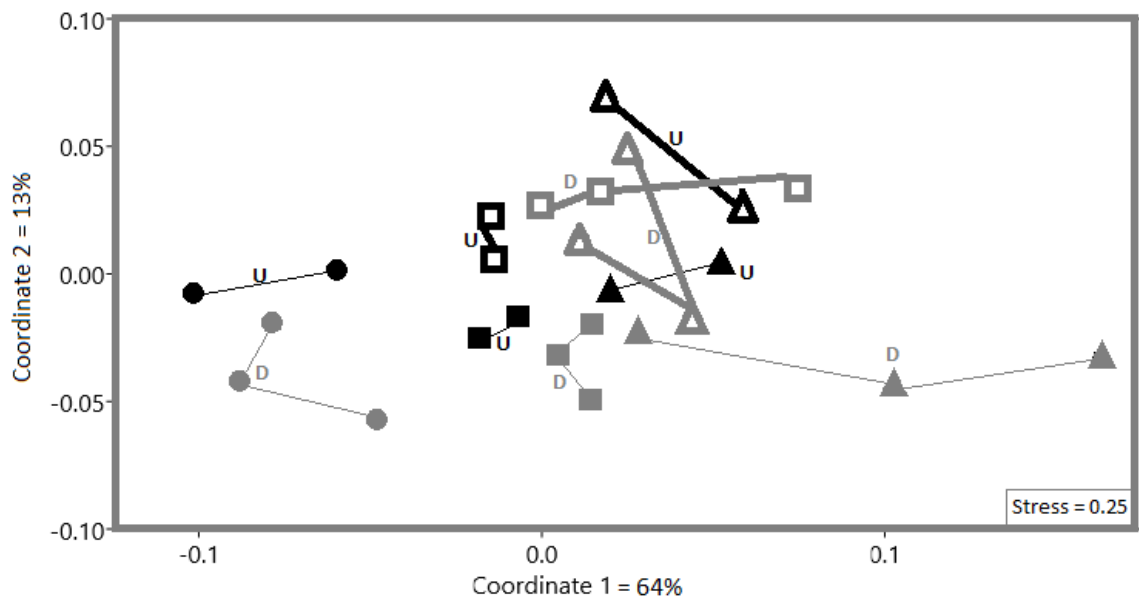


Figure 3.4. NMDS plot shows variation upstream (U - black) and downstream (D - grey) sites of the respective edge (unfilled shapes,) and centreline habitat (filled shapes) of the water abstraction point, 1.T on the tributary at three occasions depicted by shape: circle - During abstraction, square - immediate post-abstraction, triangle- three weeks post-abstraction.

3.3.3.2. Functional groups based on life history

A total dissimilarity of 48.96% was recorded between the abstraction upstream and downstream sites of centreline and edge habitats over the study period through the SIMPER analysis. The SIMPER analysis helped identify taxa that contributed to 95% dissimilarity in the dataset (Table 3.4), which were grouped as univoltine or multivoltine (Boothroyd, 1999; Hogg, Willmann-Huerner, & Stevens, 2002; Monson & Emberson, 2003; NIWA, 2016; Steedman & Anderson, 1985; Winterbourn & Harding, 1993; Winterbourn, 2004; Wissinger, Greig, & McIntosh, 2009)

Table 3.5. List of 10 invertebrate taxa contributing to 95% dissimilarity in upstream and downstream sites at centreline and edge habitat of the water abstraction point on the tributary of the Manuherikia River at the three occasions of the study. They have been grouped as multivoltine and univoltine (Boothroyd, 1999; NIWA, 2016; Steedman & Anderson, 1985; Winterbourn & Harding, 1993; Winterbourn, 2004).

