The influence of connectivity on the functional role of a natural and re-constructed side-arm in the lower Waikato River

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Abstract

This thesis was a comparative study of a natural and a recently re-constructed (artificial) side-arm in the lower Waikato River. A twelve monthly temporal investigation into (i) the physico-chemical variables, nutrient and suspended solid dynamics; and (ii) phytoplankton and zooplankton abundance and community composition was carried out in order to compare each side-arm with the river, and any patterns occurring within the side-arm longitudinally. The study was based on three observed phases of connectivity of the side-arms with the river flow: Phase 1 - side-arms connected with the river (late spring-summer); Phase 2 - side-arms disconnected from the river (autumn); Phase 3 - side-arms re-connected with the river (winter). Functional roles described for side-arms in the literature were used to assess whether the natural and artificial side-arms functioned as predicted for hydraulic retention zones during disconnection, a period of high water retention and water age.

Both side-arms were influenced by seasonal variation during the late spring-summer and winter connection with the river. High nutrient and suspended solid concentrations were observed in the natural side-arm during disconnection in contrast to predictions, and it was speculated that pest fish bio-turbation was at least in part responsible for this. Zooplankton community composition was dominated by rotifers and changed as expected in the natural side-arm between connection and disconnection with a 20-fold increase in abundance during disconnection. A considerable increase in Copepoda abundance was also observed, which suggested a positive influence of side-arm disconnection on planktivorous fish communities. The artificial side-arm removed nutrients and suspended solids from the water column as expected during disconnection. Phytoplankton biomass showed some increase within the artificial side-arm as expected, with a longitudinal decrease within the side-arm, which was speculated to be caused by biotic control by zooplankton grazing.

Differences between the artificial and natural side-arms were likely caused by physical differences in substrate, riparian vegetation and zooplankton

accumulation of diapausing eggs caused by establishment age of the side-arms.

The artificial side-arm functioned as predicted for hydraulic retention zones during disconnection, suggesting potential for side arm re-construction as a restoration method to increase lateral habitat and improve local habitat health in the lower Waikato River. Ongoing monitoring of the artificial side-arm would be beneficial to see whether increased establishment age would allow the artificial side-arm to develop functional roles indicative of a naturally occurring side-arm in the lower Waikato River.

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1 Introduction

Large rivers are dynamic and influenced by variations in hydrological, geological and climatic conditions. Connectivity with lateral habitats (Junk et al. 1989), channel complexity (Thorp et al. 2008) and diverse habitats contribute to the ecological function of the main river channel (Roach et al. 2009). Features that contribute to increased lateral habitats, channel complexity and diverse habitats include islands, secondary channels and hydraulic retention zones (HRZs) which are areas of low flow and high water retention (Schiemer et al. 2001a; Thorp et al. 2008).

This study takes large river theory and uses it to address the ecological function of an understudied habitat; areas of hydraulic retention due to varying levels of connectivity with the main channel in the lower Waikato River. By focussing on functional roles identified in the theories as important for ecological health, restoration feasibility for increasing lateral habitats can be considered based on a side-arm re-construction project that was created not for ecological restoration, but aesthetic purposes.

Several concepts and models have been developed that pertain to the energy flow, structure and productivity of biotic communities within large rivers, such as the River Continuum Concept (RCC) (Vannote et al. 1980), the Flood Pulse Concept (FPC) (Junk et al. 1989), the Riverine Productivity Model (RPM) (Thorp & Delong 1994), and more recently, the Riverine Ecosystem Synthesis (RES) model (although not limited to large rivers) (Thorp et al. 2006; Thorp et al. 2008) and the Inshore Retention Concept (Schiemer et al. 2001a). The models used to describe processes within large river systems vary from considering rivers as a separate system from their floodplains to models that highlight the importance of lateral habitat connectivity and show how the focus of research on large rivers might change with the development of these theories.

1.1   Large river theories

The River Continuum Concept (RCC)

Vannote et al. (1980) presented a concept developed to explain the community structure and function of streams that highlights relationships between the biota community composition downstream and channel morphology, biota community composition and processing inefficiencies of biota upstream. It is believed that equilibrium of efficient energy use is created due to the composition of the stream communities changing in both a longitudinal and temporal pattern to optimise on energy sources available. This theory places no importance on lateral habitats for contribution to energy sources.

The Flood Pulse Concept (FPC)

Junk et al. (1989) described a flood pulse as the driving force in river-floodplain biota, with differing degrees of flood pulses (due to duration and predictability) affecting the extent of the biological processes that occur. The main channel is expressed as a separate system that acts as a transporting vector rather than an energy source for biological processing. Compared to the RCC, less focus is placed on the influence downstream of surplus particulate matter not processed upstream. Instead it is proposed that carbon inputs from inundated terrestrial matter from lateral habitats provide the main carbon source for river production. Flood pulses are described as discrete events that have the potential to occur anywhere along a river. It is emphasised that flood pulses facilitate access to the aquatic/terrestrial transition zone. This provides for rapid recycling of allochthonous organic matter and nutrients through increased temperatures, resulting in increased productivity. More recently Tockner et al. (2000) have expanded the FPC to pay attention to not only the role temperature has on increasing productivity but also the way in which a flood occurs. Described as the flow pulse vs. flood pulse, more emphasis has been given to how the expansion of water occurs either through seepage, backwaters or active flow. How water expands across lateral habitats is believed to regulate the amount of

nutrients made available and the physical conditions in which organisms such as phytoplankton and juvenile fish can thrive.

Riverine Productivity Model (RPM)

Thorp & Delong (1994) take an alternative view to the previous two concepts by placing importance on autochthonous production and direct inputs from the riparian zone as sources of carbon that drive large river food webs highlighting the importance of lateral habitats. Upstream allochthonous inputs are believed to be greater in volume than autochthonous and riparian inputs, but the latter two are better assimilated and are therefore believed to be the major carbon sources (Thorp & Delong 2002; Thorp et al. 1998). However, as riparian inputs only contribute a minor amount of carbon into the system, autochthonous inputs are believed to be the dominant carbon source for driving large river food webs (Thorp et al. 1998).

The Inshore Retention Concept (IRC)

Schiemer et al. (2001a) focus on a broader scope of biological function instead of the previous emphasis on trophic interactions. The IRC, which is limited to lateral habitats proposed that areas of inshore retention are important for their role in productivity of zooplankton and juvenile fish growth. Areas of inshore retention are characterised by hydraulic conditions such as low current velocity, ability to retain particulate matter as food, provide a refuge habitat for biota and downstream supply of juvenile fish after wash-out events. This concept is thought to be critical to rivers that have been altered or regulated due to the corresponding reduction in connectivity between the main channel and lateral habitats (Schiemer et al. 2001a). The weight the IRC places on lateral complexity highlights the significance of hydraulic retention zones. A limited knowledge base is also identified, for areas that have variable but regular connectivity, as opposed to research that is more commonly applied to areas of rivers that become periodically inundated such as floodplains (Thorp et al. 2008).

Riverine Ecosystem Synthesis (RES)

Thorp et al. (2006; 2008) put forward the heuristic Riverine Ecosystem Synthesis (RES), a model intended for application in dynamic river systems. The RES provides a framework for understanding complex longitudinal and lateral patterns formed by hydrogeomorphic processes, along with temporally and spatially variable ecological patterns. By using a hierarchical patch dynamics model and breaking the system into model tenets, a more applicable method of describing how large river systems operate is achieved (Thorp et al. 2006). The hierarchical patch dynamic model requires breaking a river system into different 'functional process zones' (FPZs) that are defined by physical aspects such as the flow regime and structural complexity, that make up a section of a river due to their role in ecological functioning. The model tenets described in the RES, are used to address distribution of species, community regulation, and ecosystem and riverine landscape processes of different FPZs (Thorp et al. 2008).The tenets proposed by Thorp et al. (2008) that are most applicable to this study follow.

Model tenet 4: Hydrologic retention

Thorp et al. (2008) claim hydrologic retention (referred elsewhere as hydraulic retention or slow moving water) has negative impacts for some species through a change in environmental conditions (e.g. dissolved oxygen), dispersal mechanisms for reproduction, and access to drifting food. Positive effects of hydrologic retention described include conditions that provide refuge, providing juvenile fish rearing habitat and high productivity. Reinforcing the ideas proposed in the IRC, this tenet claims that an increase in hydrologic retention in a river, due to an increase in hydrogeomorphic complexity, will lead to an increase in community diversity.

Model tenet 10: Primary productivity within FPZs

Areas with higher geomorphic complexity, maximum amount of hydrologic retention and maximum substrate exposed to photosynthetic available radiation will have the highest amount of autotrophy (Thorp et al. 2008).

Model tenet 13: Nutrient spiralling

Nutrient spiralling; the combination of nutrient cycling and downstream transport of nutrients decreases with hydrologic retention and floodscape storage. Three aspects are attributed to the reduction in nutrient spiralling in areas of hydrologic retention: minimal currents cause storage of detritus and sediments, enhanced nutrient sequestration and biotic emigration, and increased anoxic conditions that encourage nutrient transformation (Thorp et al. 2008).

Model tenet 16: Connectivity

Low lateral connectivity implies high retention and increased water age. Aspects that will be affected by connectivity are oxygen tension; viscosity of water, dissolved nutrient concentrations, organic content of the sediment, water temperatures, turbidity, productivity rates and community composition. It is inferred that low connectivity will positively affect population density, productivity and community diversity of organisms that have low tolerance for high velocities and turbidity. Connectivity will negatively affect organisms that find currents, higher oxygen tension and greater additions of nutrients advantageous. This model tenet predicts maximum bio-complexity at intermediate levels of connectivity (Thorp et al. 2008). This tenet also uses the characteristics of hydrologic retention in tenet 4 to highlight that the period of hydrologic retention in a system is just as important as the occurrence of hydrologic retention.

The IRC and the RES highlight the importance of lateral connectivity and provide a basis for investigating how lateral habitats in the lower Waikato River may operate ecologically with regard to plankton, nutrient and suspended solid dynamics. These theories indicate a positive relationship between increasing lateral habitat area and increasing ecosystem health through providing more suitable habitat for primary productivity that will have positive flow-on effects through to higher trophic levels. If a natural HRZ in the lower Waikato River functions as expected for HRZ characteristics in the models, and a restored HRZ functions the same as the natural HRZ, it would

indicate that restoration of the lateral habitat would be beneficial to promote ecosystem health of the lower Waikato River.

1.2 Lateral connectivity: Hydraulic retention zones (HRZs)

HRZs occur where there is minimal current, usually along the edges of the river where retention characteristics vary depending on the main channel flow regime. HRZs such as embayments, backwaters (areas where water flows backward into a side channel at high flows creating hydraulic retention by preventing water from exiting into the main channel) and side-arms (a side channel that is cut off from the main channel at low flows creating hydraulic retention) decrease water velocities and reduce connectivity with the main channel.

Internationally, many studies have highlighted the significant role that HRZs can play in large river ecosystems through contributing autochthonous carbon to the food web of the main channel (Preiner et al. 2008) and being 'hot spots' for biogeochemical processes such as transformation and production of organic matter (Schiemer & Hein 2007). HRZ habitat characteristics include reduced flow, increased substrate stability, sediment accumulation, increased light and temperature conditions and high nutrient availability (Schiemer & Hein 2007). Retention in a river refers to the physical ability to retain and process organic matter and nutrients (Schiemer et al. 2001a).

Reductions in water velocity and connectivity in HRZs are sufficient to provide suitable habitat for aquatic organisms during different life stages as HRZs provide an important source of food that boosts primary and secondary production in the main channel when reconnection occurs (Schiemer et al. 2001a).

Tockner et al. (1999) break the processes occurring in HRZs into phases of biological control (low connectivity), primary production (intermediate connectivity) and transport (pulses of high connectivity), as also illustrated by Preiner et al. (2008) in Figure 1-1. The phases make up a conceptual model which links hydrological connectivity with ecological processes. Side-arms are subject to changes in connectivity with the main river channel ultimately due to changes in main river flow,

causing a change in biological function, through phases of transportation, storage and transformation of organic matter (Preiner et al. 2008; Schiemer & Hein 2007; Schiemer et al. 2006; Schiemer et al. 2001a).
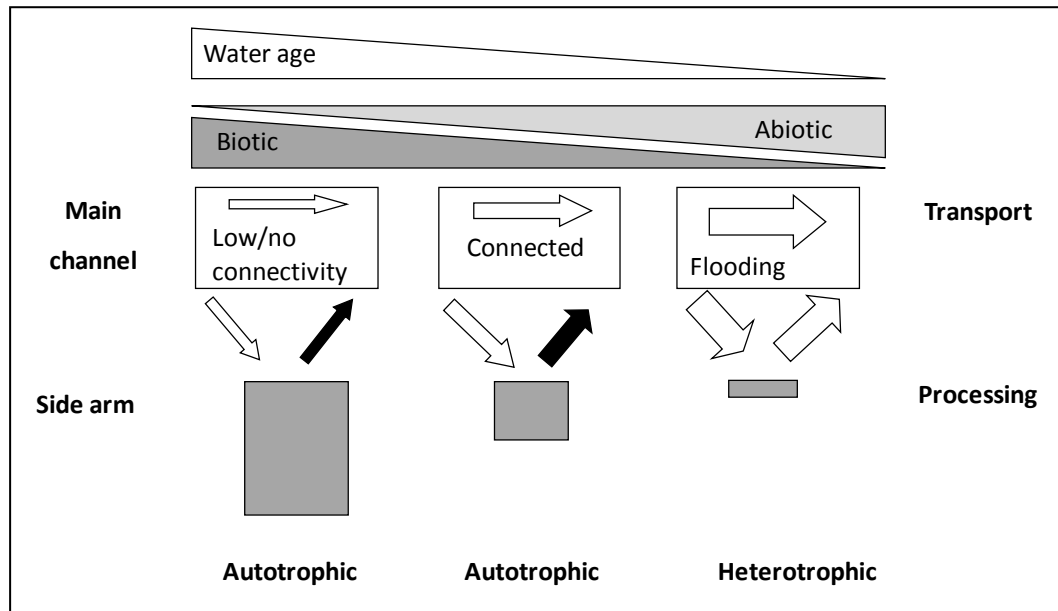
Figure 1-1 Schematic diagram adapted from Preiner et al. (2008) showing carbon transport and transformation of the Regelsbrunn side-arm system at different hydrological conditions. Arrows indicate amount and direction of river input and processed water (white and black arrows, respectively).

The variable nature of side-arms through connectivity, flow and consequently retention time, results in a variation in biological composition. A side-arm with a high residence time would be expected to become a storage zone for zooplankton (Reckendorfer et al. 1999; Schiemer et al. 2001a), while at intermediate residence times when surface water has recently increased providing nutrients, phytoplankton would dominate (Preiner et al. 2008; Schiemer et al. 2001a). Further studies focussing on 'water age' or retention time are important for determining the significance of hydrological control of water column processes (Schiemer et al. 2006). The roles carried out in a river-floodplain segment in the Danube, Austria, demonstrate how a HRZ can act as both a source of algal biomass and dissolved organic carbon, and as a sink for suspended sediments, particulate organic matter and nutrients (Preiner et al. 2008; Tockner et al. 1999).

With the importance of HRZs such as side-arms being highlighted widely in the literature, it is of concern that these habitats are subject to decline due to flood protection measures, channel dredging and other practices that cause homogenisation of river channels (Schiemer et al. 2006; Schiemer et al. 2001a; Schiemer et al. 2001b; Tockner & Stanford 2002).

Construction of side-arms has been explored as a possible restoration method by re-constructing artificial side-arms or reconnecting original side-arms. The goal for restoration is to retain or regain functionality both in terms of whole ecosystem health and localised habitat quality (Schiemer et al. 2007). The retention of the water in side-arms may allow for more gradual processes of inundation and exchange which provide an opportunity for higher overall productivity in the main river channel (Tockner et al. 1999).

Previous studies that have examined the effect of implementation of artificial side-arms include the widely published 'Danube Restoration project' (DRP) which was developed in the river Danube, Austria, in 1996 to enhance hydrological connectivity between the main river channel and former side-arms (Hein et al. 2004; Hein et al. 1999; Hein et al. 2005; Preiner et al. 2008; Schiemer et al. 1999; Tockner et al. 1999; Tockner et al. 1998). It was believed that the Danube restoration project would be a success if it maintained a balance between retention and export of nutrients and organic matter (Tockner et al. 1999). The project was successful, and the restored river portion now supports increased aquatic primary production and biodiversity (Preiner et al. 2008).

The development of large river concepts emphasises the need to view the rivers as laterally complex 'riverscapes' rather than separate areas of main river channel and isolated floodplains (Roach et al. 2009; Thorp et al. 2008). Few HRZ studies have been carried out internationally, with even fewer having a focus on New Zealand Rivers. There is still work to be done in order to understand the role of connectivity and how changes to the extent of HRZs affect river communities and ecosystem function (Thorp et al. 2008; Ward et al. 2002).

1.3 Lower Waikato River (LWR)

The Waikato River reach begins in the upper head waters of the Taupo Volcanic Zone in the centre of the North Island (Chapman 1996) and ends at Port Waikato (Te Pūaha o Waikato) where it enters the Tasman Sea (Collier et al. 2010). The 'lower Waikato River' is defined as the portion of river that spans from the outlet of the hydro-dam at Karipiro to Tuakau (Chapman 1996) where the river delta commences (Collier et al. 2010).

Geological history

The volcanically active area of the central North Island has led to an intricate geological history of the Waikato River. The river has changed paths from its origin at Lake Taupo to an outlet at the Hauraki Gulf, to the current outlet of Port Waikato. Vegetation cover in the River's catchment was largely destroyed due to volcanic eruptions leading to extensive erosion and transport and deposition of sediment in the River. This change in the River's course was dynamic until vegetation cover established again in the catchment. Along with the rise in sea level, the low load bearing river became trapped in the current Hamilton basin course (Collier et al. 2010).

Ecological significance

The Waikato River is believed to have the most diverse fish fauna of any river in New Zealand attributable to the size and diversity of habitats, coupled with introduction of exotic species (Chapman 1996). The flow regime of the river is important for fish migration and spawning events. Aartificial alterations of this regime can have negative impacts on native fish fauna by reducing suitable habitat for key life-stages of native fish species (David & Speirs 2010).

Phytoplankton thrive in favourable conditions of light, temperature and nutrients (Hamilton & Duggan 2010). Phytoplankton content of the lower river is considered to be influenced by the hydro-dams which, due to nutrient enrichment and impoundment, provide suitable habitat for biomass to increase to a level that alters turbidity downstream (Chapman 1996). Phytoplankton biomass can become a

concern when toxic blue-green algae make up a high proportion of the biomass leading to water being declared as unsafe for public health (Vant 2010).

Zooplankton; rotifers (phylum Rotifera), cladocerans and copepods (phylum Crustacea), feed on phytoplankton and bacteria and are sensitive to environmental conditions such as temperature, food quality and composition, turbulence and suspended sediments. These factors contribute to variable population sizes and compositions of zooplankton communities in the Waikato River (Hamilton & Duggan 2010).

Anthropogenic pressures

The River, although altered extensively by natural changes through volcanism and climate change, has been most affected by anthropogenic impacts since the arrival of Polynesians (Chapman 1996). Said to be one of the most human-impacted river systems in New Zealand, the Waikato River has been used for, and suffered effects from, power generation (hydro, geothermal and thermal), flood control, agriculture, forestry and waste disposal (Chapman 1996). The Lower Waikato River is primarily affected by wetland habitat losses due to drainage for pastoral conversion, eutrophication and chemical and thermal pollution due to waste disposal and power generation (Chapman 1996). Flood control has a significant effect of regulating water flow into the lateral extent of the river, which, along with sand mining, wetland drainage and land clearance has altered lateral habitats in the Waikato River (Collier et al. 2010).

Cultural significance

The Waikato River has cultural significance for tangata whenua who have resided in close proximity to it for centuries. The significance is in the river's ability to offer spiritual and material resources such as food and act as a travel and transport route (Watene-Rawiri & Flavell 2010). The Waikato River was, in August 2008, the subject of the Waikato-Tainui river settlement (Watene-Rawiri & Flavell 2010). In effect, the settlement promotes the input into the management of the river to promote health and wellbeing of the river by Tainui (Waikato iwi) (Guardians Establishment

Committee 2009; Watene-Rawiri & Flavell 2010). As a result of the river settlement, funding has been set aside for restoration of the Waikato River (Speirs et al. 2010).

Research

This section has highlighted that the health of the Waikato River is important not only for recreation and cultural significance, but also for ecological and environmental sustainability. Restoration methods that can maintain and enhance large river ecological values have not been widely studied in New Zealand, so knowledge of possible restoration methods in the Waikato River have relevance not only to that river, but also potentially other rivers in New Zealand. This study of side-arms on the lower Waikato River will contribute to a low information base on the river's ecological function.

The Waikato River lends itself to a study on HRZs as it has been subject to extensive flood protection measures (Speirs et al. 2010) effectively reducing lateral connectivity. In 2008, a side-arm was re-constructed near Huntly for aesthetic purposes (Waikato Times. 2008), providing an ideal platform for this comparative study. If re-constructed side-arms are proven through this study to function in a similar way ecologically to natural side-arms then side-arm reconstruction and reconnection may prove to be a useful river restoration method (Simons et al. 2001) in the lower Waikato River, as they have been shown to be internationally.

Measurements of ecosystem health

The theoretical basis of HRZs focuses on nutrient and sediment dynamics and productivity, and how these are affected by different hydrological regimes of the river. A study that measures nutrients, suspended solids, temperature, conductivity, dissolved oxygen and pH would provide sufficient background into the physico-chemical (interaction of physical and chemical) dynamics of a HRZ. Examining the abundance, assemblage and biomass of phytoplankton through algal counts and chlorophyll *a* concentration, respectively, would allow insights into HRZ autotrophy and primary productivity. Zooplankton abundance and assemblage data would compliment information on phytoplankton and give a general indication of trophic

interactions, as well as allowing for speculation on flow-on effects for higher trophic levels. Studying this suite of factors over time would capture the influence of connection of HRZs have with the river.

1.4 Aims and Objectives

The major aim of this study was to determine the influence hydrological connectivity with the river has on side-arm function. This was achieved through, (i) measuring differences between side-arms and the main river with regards to plankton, nutrient and suspended solid dynamics, and (ii) determining whether a re-constructed side-arm functions in a similar way to natural side-arms.

The overarching aim was addressed through the following objectives:

1) To determine temporal nutrient processing patterns by analysing whether concentrations (nitrogen and phosphorus) and other water column variables, such as suspended solids and chlorophyll *a,* differ within side-arms longitudinally and compared to river concentrations,

2) To determine whether phytoplankton and zooplankton community composition differs between natural and re-constructed side-arms and the main river channel with regard to the three different phases of connectivity,

3) To determine the functional role for each side-arm at each connectivity phase based on dominant plankton species and differences in nutrient and suspended solids concentrations within side-arms,

4) To determine whether the natural and re-constructed side-arms are comparable to other side-arms in the lower Waikato River by comparing the phytoplankton community composition, nutrient concentrations and physico-chemical parameters outlined above, to seven naturally occurring side-arms in the lower Waikato River, and

5) To determine whether the natural and re-constructed side-arms function in a similar way, and thereby infer whether side-arm construction could be used to restore lateral processes in the lower Waikato River.

2   Materials and Methods

2.1   Study sites: the lower Waikato River

The Waikato River is the longest river in New Zealand with a reach of around 442 km (Collier et al. 2010) and catchment area of approximately 13% of the North Island (Chapman 1996). Mean annual rainfall taken from Hamilton is 1150 mm, with highest rainfall in the Waikato catchment occurring during winter and lowest during summer; monthly averages indicate that July is the highest and February is the lowest (Brown 2010).

The sediment load of the lower Waikato River is primarily influenced by the natural geology of the Waipa tributary, which is believed to contribute two-thirds of the sediment load that is delivered to the coast. The hydro-dams upstream of the lower reach influence this progression, by entrapping sediment that should be delivered downstream (Hill & Quinn 2010).

The nutrient content of the Waikato River is not influenced greatly by point-source discharges, instead it is related to runoff from land that is used for pastoral farming (Vant 2010). The land use of the catchment area of the lower Waikato River is primarily intensive agriculture and this area maintains the largest human population (Chapman 1996).

The flow regime in the Waikato River is has been modified by the implementation of hydro-dams and flood protection measures in order to provide for efficient hydro-electricity generation and to regulate flows to prevent flooding, resulting in an artificially constrained flow regime (Brown 2010) that may result in low connectivity between the main channel and lateral habitats.

Temporal study sites

River sites were located according to Figure 2-1 and Figure 2-2, one upstream of the reach of the river containing the side-arms, one in between the two side-arms and upstream of the Lake Hakanoa outlet, and one downstream of the side-arm reach.

Each site was on the true right of the river channel, on the same bank that the side-arms and Lake Hakanoa outlet were connected to.
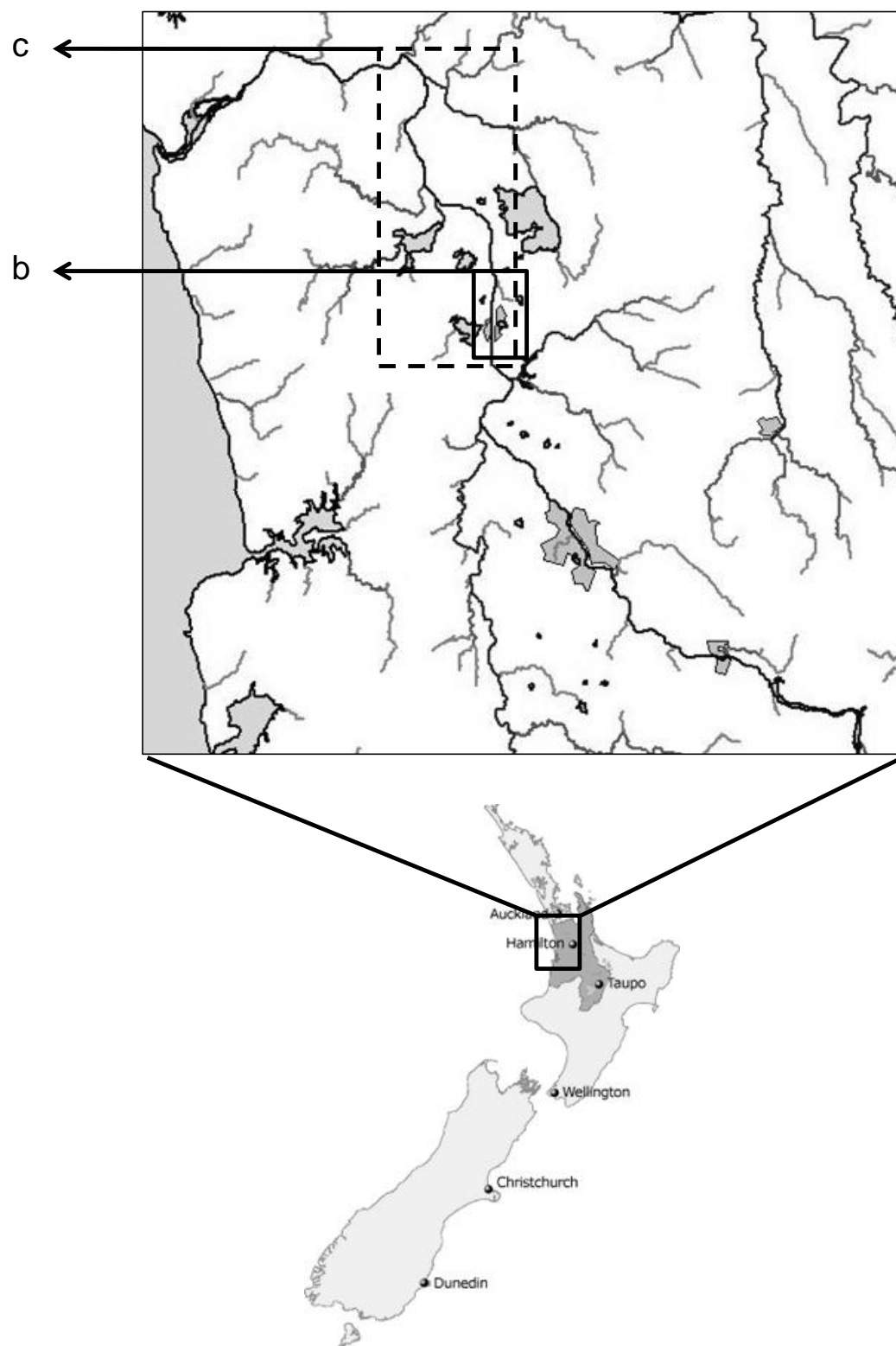
Figure 2-1 Lower Waikato River illustrating locations of study sites. Map sourced from Environment Waikato (2011).
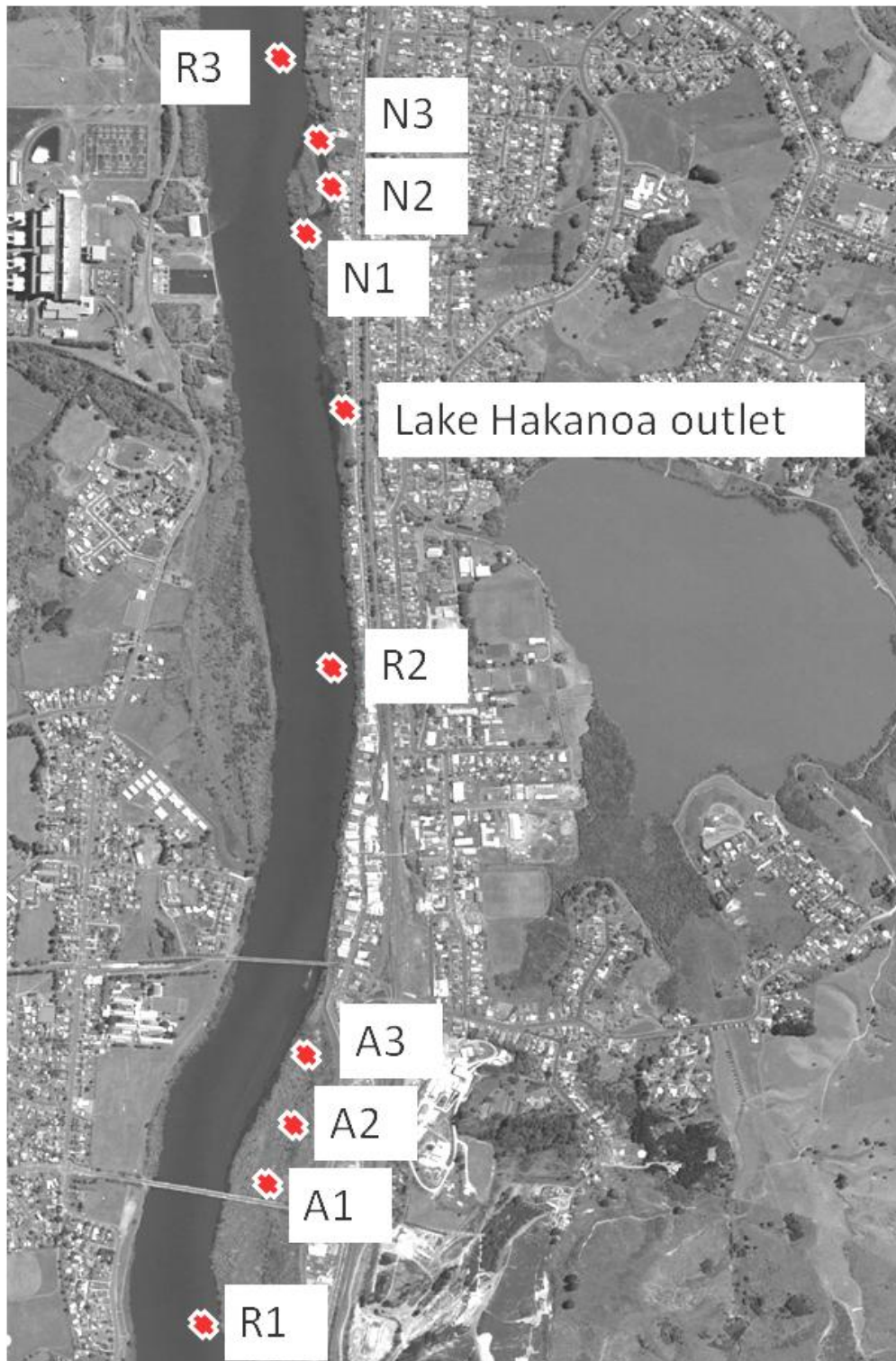
Figure 2-2 Twelve-month temporal study. River sites; R1 (upstream of side-arms), R2 (in between side-arms), R3 (downstream of side-arms). Artificial side-arm sites; A1 (inlet), A2 (middle) and A3 (outlet). Natural side-arm sites; N1 (inlet), N2 (middle) and N3 (outlet).
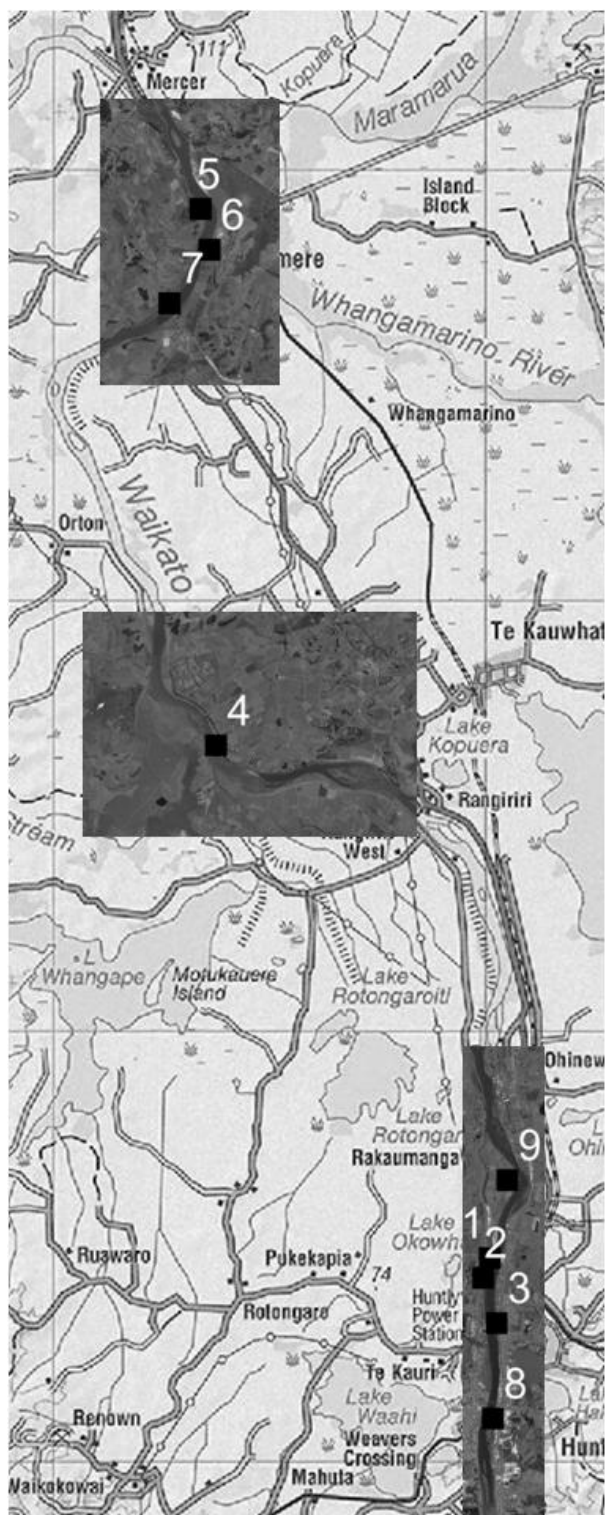
Figure 2-3 Spatial survey between Huntly and Mercer. A total of 9 sites including the natural (site 3) and artificial (site 8) side-arms from the temporal study.

The re-constructed side-arm was termed 'artificial' for this study. The artificial side-arm was a Huntly community project that aimed to provide a recreational facility and improve the aesthetic environment. In 2008 construction of the side-arm commenced involving digging channels into a pre-existing side-arm remnant that was blocked off due to stop bank implementation. The outcome of the construction was a 497 m long side-arm with a maximum depth of 3 m. Due to the age of the side-arm; riparian vegetation was minimal at the time of the study resulting in an exposed site. Sample sites were located at the inlet, approximately midway and at the outlet of the side-arm (Figure 2-1 & Figure 2-2).

The Lake Hakanoa outlet (Figure 2-1 & Figure 2-2) was sampled to rule out any effect lake water may have on the natural side-arm sites beginning 467 m downstream, and on the river site downstream of the natural side-arm. This outlet releases Lake Hakanoa water into the Waikato River in an outlet stream after travelling through a culvert under a road. At times of high river flow, this culvert was closed to prevent river water from flooding the lake resulting in a sample site that was an extension of the main river channel.

The natural side-arm site, located 2 km downstream of the artificial outlet, was 310 m long and had extensive riparian vegetation. As for the re-constructed side-arm sample sites were located at the inlet, approximately midway and at the outlet of the side-arm (Figure 2-1 & Figure 2-2).

Spatial survey study sites

Sites were selected from aerial photographs of the lower Waikato River. Any possible side-arms were ground-truthed, and confirmed side-arms were sampled. A total of nine side-arms were surveyed (Figure 2-1 & Figure 2-3); two of these were the temporal artificial and natural side-arms, and one of the remaining seven was removed from analysis due to missing data.

2.2   Sample collection

Temporal study: monthly sampling

Sampling for the temporal study was carried out at four sampling locations; a naturally occurring side-arm, an artificial side-arm, the main river channel and the outlet of Lake Hakanoa which entered the river upstream of the natural side-arm (Figure 2-2). Each sampling location was divided into three sampling sites, except for the lake outlet which had only one sampling site; thus there were a total of 10 sampling sites on each occasion; three on the river, three in each of the two side-arms and one at the Lake Hakanoa outlet.

The connectivity ranking comprised of five levels of connectivity based on how connected the side-arm was with the river: level one was complete connection, level two was complete connection with lower flow than the main channel, level three was connection of side-arm at inlet site but not at outlet site, level four was connection at outlet site but not inlet site, and level five was complete disconnection. River levels from a permanent flow recorder station were provided by the National Institute of Water and Atmospheric Research was used to determine the amount of time the river was at or below the observed river level to indicate the period of different levels of disconnection. Phytoplankton samples were collected from the surface water in a 250 ml sampling container attached to a pole, one meter away from boat ('river' samples) or from a sampling position on shore ('side-arm' and 'tributary' samples) at each site. Samples were preserved immediately using 2 ml of Lugols iodine. Zooplankton samples were collected by filtering a known volume of at least 30 l of surface water through a 45 µm mesh net to ensure retention of rotifers. Surface water

was used based on the assumption that the sites sampled were evenly mixed vertically.

Each sampling site was visited at monthly intervals from November 2009 until October 2010 (twelve-month period), with all samples collected over 1-5 days. Water samples were collected for phytoplankton, zooplankton, chlorophyll *a* (as an indicator of phytoplankton biomass), total and dissolved nutrients, and total suspended and volatile solids. Physico-chemical measurements taken at each site on each sampling occasion comprised of temperature and conductivity, measured using a YSI 30 salinity, conductivity and temperature meter (Yellow Springs Instruments, Ohio, USA). Dissolved oxygen was measured using a YSI model 55 handheld DO system meter (Yellow Springs Instruments, Ohio, USA). A YSI EcoSense pH10 pen was used to measure pH (Yellow Springs Instruments, Ohio, USA). All meters used were calibrated before use and placed in the sampling site water column until readings stabilised A measure of connection between each side-arm and the main river channel was recorded for each of the twelve temporal sampling occasions.

Chlorophyll *a* samples were collected in the same manner as plankton. A 60 ml sample of water was filtered onto a 0.45 μm glass fibre filter which was then folded in half and wrapped in tinfoil to prevent light exposure. Samples were stored on ice out of sunlight until they could be transferred to a freezer (-20 °C) for storage (within 6 hours). This water was also used for the collection of total and dissolved nutrients. Total nutrients involved the collection of 14 ml unfiltered water while dissolved nutrients required 14 ml of filtered water; both were collected in falcon tubes and stored on ice until they could be frozen.

Total suspended solids water samples were collected by extending a clean plastic 2 l bottle at arm's length from the boat or shore to collect surface water. Samples were kept on ice until they could be stored in a refrigerator at 4 °C prior to analysis.

Flow was measured using the General Oceanics digital flow meter 2030 R6 at the inflow and outflow sites of each side-arm on each of the monthly sampling occasions. At low flows a high resolution rotor was fitted onto the flow meter for low-speed

applications. The current meter gauging methods outlined in Fenwick (1994) were used for all flow measurements. The width of each site was measured using a measuring tape at a right angle to the direction of flow, followed by depth measurements using a wading rod or measuring tape at set intervals; depth measurements defined the cross-sectional area and acted as the location for current meter velocity measurements. At each site three depth measurements were taken across the width of the channel; true left, centre and true right. At flows with a depth <30 cm, the surface one-point method was used (Fenwick 1994) due to other methods being infeasible. This method involved flow measurements being taken at one point on the surface at the three depth measurement sites (true left, centre and true right). At flows with a depth >30 cm, flow measurements were taken at 0.2, 0.6 and 0.8 of the depth below water surface to produce a mean velocity in the vertical by averaging the three values for each of the true left, centre and true right sites.

Temporal study: continuous measurements

Continuous dissolved oxygen monitoring was conducted on two occasions, one in summer 2009 (January) and one in winter 2010 (July), with the intention of calculating ecosystem metabolism. Solute retention time and macrophyte cover of the artificial side-arm were also estimated concurrently on some of these occasions. Metabolism was to be measured using the two-station open water metabolism method outlined in Grace and Imberger (2006) whereby the changes in dissolved oxygen between two dissolved oxygen measuring devices allow for the calculation of aerial photosynthetic and respiration rates. The two-station method was carried out by deploying the Zebra-Tech D-Opto dissolved oxygen logger (Zebra-Tech Ltd. Nelson, NZ) in the artificial side-arm upstream of the YSI 6-Series multi-parameter water quality sonde (Yellow Springs Instruments, Ohio, USA) located at the outlet. Both logging systems recorded dissolved oxygen for a minimum of 48 hours at 15 minute intervals. The sonde also recorded conductivity and temperature during this period. Ecosystem metabolism calculations were not carried out because of unsuccessful data acquisition caused by variable flows which altered tracer measurements invalidating metabolism retention assumptions.

TidbiT v2 temperature loggers (Onset Computer Corporation, Massachusetts, USA) were placed in the inlet and outlet of each side-arm in summer from 17 December 2009 until 10 March 2010 and were set to record every 15 minutes.

Spatial survey sampling

A one-off spatial survey was carried out in March 2010 by sampling nine side-arms (eight natural and one artificial) between Huntly and Mercer. Each side-arm had four sites sampled; one river site adjacent to the side-arm, one side-arm inflow, one site between the inflow and outflow (middle), and the outflow of the side-arm, resulting in 34 sites. One side-arm subsequently had one site excluded due to inaccessibility; this side-arm was excluded from later analysis. Sampling included the one-off measurement of physico-chemical characteristics (temperature, dissolved oxygen, pH and conductivity), chlorophyll *al*, and water samples for total and dissolved nutrients, and total suspended solids, and phytoplankton using the same methods as for temporal sampling. A ranking of connectivity for each of the nine sites was made using the same method as the temporal sampling.

2.3 Analysis

Dissolved and filtered nutrients

Nutrient analyses were performed using a discrete analyser, Aquakem 200 Cd (discrete photometric analyser). Analyses for ammonium (NH_4-N), nitrite (NO_2-N) and dissolved reactive phosphorus (PO_4-P) were carried out using standard Aquakem methods. Nitrate (NO_3-N) was calculated through subtracting NO_2-N values from NOx-N values post analysis. Total nitrogen (TN) and total phosphorus (TP) were digested using a modified simultaneous persulfate digestion method (Ebina et al. 1983; Johnes & Heathwaite 1992). Samples were digested along with calibration standards. Post-digestion, samples were checked for acidity and neutralised before analysis using aliquots of NaOH solution. Samples were analysed for TN and TP on the Aquakem analyser using modified EPA methods 365.3 and 353.1 (U.S. Environmental Protection Agency. 1983; U.S. Environmental Protection Agency. 1991). Milli-Q water was used in preparing all standards and reagents. Stock

standards were prepared from analytical reagent-grade chemicals, and stored in clean bottles at 4 °C. Working standards were prepared by diluting stock standards with Milli-Q water. Before each batch of samples was analysed, calibration standards were run and calibrated on the Aquakem discrete analyser software (Aquakem Konelab software; version 7.2). Four checking standards were used every 30 samples. Quality control standards were run every 40 samples.

Total suspended solids

A standard protocol was used in the laboratory (Paul 2009a) for determining total suspended solids (TSS), based on APHA (Eaton & Franson 2005). To prepare for both analyses, 47 mm diameter GC50 45 µm glass fibre filters were placed in aluminium foil dishes were pre-combusted at 550 °C in a Vulcan 3-1750 muffle furnace for 4 hours after being placed with forceps in a 300 ml Advantec filter holder which was attached to a Gast vacuum pump and washed three times with 20 ml of deionised water. The filters in foil cases were weighed to the nearest 0.1 mg once cooled, after pre-combustion. The pre-combusted filter was then placed, using forceps, onto the filter holder attached to the vacuum pump. A known amount of homogenised sample water was filtered (enough sample water to produce 2.5 to 200 mg dried residue). The filter was washed using three successive applications of 10 ml deionised water, making sure to rinse the filter holder of any sample remaining. Air was sucked through to allow as much moisture to be removed from the filter as possible before the filter was removed from holder and placed in foil case with forceps. Filters in a foil dishes were dried in a pre-heated Contherm digital series oven at 105 °C for 4 hours, and then weighed to the nearest 0.1 mg, once cooled, in a sealed box with dried silica. The calculation for TSS is as follows:

$$Total\ suspended\ solids\ (mg/L) = \frac{(A - B) \times 1000}{sample\ volume\ (mL)}$$

Where:

A= weight of filter + dried residue (mg)

B= weight of filter (mg)

The first month of samples (November) was lost due to analytical problems along with one January sample.

Chlorophyll a *analysis*

The standard protocols for fluorometric determination of chlorophyll *a* pigment were followed (Hauer & Lamberti 1996; Paul 2009b; Wef 1995; Wetzel & Likens 1990). Chlorophyll *a* samples were stored for a maximum of three weeks prior to analysis. Filters were removed from the freezer and while remaining in the dark each filter was ground with 5 mls 90% (v/v) buffered acetone in a mortar and pestle rinsed with buffered acetone. The filter was ground to a slurry and transferred to a clean, labelled centrifuge tube. The mortar then had up to 5 ml buffered acetone added to rinse any remaining slurry which was added to the centrifuge tube. The centrifuge tube was made up to a total of 10 ml with buffered acetone. The tube was capped, shaken and kept in the dark while it steeped for 2-24 hours (tubes were shaken at least once during this period) at 4 °C. After a steeping period, tubes were shaken vigorously and centrifuged in the Jouan B4i centrifuge for 10 minutes at 3300 rpm. Samples were left to stand for 30 minutes in the dark to come to room temperature before proceeding to analysis.

For chlorophyll *a* analysis the 10 AU Fluorometer (Turner design) was turned on 30 minutes prior and the sensitivity setting was adjusted to high. A glass cuvette cleaned and rinsed with buffered acetone had 5 ml buffered acetone added which was placed into the fluorometer to produce a blank reading. Each sample had 5 ml supernatant added to a clean glass cuvette which was placed in, and read by, the fluorometer for which the florescence value was recorded. If readings were over the detection limit, the sample was diluted with one-half buffered acetone until a reading was achieved. The dilution factor was recorded. The addition of 150 µl of 0.1 N HCl was then carried out for analysis of phaeopigment, followed by tapping on the side of the cuvette to ensure mixing of acid into sample. After 90 seconds, the fluorescence was re-measured and recorded.

The concentration of chlorophyll *a* in each sample was calculated as:

$$Chlorophyll \ a \ (\mu g \ L^{-1}) = F_s \left[\frac{r}{(r-1)(R_1 - R_2)} \right] \times \left[\frac{V_e \times df}{V_f} \right]$$

Where:

F_s= response factor for sensitivity setting

R_1= reading before acidification minus blank reading

R_2= reading after acidification minus blank reading

r= (R_1/R_2)

df= dilution factor

V_e=extraction volume

V_f= volume of water filtered

Phytoplankton identification and enumeration

An analytical procedure described in Paul (2007) was used for phytoplankton analysis (Hötzel et al. 1999; Sandgren & Robinson 1984; U.S. Environmental Protection Agency 2007). Phytoplankton samples were gently mixed by inverting sample containers 12 times over a minimum of 30 seconds. The samples were immediately sub-sampled by transferring 1-10 ml of sample into a Utermöhl chamber using an auto-pipettor. Prior to sub-samples being transferred into the chamber, 5 ml of reverse osmosis (RO) water was added to the chamber to ensure even settling of sub-samples. The sub-samples were covered with glass slides and settled for a minimum of 6 hours on a flat surface in the dark.

An Olympus 1x71 inverted microscope was used for the analysis. A count of 100-150 planktonic units was made for the dominant taxa/taxon; if this was not achieved in one transect, dominant taxa were counted in additional transects.

Cell concentrations were calculated as:

$$N = Cf \ (\frac{A}{baV})$$

Where:

N= number of algal cells per ml in original water sample

C= total number of algal cells counted in all transects

A= total area of bottom of settling chamber (mm^2)

a= total area of transect (mm^2)

b= number of transects counted

f= dilution or concentration factor

V= volume of lake water that was settled (ml)

Zooplankton identification and enumeration

Analyses were carried out on zooplankton samples collected three-monthly (i.e., four of the possible twelve month sample sets were analysed, representing a seasonal survey) (December 2009 and March, June and September 2010) and not for the spatial survey due to time constraints. Inverted zooplankton samples were emptied into a 40 µm mesh strainer and rinsed with tap water. When ethanol was rinsed off, the contents of the strainer were poured into a 50 ml measuring cylinder and the strainer was rinsed into the measuring cylinder to ensure no remnants of the sample remained. The sample in the measuring cylinder was made up to a known volume (e.g. 30 ml) with tap water. The sample was then sub-sampled by inserting a 5 ml autopipette and drawing a figure of eight in the sample to ensure even mixing. A known volume (e.g. 10 ml of 30 ml) was then removed with the autopipette. This sub-sample was then released into a sorting plate. The sub-sample was analysed under a Olympus SZ60 compound microscope by counting and identifying to species level all of the individuals in the sorting plate. Sub-sampling each sample continued until a minimum of 300 individuals or the whole sample had been counted.

Statistical analysis

Standard error of the mean was calculated for nutrient, suspended solid, chlorophyll *a* and physico-chemical variable data. The standard error (SE) was estimated by the standard deviation divided by the square root of the sample size (Quinn & Keough 2002).

Temporal study

Preliminary analysis using Principal Component Analysis (PCA) was used to explore groupings for subsequent statistical analysis (Quinn & Keough 2002). Two factor planes were used as they explained >50% of the total variability in the data. A correlation matrix with physico-chemical variables, nutrients, suspended solids and chlorophyll *a* concentration for each location (inlet, middle and outlet) from each habitat (artificial and natural side-arms and river) identified all nine sites being grouped by three discrete groups of months. The months that grouped together indicate three different phases of side-arm connection with the main river channel:

- Phase 1, November 2009-February 2010 (late spring-summer), the side-arms were connected to the river;

- Phase 2, March-May 2010 (autumn), the side-arms had some level of disconnection with the river; and,

- Phase 3 June-October 2010 (winter), the side-arms were connected to the river again.

Therefore data were statistically analysed based on these *a-priori* connectivity phases for all temporal data.

A two-way analysis of variance (ANOVA) was implemented in STATISTICA (Stat Soft Inc. Oklahoma, U.S.A.; version 9) to test for any significant differences in nutrient concentrations (NH_4-N, NO_3-N, PO_4-P, TN and TP), TSS and chlorophyll *a* concentrations and zooplankton abundances between habitats (artificial and natural side-arms and river), between connectivity phases, and for any interaction between these two factors. Outlet samples were used for the side-arm habitats in order to test differences in samples that had already travelled through the side-arm, and achieved maximum processing, and would be inputting processed water back into the river. In the case of zooplankton abundance statistics, an average of all three sites were used for the side-arms and river. *P* values <0.05 were considered significant. A post-hoc test (Tukey test) was used to identify which habitat/s and/or connectivity phases were causing significant differences. All data was normalised by monthly river averages, and log or Box-Cox transformed where necessary. Data was tested for the

assumptions of ANOVA by using Levene's test for homogeneity of variances and the K-S and Lilliefors test to test for normal distribution along with visual inspection of predicted vs. residual plots.

A one-way ANOVA was used to test for significant differences of nutrient, TSS and chlorophyll *a* concentrations in the inlet, middle and outlet samples in each of the three connectivity phases. The same normalisation, transformations, tests for assumptions and post-hoc tests were used as above.

Non-metric multi-dimensional scaling (MDS) plots were produced in Primer (Primer-E Ltd, Plymouth, U.K.; version 6), using temporal phytoplankton and zooplankton species abundance data, in order to identify community composition similarities with regard to habitat (inlet, middle and outlet samples from artificial and natural side-arms and the river) and connectivity phase. Interpretation of MDS plots is based on the understanding that points close to each other were more similar in terms of community composition than those plotted further away. A stress value of <0.2 indicates the MDS plot was at the acceptable level to represent data reliably in two-dimensional space (McCune et al. 2002). Where stress values >0.2 occurred, data was analysed in three-dimensional space and presented in pairs of axes in two-dimensional space for easy interpretation. Vector plots were overlaid with a Spearman correlation coefficient of r_s >0.2, using physico-chemical data to identify how community composition may have been influenced by physico-chemical variables. A two-way PERMANOVA was used to test for any significant differences in community composition between habitats (artificial and natural side-arms and river), between connectivity phases, and for any interaction between these two factors. PERMANOVA *P* values <0.05 were considered significant. Pair-wise tests in PERMANOVA were used to identify which habitat/s and/or connectivity phases were causing significant differences.

A one-way PERMANOVA was used to test for significant differences of phytoplankton community composition between the inlet, middle and outlet samples

in each of the three connectivity phases. The same transformations and pair-wise tests were used as above.

Spatial survey

Principal Component Analysis (PCA) was used to explore groupings of sites. Two factor planes were used as they explained >50% of the total variability in the data. A correlation matrix was used with physico-chemical variables, nutrients, suspended solids and chlorophyll *a* concentration for each replicate (inlet, middle and outlet) from each of the 8 sites.

Using STATISTICA, a one-way ANOVA was used to test for any significant differences in nutrient concentrations (NH_4-N, NO_3-N, PO_4-P, TN and TP), TSS values and chlorophyll *a* concentrations between the eight spatial side-arm sites. Inlet, middle and outlet samples within each site were used as replicates. *P* values < 0.05 were considered significant. A post-hoc test (Tukey test) was used to identify which habitat was causing significant differences. All data were normalised by the river values taken at the upstream end of each site, and the same transformations and tests for assumptions were used as above.

Non-metric MDS plots were produced in Primer using spatial phytoplankton species abundance data in order to explore community composition similarities with regard to habitat. Vector plots were overlaid with a Spearman correlation coefficient of r_s >0.2, using physico-chemical data to identify how community composition is influenced by physico-chemical variables. Connectivity ranking was an included variable. A one-way PERMANOVA was used to test for any significant differences in community composition between habitats. PERMANOVA *P* values <0.05 were considered significant. Pair-wise tests in PERMANOVA were used to identify which habitat/s was causing significant differences.

3 Results: Connectivity phases

The aim of this study was to determine the influence hydrological connectivity of side-arms and the river. A Principal Components Analysis (PCA) with a correlation matrix was used to identify the role of connectivity of side-arms with the main river channel in the lower Waikato River based on nutrients (TP, NO_3-N, NH_4-N, TP and PO_4-P), TSS, chlorophyll *a* and other physico-chemical data (temperature, conductivity, dissolved oxygen and pH). To investigate the role of connectivity, the twelve month sampling period was broken up into three periods based on monthly observation data (Table 3-1). The artificial and natural side-arms were assigned the same connectivity ranking for each month.

Table 3-1 Monthly observations of connectivity status between artificial and natural side-arms and the main river channel. Connectivity rankings indicate: 1, completely connected, 3, connection at inlet but not outlet, 4, connection at outlet but not inlet, 5, complete disconnection. Connectivity rankings presented apply to the artificial and natural side-arms as they had the same rankings.

Month	Year	Connectivity Phase	Season	Connectivity ranking*
Nov	2009	1	Late spring-summer	1
Dec	2009	1		1
Jan	2010	1		1
Feb	2010	1		1
Mar	2010	2	Autumn	3
Apr	2010	2		4
May	2010	2		5
Jun	2010	3	Winter	1
Jul	2010	3		1
Aug	2010	3		1
Sep	2010	3		1
Oct	2010	3		1

Ranking of 2 (Completely connected with high retention) was not recorded during the temporal study).

A pattern of grouping by connectivity phase was evident for the artificial and natural side-arm sites (Figure 3-1a, b). Figure 3-1b illustrates that the natural side-arm inlet grouped connectivity phase 1 and 2 together, similar to the pattern observed in the river sites at the same time period (November-May). The river sites overlap from November to May, these groups had different properties than the group of June to October (Figure 3-1c).

Physico-chemical properties based on connectivity of the side-arms with the river are discussed further in subsequent sections.

a)
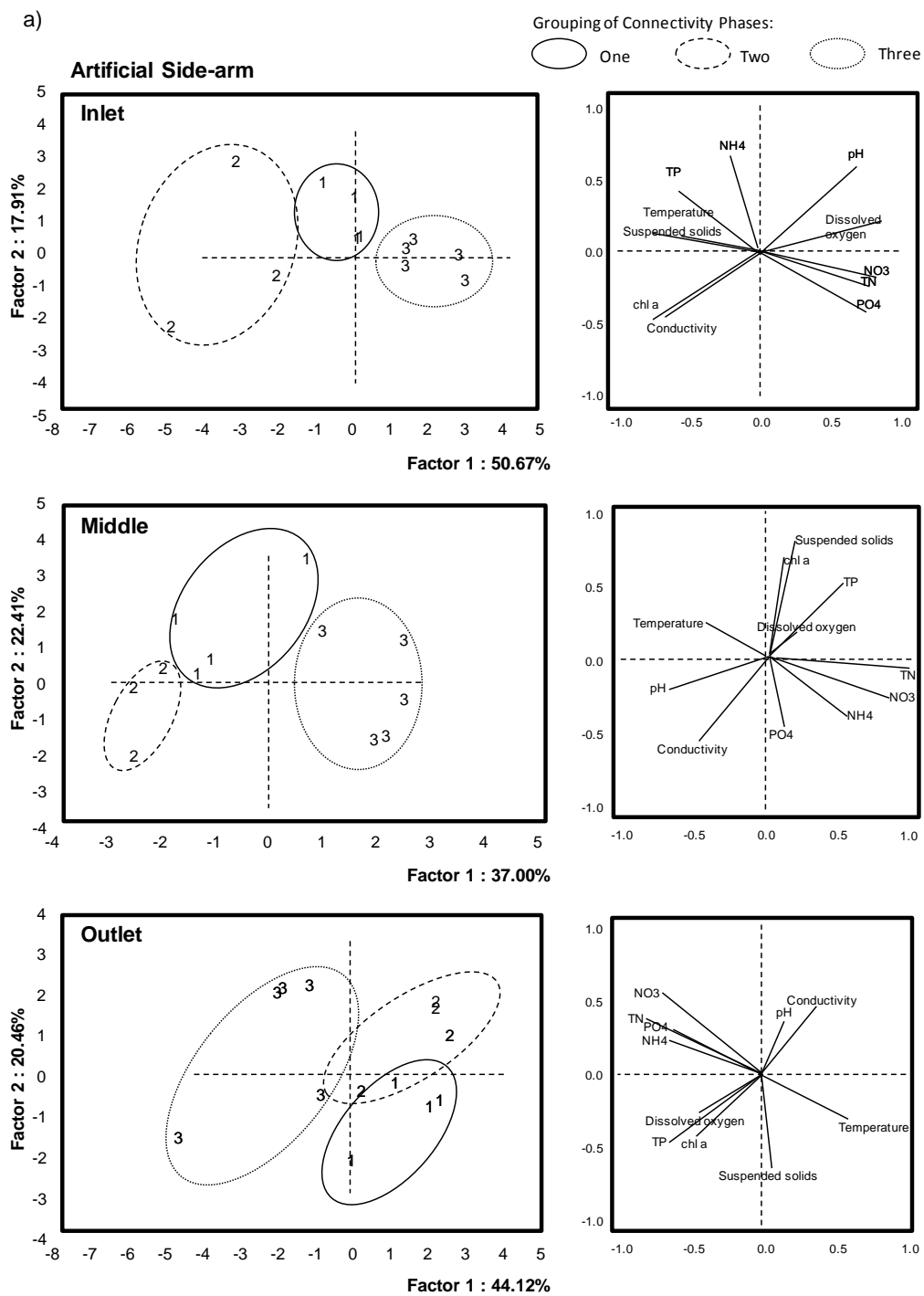
b)
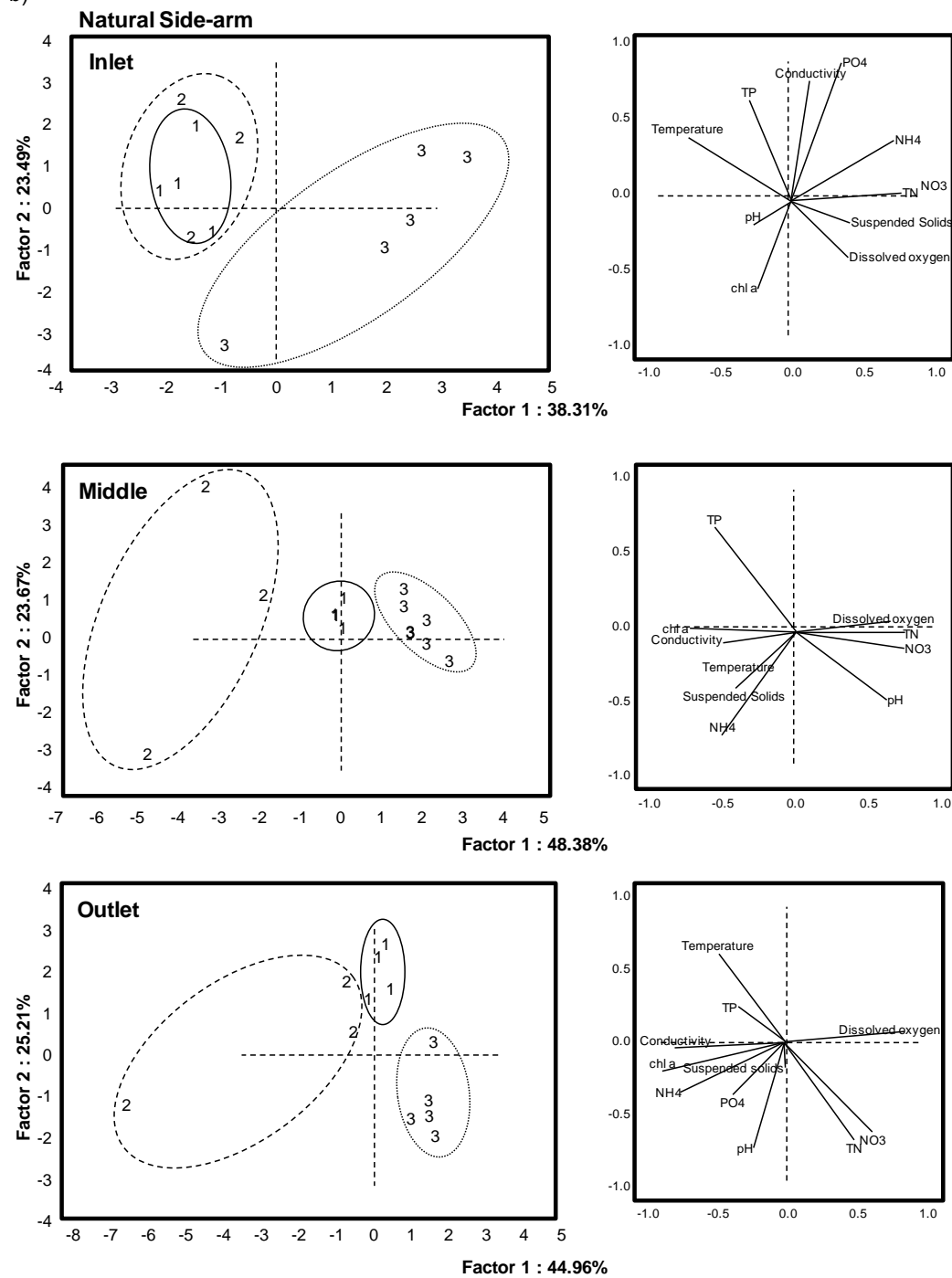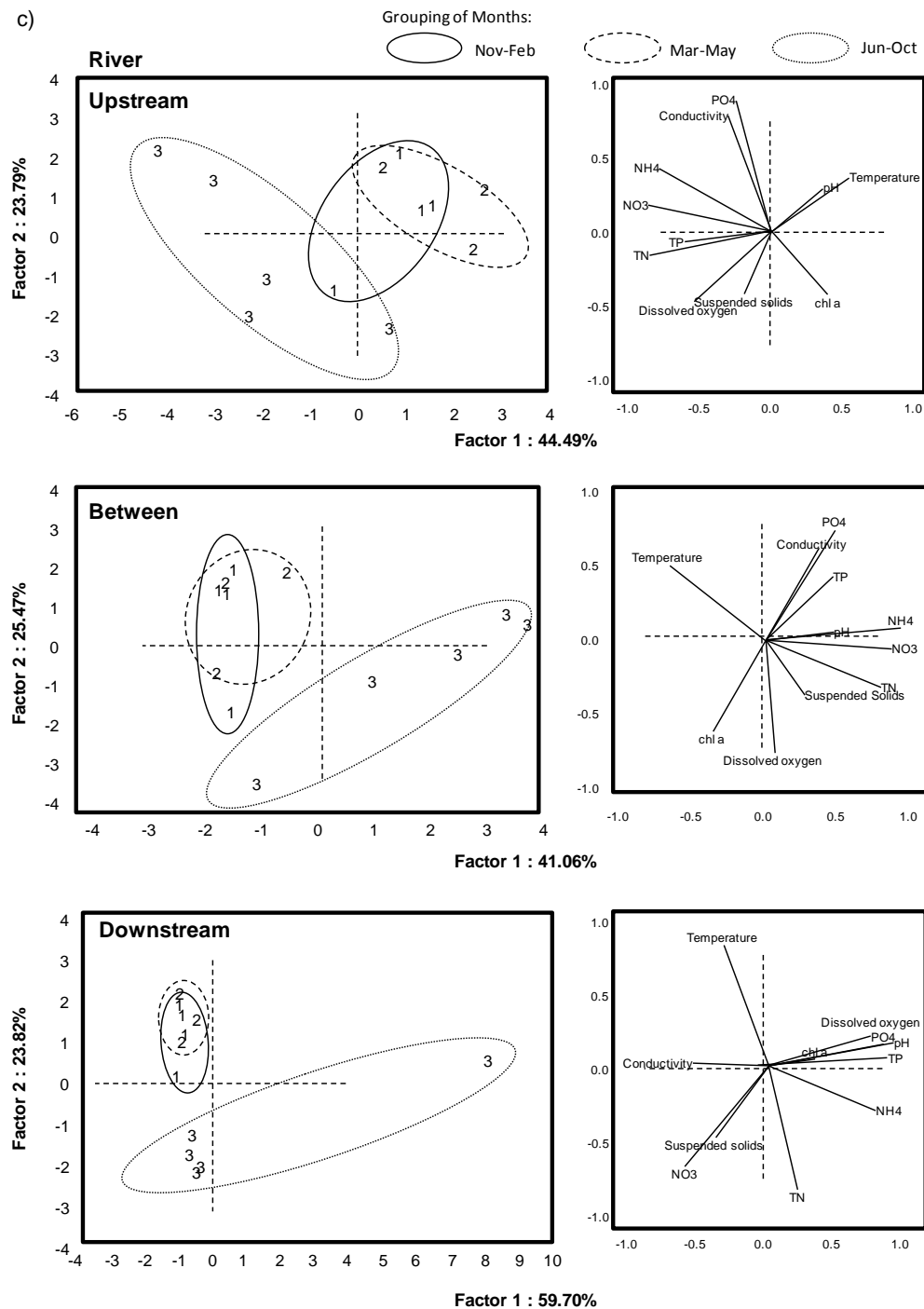
Figure 3-1a and b Principal Components Analysis (PCA): Groups based on proposed connectivity phases (1-3) for each side-arm site (artificial and natural side-arm inlet, middle and outlet sites). Figure 3-2c is grouped based on month (November 2009- Feb 2010, March-May2010 and June-October 2010) for the river sites (upstream, in-between and downstream of side-arm sites in the temporal study). The correlation plots on the right were based on two factors, using physico-chemical, nutrient, suspended solids and chlorophyll *a* data.