Order	Taxon	Type of life history
Ephemeroptera	<i>Deleatidium</i>	Multivoltine
Trichoptera	<i>Pycnocentria</i>	Univoltine
	<i>Oecetis</i>	Univoltine
	<i>Olinga</i>	Univoltine
	<i>Aoteapsyche</i>	Univoltine
	<i>Austrosimulium</i>	Multivoltine
Diptera	<i>Eukiefferiella</i>	Multivoltine
	<i>Hydora</i>	Univoltine
Coleoptera	<i>Zelandobius</i>	Univoltine
Plecoptera	<i>Oligochaeta</i>	Multivoltine

The benthic invertebrate densities of multivoltine taxa at the centreline downstream sites of the water abstraction point on the tributary (1.T) were higher than that of univoltine taxa on all occasions (Figure 3.6). The same pattern was observed at edge sites. Over time, on each occasion, benthic macroinvertebrate densities declined but on the three weeks post-abstraction (3PA) occasion, the density of multivoltine taxa along the edge upstream and downstream sites were higher than that of the previous occasion (IPA). However, by the 3PA occasion, the density of the univoltine taxa upstream and downstream of the edge habitat declined, relative to IPA.

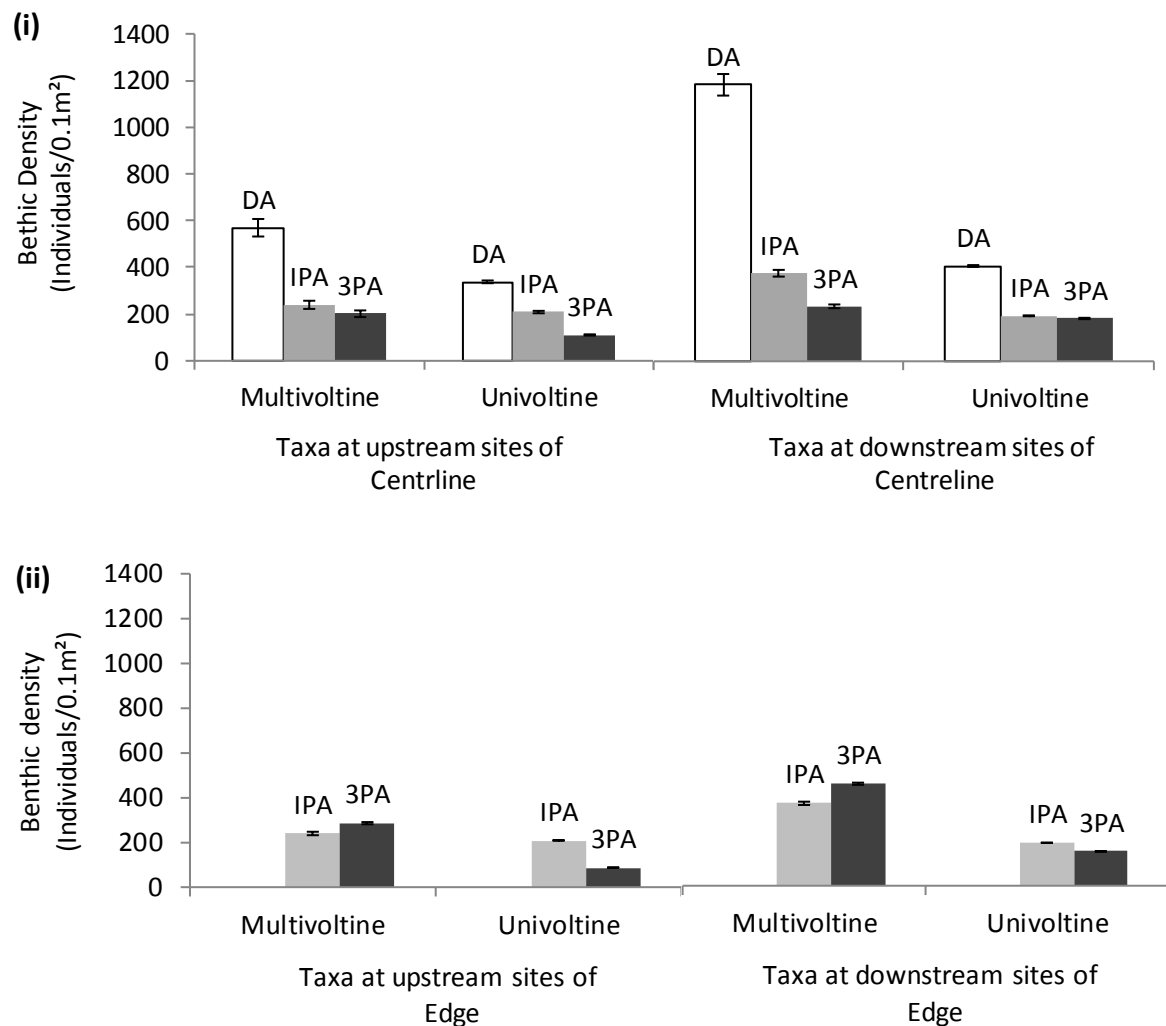


Figure 3.5. Total mean densities of 10 benthic macro-invertebrate taxa (contributing to 95% dissimilarity) grouped as univoltine or multivoltine based on their life histories at upstream and downstream sites of the water abstraction point at the respective **(i)** centreline and **(ii)** edges of the tributary at the three occasions of study: during abstraction (DA) in white bars, immediate post-abstraction (IPA) in light grey bars and three weeks post-abstraction (3PA) in dark grey bars. The occasions are labelled on the bars.

3.4. Discussion

The aim of this chapter was to quantify the effect of water abstraction on the re-colonisation of the rewetted channel edges of the Dunstan Creek tributary to supplement the information provided by the previous chapter on the recovery of benthic invertebrates in the permanent Manuherikia River. It was found that benthic invertebrate re-colonisation of the recently wetted edges lagged in the sites downstream of water abstraction when compared to the upstream sites at the immediate post-abstraction occasion (IPA) during the seasonal high discharge period. On the same occasion, the downstream centreline densities saw a significant reduction from the previous occasion, during abstraction (DA). These findings suggest that water abstraction slows the rates of re-colonisation at the edges, by affecting the centreline benthic densities during abstraction, which are a source of the re-colonising invertebrate populations (Mackay, 1992; Shearer, Stark, Hayes, & Young, 2003) and therefore, slowing the rate of recovery of downstream benthic invertebrates after abstraction ceases and seasonal high discharge periods return. Consequently, the results of the study support the hypothesis that the invertebrate densities of re-colonised rewetted channel edges downstream of water abstraction at IPA occasion would be lower than the densities of rewetted edges upstream.