4 Results: Temporal study physical and chemical dynamics

An objective in this study was to determine temporal nutrient processing patterns by analysing whether concentrations of nitrogen and phosphorus species and other water column variables such as suspended solids differ compared to river concentrations. Nutrients, suspended solids and physico-chemical variables were spot-measured monthly for twelve months (November 2009-October 2010) in the side-arms and river. Measurements were also taken continuously within the side-arms for water temperature and dissolved oxygen at various time scales.

4.1 Side-arm flow regime

River level data taken from the Tainui Bridge in Huntly demonstrates intermediate river levels from November to February, with moderate fluctuations (Figure 4-1). Low river level between March and May was observed with minimal fluctuation. High river levels were measured with high fluctuations during winter (June to October).
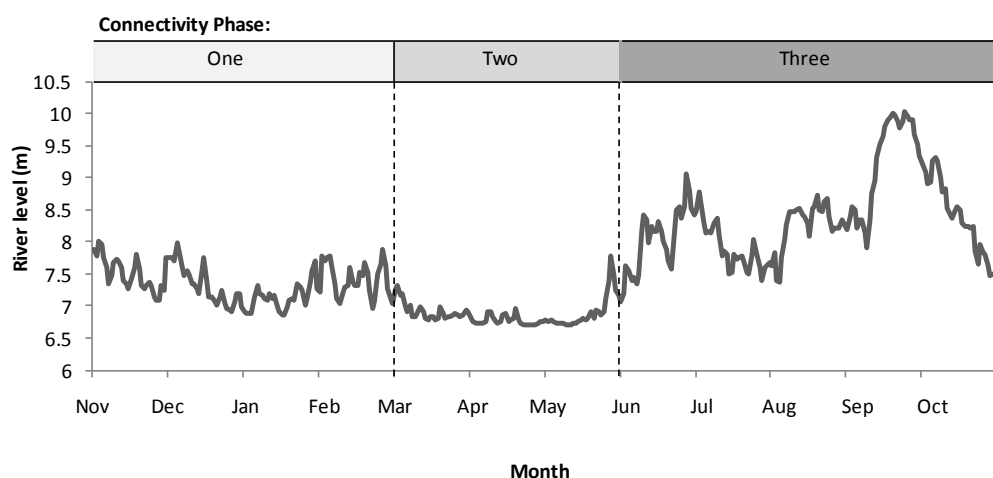
Figure 4-1 River level taken from the flow recorder at Tainui Bridge, Huntly, for the temporal sampling period (November 2009-October 2010). Connectivity phases are shown: Phase 1 (November 2009-February 2010) connected with the main river channel; phase 2 (March 2010-May 2010), some form of disconnection between the side-arms and the main river channel; and phase 3 (June 2010-October 2010), connected with the main river channel.

The level of the river at the time of monthly observations was taken for each disconnected observation and used to determine the period of time the side-arms were disconnected from the river over the twelve month sampling period (Table 4-1).

The side-arms were disconnected for almost 20% of the sampling period with three out of twelve sampling months (25%) classed as disconnected; (connectivity phase 2).

Table 4-1 Period of side-arm disconnection from the main river channel during the twelve-month sampling period using observations of disconnection of both side-arms and corresponding river level (number of days and percentage of sampling period). See Table 3-1 for definitions of connectivity rankings.

Observed Connectivity ranking	Observed River level (m)	Number of days	Percentage of time
3	6.899	19	5.2%
4	6.828	37	10.1%
5	6.725	16	4.4%
Total	**<6.899**	**72**	**19.8%**

Flow in the artificial and natural side-arms was low during connectivity phase 1 (<0.5 m^3s^{-1}), non-existent during phase 2 and high during phase 3 (2.0-43.0 m^3s^{-1}) (Figure 4-2). Side-arm retention was therefore high during phases 1 and 2, and low during phase 3 for both side-arms. During connectivity phase 2, the side-arms experienced differing levels of disconnection; 19 days of inflow connection with high retention, 37 days of no inflow but possible backwater connection with high retention, and 16 days of no incoming water and high retention (Table 4-1).
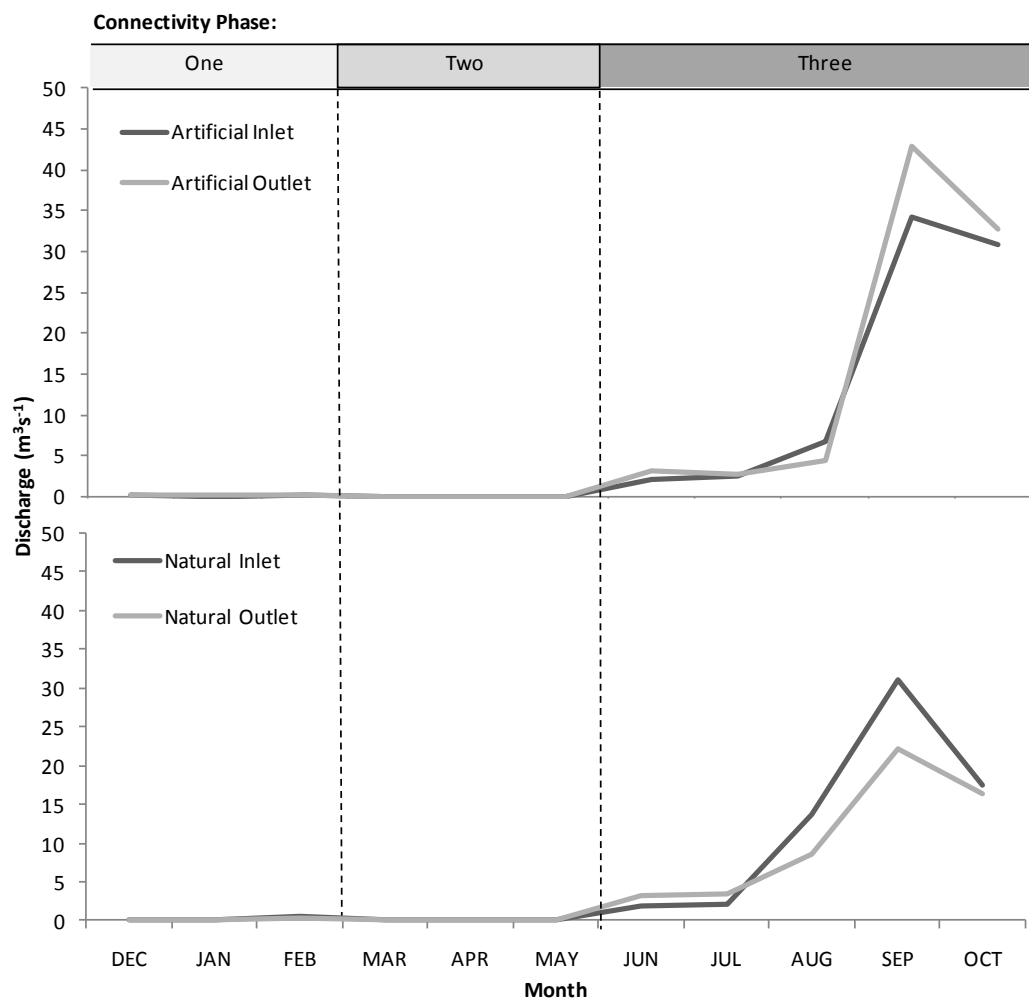
Figure 4-2 Monthly discharge at inlet and outlet of the artificial and natural side-arms. Connectivity phases 1-3 are labelled according to definition in Table 3-1.

Differences in discharge between the inlet and outlet during connectivity phase 3 were the artificial side-arm outlet having higher discharge at times than the inlet., the natural side-arm demonstrated the opposite; the outlet was lower in discharge than the inlet (Figure 4-2).

4.2 Continuous measurements

Dissolved oxygen (DO) data were obtained in the artificial side-arm over a minimum of 48 hours on two occasions; 27-30 January 2010 and 13-16 July 2010. They showed diel fluctuations of increased DO during the day time. There did not appear to be any clear lag between the upstream and downstream stations (Figure 4-3). The

diurnal range appeared to be roughly double in January when DO ranged from 4.1 to 14.3 mg/l, compared to July when the range was 6.4-11.1mg/l.
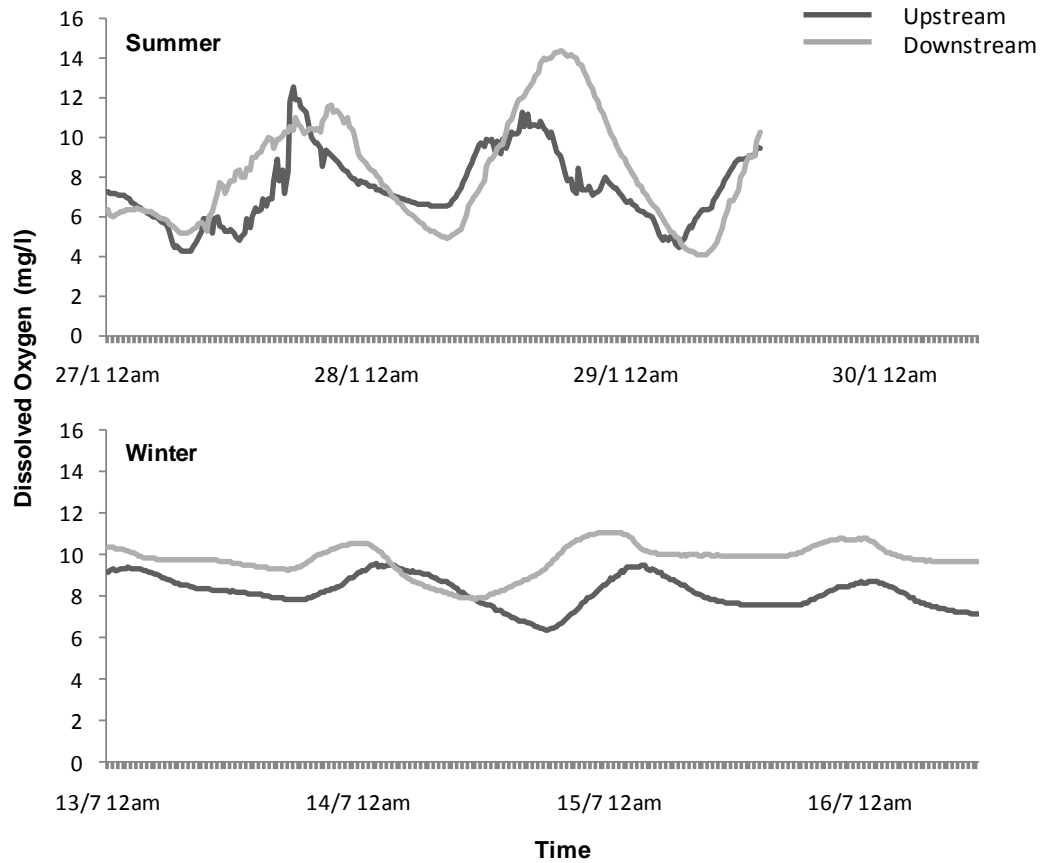
Figure 4-3 Diel dissolved oxygen measurements logged on two occasions in the artificial side-arm; January 2010 and July 2010 for a minimum of 48 hours. Upstream data set was obtained from a station situated in the middle distance of the side-arm, downstream data set was from a station at the outlet of the side-arm.
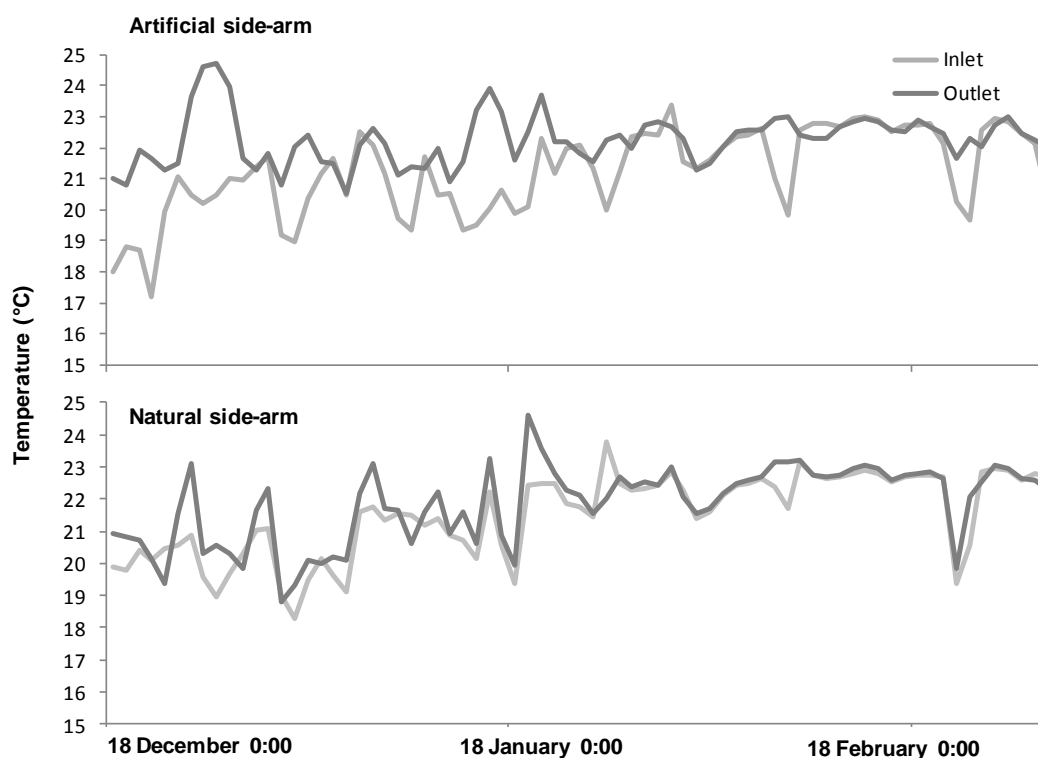
Figure 4-4 Mean daily water temperature data over a three-month summer period (December 2010-February 2010) from the artificial and natural side-arms at the inlet and outlet points of each side-arm.

Water temperature was logged at four sampling locations (inlet and outlet sites for the artificial and natural side-arms). In summer between 18 December 2009 and 28 February 2010 when the side-arms were connected with the main river channel (Figure 4-4). There are large ranges in temperature over the three-month logging period (artificial side-arm inlet 17.2-23.4°C, outlet 19.6-24.7°C; natural side-arm inlet 18.3-23.8°C, outlet 15.4-24.6°C). The mean temperature in the artificial side-arm inlet was 21.2°C, whilst the outlet had a slightly higher mean of 22.3°C. The natural side-arm inlet mean was 21.5°C and the outlet mean was 21.9°C. Both the mean values and the trend of increase in temperature downstream were similar between the two side-arms. Although continuous monitoring was not conducted during the phase 2 disconnection period, spot water temperature measurements indicate a maximum value of (inlet 20.5°C, outlet 21.9°C; inlet 23.1°C, outlet 22.4°C) in the artificial and natural side-arm, respectively during March-May 2010 (see section 4.3).

4.3   Monthly measurements: Between habitat variation

Monthly spot measurements were measured at one point once on each sample collection day for temperature, conductivity, dissolved oxygen, pH, nutrients and total suspended solids. These measurements were taken from the artificial and natural side-arm outlets and the three river sites to be compared between habitats and connectivity phases.

Physico-chemical factors at the side-arm outlets and the three river sites varied with time and between habitats (Figure 4-5). Temperature was consistent among habitat types but varied between connectivity phases, with phase 1 having the highest temperatures and phase 3 having the lowest (phase 1 range, 15.7-24.5°C; phase 3 range, 10.7-14.4°C) (Figure 4-5a).

Specific conductivity was consistent between river sites (143.0-196.9 µs cm^{-1}) across the twelve-month sampling period (presented for convenience in Figure 4-5 as connectivity phase 1 to 3). An increase in conductivity was evident in the artificial and natural side-arm outlets between connected phase 1 and disconnected phase 2. Artificial side-arm outlet means were 167.7 µs cm^{-1} (phase 1) and 196.1 µs cm^{-1} (phase 2). Natural side-arm outlet means were 164.9 µs cm^{-1} (phase 1) and 225.8 µs cm^{-1} (phase 2). Conductivity for phases 1 and 3 in the side-arm outlets were the same as the river (143.0 and 196.9 µs cm^{-1}, respectively) (Figure 4-5b).

Dissolved oxygen was not reduced substantially from saturation (>83.4% or 6.4 mg/l) in the river and artificial side-arm outlet across all connectivity phases. The river sites showed a gradual increase in dissolved oxygen between phase 1 and 3 (7.1-10.1 mg/l to 8.8-11.7 mg/l) (Figure 4-5c). The natural side-arm outlet exhibited a decrease in mean dissolved oxygen between phase 1 and the disconnected phase 2 (7.7 mg/l to 5.3 mg/l). Phases 1 and 3 in the natural side-arm outlet reflected the DO of the river. The artificial side-arm outlet had consistently high DO similar to the range observed in the river.

pH (Figure 4-5d) was higher in autumn (March-May) across all habitat types (connectivity phase 2).
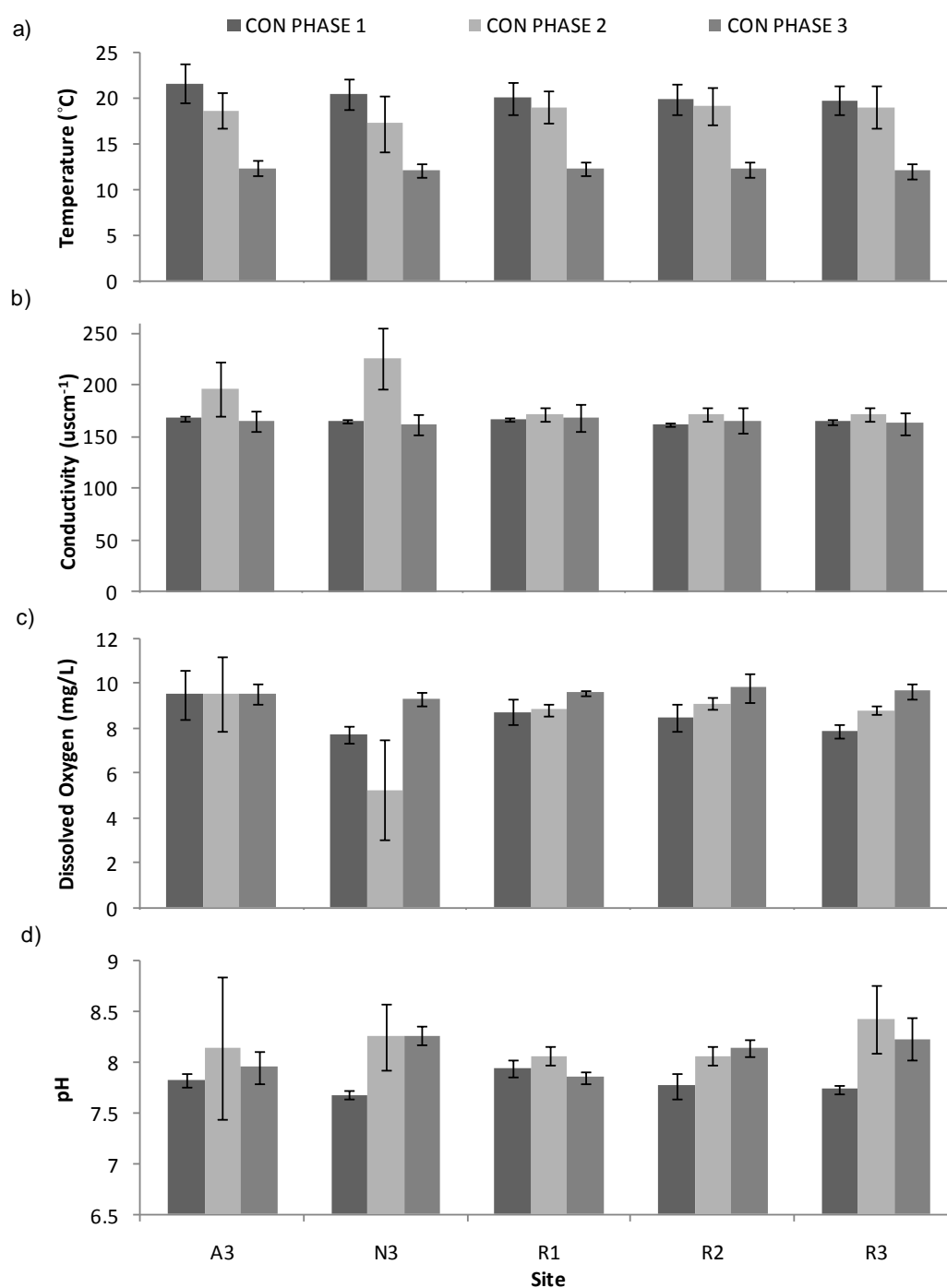
Figure 4-5 Physico-chemical variables, a) temperature, b) specific conductivity, c) dissolved oxygen and d) pH, for artificial side-arm outlet (A3), natural side-arm outlet (N3), and three river sites (R1-R3), at three different connectivity phases (refer to definition of connectivity phases in Table 3-1) . Values represent means ± S.E. (Refer to Appendix 1 – Nutrients & physico-chemical raw data for raw data)

Nutrients were measured at the outlet of each side-arm and the three sites of the river and compared at each connectivity phase. There was a general trend across the artificial side-arm outlet and river sites for a gradual increase in ammonium concentrations between connectivity phases 1 and 3 (artificial side-arm outlet mean from 0.02 to 0.05 mg/l, river mean from 0.03 to 0.06 mg/l) (Figure 4-6a). ANOVA results in Table 4-2 revealed a significant effect of habitat type, connectivity phase, and an interaction between habitat type and connectivity phase (difference between habitat types in a certain connectivity phase). Post-hoc tests confirmed that the natural side-arm outlet had a significantly higher ammonium concentration than the artificial side-arm outlet and the river sites during connectivity phase 2 (Table 4-3).
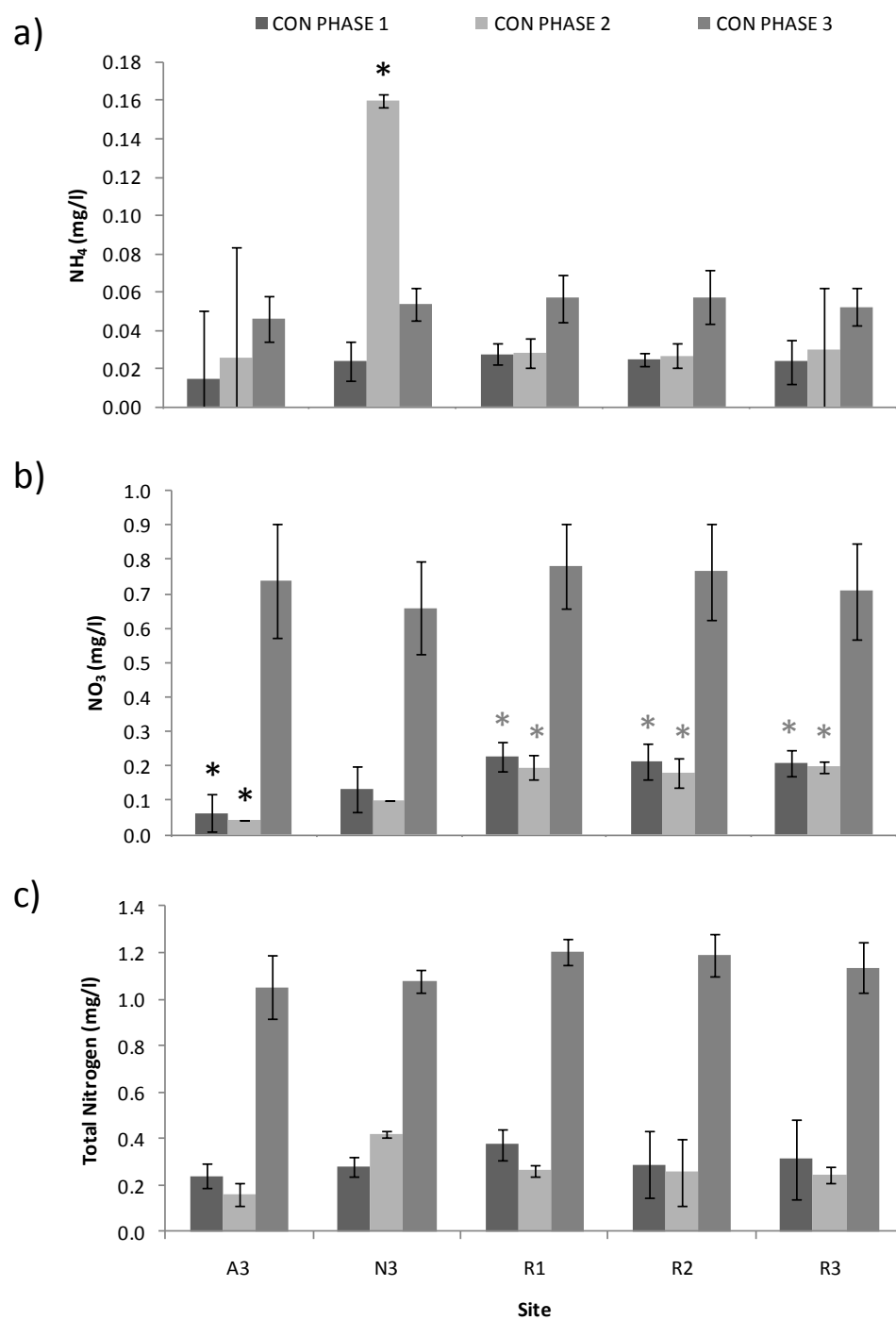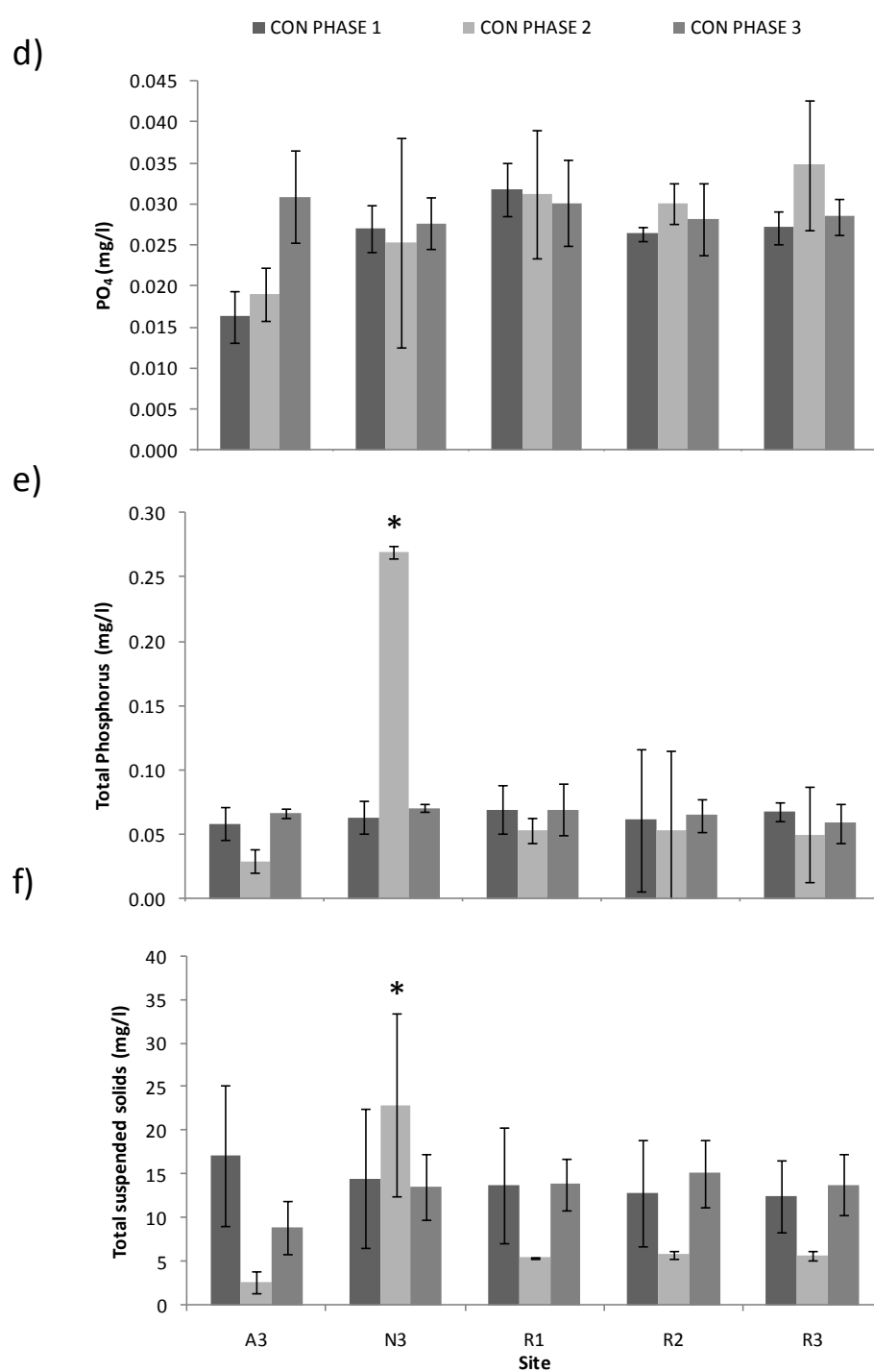
Figure 4-6 a-f Ammonium (NH$_4$-N), Nitrate (NO$_3$-N), Total nitrogen (TN), Phosphate (PO$_4$-P), Total phosphorus (TP), and total suspended solid concentrations for artificial side-arm outlet (A3), natural side-arm outlet (N3), and three river sites (R1-R3), at three different connectivity phases (refer to definition of connectivity phases in Table 3-1). Values represent means ± S.E. Asterisks mark the significant difference between the corresponding site and all other sites in that connectivity phase. Grey asterisks are used to indicate a significant difference between the black asterisk site and only the grey asterisk sites. See Table 4-2 for ANOVA results and Table 4-3 for full post-hoc test results. (Refer to Appendix 1 – Nutrients & physico-chemical raw data for raw data)

Table 4-2 Results of a two-way analysis of variance, testing the effect of habitat type (three river sites and outlet sites from the artificial and natural side-arms) and connectivity phase (Con Phase) (refer to definition of connectivity phases in Table 3-1) on nutrient concentrations (ammonium (NH_4-N), nitrate (NO_3-N), total nitrogen (TP), phosphate (PO_4–P) and total phosphorus (TP)). Significant effects ($P<0.05$) are indicated in bold.

	Effect	SS	DF	MS	F	P
NH_4-N	Habitat	0.729	4	0.182	6.217	**0.000**
	Con Phase	0.362	2	0.181	6.175	**0.004**
	Habitat*Con Phase	0.990	8	0.124	4.217	**0.000**
NO_3-N	Habitat	2.594	4	0.648	18.092	**0.000**
	Con Phase	0.784	2	0.392	10.941	**0.000**
	Habitat*Con Phase	1.457	8	0.182	5.081	**0.000**
TN	Habitat	0.947	4	0.237	13.051	**0.000**
	Con Phase	0.180	2	0.090	4.959	**0.011**
	Habitat*Con Phase	1.289	8	0.161	8.886	**0.000**
PO_4-P	Habitat	0.526	4	0.134	2.995	**0.028**
	Con Phase	0.186	2	0.093	2.121	0.131
	Habitat*Con Phase	0.628	8	0.079	1.788	0.104
TP	Habitat	0.236	4	0.059	7.805	**0.000**
	Con Phase	0.006	2	0.003	0.382	0.684
	Habitat*Con Phase	0.229	8	0.029	3.786	**0.001**

Table 4-3 Post-hoc Tukey test results showing the significant difference between habitat types (three river sites; R1, R2, R3, and outlet sites from the artificial, A, and natural, N, side-arms) within each connectivity phase (1-3) (refer to definition of connectivity phases in Table 3-1) with regard to nutrient concentrations (ammonium (NH_4-N), nitrate (NO_3-N), total nitrogen (TP), phosphate (PO_4-P) and total phosphorus (TP)). Significant effects ($P<0.05$) are indicated in bold. NS denotes no significant difference. The less than, greater than and equals symbols indicate differences between actual values.

	Connectivity phase	Post-hoc result
NH_4-N	1	NS
	2	**R1=R2=R3=A<N**
	3	NS
NO_3-N	1	**R2=R3=(R1<N)<(A=N)**
	2	**R2=R3=(R1<N)<(A=N)**
	3	NS
TN	1	**R2=R3=N=(R1<A)**
	2	**R1=R2=R3=A<N**
	3	NS
PO_4-P	1	NS
	2	NS
	3	NS
TP	1	NS
	2	**R1=R2=R3=A<N**
	3	NS

Nitrate concentrations showed a general increase between connectivity phases 2 and 3 across all habitats which could be attributable to seasonal effects (artificial side-arm outlet 0.04 mg/l to 0.74 mg/l; natural side-arm outlet 0.10 mg/l to 0.66 mg/l; river 0.19 mg/l to 0.75 mg/l) (Figure 4-6b). ANOVA results revealed highly significant effects of habitat type, connectivity phase and the interaction between habitat type and connectivity phase (Table 4-2). Post-hoc tests (Table 4-3) confirmed that, for the artificial side-arm outlet, nitrate concentrations at connectivity phases 1 and 2 were significantly different to river sites but not the natural side-arm outlet.

Total nitrogen concentrations (Figure 4-6c) displayed the same trend as nitrate; increasing concentrations between the second and third connectivity phase across all

habitat types, as nitrate is a major part of total nitrogen (artificial side-arm mean from 0.16 mg/l to 1.1 mg/l, natural side-arm mean from 0.42 mg/l to 1.08 mg/l, and river mean from 0.25 mg/l to 1.18 mg/l). ANOVA results revealed significant effects of habitat type and connectivity phase, and a significant interaction between habitat type and connectivity phase (Table 4-2). Post-hoc tests confirmed that total nitrogen concentrations in the artificial side-arm outlet (0.24 mg/l) at phase 1 were significantly lower than the levels in one river site (R1) (0.37 mg/l). Post-hoc results also confirmed that the natural side-arm outlet at phase 2 (0.42 mg/l) was significantly higher in total nitrogen concentration than the artificial side-arm outlet (0.16 mg/l) and river (0.25 mg/l) in that connectivity phase.

Phosphate concentrations showed no pattern over time from connectivity phases 1 to 3 in any of the habitat types (Figure 4-6d). Although ANOVA results revealed an overall significant effect of habitat type, likely reflecting the lower phosphate values in the artificial side-arm outlet in phases 1 and 2 (Table 4-2), post-hoc tests revealed no significant differences between habitat types (Table 4-3).

Total phosphorus concentrations were <0.07mg/l for the artificial side-arm outlet and the river sites during all three connectivity phases (Figure 4-6e). ANOVA revealed a significant effect of habitat type and an interaction between habitat type and connectivity phase (Table 4-2). Post-hoc tests in Table 4-3 confirmed a significant difference between the natural side-arm outlet and the artificial side-arm outlet and river at connectivity phase 2.

Measured total suspended solids (TSS) were analysed for variation between the side-arm and river habitats at each connectivity phase. Comparison between connectivity phase 1 (Figure 4-6f) and the other two phases were treated with caution as the number of samples within the connectivity phase 1 dataset was reduced due to analytical error around measuring equipment detection limits. There was a drop in TSS for the artificial side-arm outlet and river sites during connectivity phase 2 (Figure 4-6f), in contrast, there was a peak in the natural side-arm outlet TSS in connectivity phase 2.

ANOVA results revealed a significant effect of habitat type ($F_{4,39}$=6.2, P<0.001) and an interaction between habitat type and connectivity phase ($F_{8,39}$=5.1, P<0.001) on TSS. Post-hoc tests revealed significantly higher TSS concentrations in the natural side-arm outlet (mean, 22.92 mg/l) at connectivity phase 2 compared to the artificial side-arm outlet (mean 2.56 mg/l) and river habitats (mean 5.62 mg/l) at the same connectivity phase.

4.4   Monthly measurements: Within side-arm habitat variation

Monthly spot measurements as described previously were also taken from the artificial and natural side-arms at the inlet, middle and outlet to be compared between locations within each connectivity phase.

Temperature appears to be consistent longitudinally within both side-arms across all connectivity phases (Figure 4-7a, b)

For connectivity phases 1 and 3 there did not appear to be any difference in specific conductivity within side-arm habitats (Figure 4-7c, d). In connectivity phase 2 however, both the artificial and natural side-arms showed differences in conductivity between locations. The artificial side-arm appeared to have higher concentrations at the inlet and outlet sites (means: inlet 245.1 µs cm^{-1}, middle 181.4 µs cm^{-1}, and outlet 196.1 µs cm^{-1}). The natural side-arm appeared to increase longitudinally between the inlet and the outlet sites (means: inlet 172.0 µs cm^{-1}, middle 219.2 µs cm^{-1} outlet 225.8 µs cm^{-1}).

Dissolved oxygen concentrations showed a similar pattern to that of conductivity with no difference apparent within side-arms in phases 1 and 3 (Figure 4-7e, f). However, there was, like conductivity, a difference in DO within each side-arm during connectivity phase 2. The artificial side-arm had low concentrations at the inlet (4.1 mg/l), and high concentrations at the outlet (9.5 mg/l) (Figure 4-7e). The natural side-arm showed a decrease in DO between the inlet (8.0 mg/l), and middle (1.9 mg/l) sites, then an increase in concentration at the outlet site (5.3 mg/l) (Figure 4-7f).

Each side-arm maintained a stable pH throughout the three connectivity phases, except for the middle site in the artificial side-arm which had a pH of 10.0 during connectivity phase 2(Figure 4-7 g, h).
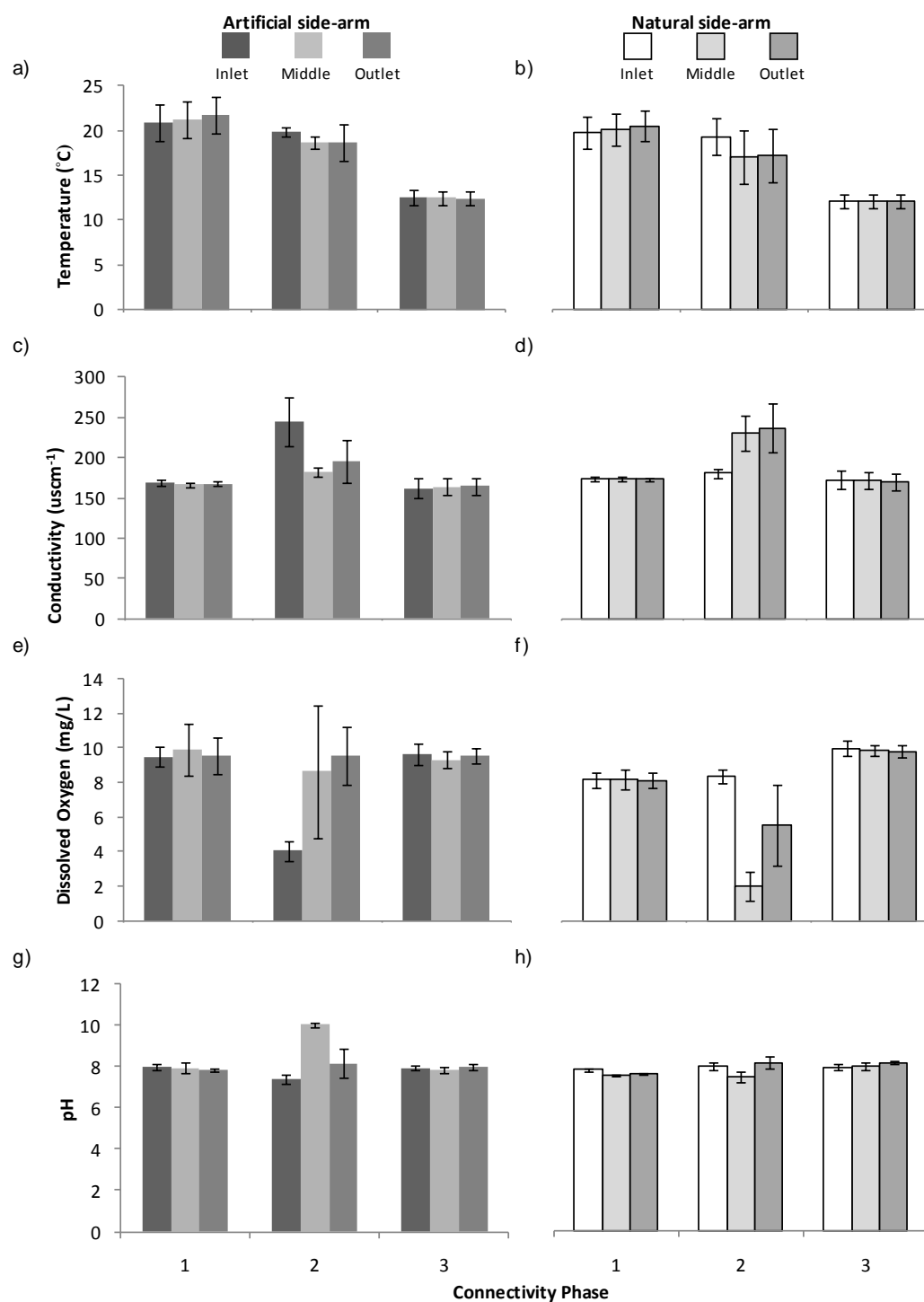
Figure 4-7 Physico-chemical variables in the artificial and natural side-arms (inlet, middle and outlet sites over twelve-month sample period); a) temperature in artificial side-arm, b) temperature in natural side-arm, c) specific conductivity in artificial side-arm, d) specific conductivity in natural side-arm, e) dissolved oxygen in artificial side-arm, f) dissolved oxygen in natural side-arm, g) pH in artificial side-arm, and h) pH in natural side-arm, at three different connectivity phases (refer to definition of connectivity phases in Table 3-1). Values represent means ± S.E. (Refer to Appendix 1 – Nutrients & physico-chemical raw data for raw data)

Nutrients measured were analysed for variation within each side-arm at each connectivity phase in order to understand longitudinal patterns occurring within each side-arm. The ammonium concentrations presented in Figure 4-8 revealed ammonium concentrations of the natural side-arm increased between the inlet and outlet at connectivity phase 2. Ammonium concentrations varied between 0.015–0.056 mg/l for the artificial side-arm and between 0.024–0.160 mg/l for the natural side-arm over the three connectivity phases. However, the ANOVA and post hoc test results did not indicate statically significant differences along either side-arm.
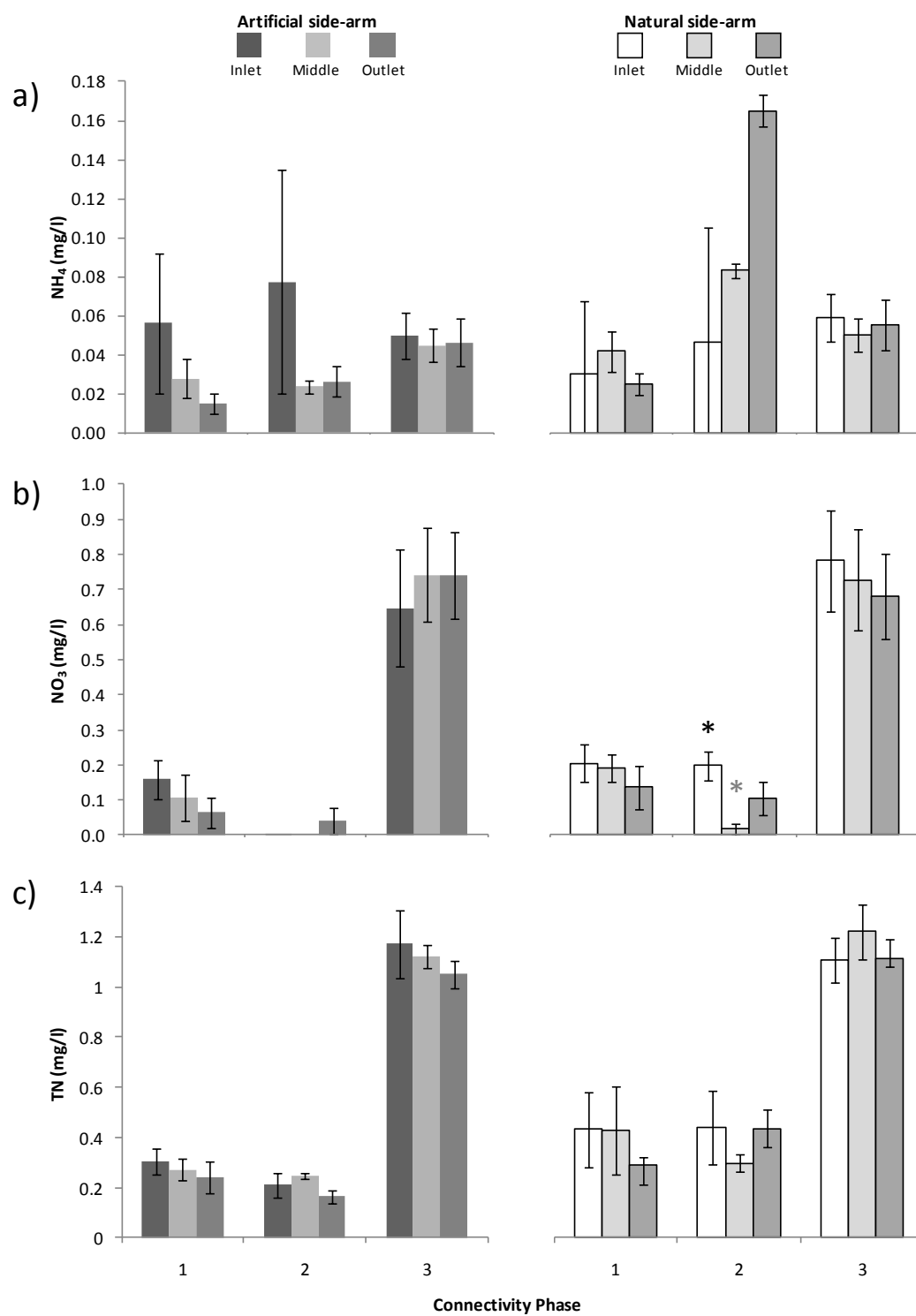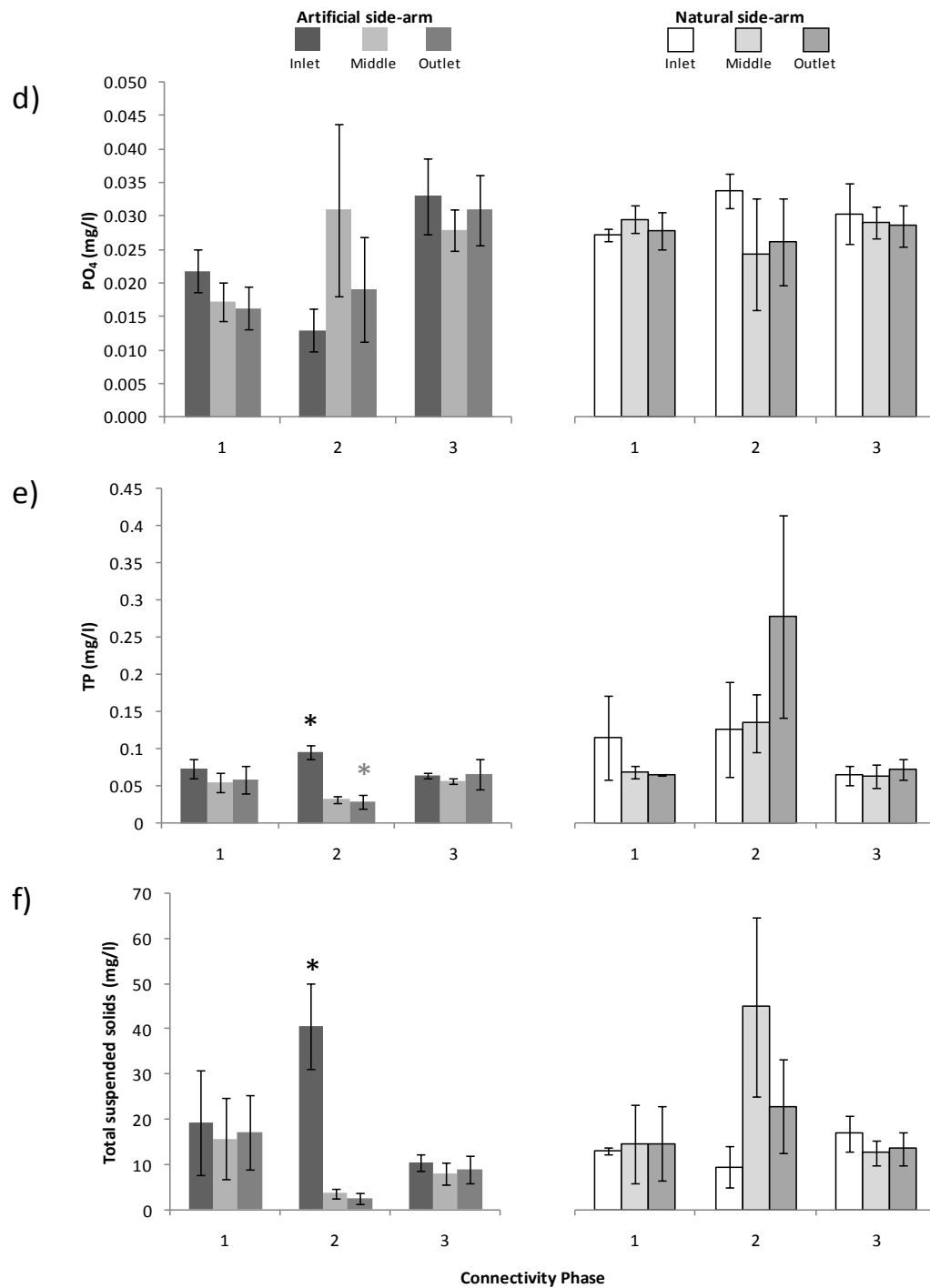
Figure 4-8 a-f Ammonium (NH_4-N), Nitrate (NO_3-N), Total nitrogen (TN), Phosphate (PO_4-P), Total phosphorus (TP), and total suspended solid concentrations for three locations within each of the artificial and natural side-arms (inlet, middle and outlet), at three different connectivity phases 1-3; (refer to definition of connectivity phases in Table 3-1). Values represent means ± S.E. Asterisks mark the significant difference between the corresponding site and all other sites in that connectivity phase (within the specific side-arm; artificial or natural). Grey asterisks are used to indicate a significant difference between the black asterisk site and only the grey asterisk site/s. (Refer to Appendix 1 – Nutrients & physico-chemical raw data for raw data)

Nitrate (NO_3-N) concentrations in the artificial and natural side-arm outlets both appeared to decrease between the inlet and outlet sites for connectivity phase 1 (artificial side-arm inlet mean 0.158 mg/l and outlet mean 0.064 mg/l; natural inlet mean 0.198 mg/l and outlet mean 0.132 mg/l) (Figure 4-8b). ANOVA results highlighted a significant effect of location (inlet, middle and outlet) for the natural side-arm ($F_{2,27}$=10.4, P<0.001); post-hoc test results revealed a significant difference occurred between the inlet (0.191 mg/l) and middle (0.016 mg/l) site at connectivity phase 2.

The range of total nitrogen concentrations presented in Figure 4-8c exhibited no clear pattern between different locations (inlet, middle or outlet) in the artificial or natural side-arms. ANOVA results suggested a significant effect of location in the artificial side-arm ($F_{2,27}$=3.6, P=0.042); however, post-hoc tests indicated no significant difference between pairs of locations.

Phosphate (PO_4-P) concentrations (Figure 4-8d) showed no difference between location for the artificial or natural side-arms. ANOVA results revealed no significant effect of location type at any of the connectivity phases.

Total phosphorus concentrations for each location (inlet, middle and outlet) for the artificial and natural side-arms appeared to be similar to each other. An exception to this was for the artificial side-arm at connectivity phase 2 where the inlet concentration of 0.096 mg/l appeared larger than the middle; 0.032 mg/l, and outlet; 0.029 mg/l concentrations (Figure 4-8e). ANOVA results indicated a significant effect of location (inlet, middle or outlet) for the artificial side-arm ($F_{2,26}$=6.5, P=0.004); a post-hoc test confirmed a difference between the inlet and outlet sites during connectivity phase 2.

Suspended solid measurements were analysed for variation within each side-arm in order to understand longitudinal patterns. As mentioned above, statistical validity of connectivity phase 1 in Figure 4-8f was treated with caution as the number of samples within the connectivity phase 1 data set was reduced due to analytical error around measuring equipment detection limits (Figure 4-8f). During connectivity

phases 1 and three there was no trend in the TSS concentration between locations within each of the side-arms (Figure 4-8f). During connectivity phase 2 however, TSS was higher in the inlet, (40.6 mg/l) compared to the middle (3.7 mg/l) and outlet (2.6 mg/l) of the artificial side-arm. The natural side-arm appeared to have higher TSS concentration in the middle (44.9 mg/l) and outlet (22.9 mg/l) sites compared to the inlet (9.4 mg/l) during connectivity phase 2. ANOVA results confirmed a significant effect of location (inlet, middle or outlet) in the artificial side-arm ($F_{2,24}$=16.4, P<0.001), but not for the natural side-arm. Post-hoc test results indicated the inlet in the artificial side-arm was significantly higher than the middle and outlet sites for connectivity phase 2.

5   Results: Temporal study phytoplankton dynamics

An objective of this study was to determine whether phytoplankton community composition and dominant species differed between natural and artificial side-arms and the river with regard to different phases of connectivity. Twelve monthly (November 2009-October 2010) samples were collected for phytoplankton analysis along with chlorophyll *a* concentrations to act as an indicator for phytoplankton biomass.

5.1   Monthly measurements: Between-habitat variation

Phytoplankton biomass (chlorophyll *a*) and community composition data were analysed from the artificial and natural side-arms (inlet, middle and outlet sites) and the three river sites to be compared between habitats and connectivity phases.

Figure 5-1 illustrated consistent Chlorophyll *a* concentrations over time at the river sites, but concentration differed across connectivity phases in the artificial and natural side-arm habitats at connectivity phase 2. ANOVA results revealed a significant effect of habitat type ($F_{4,45}$=5.7, P<0.001) and an interaction between habitat type and connectivity phase ($F_{8,45}$=2.6, P<0.05). Post-hoc tests confirmed a significant difference between the natural side-arm (mean 18.04 µg l^{-1}) and artificial side-arm (mean 3.93 µg l^{-1}) outlets at connectivity phase 2
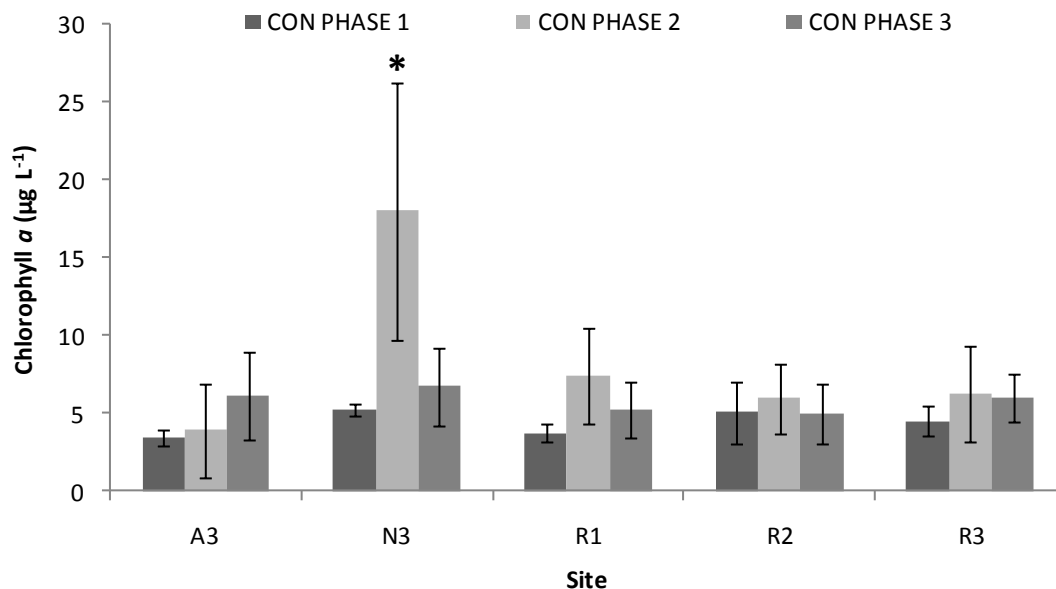
Figure 5-1 Chlorophyll *a* concentrations for the artificial side-arm outlet (A3), natural side-arm outlet (N3), and three river sites (R1-R3), at three different connectivity phases 1-3; (refer to definition of connectivity phases in Table 3-1). Values represent means ± S.E. Asterisk indicates significant difference between the artificial side-arm and natural side-arm at connectivity phase 2.

The species richness varied between habitats and across connectivity phases (Figure 5-2). The river was notably lower in species richness at each connectivity phase compared to the side-arm habitats. During March-May (equivelant to side-arm connectivity phase 2), the river had its highest number of species (16 species).

The artificial and natural side-arms had very similar species numbers (41-44 species), except for in connectivity phase 2 when the number of species the natural side-arm exceeded that in the artificial side-arm. It appears that the number of species in both side-arms decreased during connectivity phase 2 most notable in the artificial side-arm. The natural side-arm had a relatively constant number of species 37-41 species during phases 1-3, while the artificial side-arm was more variable (phase 1, 44 species; phase 2, 29 species; phase 3, 42 species). Diatoms and chlorophytes were the dominant taxa at all sites at all connectivity phases.
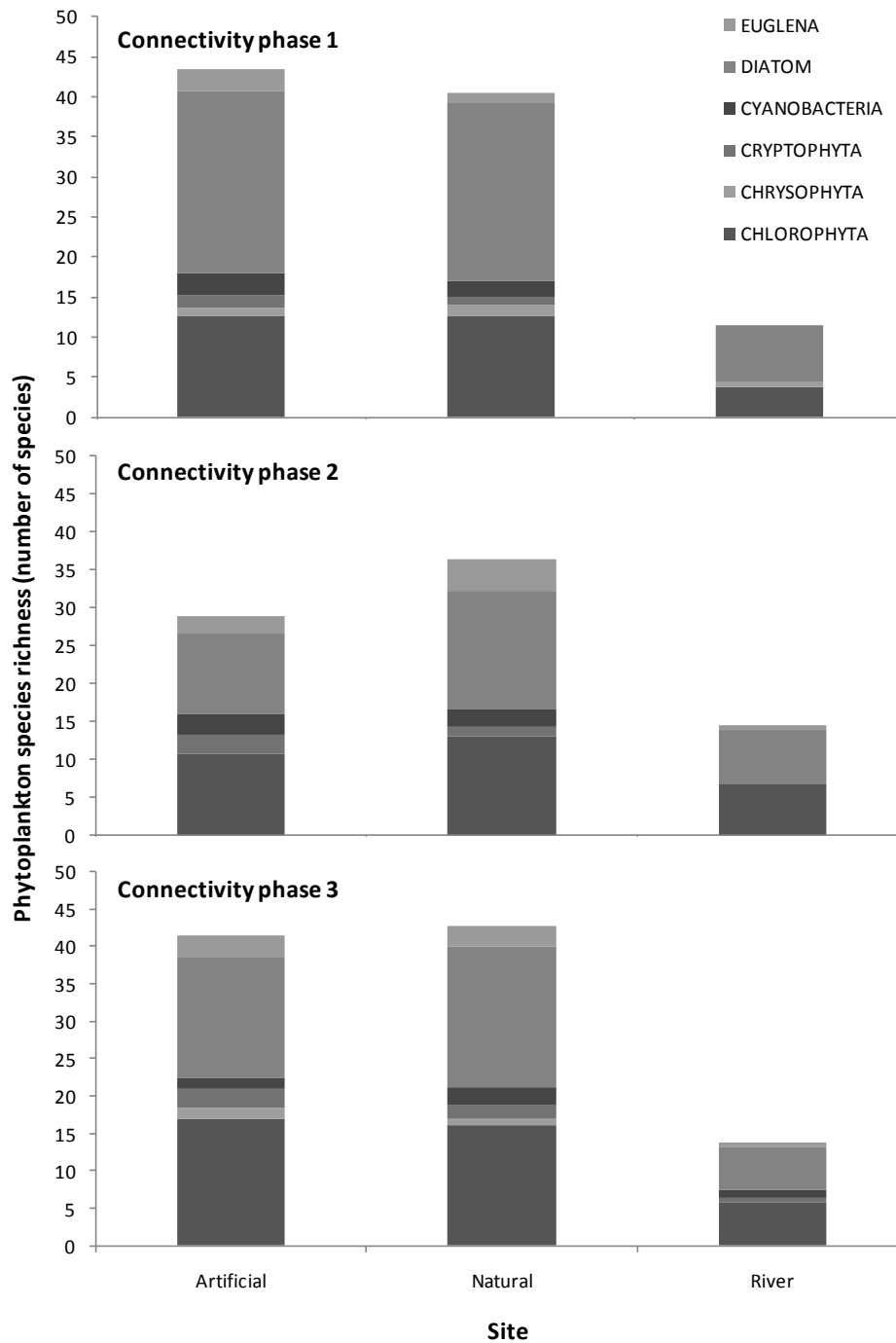
Figure 5-2 Phytoplankton species richness in each Phyla for each habitat type (artificial or natural side-arm and river) at each connectivity phase (for a definition of these see Table 3-1).

The dominance of phytoplankton phyla was based on number of species within each phyla (species richness), dominant species were based on abundance and biomass (based on observation). The dominant species in the artificial side-arm during

connectivity phase 1 were *Asterionella* spp., *Fragilaria* spp., *Chlamydomonas* spp. and *Aulacoseira* spp. The dominant species in the natural side-arm during connectivity phase 1 were *Asterionella* spp. and *Fragillaria* spp. *Aulacoseira* spp. and *Chlorella* spp. were the next dominant species, respectively. *Fragillaria* spp. and *Asterionella* spp. were the dominant species in the river between November and February (Table 5-1).