On the last sampling occasion, three weeks after irrigation had ceased, the benthic invertebrate densities at downstream edge sites were similar to upstream edge sites of the water abstraction point, while densities at the downstream centreline sites were not all similar to the upstream centreline sites of the permanently wetted channel. This pattern may be explained by the habitat preference of re-colonising benthic invertebrates. The lower velocities and absence of didymo along the recently wetted edge habitat may create a more favourable habitat into which many benthic macroinvertebrates may prefer to settle (Boyero & Bosch, 2004; Jowett, et al., 1991; Mackay, 1992; Principe & Corigliano, 2006). In

addition, these results do not support the hypothesis that the density of re-colonised rewetted channel edges downstream of water abstraction would be lower than upstream 3 weeks after normal discharge resumed.

Three weeks after water abstraction ceased (3PA), benthic invertebrate densities of all sites of the centreline and edge habitats declined compared to the immediate post-abstraction occasion (IPA), except the densities of multivoltine taxa at the U and D edge sites at 3PA, which were higher than those on the IPA occasion. The univoltine taxa densities at edge habitat follow the pattern of the centreline site densities - they were lower on the 3PA occasion, as compared to the IPA occasion. Thus, the results support the hypothesis that the densities of univoltine taxa would be lower downstream, contributing to differences in the community structure. These findings suggest that multivoltine taxa drive the recovery of densities downstream of water abstraction and are more resilient than univoltine taxa to the impacts of water abstraction. This is as expected, given that the multivoltine taxa reproduce asynchronously throughout the year (Winterbourn & Harding, 1993; Winterbourn, 2004) while the univoltine taxa in New Zealand typically reproduce in the autumn months of April-May (Hogg, Willmann-Huerner, & Stevens, 2002; Monson & Emberson, 2003; Wissinger, Greig, & McIntosh, 2009), coinciding with the IPA sampling date. In addition, the findings of previous chapter also showed that univoltine densities declined in the permanently wetted channel, which is ultimately the invertebrate source of edge re-colonisation.