Table 5-1 Dominant phytoplankton species with abundance values (cells/ml) for the artificial and natural side-arms and river at each connectivity phase. Refer to Appendix 2 – Phytoplankton raw data for more information.

Habitat	Connectivity phase				
Artificial side-arm	1	*Asterionella*	*Fragilaria*	*Chlamydomonas*	*Aulacoseira*
		1113.1	456.5	209.9	187.5
	2	*Cryptomonas*	*Chlorella*	*Cocconeis*	*Chlamydomonas*
		2012.5	781.2	610.4	286.1
	3	*Asterionella*	*Dinobryon*	*Aulacoseira*	*Chlorella*
		1059.2	458.1	344.3	156.7
Natural side-arm	1	*Fragilaria*	*Asterionella*	*Aulacoseira*	*Chlorella*
		1442.9	1303.3	289.5	234.7
	2	*Chlorella*	*Aulacoseira*	*Trachelomonas*	*Chlamydomonas*
		2860.3	594.7	541.6	420.4
	3	*Asterionella*	*Aulacoseira*	*Selenastrum*	*Chlorella*
		1342.9	463.1	352.2	133.7
River	1	*Fragilaria*	*Asterionella*	*Chlorella*	*Aulacoseira*
		1666.3	74.7	273.7	244.8
	2	*Chlorella*	*Aulacoseira*	*Mougeotia*	*Kirchneriella*
		1503.6	478.4	337.2	135.9
	3	*Asterionella*	*Aulacoseira*	*Selenastrum*	*Chlorella*
		1088.0	467.8	333.1	211.4

Cryptopmonas spp. and *Chlorella* spp. were the most dominant species in the artificial side-arm during connectivity phase 2. During connectivity phase 2, the natural side-arm was dominated by *Chlorella* spp., while *Aulacoseira* spp. and *Trachelomonas* spp. followed. The dominant species in the river during March-May were *Chlorella* spp., *Aulacoseira* spp., and *Mougeotia* spp. (Table 5-1).

Asterionella spp., followed by *Selenastrum* spp. and *Aulacoseira* spp. were the most dominant species for the artificial and natural side-arm and river during connectivity phase 3 (June-October) (Table 5-1).

Statistical analysis into whether Lake Hakanoa samples had any effect on downstream samples (natural side-arm inlet, middle and outlet, and river downstream of side-arms) was not possible due to the small number of samples analysed; therefore, visual inspection of the data was used instead.

Phytoplankton community composition was displayed in a non-metric multi-dimensional scaling (MDS) plot (Figure 5-3) based on log(x+1) transformed total abundances. Abundance data was from each side-arm site (inlet, middle and outlet), each river site (upstream, middle and downstream) and the lake hakanoa outlet for 12 months. Figure 5-3 shows that the side-arm and river sites grouped closely together relative to Lake Hakanoa which grouped to the left of the ordination towards Axis 1, except for one point that is related to high flows when the lake was shut off from the outlet to prevent flooding. This plot suggests that the Lake Hakanoa outlet did not influence phytoplankton community composition of the natural side-arm or the downstream river site.
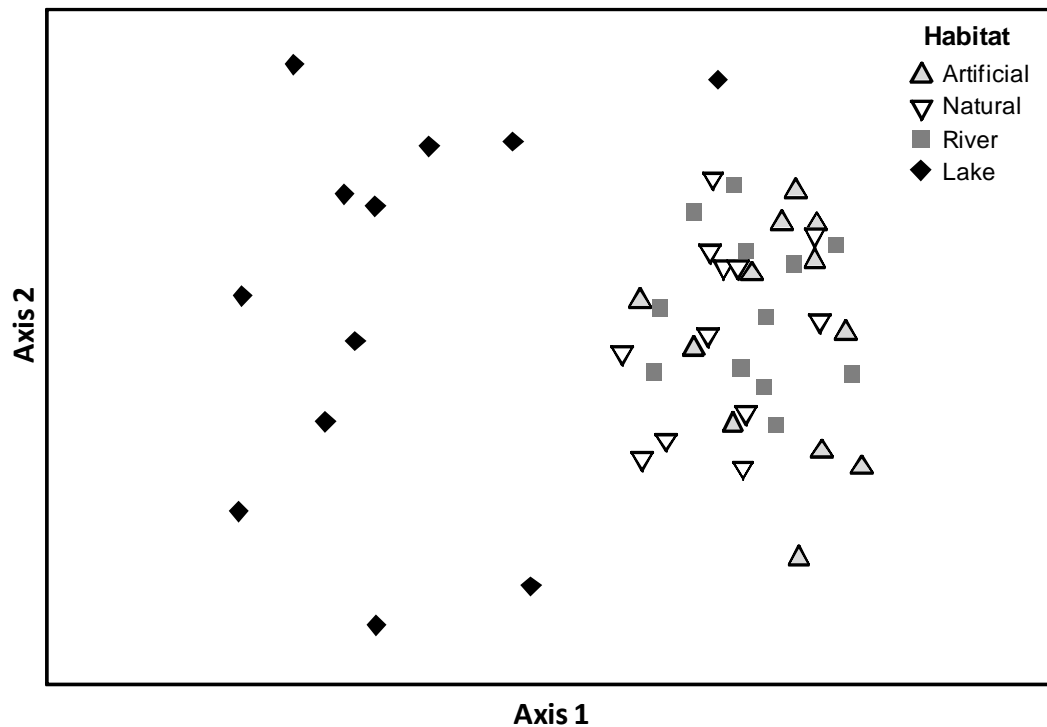
Figure 5-3 Multi-dimensional scaling plot showing phytoplankton community composition using mean monthly (November 2009-October 2010) abundances from all sites within the artificial side-arm, natural side-arm, river and Lake Hakanoa outlet. This plot has a 2D stress value of 0.19.

Phytoplankton community composition is presented in a series of non-metric multi-dimensional scaling (MDS) plots (Figure 5-4) based on log(x+1) transformed total abundance data was from each side-arm site (inlet, middle and outlet), each river site (upstream, middle and downstream) for 12 months. A plot was made for both habitat type and connectivity phase to explore possible relationships; the connectivity plot is presented here as no relationships were revealed in the habitat type plot. Figure 5-4a revealed that phytoplankton community composition was strongly related to the connectivity phase in which samples were taken, this was particularly clear in the Axis 1 vs Axis 2 plot. Connectivity phase 2 appeared to have the greatest variability (i.e., greatest dispersal of points in ordination space) compared to phases 1 and 3. Figure 5-4b illustrates the relationship between physico-chemical factors, with the longest vectors having the strongest relationship. In the Axis 1 vs 2 plot, nitrate and total nitrogen appeared to be most related with connectivity phase 3, while phases 1 and 2 did not appear to have a clear relationship with any of the variables.

PERMANOVA results revealed significant effects of habitat type (Pseudo-$F_{2,99}$=4.4, p<0.001) and connectivity phase (Pseudo-$F_{2,99}$=14.7, p<0.001), and an interaction between habitat type and connectivity phase on phytoplankton community composition (Pseudo-$F_{4,99}$=2.1, p<0.001). Pair-wise tests confirmed significant differences between the artificial side-arm habitat and both the natural side-arm and river habitats at connectivity phase 1, significant differences between all habitats at phase 2, and significant differences between the artificial side-arm and natural side-arm habitats at phase 3. This analysis shows significant differences between each connectivity phase for each habitat, indicating a change in community composition in the artificial and natural side-arms and river habitat between each connectivity phase.
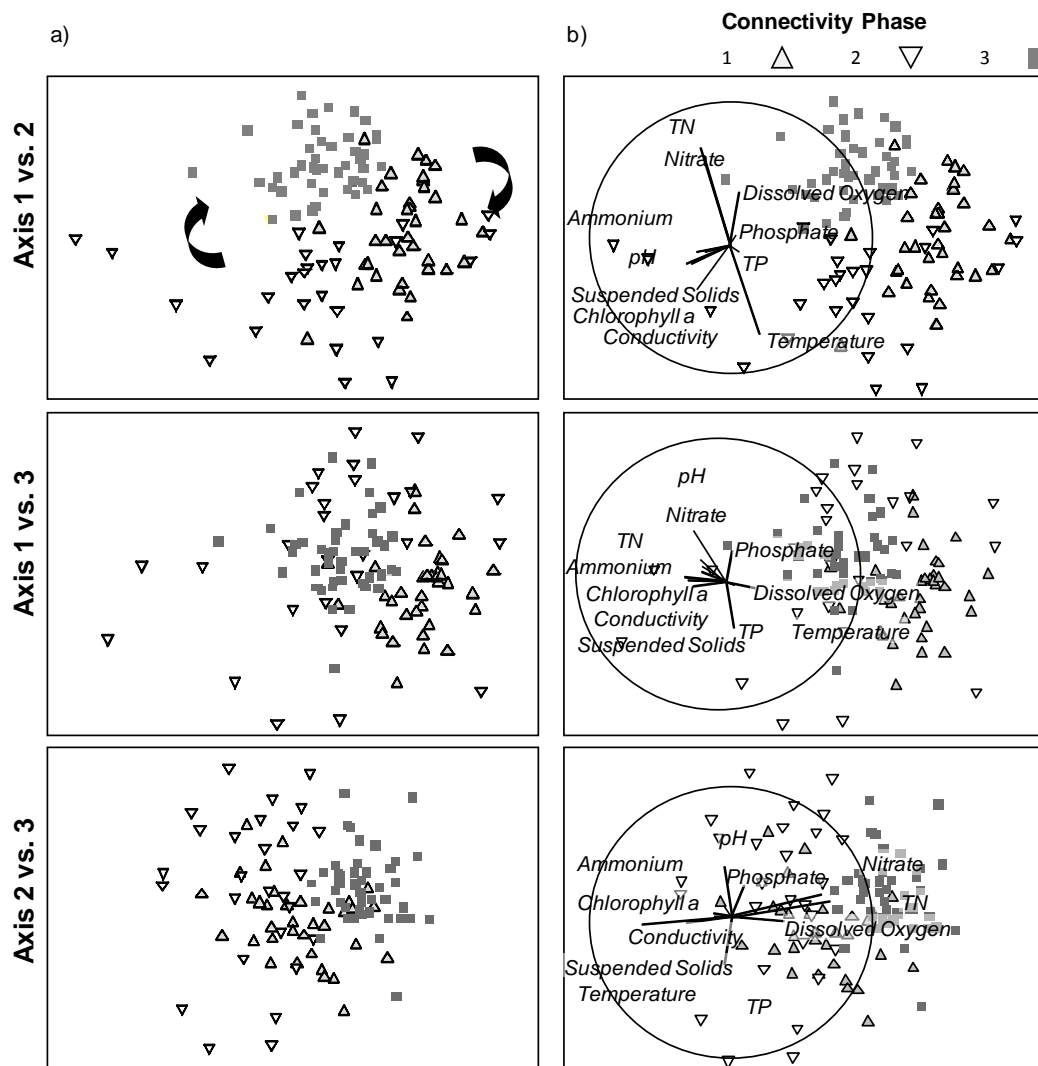
Figure 5-4a Multi-dimensional scaling (MDS) plot showing phytoplankton community composition at three different connectivity phases (refer to definition of connectivity phases in Table 3-1) using monthly (November 2009-October 2010) abundance values from habitats (artificial side-arm, natural side-arm and river). Three sets of co-ordinates (axis: 1vs.2, 1vs.3, and 2vs.3) present the 3 dimensional plot as 2-D graphs. Arrows indicate direction of composition moving from connectivity phase 1 to 2 to 3. Figure 5-5b a vector plot using physico-chemical data. All plots had a 3-D stress value of 0.19.

5.2 Monthly measurements: Within side-arm habitat variation

Phytoplankton biomass (chlorophyll *a*), and community composition data was analysed from the artificial and natural side-arms (inlet, middle and outlet sites) and the three river sites to be compared between locations within each connectivity phase.

Chlorophyll *a* concentration displayed consistent values between locations (inlet, middle and outlet) at connectivity phases 1 and 3 (Figure 5-6). The artificial side-arm revealed higher chlorophyll *a* concentration in the inlet at connectivity phase 2 than the middle or outlet sites, which exhibited values similar to phases 1 and 3 (inlet 28.29 µg l^{-1}, middle 5.51 µg l^{-1}, outlet 3.93 µg l^{-1}). The natural side-arm had higher chlorophyll *a* concentration in the middle and outlet sites compared to the inlet site at connectivity phase 2 (inlet 18.16 µg l^{-1}, middle 18.04 µg l^{-1}, outlet 7.81 µg l^{-1}).
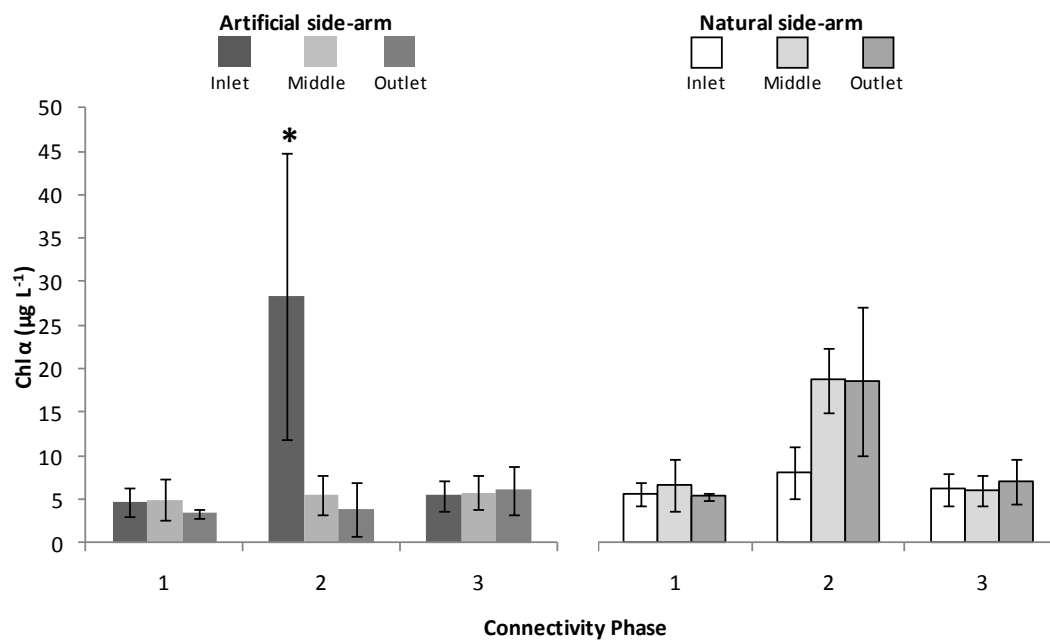
Figure 5-6 Chlorophyll *a* concentration for three locations within each of the artificial and natural side-arms (inlet, middle and outlet) at three different connectivity phases 1-3; (refer to definition of connectivity phases in Table 3-1). Values represent means ± S.E. Asterisk indicates significant difference between the inlet site and the middle and outlet sites of the artificial side-arm at connectivity phase 2.

ANOVA results revealed a significant effect on chlorophyll *a* of location type (inlet, middle and outlet) ($F_{2,27}=9.6$, $P<0.001$) in the artificial side-arm. Post-hoc results revealed the inlet was significantly different to the middle and outlet sites at connectivity phase 2, but there was no significant effect of location for the natural side-arm.

Phytoplankton community composition for each side-arm was assessed for significant effect of location type within the side-arm (inlet, middle and outlet) in order to understand how composition changed longitudinally within each side-arm at each

connectivity phase. MDS plots revealed no patterns between location within the artificial side-arm for phases 1 and 3. During connectivity phase 2, however, there was clear grouping by location (Figure 5-7a-c). MDS plots for the natural side-arm revealed no clear grouping of locations during any of the connectivity phases (Figure 5-7d-f). PERMANOVA results revealed a significant effect of location in the artificial side-arm (Pseudo $F_{2,27}$=1.8, P=0.23), but not the natural side-arm. Pair-wise comparisons revealed no significant difference between different location types (inlet, middle or outlet) in the artificial side-arm within each connectivity phase. These results suggest that phytoplankton community composition did not differ significantly between locations within the artificial or the natural side-arm at any connectivity phase.
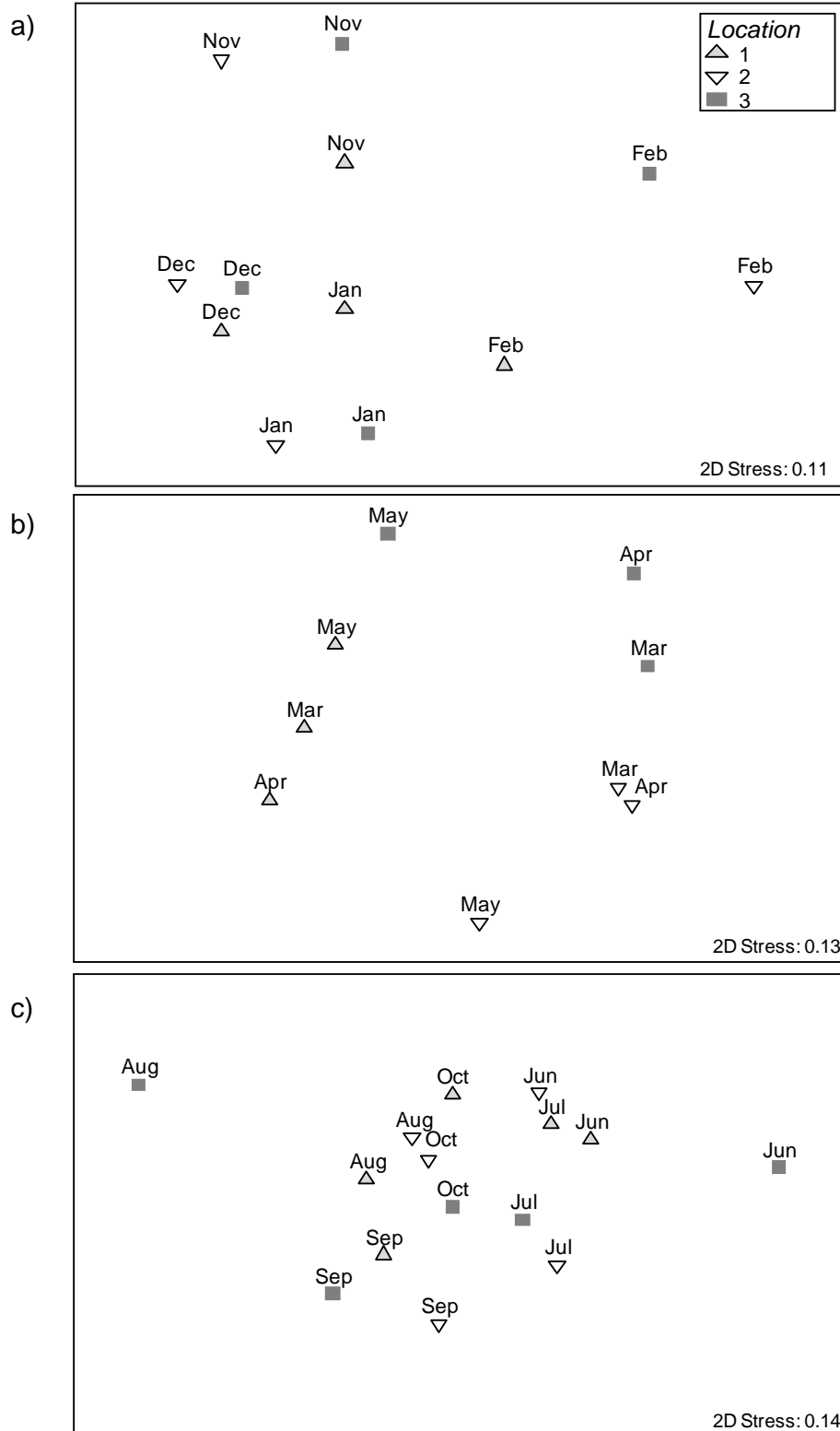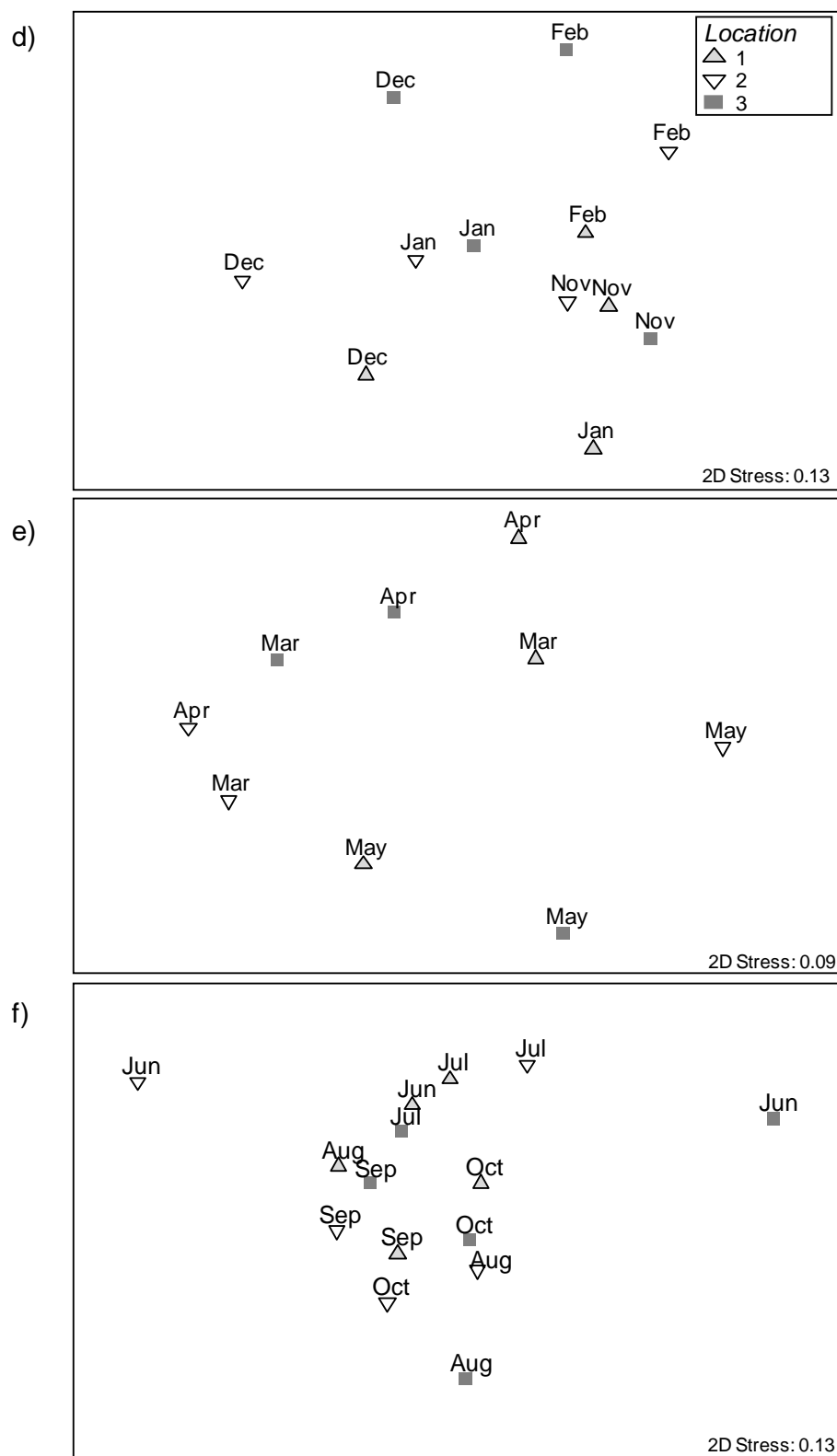
Figure 5-7 Phytoplankton community composition for within artificial side-arm effects. Plotted by location (1, inlet, 2 middle and 3, outlet), for each connectivity phase (see table Table 3-1). Plot a-c, phase 1-3 in the artificial side-arm, plot d-f, phase 1-3 in the natural side-arm.

6   Results: Temporal study zooplankton dynamics

An objective of this study was to determine whether zooplankton community composition and dominant species differed between natural and artificial side-arms and the river with regard to different phases of connectivity. Three-monthly (December 2009, March, June and September 2010) samples were collected from the side-arms and river for zooplankton analysis.

6.1   Three-monthly measurements: Between habitat variation

Zooplankton abundance and community composition data were analysed from the artificial and natural side-arms (inlet, middle and outlet sites) and the three river sites to be compared between habitats and connectivity phases.

Zooplankton species richness varied across habitats and across connectivity phases (Figure 6-1). The river habitat had the greatest number of species in side-arm connectivity phases 1 (18 species) and 2 (11 species) out of all the habitats.

All habitats had a lower number of species during connectivity phase 2 (7-11 species) than phase 1 (16-18 species) or phase 3 (11-15 species) (Figure 6-1). The natural side-arm had higher species richness than the artificial side-arm in connectivity phase 1 and vice-versa in phase 2. During connectivity phase 3 both side-arms had a similar number of species and were both higher in species richness than the river. Rotifers were the dominant taxonomic group for all habitats during all three connectivity phases.
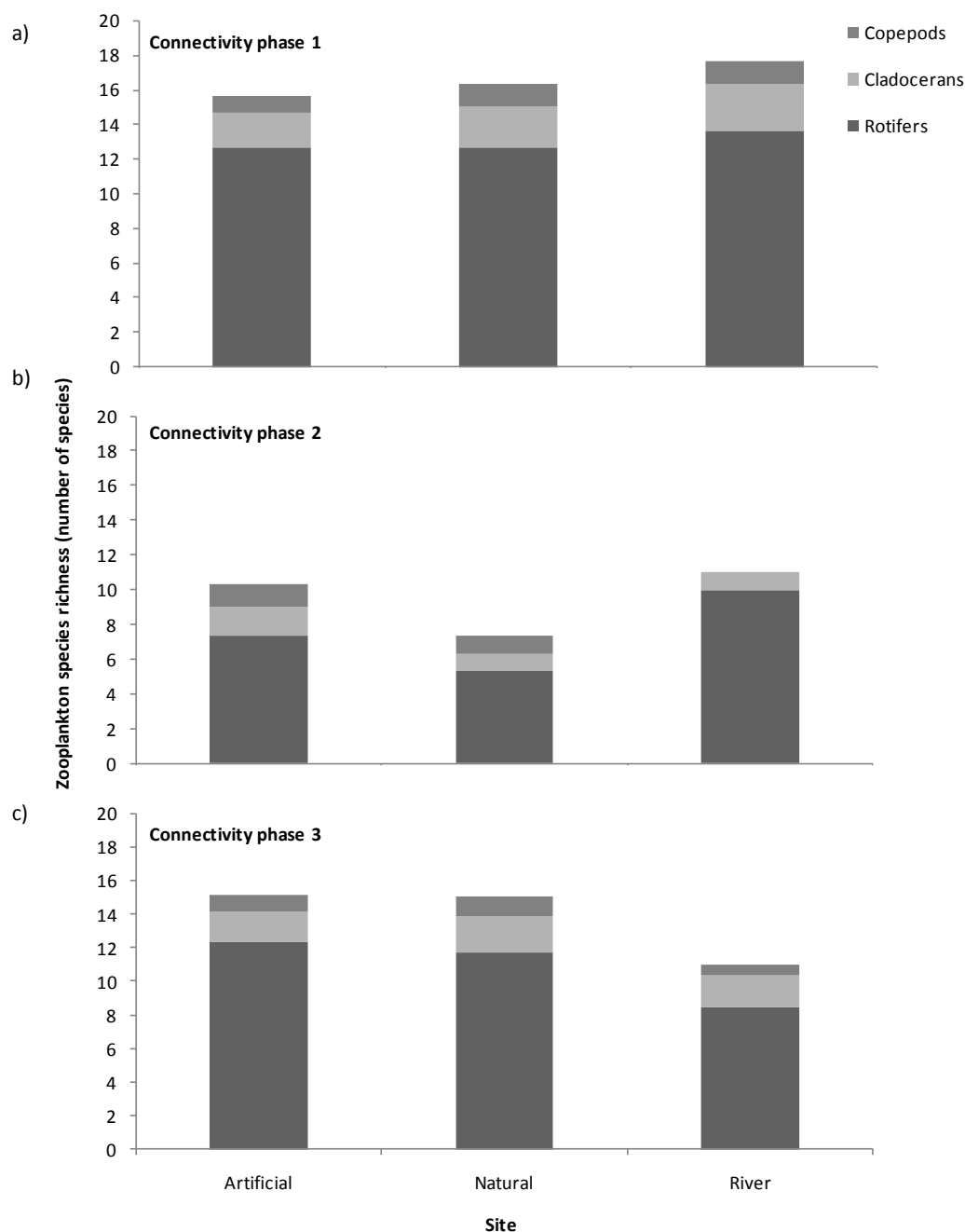
Figure 6-1 Zooplankton species richness in each Phyla for each habitat type (artificial or natural side-arms and river) at each connectivity phase; a) connectivity phase 1, b) connectivity phase 2 and c) connectivity phase 3 (for a definition of these see Table 3-1).

Dominant species based on abundance in the artificial side-arm during connectivity phase 1 were *Ascomorphella volvocicola*, *Brachionus calysiflorus* and *Euchlanis dilatata.* In the natural side-arm the dominant species were *Euchlanis dilatata*, bdelloids, and *Ascomorphella volvocicola*. The dominant species in the river in

December 2009 were *Ascomorphella volvocicola*, *Brachionus calysiflorus* and *Synchaeta oblonga* (Table 6-1). For this time period, the natural side-arm had the highest zooplankton abundance, followed by artificial side-arm and river abundances which were similar (natural side-arm 9.9 individuals/ml, artificial side-arm 3.9 individuals/ml, river 3.6 individuals/ml).

Table 6-1 Dominant zooplankton species in the artificial and natural side-arms and river at each connectivity phase. Abundance data is individuals/ml. Refer to Appendix 3 – Zooplankton raw data for more information.

Habitat	Connectivity Phase			
Artificial side-arm	1	*Brachionus calyciflorus*	*Euchlanis dilatata*	*Synchaeta oblonga*
		0.8	0.4	0.2
	2	Bdelloids	Cyclopoid	*Euchlanis dilatata*
		0.1	0.09	0.8
	3	Bdelloids	*Synchaeta oblonga*	*Trichocerca pusilla*
		0.7	0.3	0.2
Natural side-arm	1	*Euchlanis dilatata*	Bdelloids	*Brachionus calyciflorus*
		3	1.7	0.7
	2	Bdelloids	Cyclopoid	*Euchlanis dilatata*
		177	18	4
	3	Bdelloids	*Bosmina meridionalis*	*Trichocerca pusilla*
		0.7	0.2	0.2
River	1	*Brachionus calyciflorus*	*Synchaeta oblonga*	Bdelloids
		0.8	0.3	0.2
	2	*Brachionus calyciflorus*	Bdelloids	*Bosmina meridionalis*
		0.3	0.2	0.2
	3	Bdelloids	*Trichocerca pusilla*	*Bosmina meridionalis*
		0.5	0.1	0.1

Connectivity phase 2 was associated with a decline in zooplankton abundances for the artificial side-arm with a total of 0.7 individuals/ml. The dominant species were *Lecan bulla,* bdelloids and *Euchlanis dilatata*. The natural side-arm had a 20-fold increase in abundance, with a total of 208 individuals/ml. The dominant species in the natural side-arm was bdelloids followed by Cyclopoid copepods. *Brachionus calysiflorus* and bdelloids were the dominant species in the river in March, with a total of 1.0 individuals/ml (Table 6-1).

High river flows in connectivity phase 3 (June and September) were associated with an increase in average total abundance to 2.0 individuals/ml in the artificial side-arm. The natural side-arm had a reduced average total abundance of 2.2 individuals/ml. The river had an average of 1.4 individuals/ml. The dominant species for all habitats were bdelloids, *Synchaeta oblonga*, *Trichocerca pusilla* and *Bosmina meridinalis,* respectively (Table 6-1)*.*

ANOVA results revealed a significant effect of habitat ($F_{2,3}$=5804.2, P<0.001), connectivity ($F_{2,3}$=4785.7, P<0.001) and on interaction of habitat and connectivity ($F_{4,3}$=4992.7, P<0.001). The post-hoc test revealed significantly higher zooplankton abundances in the natural side-arm during connectivity phase 2 compared to abundances in the artificial side-arm and the river.

Zooplankton abundance data were grouped into crustacean abundance and rotifer abundance in separate non-metric multi-dimensional scaling (MDS) bubble plots (

Figure 6-2) to investigate how abundances change between sites and connectivity phases. Bubbles that represented total abundances provided a visual representation of habitat types and connectivity phases.

Figure 6-2a and b indicate Lake Hakanoa was positioned away from the side-arm and river samples for each month and corresponding side-arm connectivity phase. The dominant species for the Lake Hakanoa outlet were: *Bosmina meridionalis* (8.0 individuals/ml) in phase 1 (December); *Trichocerca stylata* (0.15 individuals/ml) in phase 2 (March); *Filinia terminalis* (53.2 individuals/ml), *Daphnia* (38.8 individuals/ml) and *Bosmina meridionalis* (28.4 individuals/ml) (June); and *Asplachna priodonta* (0.2 individuals/ml) (September) in phase 3. The results suggest that the Lake Hakanoa outlet did not affect downstream sites (natural side-arm and downstream river site) in terms of zooplankton community composition. Interestingly, during connectivity phase 2, the natural side-arm had similar community composition to the phase 1 lake sample.
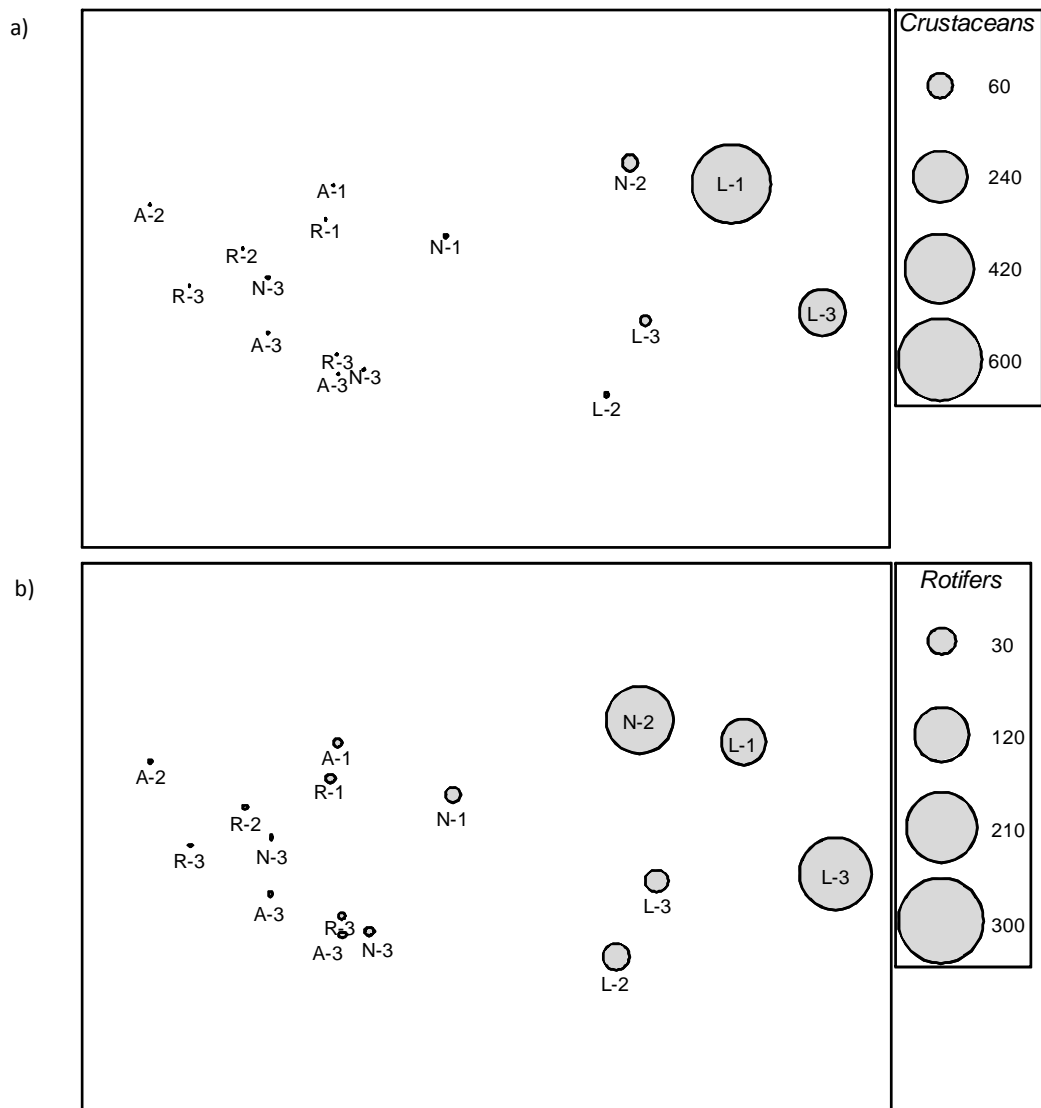
Figure 6-2 Multi-dimensional scaling (MDS) bubble plot showing a) number of crustacean individuals and b) number of rotifer individuals at three different connectivity phases 1-3 (refer to definition of connectivity phases in Table 3-1) using three-monthly (December 2009, and March, June and September 2010) abundance values from all habitats (A, artificial side-arm, N, natural side-arm, R, river and L, Lake Hakanoa). Labels denote habitat – connectivity phase (e.g N-1, Natural side-arm- phase 1).

Figure 6-2a and b illustrated that the natural side-arm habitat had the greatest abundance out of all habitats in connectivity phase 2. Lake Hakanoa had the greatest abundance in December, June and September (connectivity phases 1 and 3).

Zooplankton community composition was displayed in a non-metric multi-dimensional scaling (MDS) plot (Figure 6-3) based on log(x+1) transformed total abundances. Abundance data was from each side-arm site (inlet, middle and outlet), and each

river site (upstream, between and downstream of side-arms) for four months (i.e.,three-monthly samples; December 2009 and March, June and September 2010). A plot was made for both habitat type and connectivity phase to explore possible relationships; the connectivity plot is presented here as no relationships were revealed on the habitat type plot.
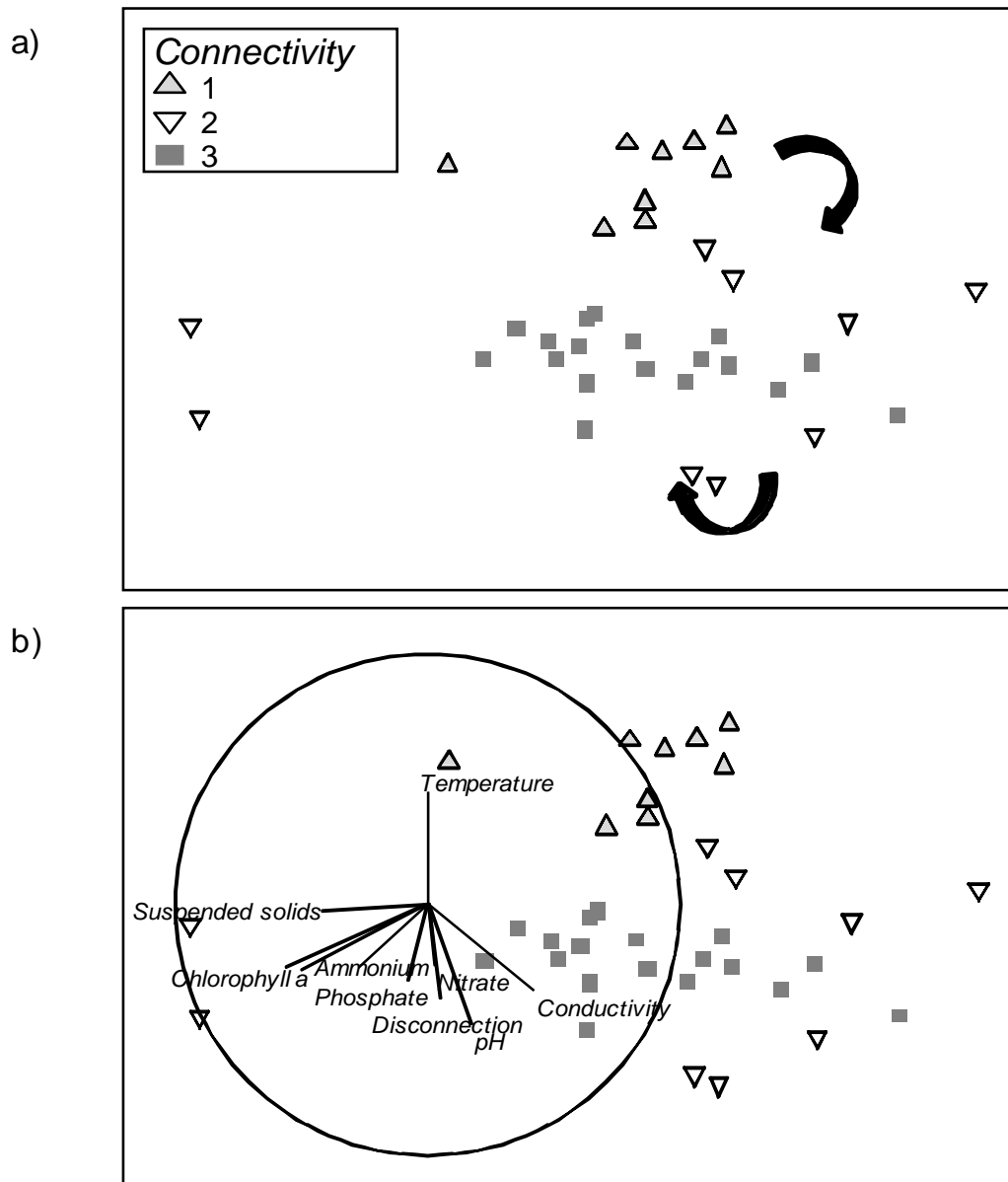
Figure 6-3a Multi-dimensional scaling plot showing zooplankton community composition at three different connectivity phases 1-3; (refer to definition of connectivity phases in Table 3-1) using three-monthly (December 2009 and March, June and September 2010) abundance values from all habitats (artificial side-arm, natural side-arm and river). Arrows indicate change in connectivity phase. Figure 6-3b is a vector plot using physico-chemical data overlaid with a Spearman correlation coefficient of r_s >0.2. All plots had a 2D stress value of 0.1

Figure 6-3a revealed that zooplankton community composition was strongly related to the connectivity phase. Points from connectivity phase 2 appeared to have the greatest variability (i.e., greatest spread of points along axis 1) compared to the spread for the other phases.

Figure 6-3b displayed the relationship between physico-chemical factors and zooplankton community composition where factors on the vector overlay with the longest line had the strongest relationship. High temperature levels appeared to be the most related to connectivity phase 1. Conductivity appeared to be most closely related in connectivity phase 3.

PERMANOVA results revealed a significant effect of habitat type (Pseudo $F_{2,27}= 2.1$, P=0.012) and connectivity phase (Pseudo $F_{2,27}=8.2$, P<0.001), and a border line significance interaction between habitat type and connectivity phase (Pseudo $F_{4,27}=1.5$, P=0.050). However, pair-wise tests did not reveal any significant differences between pairs of habitat types or connectivity phases.

7 Results: Spatial survey

The final objective of this study that is presented in the results section was to determine whether natural and re-constructed side-arms are comparable to other side-arms in the lower Waikato River. This was carried out by comparing phytoplankton community composition and biomass (as indicated by chlorophyll *a*), nutrient and suspended solid concentrations and physico-chemical variables, to naturally occurring side-arms in the lower Waikato River. Nine side-arms were studied in a one-off spot measurement at the inlet, middle and outlet of each side-arm in March 2010. Seven of these side-arms were naturally occurring and applicable to this study, one of these seven included the natural side-arm studied monthly. Corresponding river measurements were also made, but as this study was concerned with direct comparisons between the side-arms river data is not presented in this section (refer to Appendix 4 – Spatial survey river data for this data).

7.1 Connectivity

The spatial survey resulted in nine side-arm sites with varying ranks of connectivity (Table 7-1) being sampled in March 2010. The rankings are based on the rankings used in the temporal study (Table 4-1) with the addition of ranking 2; side-arm connection with the main river channel but with high water retention.

Table 7-1 Connectivity rankings from one-off sampling of nine side-arms in survey conducted March 2010. Connectivity rankings indicate side-arm connection with main river channel: 1, completely connected; 2, connected with high water retention; 3, connection at inlet but not outlet; 4, connection at outlet but not inlet; 5, complete disconnection. Site 4 is shaded to denote the exclusion of this site from the analysis.

Site number	Connectivity ranking
1	1
2	4
3	3
4	4
5	1
6	4
7	2
8	5
9	3

A Principal Components Analysis (PCA) of physico-chemical variables, nutrients, total suspended solids and chlorophyll *a* data (Figure 7-1) was used to identify whether the side-arm samples (inlet, middle ,outlet) were grouped based on site. All sites except site 9 generally grouped together indicating similar physico-chemical conditions. It was not clear what was driving variability at site 9, but this not appear to be related to connectivity.
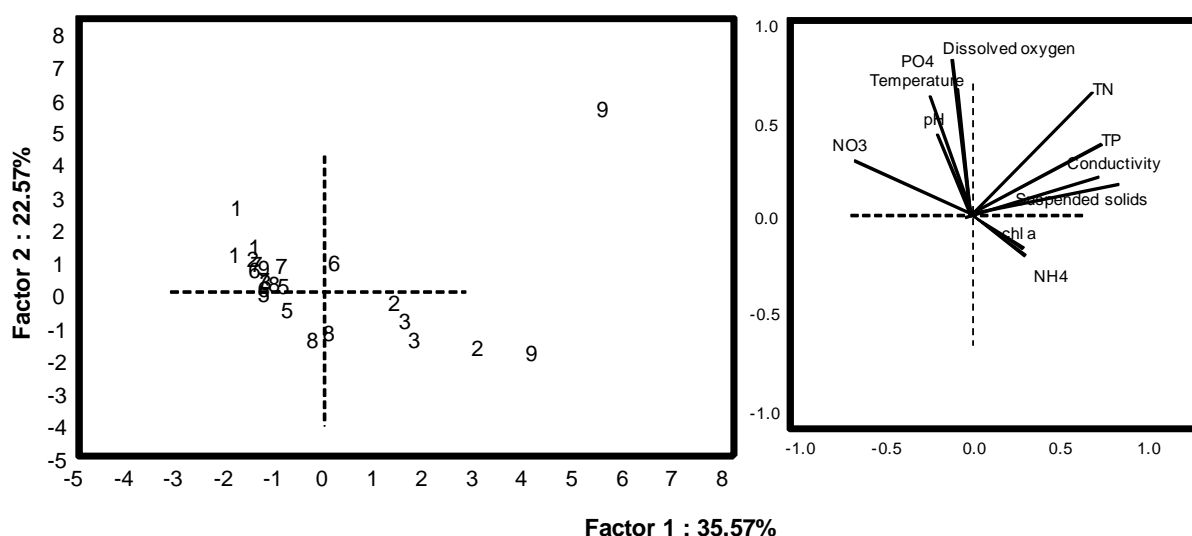
Figure 7-1 Principal components analysis (PCA) of spatial survey sites (1-9; see Table 7-1) using physico-chemical, nutrients, suspended solids and chlorophyll *a* variables for the correlation where two factors are presented.

7.2 Physico-chemical factors

Temperature ranged from 17.9-24.7°C (Figure 7-2a) across all spatial sites and revealed no pattern with regard to connectivity ranking (Figure 7-2a). Conductivity was consistent at sites 1, 5, 7, 2, 6 and 8 (range, 163.8-192.7 µs cm^{-1}) which had varied connectivity rankings (Figure 7-2b). Sites 3 (217.3 µs cm^{-1}) and 9 (279.0 µs cm^{-1}), each with a connectivity ranking of 3, had the highest conductivity.

Dissolved oxygen was notably lower in sites 3, 2 and 8; sites with low connectivity (Figure 7-2c). Sites 3, 2 and 8 had average dissolve oxygen concentrations of 3.5 mg/l, 6.2 mg/l, 6.5 mg/l respectively.

All sites produced pH values relatively similar to each other with a range of 7.17-8.79 (Figure 7-2 d).
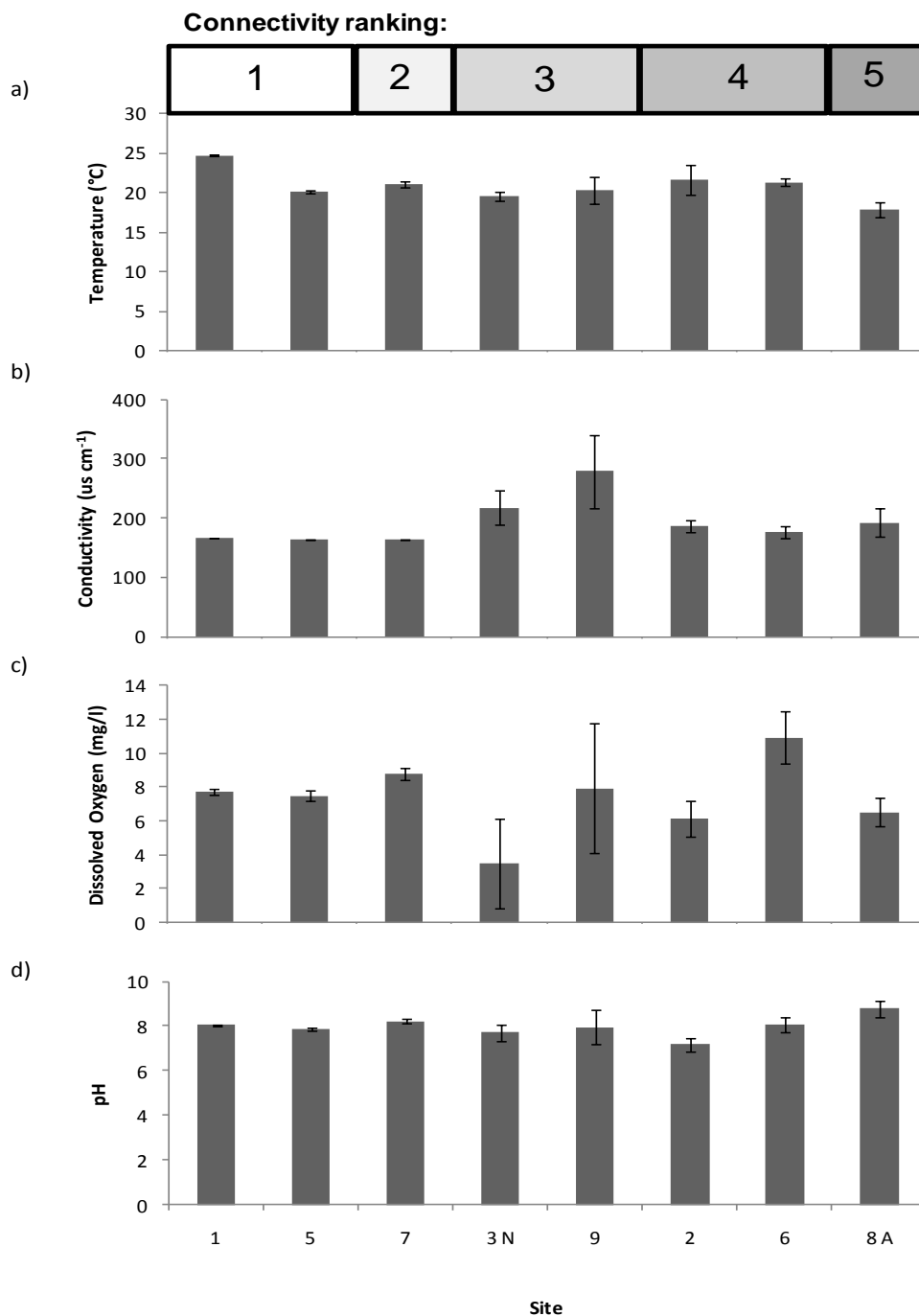
Figure 7-2 (Previous page) Physico-chemical concentrations from the one-off spatial survey (sites 1-9) including the artificial (8) and natural (3) side-arms. a) Temperature, b) specific conductivity, c) dissolved oxygen, and d) pH. Order that sites are presented along the x-axis indicates high connection with the main river channel on the left, moving towards complete disconnection on the right (see Table 7-1 for site connection rankings). Values represent means ± S.E.

Ammonium (NH_4-N) concentrations appeared lowest at site 6 with an average of 0.002 mg/l (Figure 7-3).
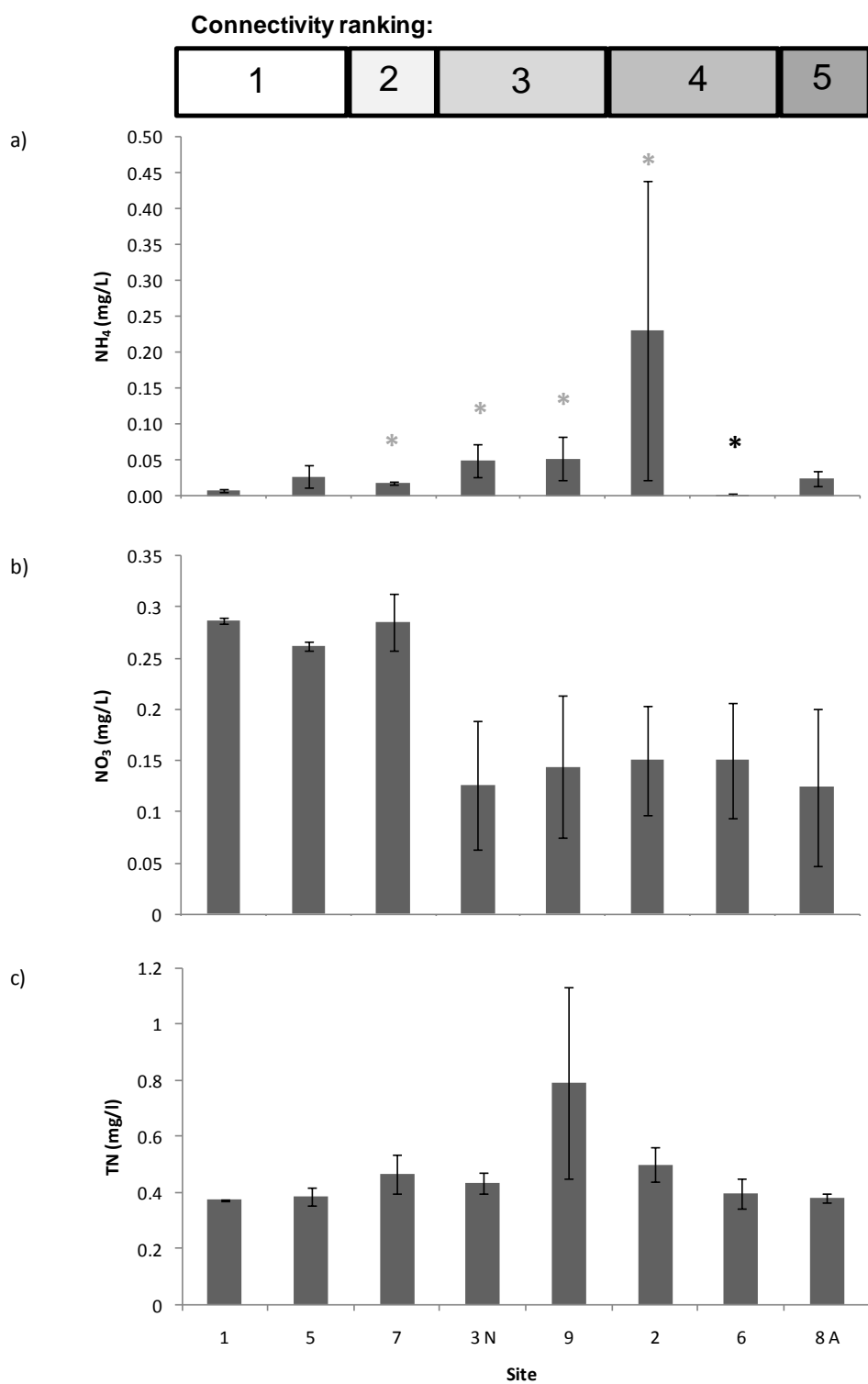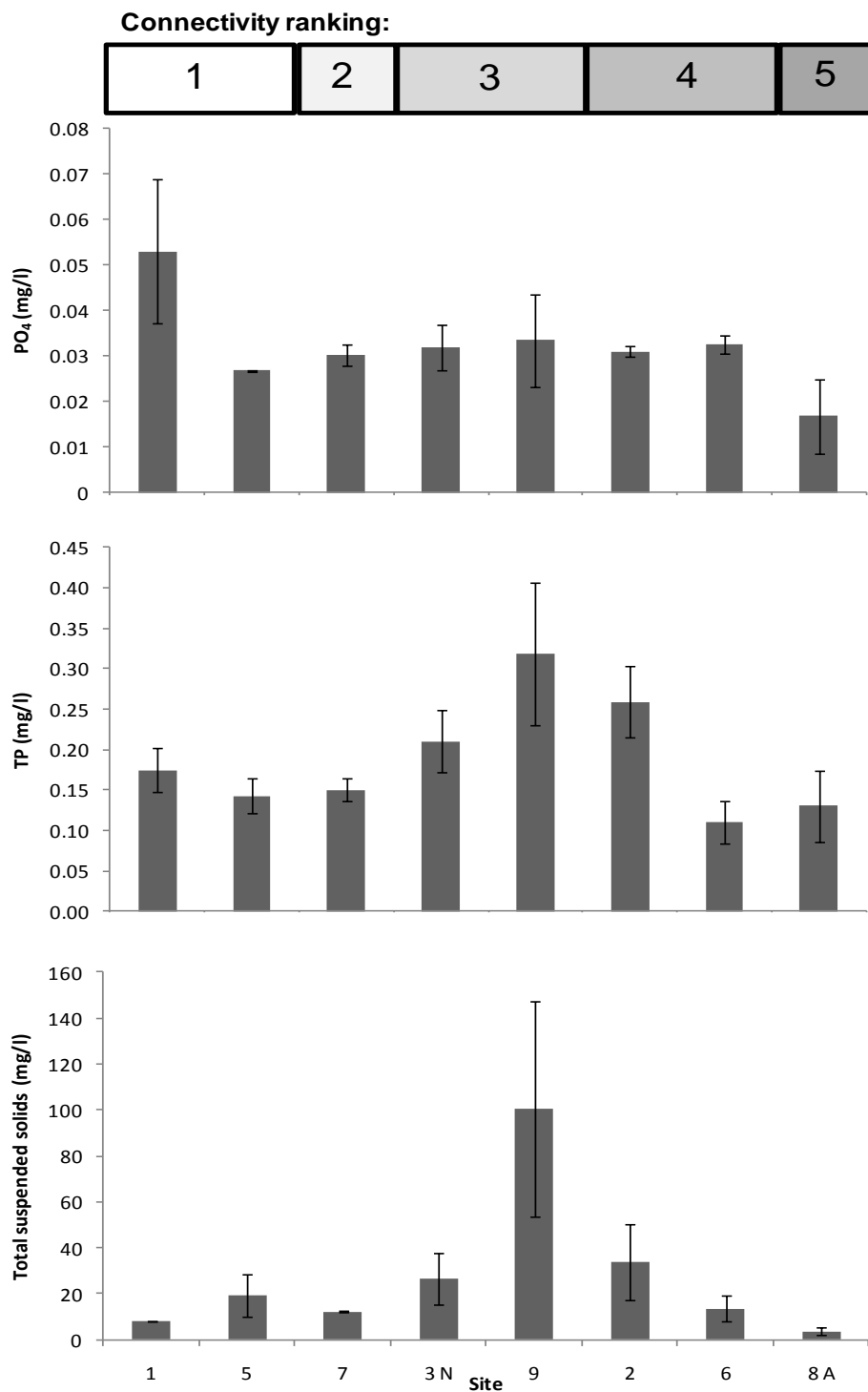
Figure 7-3a-f Ammonium (NH$_4$-N), Nitrate (NO$_3$-N), Total nitrogen (TN), Phosphate (PO$_4$-P), Total phosphorus (TP), and total suspended solid concentrations from the one-off spatial survey (sites 1-9) including the artificial (8) and natural (3) side-arms from the temporal study. Order that sites are presented along the x-axis indicates high ranking of connection with the main river channel on the left, moving toward complete disconnection on the right. Values represent means ± S.E. Asterisks in Figure 7-3a mark the significant difference between site 6 and sites 7, 3 (natural side-arm), 9 and 2 for ammonium concentration.

ANOVA results revealed a significant effect of site ($F_{7,16}$=6.7 P=0.001), and post-hoc tests confirmed that site 6 had significantly lower ammonium concentration to sites 7 (0.018 mg/l), 3 (natural temporal side-arm; 0.049 mg/l), 9 (0.052 mg/l) and 2 (0.231 mg/l) but was statistically the same as sites 1, 5 and 8 (artificial temporal side-arm).

The sites with low connectivity had nitrate (NO_3-N) values in the range of 0.038-0.284 mg/l, while sites with connection to the main river channel (1, 5, and 7) had higher concentrations in the range 0.253-0.340 mg/l (

Figure 7-3b. ANOVA results revealed no significant effect of site on nitrate concentration.

Total nitrogen appeared to be consistent across all sites (range 0.372-0.499 mg/l) except for site 9 which had a higher mean of 0.789 mg/l (

Figure 7-3c. ANOVA results revealed no significant effect of site on total nitrogen concentration.

The highest phosphate (PO_4-P) concentration was taken from highly connected site 1 with an average of 0.053 mg/l, while the lowest concentrations were obtained from highly disconnected site 8 (artificial temporal side-arm), with an average of 0.007 mg/l (

Figure 7-3d. Sites with connectivity rankings in between sites 1 and 8 had consistent concentrations (0.027-0.034 mg/l). ANOVA results revealed no significant effect of site on phosphate concentration.

Total phosphorus concentration was relatively consistent across sites 1, 5, 7, 6 and 8 (artificial temporal side-arm) (0.110-0.174 mg/l), while sites 3 (natural temporal side-arm), 9 and 2 had higher total phosphorus concentrations (0.210 mg/l, 0.319 mg/l, and 0.259 mg/l, respectively) (

Figure 7-3e. ANOVA results revealed no significant effect of site on total phosphorus concentration.

Total suspended solid (TSS) concentrations varied across all sites and therefore connectivity rankings (

Figure 7-3f. Site 9 had the highest TSS (average 100.4 mg/l), but ANOVA results revealed no significant effect of site on TSS concentration.

7.3 Phytoplankton dynamics

Chlorophyll *a* concentration presented in Figure 7-4 illustrates an increase in chlorophyll *a* concentration with decrease in connectivity (i.e. greater disconnection is associated with high chlorophyll *a*). ANOVA results revealed no significant effect of site on chlorophyll *a* concentration.
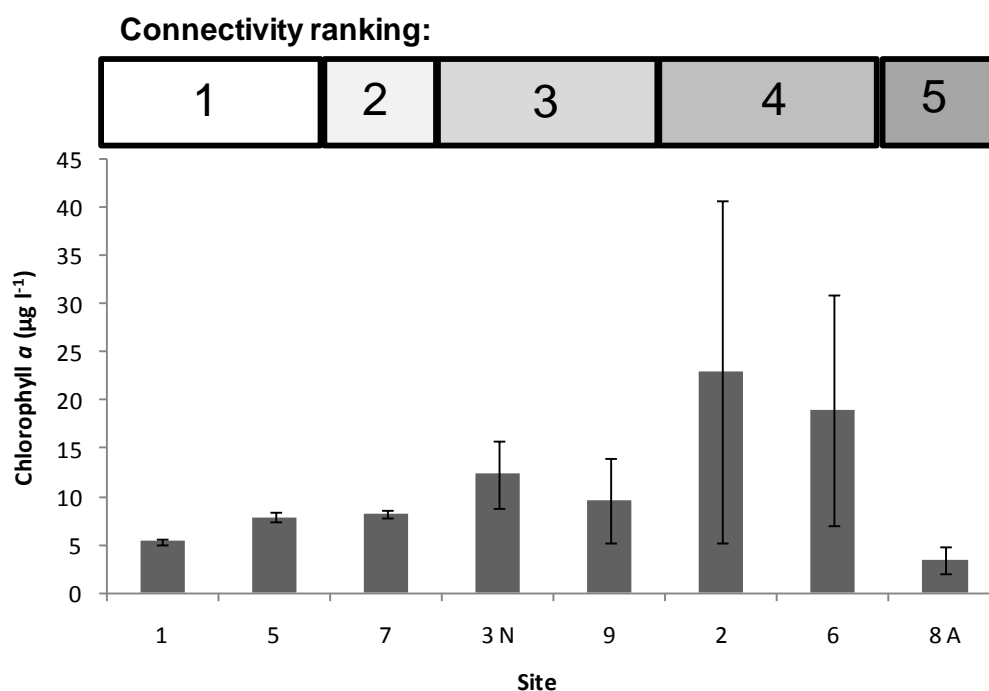
Figure 7-4 Chlorophyll *a* concentrations from the one-off spatial survey (sites 1-9) including the artificial (8) and natural (3) side-arms from the temporal study. Order that sites are presented along the x-axis indicates high ranking of connection with the main river channel on the left, moving toward complete disconnection on the right (see Table 7-1 for site connection rankings). Values represent means ± S.E.

Phytoplankton community composition was presented in a non-metric multi-dimensional scaling (MDS) plot based on transformed (log x+1) total abundances from the one-off spatial survey (sites 1-9) including the artificial (8) and natural (3) side-arms from the temporal study. Figure 7-5a revealed that phytoplankton

community composition was not grouped out by differing sites, suggesting that no one site is clearly different to the others. Figure 7-5a revealed that connectivity ranking produces groups and illustrates how high the variation is within several sites (9, 3 temporal natural site, 6, and 2) which were the side-arms with the highest disconnection. Figure 7-5b illustrated the relationship between physico-chemical factors which did not show any clear relationship with site and any of the variables.