3.5. Conclusion

When seasonal high discharge periods gradually returned, the benthic invertebrate re-colonisation of recently wetted channel edges was slowed down by water abstraction in the previous seasonal low discharge period by affecting the benthic densities in the permanent channel during abstraction. This in turn, caused a delay in recovery of centreline benthic

densities downstream of water abstraction. The invertebrate univoltine taxa appear to be less resilient to the impacts of water abstraction than the multivoltine taxa. Multivoltine taxa therefore, drive the recovery of benthic invertebrate densities following the period of water abstraction.

Chapter 4. General discussion

4.1. Introduction

Understanding the impacts of water abstraction on rivers will advance the development of improved approaches for the management of rivers as a resource (Anderson, et al., 2019). New Zealand depends on the ecological values of rivers to derive economic gains from water abstraction for irrigation (New Zealand Government, 2020; Stats NZ, 2017; Trading Economics, 2020). The majority of the studies concerning the impacts of seasonal water abstraction on the permanent rivers of New Zealand, and elsewhere, focus on the impacts on fauna during abstraction (Dewson, James, & Death, 2007a). The response during abstraction, as well as recovery from the impacts after water abstraction had ceased, was explored in this study. Chapter 2 focused on the invertebrate response and recovery in the permanently wet channel along the Manuherikia River of New Zealand. Coinciding with the cessation of the seasonal water abstraction is the resumption of seasonal high discharge period, which creates opportunities for the re-colonisation of re-wetted channel edges, which was studied in detail in Chapter 3 to complement the findings of Chapter 2.

4.2. Review of findings

4.2.1. Response and recovery

As seen in Chapter 2, benthic invertebrate densities and community structure are affected by the prolonged period (four months) of summer water abstraction that causes a >50% reduction in the magnitude of discharge. Four-month long water abstraction in Dunstan Creek concentrated benthic invertebrates into the reduced permanent wetted channel. Studies of one-month long water abstraction in the streams of New Zealand display results similar to the

results of the water abstraction in tributary Dunstan Creek of this study (Dewson & Death, 2007; Dewson, Death, & James, 2003; Dewson, James, & Death, 2007b). Further downstream, in the mainstem of the Manuherikia River, water abstraction was associated with a reduction in benthic macroinvertebrate densities. The pattern of the response to water abstraction in the mainstem in this study is similar to the reduction in densities reported in response to two months of experimental 25% reduction in the magnitude of a New Zealand river's discharge, as reported by James & Suren (2009), and to four months of >90% abstraction of the natural discharge of a Hawaiian stream, as reported by McIntosh, Benbow, & Burky (2002). The recovery of densities and community structure had not occurred three weeks after water abstraction ceased and seasonal high discharge periods had returned in June. Miller, Wooster, & Li (2007) also reported that the recovery of densities and community structure had not occurred one month after resumption of the seasonal natural flow regime in a USA River after two months of >90% water abstraction. The recovery of benthic macroinvertebrate densities following the cessation of water abstraction in the permanently wet channel was more lagged in the mainstem relative to the tributary Dunstan Creek, which had a natural flow regime in this study. The resilience of the benthic invertebrates in Dunstan Creek to water abstraction was higher relative to the mainstem sites further downstream, which were subject to flow regulation and land-use impacts. Despite that resilience, higher relative densities of multivoltine macroinvertebrate taxa were found downstream of all three water abstraction points compared to univoltine taxa at all sampling dates, significantly contributing to the difference in community structure due to water abstraction along the river. This difference in community structure due to life history traits was also reported by Salmaso, et al. (2018) in a river in Italy in response to season long water abstraction.

4.2.2. Re-colonisation and recovery

Chapter 3 confirmed that when seasonal high discharges return, the time taken for benthic macroinvertebrates to re-colonise the recently wetted channel edges influences the recovery of the overall community at edges and centreline sites. The recovery is delayed by the impact on the densities of benthic macroinvertebrates in the permanently wet channel during abstraction. The invertebrates of the permanently wet channel represent the source of colonists for the rewetted edges (Brittain & Eikelan, 1988; Mackay, 1992). Changes in the community composition caused by the lower resilience of macroinvertebrate univoltine taxa further delay recovery, with multivoltine taxa playing a significant role in the re-colonisation of rewetted channel edges. Impact on the invertebrate densities during water abstraction translates into a delay in re-colonisation of the recently wetted edges post-abstraction, which in turn causes a lag in the overall recovery of benthic communities seen in the current study and possibly in the study of recovery from water abstraction in a USA river of Miller, Wooster, & Li (2007).