PERMANOVA results revealed significant effect of site (Pseudo $F_{7,16}$=1.6 P=0.028). Pair-wise tests were inconclusive as they produced no significant differences between sites.
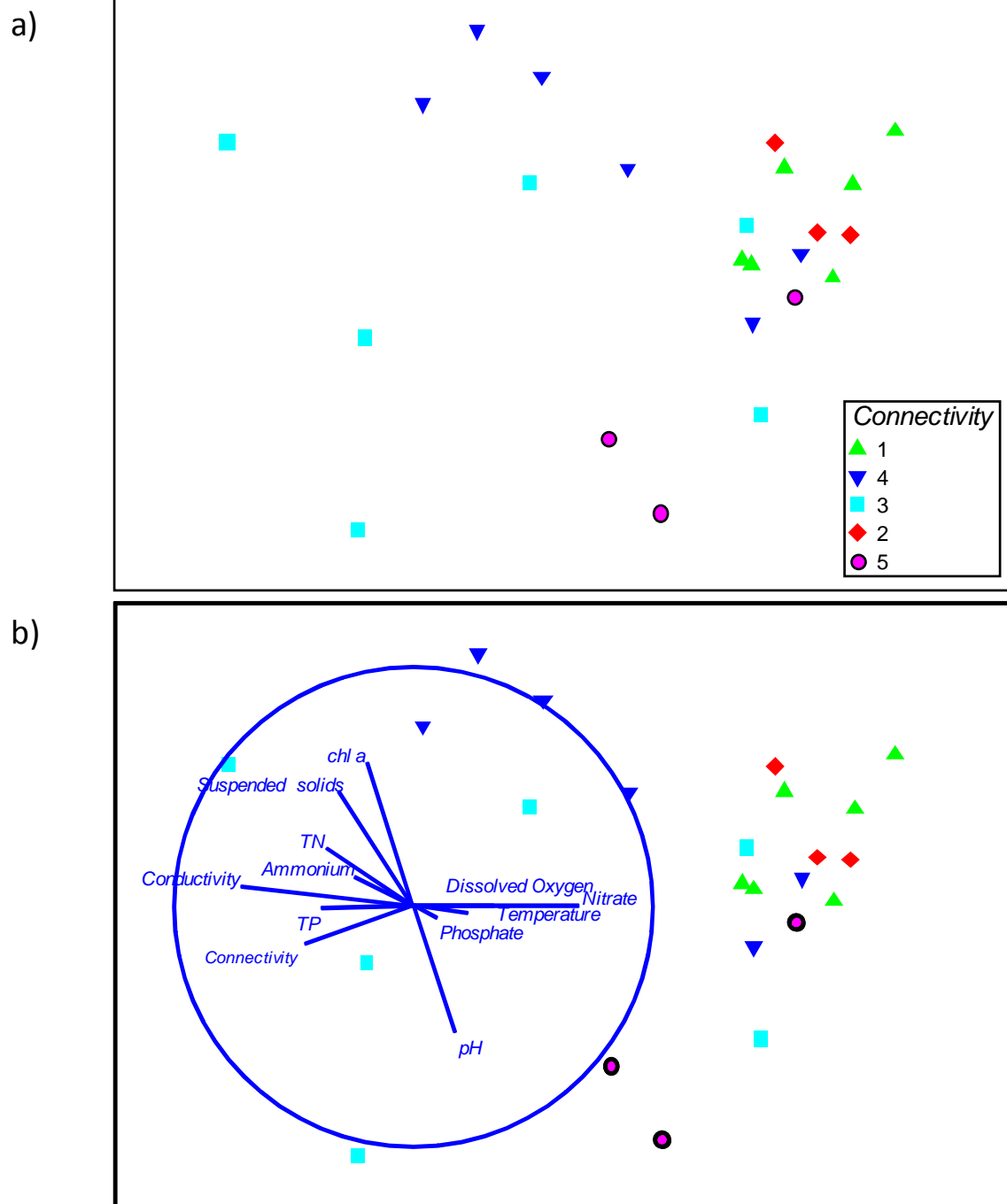
Figure 7-5a and b Multi-dimensional scaling plot showing phytoplankton community composition using total abundance data from the one-off spatial survey (sites 1-9) including the artificial (8) and natural (3) side-arm from the temporal study, Plot a grouped by connectivity ranking (Table 7-1 for definition of connectivity rankings). Plot b vector plot using physico-chemical data overlaid with a Spearman correlation coefficient of r_s >0.2. All plots had a 2D stress value of 0.15.

The species richness within each site varied across all connectivity rankings (Figure 7-6). Site 9 had the largest number of Phyla (7 Phyla, 25 species), while site 8 (temporal study artificial site) had the largest number of species (6 Phyla, 31 species), followed by site 1 (5 Phyla, 27 species). All sites were made up by a majority of diatoms and Chlorophyta.
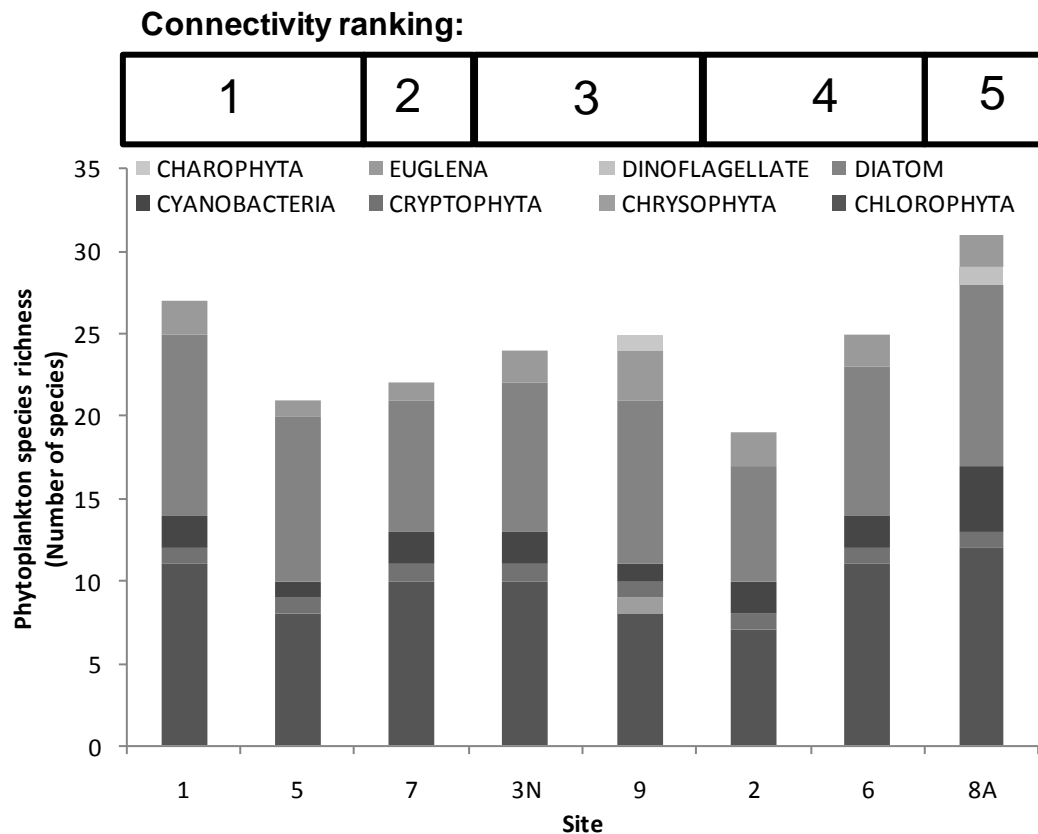
Figure 7-6 Phytoplankton species richness determined by number of species in each phylum for each site in the spatial survey (1-9) including the artificial (8) and natural (3) side-arm from the temporal study.

8 Discussion

The major objective of this study was to determine the influence of hydrological connectivity with the main river channel on side-arm functional roles. Monthly plankton, nutrient and suspended solids and physico-chemical data for different connectivity phases provided evidence into the function of an artificial and a natural side-arm. This provided an indication of whether side-arm reconstruction would be suitable for restoring lateral habitat processes in the lower Waikato River. The potential for restoration of lateral habitat processes was determined by how well the side-arm's functional roles during high retention met those described in the Inshore Retention Concept (IRC) (Schiemer et al. 2001a) and the selected tenets in the Riverine Ecosystem Synthesis (RES) (Thorp et al. 2006; Thorp et al. 2008) described in sections 0 and 0.

Three connectivity phases were identified as grouping factors through Principal Components Analysis (PCA), indicating similar physico-chemical, nutrient, suspended solids and plankton conditions within each phase;

- Phase 1; November 2009-February 2010 (late spring-summer) - the side-arms were connected with the main river channel;
- Phase 2; March-May 2010 (autumn) - some form of disconnection occurred between the side-arm and the main river channel;
- Phase 3; June-October 2010 (winter) – connection was re-established.

In this study the ability of the natural side-arm to represent other naturally occurring side-arms which were at least partly disconnected from the lower Waikato River was determined by a spatial survey. This survey indicated significant differences in only one variable (ammonium) and one site; all other disconnected sites exhibited the same pattern as the natural side-arm sampled monthly.

All physico-chemical and biological patterns in this survey indicated a strong effect of connectivity with the main river on side-arm function. Importantly, the spatial study demonstrated how the side-arms varied in

their phase of connectivity, which highlights the difficulty in finding one site to represent the lower Waikato River's natural side-arms at a single point in time. For the purpose of this study, it is satisfactory to acknowledge that the intensively-studied natural side-arm site was not a major outlier with regard to six other natural side-arms. The possible downstream effect on plankton community composition of the Lake Hakanoa outlet was proven to be undetectable on the natural side-arm.

The following discussion focuses on the intensively-studied artificial and natural side-arms which both presented different physical characteristics that may have influenced their functional roles. The artificial side-arm was newly established and had exposed sediments that can strongly sorb phosphorus (Schorer & Eisele 1997), less developed riparian vegetation, and was also likely to have a limited pool of diapausing eggs deposited by zooplankton (Hairston Jr 1996). The natural side-arm had established riparian vegetation that may have provided additional allochothonous carbon inputs (Junk et al. 1989) and greater regulation of water temperatures, although this was not evident in logged temperature data over summer prior to disconnection.

The sand substrate of the artificial side-arm appeared to allow sub-surface seepage from the river during the initial stages of disconnection and possibly at higher river flows. In contrast, the silt substrate in the natural side-arm had high suspended solid concentrations, indicating re-suspension during disconnection. The artificial side-arm revealed a gain in discharge along its length during winter, which may have been caused partly by inputs such as stormwater from outlet pipes identified entering the side-arm. It is possible that inputs of stormwater also occurred in the natural side-arm, although no pipes were observed over the study duration. The natural side-arm, in contrast to the artificial side-arm, showed a decrease in flow at the outlet compared to the inlet in winter, and this is likely due to overtopping of the natural side-arm banks during high river levels.

The river had a seasonal discharge pattern that influenced connectivity of the side-arms. High river levels and flow fluctuations occurred during winter (June to October) due to greater rainfall and overland runoff at this time. The Waipa River influences the hydrology of the lower Waikato River considerably due to a catchment of geology with low infiltration rates that result in high flood peaks and low flows during periods of low rainfall (Brown 2010). During autumn, the side-arms exhibited three levels of disconnection. Based on corresponding river levels, when the disconnection phase began in March, the side-arms had 19 days of disconnection at the outlet but not the inlet. Following this, there were 37 days of disconnection at the inlet but not the outlet, resulting in possible backflow inputs from the river. The final form of disconnection was for 16 days, when the side-arms were completely disconnected from the river and had one period of flood pulse, 3 days after the first period of complete disconnection. For the purposes of analysis, the variation in disconnection during autumn was treated as one phase of disconnection.

8.1   Physico-chemical characteristics of the studied side-arms

High conductivity observed in both side-arms during autumn disconnection demonstrates the effects of evaporative concentration of salts and therefore the more prolonged retention of river water in the side-arms at this time (Grace & Imberger 2006). Rivers provide side-arm habitats with pulses of nutrients (Hein et al. 2003; Schiemer & Hein 2007; Schiemer et al. 2006; Tockner et al. 1999) determined by the hydrological regime (Hein et al. 2005; Preiner et al. 2008; Tockner et al. 1999). Hydrology influences connectivity of side-arms with the main river channel, which in turn determines the quantity and duration of inputs of nutrients and phytoplankton, and of physical disruption to habitat stability (Amoros & Bornette 2002; Reynolds 1984; Van den Brink et al. 1994). Low river flows lead to formation of hydraulic retention zones, increasing water age and that increases primary production and nutrient cycling (Hein et al. 2005; Preiner et al. 2008; Schiemer & Hein 2007; Schiemer et al. 2006; Tockner et al. 1999).

The artificial side-arm showed a significant decrease in total suspended solids between the inlet and outlet during autumn disconnection, the period of high water residence time, indicating that sediment deposition was occurring. Sedimentation is influenced by the river's hydrological regime (Preiner et al. 2008; Schiemer & Hein 2007; Schiemer et al. 2006; Tockner et al. 1999). At high flows, transportation of organic and inorganic particulate matter occurs rapidly between the river and side-arms (Preiner et al. 2008; Tockner et al. 1999). At low flows, sedimentation of the particulate matter occurs within the side-arm (Schiemer & Hein 2007; Tockner et al. 1999). Because of the increased time for sedimentation during low flows, accumulation of fine sediment occurs which may result in the compaction of substrate and subsequently the reduction of exchange processes with sub-surface waters and the side-arm (Brunke & Gonser 1997; Schiemer & Hein 2007). Interestingly, the natural side-arm did not show decreasing suspended solids at any connectivity phase. Rather, significantly higher suspended solid concentrations were measured in the natural side-arm compared to the river during autumn disconnection.

During late spring-summer connection and autumn disconnection, at a time of increased retention, the artificial side-arm had high deposition of suspended solids, and high temperatures and macrophyte biomass leading to significantly lower nitrate levels than in the river. Nutrient content increases with river inflow into the side-arm habitats due, in part, to incoming suspended particles and dissolved nutrients. Because of sedimentation and immobilisation by algal and plant matter, these nutrients should decrease in retention areas with increasing distance from the river input (Coops et al. 2008; Gregory et al. 1991). In autumn disconnection, dissolved oxygen levels were similar in the artificial side-arm outlet and the river, but low values at the inlet and middle of the artificial side-arm indicate potential for development of anoxic conditions in some areas. Backwater habitats have potential to act as areas of high denitrification, a process that uses nitrate in the water when there are conditions of anoxia, high organic matter and high temperature. During low

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flows, denitrification and rapid assimilation by macrophytes, result in nitrate levels remaining very low (Coops et al. 2008; Houser & Richardson 2010).

In contrast, the natural side-arm outlet had similar levels of nitrate as the river throughout the year including when there were high temperatures and low dissolved oxygen during late spring-summer connection and autumn disconnection. During the autumn disconnection, there was a significant increase in nitrate in the inlet compared to the middle station. Biological assimilation possibly occurred longitudinally between the inlet and middle, but the increase in nitrate at the outlet indicates a nitrate input that outweighs assimilation. The natural side-arm had a significant increase in total nitrogen compared to the main river during autumn disconnection which was due to a significant increase in ammonium. The decay of macrophyte biomass in the high-temperature low-oxygen environment could reduce nitrification while there was ongoing ammonification in the natural side-arm. The decline in pH noted over summer and in the middle site during disconnection could be an indication of macrophyte decay which would likely result in breakdown of large amounts of organic material and release of CO_2, resulting in a readjustment of carbonate-bicarbonate equilibrium (Wetzel 1975). A study on the upper Mississippi River found that, in areas with high water retention, anoxia and high organic content, there was low nitrate and high ammonium (Cavanaugh et al. 2006). An increase in ammonium can be attributed to the decay of macrophytes in summer-autumn that mobilise dissolved nutrients (Barko & Smart 1980; Coops et al. 2008).

Significantly lower total phosphorus concentrations in the outlet compared to the inlet of the artificial side-arm during autumn disconnection could be attributable to increased sedimentation occurring longitudinally in the side-arm, and as a result of biotic controls influencing phosphorus cycling between particulate and dissolved phases. Sorption of phosphorus to suspended solids may have been important in transitions between dissolved and particulate forms of phosphorus. It has been noted in river systems that low flow events produce opportunities for increased

assimilation of phosphate by plants (Houser & Richardson 2010). During disconnection, the artificial side-arm had an extremely high pH, possibly due to high rates of photosynthesis (Wetzel 1975) by the large macrophyte community present at this time.

Koi carp (*Cyprinus carpio*) were an invasive fish species regularly observed in both the artificial and natural side arms. The increase in suspended solids, ammonium, total nitrogen and total phosphorus found in the natural side-arm outlet compared to the river during autumn disconnection could be caused by the impact of trapped pest fish. Koi carp are known to degrade water quality through benthic feeding (Daniel 2009; Hicks et al. 2010). Bio-turbation, the behavioural disruption of sediments, results in the resuspension of nutrients from the sediments, and adversely affects macrophytes through increased turbidity limiting photosynthesis (Daniel 2009; Hein et al. 2005; Hicks et al. 2010; Houser & Richardson 2010). The decomposition of macrophytes, which would be strongly limited by light because of sediment resuspension (Hein et al. 2005; Houser & Richardson 2010), and the ammonium produced by the carp and other trapped fish during excretion could also account for increased ammonium in the natural side-arm (Higgins et al. 2006).

8.2   Biological characteristics of the studied side-arms

Species richness of phytoplankton in the current study was higher than the river in the artificial and the natural side-arms at all connectivity phases. Zooplankton species richness was higher in the artificial and natural side-arms compared to the river during winter connection when river levels were high. This is unexpected as high residence time correlates with high species richness (Salmaso & Zignin 2010; Schiemer & Hein 2007). However, while hydraulic retention was limited during this connectivity phase, it is possible that higher hydraulic retention still occurred in the side-arms compared to the river during high river flows. Factors promoted by high residence time in side-arms, such as substrate stability, sediment accumulation, and high light and nutrient availability, can lead to high species diversity of benthic invertebrates, periphyton, plankton and fish in side-arm habitats (Salmaso & Zignin 2010; Schiemer & Hein 2007). The

increase in zooplankton biomass in the natural side-arm during disconnection would be expected to contribute to the growth of fish in this river. It was shown in previous studies that increased retention fosters fish by providing refuge from high velocities and indirectly by providing them with adequate food sources (Salmaso & Zignin 2010; Schiemer & Hein 2007).

The current study showed that diatoms and Chlorophyta were the dominant phytoplankton Phyla in the river over the twelve month sampling period, similar to other studies in the Waikato River (Faithfull & Hamilton 2006; Hamilton & Duggan 2010). These findings are supported by literature pertaining to large rivers that suggest large river phytoplankton communities are expected to be dominated by diatoms and green-algae (Wehr & Descy 1998). The natural side-arm had the same phytoplankton community composition as the river during late spring-summer and winter connection, while the artificial side-arm had the same community composition as the river only during winter connection. Community composition in the side-arms that was the same as the river during connection reflects the side-arm's medium-high flows and constant source of river phytoplankton. This explains why the most diverse Phyla for all three habitats for the twelve-month period were the expected large river dominant phytoplankton, diatoms and Chlorophyta. Late spring-summer connection was dominated by *Asterionella* spp. and *Fragillaria* spp. in all three habitat types; species indicative of mixed, eutrophic habitats (Reynolds et al. 2002) possibly reflecting the constant input of nutrients and high light and temperatures in this phase.

During autumn disconnection, conditions of low flow, high temperatures, light and suspended solids within both side-arms resulted in community compositions dominated by *Cryptomonas* spp. and *Chlorella* spp., taxa in the artificial side-arm that are indicative of turbid, nutrient-rich habitats sensitive to flushing (Reynolds et al. 2002). In contrast, *Chlorella* spp., *Aulacoseira* spp. and *Trachelomonas* spp., taxa indicative of eutrophic conditions (Reynolds et al. 2002), were dominant in the natural side-arm at this time. A decrease in species richness since disconnection for both

side-arms appears to be a seasonal trend as river species richness decreased during autumn also.

In both side-arms community composition was similar to the river during winter connection when the dominant species were *Asterionella* spp., *Selenastrum* spp. and *Aulacoseira* spp., taxa adapted to high flows reflecting the change in physical conditions. Species richness in the river was lower than in each of the side-arms throughout the twelve month survey, reflecting the suitable habitat side-arms present for phytoplankton of increased retention time and habitat diversity (Van den Brink et al. 1994). The current study showed that limited fluctuations in river level height that would cause periodic connection between the river and side-arms resulted in low phytoplankton growth, as expected due to lack of continual addition of river nutrients.

Neither the artificial side-arm outlet nor the natural side-arm outlet showed significantly higher chlorophyll *a* concentrations than the river at any of the connectivity phases. Schiemer et al. (2006) suggest that the presence of phytoplankton adapted to efficient autotrophy is positively related to the frequency of flood pulses causing a short period of connection with lateral habitats. In my study there was hydraulic retention in the side-arms, due to a single disconnection event that extended over three months, rather than an intermediate level of connectivity caused by a number of high retention events in the side-arms interspersed with occasional inundation. This would suggest that the side-arms in this study only had one period of injection of river nutrients during autumn disconnection which would account for limited increases in phytoplankton biomass in the side-arms.

The artificial side-arm had significantly higher chlorophyll *a* concentration in the inlet compared to the middle and outlet during autumn disconnection. This could indicate that phytoplankton biomass (as indicated by chlorophyll *a* concentration) was increasing as expected in part of this side-arm but an unknown factor was reducing it. A possible reason for higher phytoplankton biomass at the inlet than the outlet of the artificial side-arm could be predation by zooplankton (Tockner et al. 1999).

Increases in 'water age' or retention time associated with decreasing river inflow have been shown to have a positive effect on productivity and the complexity of biotic interactions (Reynolds 1984; Schiemer & Hein 2007; Walks 2007). Typically, phytoplankton biomass peaks and then declines due to zooplankton grazing (Preiner et al. 2008; Schiemer et al. 2006; Schiemer et al. 2007).

Zooplankton species richness was higher in the side-arm habitats than in the river, possibly due to greater habitat diversity and increased primary productivity resulting in higher biomass of phytoplankton which zooplankton feed on. Zooplankton can be sensitive to environmental conditions of temperature, available food quality, turbulence and suspended solids (Gannon & Stemberger 1978; Hamilton & Duggan 2010; Lair 2006). In the current study it was observed that abundances from all habitats at all connectivity phases, including autumn disconnection, were dominated by rotifer species. This is supported by previous observations that rotifers make up the majority of the zooplankton community in the Waikato River, with cladocerans and copepods making up the remainder (Burger et al. 2002). The ability of rotifers to reproduce quickly and withstand higher water velocities due to their smaller size are adaptations likely to be responsible for their dominance (Lair 2006).

Total abundances of zooplankton were highest in the artificial side-arm and river during late spring-summer connection with a decrease in abundances in autumn disconnection and winter connection, supporting findings presented previously on the Waikato River by Burger et al. (2002). In the present study, total abundances were higher in the natural side-arm than the artificial side-arm and river during all connectivity phases, but higher still (by >200 individuals/ml) during autumn disconnection. The natural side-arm had a significantly higher chlorophyll *a* concentration indicating greater phytoplankton biomass, compared to the artificial side-arm, suggesting that zooplankton abundances would be correspondingly higher during autumn disconnection.

Zooplankton growth and survival increases with reducing water velocities. Rotifer biomass increases at low-medium residence time due to their short embryonic development (Baranyi et al. 2002; Dickerson et al. 2010; Walks 2007). Crustaceans such as copepods and cladocerans, which are more effective at grazing phytoplankton but have a longer recruitment period than rotifers (Baranyi et al. 2002; Schiemer & Hein 2007), exhibit a lag time between increased residence time and increased biomass, but dominate zooplankton assemblages due to an exponential increase in biomass during high residence times (Baranyi et al. 2002). (Baranyi et al. 2002) showed in a study on European floodplains, an exponential increase of crustaceans limiting rotifer species after 3 days of lentic conditions. However, this was not observed in the current study where a 16 day period of lentic conditions during complete disconnection occurred in May.

It could be speculated that physical differences between the natural and artificial side-arms could contribute to such different zooplankton abundances. Firstly, sub-surface seepage from the river into the artificial side-arm might have provided an adverse environment for zooplankton development due to mixing currents (Lair 2006). Secondly, the age of the side-arm could be significant with the natural side-arm having a larger store of diapausing eggs (Albritton & White 2006; Hairston Jr 1996), compared with recently formed sediments in the artificial side-arm. Another important factor to note is that because of time constraints, zooplankton data are only presented from March, the first month of autumn disconnection. It could be speculated that there was a change in zooplankton abundance in April and/or May.

Bdelloids were the dominant zooplankton in the natural side-arm during late spring-summer connection and in all habitats in autumn disconnection and winter connection, and are described as pioneer species that have the ability to withstand harsh, changing environments (Paidere et al. 2010) due to a life history trait that involves a dormant phase in undesirable conditions (Albritton & White 2006; Paidere et al. 2010; Ricci & Caprioli 2005). *Euchlanis dilatata* and *Brachionus calysiflorus* were dominant in late spring-summer connection and autumn disconnection in all habitats,

while *Trichocerca pusilla* was dominant in winter connection. Brachionids (*Brachionus calysiflorus*) are zooplankton that can withstand strong turbulence and currents. *Euchlanis dilatata*, *Brachionus calysiflorus* and *Trichocerca pusilla* are commonly found in eutrophic waters (Gannon & Stemberger 1978; Lair 2006). *Synchaeta oblonga*, dominant only in the river during late spring-summer connection and dominant in all habitats during winter connection, can withstand low temperatures. Cyclopoid copepods were the second dominant species in the natural side-arm during autumn disconnection and are considered an indicator of eutrophic conditions (Gannon & Stemberger 1978).

There were large numbers of crustacean individuals in the natural side-arm during autumn disconnection, a time when there were low abundances in a regular source of crustacean biomass to the river from Lake Hakanoa. The natural side-arm was a small habitat compared to that of Lake Hakanoa (see section Figure 2-2), this highlights the significance of higher crustacean abundances from the side-arm than the lake. At this time, the side-arm could provide a potentially important food source for fish because of the high crustacean abundances; preferentially selected as a food source for fish (Gannon & Stemberger 1978).

8.3   Functional role of the studied side-arms

Tockner et al. (1999) suggested different hydrological-ecological phases that relate to floodplain retention zones. The 'biotic interaction phase' is characterised by stagnant water, low nutrients because of high primary productivity, but low phytoplankton biomass due to high zooplankton grazing pressure. In the present study this phase is most like autumn disconnection where some form of disconnection leading to no flows and stagnant water was experienced by the artificial and natural side-arms (Table 8-1).

Table 8-1 Characteristics and corresponding ecological/functional properties of hydraulic retention zones, adapted from Tockner et al. (1999). Comparison of the current study side-arms at autumn disconnection with an example from (Tockner et al. 1999) illustrating the 'biotic interaction phase' for a floodplain on the Danube River.

Parameter	Tockner et al. (1999)	Artificial side-arm	Natural side-arm
Hydrological connectivity	Disconnected	Disconnected + seepage flow	Disconnected
Residence time	Very high (13+ days)	High (0-13+ days)	High (0-13+ days)
Nutrient level	Low	Low	Medium-High
Algal biomass	Low	Low	Low
Nutrient dynamics	Closed-system cycling	Closed-system cycling	Closed-system cycling
Sink/source of matter	Sink (autochthonous)	Sink (autochthonous)	Source (suspended solids, nutrients, zooplankton)
Ecological phase	'Biotic interaction'	Possible 'Biotic interaction'?	'Biotic interaction'

During autumn disconnection, the artificial side-arm exhibited low nutrients and low phytoplankton biomass, but speculations of zooplankton grazing pressure lack support because zooplankton abundance appeared to be lower in autumn disconnection than the previous connectivity phase. The natural side-arm fits the 'biotic interaction phase' as it experienced low phytoplankton biomass and an increase in zooplankton abundance during autumn disconnection. Increased nutrient and suspended solid levels

suggest another factor, such as bio-turbation by pest fish, was influencing plankton dynamics other than primary productivity and grazing pressure.

In the current study, both side-arms were closed system; no incoming nutrients (Tockner et al. 1999) during autumn disconnection (Table 8-1). At this time both side-arms exhibited evidence of nutrient cycling (Table 8-1) whereby the system is able to process nutrients biologically and chemically, and all outputs from processing remain in the system because of lack of transport (Tockner et al. 1999). According to the classification from (Tockner et al. 1999), the natural and artificial side-arms would fall into different categories because of their capacity to act as source or sinks of organic matter and nutrients (

Table 8-1). The artificial side-arm would be classified as a sink due to the reduction longitudinally within the side-arm of nutrients and the lack of significantly greater phytoplankton biomass exported to the river in high flows. The natural side-arm would be termed a source, as suspended solids, nutrients and zooplankton biomass increased longitudinally within the side-arm, with high flows initially exporting this material into the river (winter connection).

How well the side-arms in this study conform to proposed functional roles of lateral habitats experiencing hydraulic retention in the Inshore Retention Concept (IRC) (Schiemer et al. 2001a) and the Riverine Ecosystem Synthesis (RES) (Thorp et al. 2006; Thorp et al. 2008) gives an indication of how well artificial side-arms should perform for restoration purposes in the lower Waikato River. Tenets from the RES are discussed here with regards to the current study. Figure 8-2 illustrates artificial and natural side-arms species richness (an indication of biodiversity) while Figure 8-2 illustrates nutrient cycling and potential for transport to the river, storage of suspended solids and phytoplankton biomass (an indication of primary productivity) in a period of increased hydraulic retention during autumn disconnection.

Biodiversity

	Phytoplankton	Zooplankton
Artificial side-arm	↑	↓
Natural side-arm	↑	↓
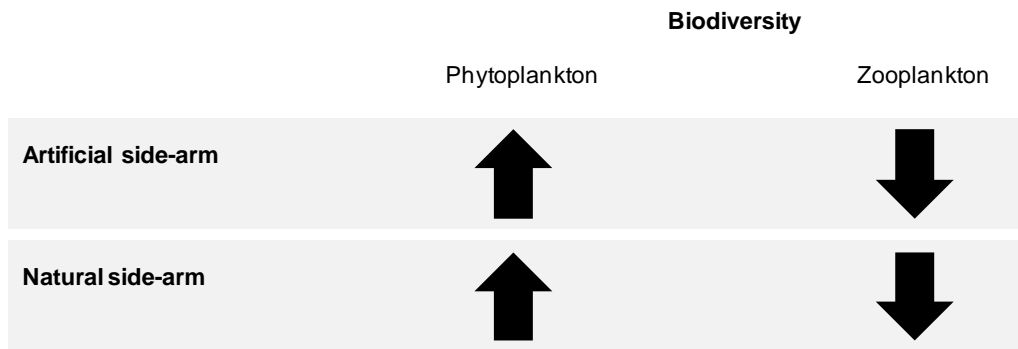
Figure 8-1 Conceptual diagram applying functional role characteristics of hydraulic retention zones to the artificial and natural side-arms during autumn disconnection compared to the river. The functional role of biodiversity is presented here as indicated by species richness. Arrows indicate the direction of species richness differences in side-arms compared to the river.

⇩ < river value　▪ = river value　↑ > river value

Artificial side-arm

Nutrient conc.	Inlet	Middle	Outlet
Total Nitrogen	=	=	=
Ammonium	=	=	=
Nitrate	⇩	⇩	⇩
Phosphate	=	=	=
Total phosphorus	↑	=	=
Suspended solids	↑	=	=
Phytoplankton Biomass	↑	=	=

Natural side-arm

Nutrient conc.	Inlet	Middle	Outlet
Total Nitrogen	↑	↑	↑
Ammonium	↑	↑	↑
Nitrate	=	⇩	=
Phosphate	=	=	=
Total phosphorus	↑	=	=
Suspended solids	↑	↑	↑
Phytoplankton Biomass	=	=	=

Figure 8-2 Conceptual diagram describing functional roles of the artificial and natural side-arms during autumn disconnection. Nutrient and suspended solid processing as well as primary production indicated by phytoplankton biomass (chlorophyll *a* concentrations) are shown compared to the river.

During autumn disconnection, the period of hydraulic retention, an increase in community biodiversity would be predicted based on the IRC and RES tenet 4 (Schiemer et al. 2001a; Thorp et al. 2006; Thorp et al. 2008). As expected, phytoplankton species richness was found to be higher than the river for both side-arms at this time (Figure 8-1).