4.3. Implications

The combined results of this study have clear implications for the energy flow through the stream food web (Weber, et al., 2007; Shearer, Stark, Hayes, & Young, 2003). The results indicate that invertebrate densities were reduced by water abstraction, and had not recovered within the study period. Reduced invertebrate abundances, particularly sustained over long periods, will impact the energetic base of the stream food web that sustains the 11 species of endemic and game fish in the Manuherikia River (Herrmann, Townsend, & Matthaei, 2012; McIntosh, et al, 2016). Therefore, the seasonal water abstraction of >50% in the Manuherikia River puts at risk the natural values of the river, which requires protection under the Resource Management Act (1991). McIntosh, Benbow, & Burky, 2002, through their study of a stream

in Hawaii, found that the water abstraction that caused a reduction in the magnitude of discharge by >50% reduced invertebrate abundances which they suggested might impact fish abundance. Benejam, et al., (2010) also reported a reduction in the abundance and size ranges of fish in response to a season long river water abstraction, which caused >50% reduction in discharge. Therefore, the productivity of the river, after abstraction has ceased is ultimately influenced by the seasonal water abstractions of >50% during the low seasonal discharge periods (Benejam, et al., 2010; McIntosh, et al, 2016; McIntosh, Benbow, & Burky, 2002).

The magnitude of reduction in invertebrate richness and abundance is linked with the extent of alteration in the natural flow regime (Bunn & Arthington, 2002). The higher resilience to the impacts of water abstraction of the invertebrate community structure of the tributary Dunstan Creek compared to the Manuherikia River mainstem highlights the importance of a natural flow regime in the management of the Manuherikia River and rivers elsewhere (Poff, et al., 1997). In addition, it makes it apparent that anthropogenic disturbances such as flow regulation by a dam and agricultural land use reduce the resilience of the invertebrate community structure, which in turn reflects the resilience of the river ecosystem (Bunn & Arthington, 2002; Dewson, James, & Death, 2007a; Lange, Townsend, & Gabrielsson, 2014).

In addition, the results also highlight the potential risk for water abstraction to endanger the populations of univoltine invertebrate taxa, which have been shown to be vulnerable to water abstraction in this study. Given that many of the univoltine taxa have restricted reproductive seasons, their ability to recover is limited (Hogg, Willmann-Huerner, & Stevens, 2002; Monson & Emberson, 2003; Wissinger, Greig, & McIntosh, 2009), which may affect the resilience of the invertebrate communities to water abstraction in the following irrigation season (Leigh, 2012).

4.4. Future research directions

The results of this study clearly suggest that recovery of benthic invertebrate densities and community structure in the permanently wet channel had not occurred within the time period of the study. Miller, Wooster, & Li (2007) found in their study of seasonal water abstraction that the recovery of invertebrate densities occurred before the next water abstraction period. Univoltine taxa in the Manuherikia River mostly lay eggs in autumn which was within the time frame of this study. However, the results suggested that the recovery of the univoltine taxa following water abstraction lagged in comparison to the multivoltine taxa. The next reproduction season would coincide with the end of the next irrigation season. Hence, more sampling dates are required, before the next irrigation season and at the start of the irrigation season, to know the time taken by univoltine taxa to recover, as well as the overall densities and community structure.

The delay in re-colonisation of recently wetted edges downstream of water abstraction suggests that recovery in shallow and wide channels could be slower as the area subject to drying and re-wetting is larger relative to the permanently wet channel, which is the source of re-colonisation (Brittain & Eikelan, 1988; Mackay, 1992). Hence, recovery from water abstraction could be affected by the channel morphology and remains to be explored for better management of river water abstractions.

Finally, the role of the invasive diatom *Didymo* in influencing the recovery of benthic densities and community structure in permanently wetted channel needs to be explored. *Didymo* flourishes under stable flows of low discharge, as seen during the months of irrigation (NIWA, 2014). It changes habitat suitability and consequently changes the community structure of the invertebrates in rivers (Kilroy, Larned, & Biggs, 2009; NIWA, 2014).

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Appendix

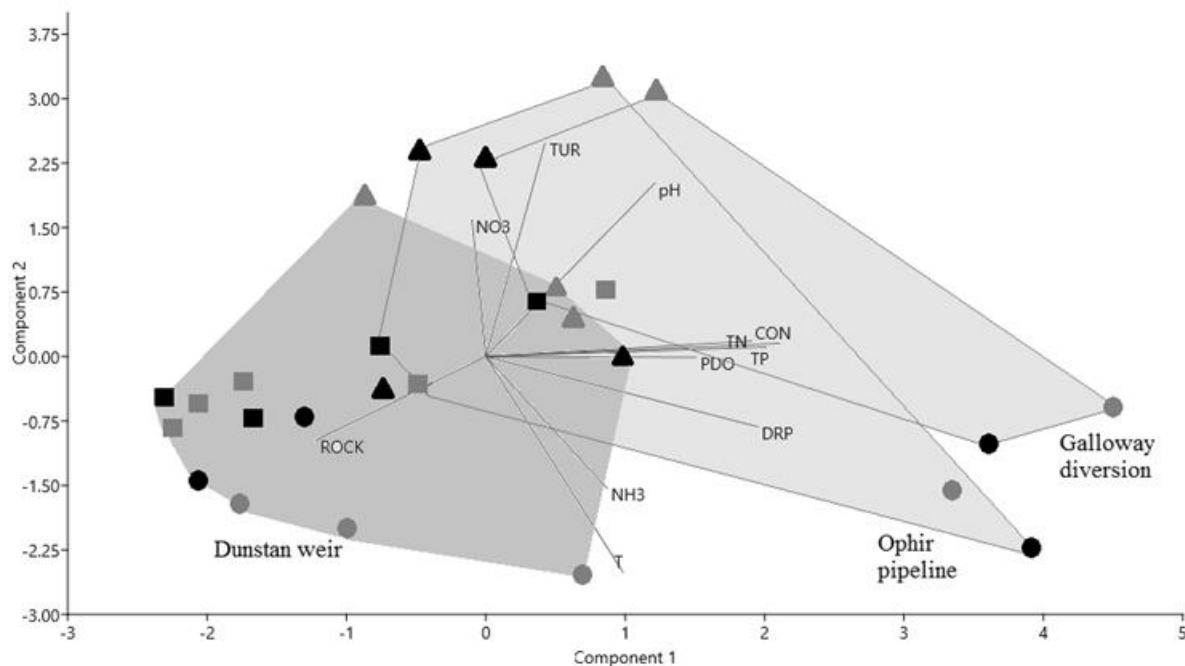


Figure A.1. Ordination PCA biplot of habitat parameters upstream (black shapes) and downstream (grey shapes) of the 1.T tributary abstraction point labelled Dunstan weir (most left convex hull), followed by convex hull of 2.M on the mainstem labelled Ophir pipeline and on the most right is the convex hull of 3.M on the mainstem labelled Galloway diversion. There is strong overlap between the convex hulls of Ophir and Galloway water abstraction points. Season the next strong gradient, is depicted by shape in each hull; ● – during abstraction (March), ■ – immediate post-abstraction (May) and ▲ - three weeks post abstraction (June). The upstream sites (black) and downstream (grey) sites are depicted by colour, but don't have a specific pattern and overlap between different convex hulls, suggesting that water quality is not affected by water abstraction. The relative loadings of mean values habitat parameters are depicted by lines labelled by name of habitat parameter. Physico-chemical variables are: CON - specific conductivity, T - temperature, PDO - per cent dissolved oxygen, pH, TUR - turbidity, ROCK - mean rock length, TN - total nitrogen, TP - total phosphorus, NH3 - dissolved ammonia, NO3 - dissolved nitrates/nitrites and DRP - dissolved reactive phosphorus. Component 1 and 2, together capture >50% variance in the dataset.

Table A.1. Relative abundance of benthic invertebrates grouped based on feeding strategies at sites of the three water takes 1.T, 2.M and 3.M. They did not vary due to water abstraction and vary slightly along the river from tributary (1.T) to mainstem (2.M, 3.M).

Water take sites	Scraper	Predator	Filter-feeder	Shredder	Deposit-feeder	Algal Piercer
1.T	40-62%	20-40%	7-24%	4-7%	1-3%	0%
2.M	38-50%	19-23%	24-38%	1-5%	0.5-5%	0-2%
3.M	34-44%	21-25%	26-37%	1-5%	0.5-6%	0-3%

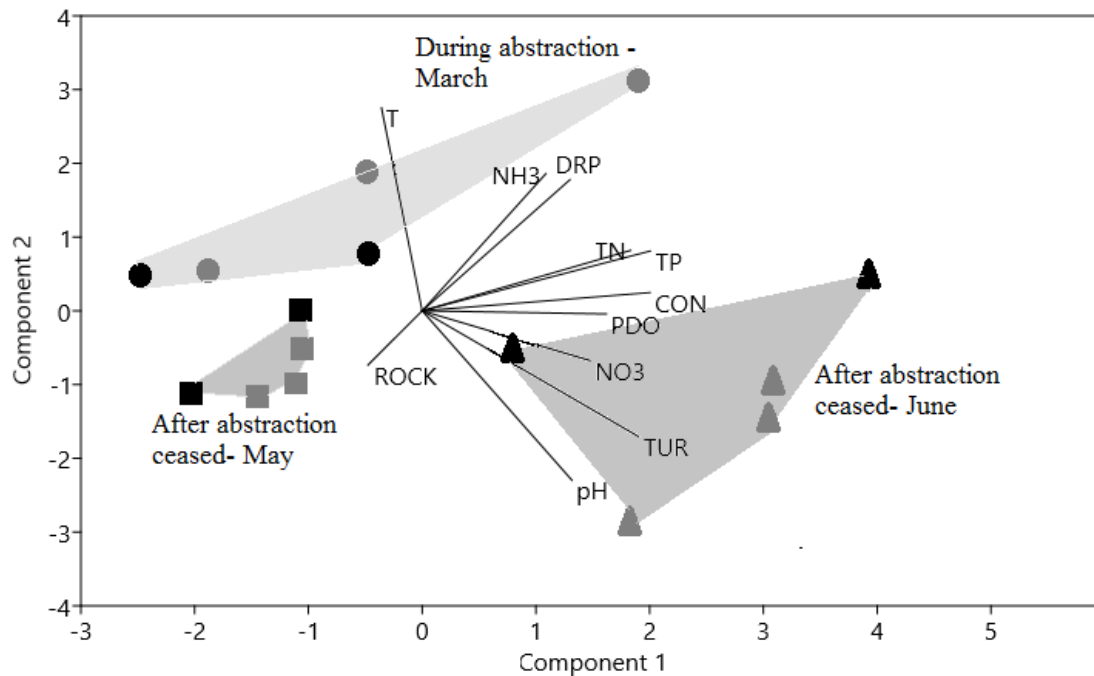


Figure A.2. Ordination PCA biplot of mean values of habitat parameters upstream (black shape) and downstream (Grey shape) of the tributary Dunstan Creek water abstraction point. The strongest gradient of season is depicted by shape and convex hulls; ● – during abstraction (March), ■ – immediate post-abstraction (May) and ▲ - three weeks post-abstraction (June). The upstream sites (black) and downstream (grey) sites are depicted by colour but there is no consistent difference between water quality upstream and downstream of water takes. The relative loadings of mean values habitat parameters are depicted by lines labelled by name of habitat parameter. Physico-chemical variables are: CON - specific conductivity, T - temperature, PDO - per cent dissolved oxygen, pH, TUR - turbidity, ROCK - mean rock length, TN - total nitrogen, TP - total phosphorus, NH3 - dissolved ammonia, NO3 - dissolved nitrates/nitrites and DRP - dissolved reactive phosphorus. Component 1 and 2, together capture >50% variance in the dataset.