Primary productivity would be expected to be higher in areas with increased hydro-geomorphic complexity and increased hydraulic retention based on RES tenet 10 (Thorp et al. 2006; Thorp et al. 2008). Side-arms are areas of high retention during disconnection, and have higher geomorphic complexity than the main river channel. Although primary productivity was not measured in this study, phytoplankton biomass (indicated by chlorophyll *a* concentration) was higher in the inlet of the artificial side-arm during autumn disconnection before being reduced, most likely by factors such as zooplankton grazing pressure. The natural side-arm did not show increased phytoplankton biomass, suggesting no increase in primary production compared to the river.

Nutrient cycling and downstream transport of nutrients would be expected to decrease with hydraulic retention according to RES tenet 13 (Thorp et al. 2006; Thorp et al. 2008). The artificial side-arm demonstrated this functional role by removing nitrate and total phosphorus from the water column longitudinally within the side-arm, along with suspended solids. This would have reduced the amount of nutrients released back into the river at the artificial side-arm outlet. The natural side-arm showed similar patterns for nitrate and total phosphorus, but in contrast, showed increases in ammonium, total nitrogen and suspended solids that would be released back in the main river channel at the outlet.

Connectivity of a habitat with the main river channel will provide maximum bio-complexity at intermediate levels of connectivity according to RES tenet 16. Intermediate connectivity can be described as disconnection causing hydraulic retention occurring many times, providing pulses of nutrients during connection, and a retention period that allows for biological processing during disconnection (Thorp et al. 2006; Thorp et al. 2008). The side-arms in this study did have hydraulic retention for a maximum duration of 72 days, and there was one connective pulse during complete disconnection, suggesting only two extended disconnection periods.

There is considerable support in the literature for the importance of pulses of river water into lateral habitats of high retention (Amoros & Bornette 2002; Hein et al. 2003; Preiner et al. 2008; Schiemer & Hein 2007; Schiemer et al. 2006; Tockner et al. 1999), a process that is determined by river discharge. River discharge with a natural hydrograph would result in high productivity in hydraulic retention zones due to a balance between retention and export of nutrients and organic matter. This balance would involve various events of inundation, promoting the export of non-refractory organic matter into the river (Schiemer et al. 2006; Thorp et al. 2006; Thorp et al. 2008; Tockner et al. 1999). The catchment geology for the lower Waikato River and its tributaries influences the flood pulses experienced in the current study's hydraulic retention zones, indicating a natural hydrograph for this area. This suggests that, while the literature provides a guide for the desired functional roles in order to improve local ecosystem health, it is important that functional roles in an artificial side-arm are similar to those of naturally occurring side-arms in the lower Waikato River rather than match functional roles of hydraulic retention zones in other systems.

9   Summary and Recommendations

An artificial side-arm was investigated for restoration of lateral habitat potential in a comparative study with a naturally occurring side-arm in the lower Waikato River. Large variation in naturally occurring side-arms in the lower Waikato River revealed in a spatial survey, suggested the selected natural side-arm was a suitable representative for the comparative study.

The outlets of the two side-arms (artificial and natural) were compared to the river in a twelve-month temporal study. Comparison was based on plankton abundance and community composition, nutrient and suspended solid dynamics and the physico-chemical variables associated with each habitat. Comparisons between the inlet, middle and outlet sites in the side-arms were carried out to determine patterns longitudinally within each side-arm.

A significant effect of side-arm connection with the river, based on seasonal hydrology was used for comparison during analysis. The twelve month survey was broken into three phases of connectivity; before disconnection in late spring-summer, during disconnection in autumn and after re-connection in winter.

It was predicted that the side-arms in this study would: (i) have high hydraulic retention, (ii) have increased primary productivity, (iii) retain nutrients and prevent their redistribution into the main river channel, and (iv) have varying levels of connectivity. As a result of providing these functional roles, the side-arms would display an overall increase in community biodiversity through species richness, increased phytoplankton biomass indicating higher primary productivity, greater storage and processing of nutrients and maximum bio-complexity compared to the river. Both side-arms performed some of these functional roles.

The autumn disconnection period led to extensive hydraulic retention within the side-arms, resulting in changes in the functional roles. The artificial and natural side-arms in this study demonstrated differences in physical structure that are likely to have caused differences observed in

nutrient, suspended solids and biological patterns during different levels of connectivity with the river.

The period of side-arm connection with the river in late spring-summer was characterised by high temperatures and low dissolved oxygen, possibly associated with decomposition of macrophytes causing low pH. Species of phytoplankton indicative of eutrophication dominated side-arms at this time, likely caused by nutrients released during macrophyte decomposition and provided by constant river inputs at medium-low river flows.

During autumn disconnection, each side-arm functioned differently. The artificial side-arm increased in phytoplankton species richness and biomass, retained suspended solids and nutrients and appeared to increase bio-complexity through possible biotic interaction of grazing zooplankton.

The natural side-arm revealed unexpected roles of providing the main river channel with increased nutrient and suspended solid loads. The natural side-arm did, however, show an increase in phytoplankton species richness and a potentially important role in generating a zooplankton food source for fish during disconnection, indicating bio-complexity. It is possible that zooplankton abundance was higher in the natural side-arm than the artificial side-arm due to the increased establishment age of the natural side-arm, coupled with zooplankton reproduction strategies. When re-connection with the river in winter occurred, the side-arms acted as extensions of the river habitat with similar plankton community compositions, nutrient and suspended solid concentrations and physico-chemical variables.

Analysis of phytoplankton and zooplankton data on a finer time scale during disconnection would show more definitive patterns of changing community composition and biotic interactions, possibly missed in this study. Evaluation of ecosystem respiration and metabolism would also be beneficial to understand the role autotrophs play during disconnection; another factor only revealed when studied on a finer time scale. Further investigation into subsurface seepage would be important for further

comparisons between side-arms, as this exchange is potentially key to functional roles during disconnection. The retention characteristics of the side-arms using a tracer would provide a quantifiable water age that would be useful in understanding nutrient uptake and sedimentation rates. Methods of pest fish exclusion could be beneficial to limit possible resuspension of sediments and increases in nutrient and sediment loads to the main river channel. The growth of riparian vegetation, a shift from sand based substrate to a substrate of higher organic matter and the accumulation of zooplankton diapausing eggs would be expected in the artificial side-arm over time; long-term monitoring of the artificial side-arm would be beneficial to see whether the functional roles change towards those of the natural side-arm.

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Appendices

Appendix 1 – Nutrients & physico-chemical raw data

A-1 Raw nutrient and physico-chemical variable data from 12 month study for the three sites within the artificial and natural side-arms and river. Nutrient, TSS and dissolved oxygen values are in mg/l. Specific conductivity (µs cm^{-1}), temperature (°C), and chlorophyll a (µg l^{-1}).

Artificial

Month	Location	NH4	NO3	PO4	TN	TP
Nov	Inlet	0.035	0.286	0.025	0.406	0.096
Nov	Middle	0.023	0.269	0.021	0.357	0.074
Nov	Outlet	0.013	0.133	0.019	0.385	0.105
Dec	Inlet	0.149	0.173	0.014	0.357	0.087
Dec	Middle	0.035	0.091	0.016	0.311	0.058
Dec	Outlet	0.028	0.122	0.021	0.268	0.055
Jan	Inlet	0.026	0.076	0.024	0.231	0.059
Jan	Middle	0.006	0.000	0.022	0.191	0.068
Jan	Outlet	0.007	0.000	0.016	0.141	0.046
Feb	Inlet	0.015	0.099	0.025	0.224	0.049
Feb	Middle	0.046	0.070	0.011	0.226	0.024
Feb	Outlet	0.011	0.000	0.009	0.164	0.029
March	Inlet	0.016	0.000	0.013		
March	Middle	0.028	0.000	0.015	0.230	0.026
March	Outlet	0.041	0.008	0.010	0.166	0.021
April	Inlet	0.025	0.000	0.019	0.148	0.084
April	Middle	0.026	0.000	0.056	0.272	0.030
April	Outlet	0.023	0.114	0.035	0.206	0.048
May	Inlet	0.192	0.000	0.008	0.270	0.107
May	Middle	0.017	0.000	0.021	0.235	0.041
May	Outlet	0.015	0.002	0.013	0.118	0.018
June	Inlet	0.054	0.626	0.038	1.117	0.069
June	Middle	0.053	0.962	0.031	1.109	0.063
June	Outlet	0.037	0.909	0.041	1.064	0.071
July	Inlet	0.077	1.079	0.032	1.564	0.065
July	Middle	0.051	0.881	0.029	1.157	0.053
July	Outlet	0.045	0.855	0.023	1.063	0.044
Aug	Inlet	0.052	0.745	0.046	1.133	0.055
Aug	Middle	0.042	0.834	0.033	1.234	0.056
Aug	Outlet	0.046	0.873	0.039	1.123	0.048
Sep	Inlet	0.045	0.420	0.030	1.112	0.072
Sep	Middle	0.057	0.649	0.028	1.037	0.061
Sep	Outlet	0.081	0.655	0.031	1.116	0.126
Oct	Inlet	0.020	0.363	0.020	0.925	0.060
Oct	Middle	0.020	0.382	0.019	1.057	0.048
Oct	Outlet	0.022	0.405	0.020	0.890	0.044

A-1 cont.

Artificial

Month	Location	pH	Specific conductivity	Temp	DO mg/L	DO %	TSS	chl a
Nov	Inlet	8.2	164.9	15.8	9.97	100.5	42.22	8.40
Nov	Middle	8	163.9	16.2	10.76	109.8	33.33	11.00
Nov	Outlet	7.8	164.9	16.5	10.88	111.8	33.33	3.57
Dec	Inlet		177	21.3	8.06	90.8	8.33	1.98
Dec	Middle		164.3	22.1	10.57	121.7	4.67	2.12
Dec	Outlet		166.2	22.4	10.06	115.2	8.67	2.27
Jan	Inlet	7.72	165.4	22.8	9.78	114.5	7.07	4.60
Jan	Middle	8.32	165.4	24.4	12.17	145.3	9.33	3.27
Jan	Outlet	7.96	164.8	24.5	10.3	122.9	9.33	3.45
Feb	Inlet	7.91	168.5	23.6	10.12	117.8		3.89
Feb	Middle	7.48	172.2	22.5	6.1	71.4		3.33
Feb	Outlet	7.71	174.7	23.3	6.79	79.4		4.39
March	Inlet	7.26	228.4	20.5	4.12	41.4	21.89	7.63
March	Middle	10.22	185.7	18.7	0.97	10.6	4.94	9.65
March	Outlet	7.04	246.3	21.9	6.42	73.9	1.89	1.13
April	Inlet	7.03	303.6	20.3	3.02	32.7	47.67	60.74
April	Middle	10.05	188.1	19.9	11.7	127.6	1.73	1.99
April	Outlet	7.95	157.8	19.2	10.01	108	4.93	9.97
May	Inlet	7.83	203.4	18.9	5.02	69.7	52.13	16.50
May	Middle	9.81	170.4	17.4	13.23	138.2	4.27	4.90
May	Outlet	9.43	184.1	15	12.13	119.3	0.86	0.69
June	Inlet						10.20	3.55
June	Middle	7.96	183	12	8.59		5.47	3.24
June	Outlet	8.05	180.8	12	8.98	83.5	4.77	1.97
July	Inlet	8.12	191.9	11.5	9.01	82.8	11.67	1.79
July	Middle	7.9	184.8	11.5	9.18	84.3	6.79	2.59
July	Outlet	8.31	180.7	11.4	9.18	84.6	5.54	2.42
Aug	Inlet	7.73	162.8	11.3	10.93	100	7.22	4.89
Aug	Middle	7.35	157.9	11.3	10.41	95.7	5.17	4.47
Aug	Outlet	7.83	166.5	11.2	10.54	95.9	4.92	3.23
Sep	Inlet	7.84	149.5	13	8.49	80.8	15.44	9.15
Sep	Middle	7.97	149.5	13.1	8.57	81.6	15.73	10.70
Sep	Outlet	7.59	149.5	13	8.78	83	15.94	11.04
Oct	Inlet	7.98	144.4	14.5	10.11	99.1	8.31	8.11
Oct	Middle	7.79	144.4	14.6	9.81	96.4	7.11	7.87
Oct	Outlet	7.96	144.4	14.4	10.15	99.6	13.11	11.77

A-1 cont.

Natural

Month	Location	NH4	NO3	PO4	TN	TP
Nov	Inlet	0.023	0.279	0.024	0.400	0.066
Nov	Middle	0.022	0.272	0.025	0.849	0.076
Nov	Outlet	0.021	0.274	0.023	0.361	0.066
Dec	Inlet	0.037	0.264	0.027	0.761	0.254
Dec	Middle	0.052	0.202	0.033	0.318	0.079
Dec	Outlet	0.033	0.141	0.032	0.262	0.061
Jan	Inlet	0.029	0.092	0.027	0.183	0.050
Jan	Middle	0.063	0.126	0.026	0.217	0.058
Jan	Outlet	0.013	0.040	0.023	0.255	0.064
Feb	Inlet	0.028	0.157	0.027	0.322	0.076
Feb	Middle	0.025	0.144	0.030	0.270	0.053
Feb	Outlet	0.029	0.074	0.029	0.242	0.062
March	Inlet	0.049	0.162	0.034	0.709	0.245
March	Middle	0.144	0.000	0.038	0.255	0.069
March	Outlet	0.273	0.007	0.038	0.401	0.226
April	Inlet	0.052	0.141	0.028	0.252	0.064
April	Middle	0.060	0.048	0.021	0.249	0.124
April	Outlet	0.130	0.154	0.022	0.307	0.065
May	Inlet	0.033	0.271	0.036	0.318	0.058
May	Middle	0.037	0.000	0.011	0.356	0.198
May	Outlet	0.076	0.142	0.017	0.554	0.517
June	Inlet	0.066	0.987	0.037	0.986	0.067
June	Middle	0.054	0.929	0.032	1.287	0.058
June	Outlet	0.045	0.877	0.033	1.007	0.064
July	Inlet	0.071	0.952	0.034	1.327	0.054
July	Middle	0.068	0.927	0.026	1.424	0.050
July	Outlet	0.090	0.839	0.027	1.196	0.049
Aug	Inlet	0.054	0.719	0.027	1.024	0.051
Aug	Middle	0.037	0.486	0.028	1.038	0.047
Aug	Outlet	0.060	0.498	0.029	1.025	0.056
Sep	Inlet	0.078	0.742	0.031	1.074	0.098
Sep	Middle	0.060	0.753	0.032	1.184	0.107
Sep	Outlet	0.055	0.672	0.031	1.230	0.107
Oct	Inlet	0.017	0.384	0.018	0.938	0.041
Oct	Middle	0.025	0.420	0.023	0.964	0.045
Oct	Outlet	0.017	0.413	0.019	0.929	0.079

A-1 cont.

Natural

Month	Location	pH	Specific conductivity	Temp	DO mg/L	DO %	TSS	chl a
Nov	Inlet	7.8	159.4	15.8	8.23	83.4	13.89	6.96
Nov	Middle	7.6	159.7	15.9	8.65	88.2	36.67	13.15
Nov	Outlet	7.6	159.4	16.6	8.31	85.3	35.00	4.25
Dec	Inlet		164.9	19.2	6.78	72.1	12.67	2.80
Dec	Middle		169.9	20.3	6.46	74.2	7.87	2.03
Dec	Outlet		167.1	20	6.74	74.7	7.47	5.40
Jan	Inlet	7.81	165.3	21.3	8.39	95.9	11.05	4.39
Jan	Middle	7.69	164.9	21.3	7.97	88.8	5.53	3.16
Jan	Outlet	7.68	164.9	21.9	7.79	89.4	9.73	5.93
Feb	Inlet	8.07	170	22.7	7.71	90.2	14.40	7.67
Feb	Middle	7.68	169.3	23	8.14	94.7	8.18	7.58
Feb	Outlet	7.75	168	23.5	8.09	95.3	5.62	5.34
March	Inlet	8.39	167.8	23.1	7.51	87.3	7.28	3.37
March	Middle	7.75	250.1	22.5	0.92	10.6	82.22	24.69
March	Outlet	8.66	266.2	22.6	0.81	10.1	43.89	34.53
April	Inlet	8.16	164.4	18.5	7.7	82.4	18.13	13.32
April	Middle	7.81	180.5	16.7	3.45	34.5	37.78	12.46
April	Outlet	8.47	168.9	17	7.74	78.4	13.07	10.87
May	Inlet	7.7	183.8	16.4	8.69	87.9	2.76	6.73
May	Middle	7.08	227	12.1	1.36	12.6	14.78	17.33
May	Outlet	7.62	242.3	12.2	7.2	66.7	11.80	8.73
June	Inlet	8.05	181.9	11.7	8.97	82.9	15.07	4.69
June	Middle	7.94	181.1	11.7	8.99	83.1	10.47	4.59
June	Outlet	8.19	178.2	11.6	8.68	79.8	9.49	4.45
July	Inlet	7.86	185.8	11.3	9.38	85	18.92	3.45
July	Middle	8.54	183.8	11.3	9.38	85	11.17	4.66
July	Outlet	8.51	180	11.2	9.31	85.1	9.79	1.14
Aug	Inlet	8.04	160.4	10.8	10.7	97.7	11.06	5.09
Aug	Middle	8.1	161.2	10.7	10.1	91.3	9.89	5.47
Aug	Outlet	8.32	161.4	10.8	10.14	91.5	13.22	6.30
Sep	Inlet	7.82	148.5	12.9	8.8	83.3	27.61	5.42
Sep	Middle	7.92	148.6	12.9	8.74	82.5	20.92	3.55
Sep	Outlet	8.2	148.3	12.9	8.96	84.9	24.67	10.11
Oct	Inlet	8.37	143.7	14.2	9.63	93.9	11.78	11.15
Oct	Middle	7.91	143.6	14.2	9.6	93.8	10.58	10.84
Oct	Outlet	8.09	143.5	14.2	9.53	92.6	10.44	11.84

A-1 cont.

River

Month	Location	NH4	NO3	PO4	TN	TP
Nov	Upstream	0.026	0.318	0.027	0.407	0.074
Nov	Between	0.023	0.283	0.024	0.320	0.052
Nov	Downstream	0.032	0.267	0.021	0.364	0.065
Dec	Upstream	0.025	0.270	0.028	0.360	0.064
Dec	Between	0.020	0.263	0.025	0.279	0.058
Dec	Downstream	0.027	0.265	0.028	0.347	0.071
Jan	Upstream	0.040	0.178	0.043	0.273	0.068
Jan	Between	0.040	0.156	0.026	0.273	0.062
Jan	Downstream	0.015	0.127	0.025	0.259	0.061
Feb	Upstream	0.020	0.143	0.029	0.460	0.070
Feb	Between	0.017	0.157	0.030	0.279	0.073
Feb	Downstream	0.022	0.169	0.034	0.275	0.073
March	Upstream	0.023	0.138	0.028	0.249	0.058
March	Between	0.023	0.164	0.030	0.215	0.057
March	Downstream	0.023	0.163	0.029	0.227	0.058
April	Upstream	0.028	0.162	0.027	0.236	0.051
April	Between	0.027	0.171	0.024	0.250	0.051
April	Downstream	0.026	0.169	0.037	0.236	0.044
May	Upstream	0.035	0.286	0.038	0.302	0.052
May	Between	0.032	0.205	0.036	0.306	0.053
May	Downstream	0.042	0.259	0.038	0.261	0.048
June	Upstream	0.066	1.078	0.036	1.200	0.069
June	Between	0.067	1.043	0.035	1.158	0.063
June	Downstream	0.063	0.911	0.037	1.143	0.058
July	Upstream	0.101	1.157	0.041	1.417	0.074
July	Between	0.083	1.078	0.030	1.314	0.073
July	Downstream	0.076	0.928	0.029	1.369	0.067
Aug	Upstream	0.048	0.683	0.025	1.246	0.068
Aug	Between	0.046	0.560	0.025	1.291	0.051
Aug	Downstream	0.049	0.610	0.022	1.030	0.054
Sep	Upstream	0.046	0.616	0.029	1.277	0.080
Sep	Between	0.072	0.742	0.033	1.190	0.088
Sep	Downstream	0.048	0.704	0.032	1.281	0.075
Oct	Upstream	0.025	0.360	0.020	0.883	0.057
Oct	Between	0.021	0.402	0.018	0.991	0.049
Oct	Downstream	0.027	0.387	0.022	0.854	0.042

A-1 cont.

River

Month	Location	pH	Specific conductivity	Temp	DO mg/L	DO %	TSS	chl a
Nov	Upstream	8.1	164.2	15.7	10.1	101.5	30.56	4.16
Nov	Between	7.7	159.3	16.1	9.72	98.8	28.33	9.91
Nov	Downstream	7.7	160.1	16.3	8.24	84.7	22.22	4.31
Dec	Upstream		163.8	20.4	8.3	91.9	10.67	2.57
Dec	Between		160	19.6	7.19	78.7	10.27	3.75
Dec	Downstream		161.7	19.6	7.11	75.6	10.27	2.86
Jan	Upstream	7.87	168.5	21.4	8.55	97.2	4.73	3.33
Jan	Between	7.6	160.1	21.2	8.8	99.2	5.53	1.86
Jan	Downstream	7.81	165.2	20.7	8.19	91.3	4.93	4.04
Feb	Upstream	7.85	169.9	22.6	8.02	92.8	8.76	4.90
Feb	Between	8	167.9	22.8	8.22	95.5	7.10	4.90
Feb	Downstream	7.69	170.6	22.6	7.96	91.2	12.34	6.78
March	Upstream	8.24	164.9	22.4	8.36	96.4	5.61	4.79
March	Between	8.15	165.3	23.1	8.66	102	5.28	4.26
March	Downstream	8.33	165.5	23.4	8.59	103.5	4.61	4.92
April	Upstream	8.02	164.4	18.4	8.83	94.2	5.47	13.53
April	Between	8.15	164.4	18.4	9.53	102.3	6.67	10.39
April	Downstream	9.03	165.3	18	8.72	93.3	6.73	12.08
May	Upstream	7.92	184.5	16.3	9.31	95.3	5.22	3.87
May	Between	7.89	184.5	16.2	9.17	93.8	5.36	3.24
May	Downstream	7.89	185.1	15.8	9.14	92.1	5.62	1.79
June	Upstream	7.89	188	11.9	9.3	86.2	13.14	1.76
June	Between	8.33	185	11.9	9.31	85.3	16.43	2.55
June	Downstream	8.36	179.2	11.6	8.87	82.4	11.14	3.07
July	Upstream	7.97	196.9	11.3	9.43	86.7	12.79	3.42
July	Between	8.26	190.7	11.3	9.49	86.9	11.17	3.62
July	Downstream	8.72	181.4	11.2	9.64	89.5	11.54	4.62
Aug	Upstream	7.78	162.5	11	9.87	90.7	9.39	5.01
Aug	Between	8.01	159	10.9	9.85	84.3	10.56	2.53
Aug	Downstream	7.75	161.3	10.7	10.41	93.1	11.56	4.47
Sep	Upstream	7.73	149.9	12.9	9.81	83.3	22.42	6.25
Sep	Between	8	148.4	12.9	8.75	83	26.28	5.94
Sep	Downstream	8.06	148.1	12.8	9.45	99.9	24.42	9.11
Oct	Upstream	7.89	144.8	14.3	9.54	92.3	11.38	9.77
Oct	Between	8.09	143	14.2	11.67	112.2	10.98	10.32
Oct	Downstream	8.23	143.6	14.1	10.06	99	10.31	8.73

Appendix 2 – Phytoplankton raw data

A-2 Raw phytoplankton abundance data from 12 month study averaged for three sites (inlet, middle and outlet) within the artificial and natural side-arms and (upstream, between and downstream) river. Values are in cells/ml.

Habitat	Connectivity phase	*Acanthoceras Zachariasi*	*Actinastrum*	*Anabaena*	*Ankistrodesmus*	*Asterionella*	*Aulacoseira*	*Chlamydomonas*
Artificial side-arm	1	9.4	0.0	13.8	0.0	1113.1	187.5	209.9
	2	0.0	0.8	57.9	31.0	0.8	6.7	286.1
	3	2.0	0.0	0.0	15.4	1059.2	344.3	154.6
Natural side-arm	1	3.8	0.6	47.2	5.7	1303.3	289.5	0.0
	2	0.0	41.1	88.1	0.0	34.4	594.7	420.4
	3	1.5	0.0	11.1	24.3	1342.9	463.1	114.3
River	1	10.1	0.0	35.9	7.6	1390.6	244.8	1.3
	2	10.9	19.3	0.0	0.8	74.7	478.4	42.0
	3	4.0	0.0	66.5	14.4	1088.0	467.8	109.1

Habitat	Connectivity phase	*Chlorella*	*Chroococcus*	*Closterium*	*Cocconeis*	*Coelastrum*	*Crucigenia*	*Cryptomonas*
Artificial side-arm	1	111.5	0.0	5.7	22.0	45.3	0.0	31.5
	2	781.2	0.0	0.0	32.7	0.0	0.0	2012.5
	3	156.7	32.9	0.8	4.9	28.7	0.0	30.4
Natural side-arm	1	234.7	0.0	0.0	41.8	33.4	0.0	12.6
	2	2860.3	0.0	12.6	15.1	255.9	0.0	383.0
	3	133.7	12.1	0.0	6.9	4.0	0.0	21.6
River	1	273.7	0.0	0.6	15.7	84.3	0.0	15.1
	2	1503.6	0.0	0.0	15.1	88.9	0.0	25.2
	3	211.4	92.0	0.5	5.4	0.0	4.0	23.3

A-2 Cont.

Habitat	Connectivity phase	Cyclotella	Dictosphaerium	Dinobryon	Encyonema	Epithemia	Euglena	Fragilaria
Artificial side-arm	1	22.9	0.0	14.5	9.4	51.0	3.1	456.5
	2	12.6	0.0	0.0	4.2	20.1	0.0	22.7
	3	8.9	0.0	4.7	0.8	12.3	1.3	45.5
Natural side-arm	1	28.9	0.0	4.4	0.0	53.5	0.0	1442.9
	2	275.8	0.0	0.0	12.6	146.8	199.7	168.6
	3	24.3	3.0	10.6	1.0	18.1	2.3	132.9
River	1	51.6	0.0	10.1	5.0	40.3	3.1	1666.3
	2	4.2	0.0	35.2	0.0	64.6	0.8	28.5
	3	14.4	0.0	7.4	3.4	25.8	1.0	110.8

Habitat	Connectivity phase	Frustulia	Golenkinia	Gomphonema	Gonium	Kirchneriella	Mallomonas	Merismopedia
Artificial side-arm	1	6.3	0.0	1.9	2.5	0.0	1.9	270.6
	2	0.0	0.0	4.2	0.0	125.9	0.0	0.0
	3	0.5	0.8	2.3	19.1	1.0	3.0	0.0
Natural side-arm	1	6.3	0.0	15.7	0.0	26.4	0.6	103.8
	2	0.0	0.0	0.0	0.0	0.0	37.8	0.0
	3	0.8	1.5	4.5	0.0	1.0	6.9	84.6
River	1	0.0	0.0	0.0	0.0	0.0	0.0	191.3
	2	0.0	0.8	9.2	0.0	135.9	0.0	0.0
	3	0.0	0.8	0.8	11.6	5.5	2.0	0.0

A-2 Cont.

Habitat	Connectivity phase	*Micractinium*	*Microsystic*	*Mougeotia*	*Navicula*	*Nitzschia*	*Nodularia*	*Oocystis*
Artificial side-arm	1	0.0	0.0	45.9	15.1	146.0	0.0	71.7
	2	0.0	211.4	64.9	45.3	50.1	0.0	2.5
	3	6.7	458.1	0.0	0.0	9.1	0.0	15.4
Natural side-arm	1	0.0	0.0	73.6	7.6	35.2	20.1	14.5
	2	0.0	419.5	338.1	96.5	151.0	0.0	13.4
	3	0.0	1762.0	0.0	2.9	7.9	0.0	6.2
River	1	0.0	0.0	173.4	17.6	20.1	0.0	35.9
	2	8.4	0.0	337.2	15.9	19.3	0.0	9.2
	3	13.6	0.0	0.0	2.5	5.9	0.0	11.1

Habitat	Connectivity phase	*Oscillatoria*	*Pediastrum*	*Peridinium*	*Phacus*	*Pinnularia*	*Polyedriopsis*	*Pseudoanabaena*
Artificial side-arm	1	0.0	16.4	0.0	0.0	0.0	0.0	58.5
	2	0.0	6.7	18.9	0.0	0.0	0.0	610.4
	3	0.0	0.0	1.5	1.7	0.0	0.5	28.2
Natural side-arm	1	0.0	134.0	13.4	0.0	0.0	0.0	44.1
	2	4.2	126.7	0.0	0.0	0.0	33.6	1780.5
	3	0.0	122.6	1.5	0.5	0.0	0.0	104.0
River	1	0.0	57.9	0.0	0.0	0.0	0.0	0.0
	2	2.5	16.8	16.8	0.0	0.0	16.8	10.1
	3	0.0	61.8	1.5	0.0	0.5	0.5	118.3

A-2 Cont.

Habitat	Connectivity phase	*Scenedesmus*	*Selenastrum*	*Sphaerocystis*	*Staurastrum*	*Synedra*	*Trachelomonas*
Artificial side-arm	1	20.8	85.0	0.0	0.6	29.6	30.8
	2	83.9	21.0	43.6	0.8	20.1	82.2
	3	27.4	350.4	38.8	0.0	4.0	15.4
Natural side-arm	1	3.1	50.3	28.9	0.6	25.2	23.3
	2	64.6	99.0	0.0	0.0	27.7	541.6
	3	31.9	352.2	12.6	0.0	3.0	9.9
River	1	2.5	56.0	0.0	0.6	20.1	5.7
	2	30.2	69.6	236.6	0.8	14.3	29.4
	3	19.6	333.1	39.8	0.0	4.0	13.4

Habitat	Connectivity phase	Total Abundances (cells/ml)
Artificial side-arm	1	1533.8
	2	383.4
	3	1575.5
Natural side-arm	1	1650.1
	2	1178.6
	3	1957.2
River	1	1690.1
	2	626.0
	3	1749.7

Appendix 3 – Zooplankton raw data

A-3 Raw zooplankton abundance data from 12 month study (three monthly: December 2009, March, June and September 2010) averaged for three sites (inlet, middle and outlet) within the artificial and natural side-arms and (upstream, between and downstream) river. Values are in individuals/ml.

Habitat	Connectivity Phase	Ascomorpha ovalis	Ascomorphella volvocicola	Asplanchna priodonta	Bdelloids	Brachionus angularis	Brachionus bennini	Brachionus budapestinensis
Artificial	1		1.72	0.05	0.18			
Natural	1		1.70	0.12	1.68			0.01
River	1		1.43	0.09	0.24			0.03
Artificial	2				0.12			
Natural	2		0.01	0.36	177.12			0.01
River	2		0.02	0.02	0.21			0.03
Artificial	3	0.00		0.02	0.66	0.03		0.04
Natural	3		0.01	0.09	0.67		0.00	0.02
River	3		0.02	0.02	0.47			0.01

Habitat	Connectivity Phase	Brachionus calyciflorus	Brachionus quadridentatus	Cupelopagis vorax	Dicranophorus caudatus	Euchlanis dilatata	Filinia *novaezealandiae*	Filinia terminalis
Artificial	1	0.81	0.07			0.41		
Natural	1	0.69	0.32			3.05	0.01	
River	1	0.81	0.03			0.08	0.03	
Artificial	2		0.01			0.08		
Natural	2	0.02	0.49			3.95		
River	2	0.30				0.06		0.01
Artificial	3	0.01	0.07	0.02	0.00	0.01		0.02
Natural	3		0.01	0.03		0.03		0.05
River	3		0.01	0.01		0.03		0.00

A-3 Cont.

Habitat	Connectivity Phase	Hexarthra	Keratella cochlearis	Keratella tropica	Lecane bulla	Lecane flexilis	Lecane luna	Mytilina ventralis
Artificial	1		0.01	0.07	0.01			
Natural	1		0.03	0.17	0.12			
River	1	0.01	0.07	0.08	0.01			
Artificial	2			0.01	0.14		0.07	
Natural	2				2.63			
River	2		0.01	0.05				
Artificial	3	0.01	0.14	0.08	0.02	0.00		0.00
Natural	3		0.14	0.10			0.01	
River	3		0.09	0.09	0.01		0.01	

Habitat	Connectivity Phase	Platyais quadricornis	Pleurotrocha petromyzon	Polyathra dolichoptera	Pompholyx complanata	Synchaeta oblonga	Synchaeta pectinata	Testudinella patina
Artificial	1			0.03	0.01	0.21		
Natural	1			0.14		0.25		
River	1			0.04		0.26		
Artificial	2			0.01	0.01			0.01
Natural	2	0.85			1.42	0.01		
River	2			0.05		0.04		0.01
Artificial	3	0.00	0.00	0.07	0.08	0.23	0.01	
Natural	3	0.00		0.10	0.10	0.15	0.01	
River	3			0.04	0.03	0.11		

A-3 Cont.

Habitat	Connectivity Phase	Trichocerca pusilla	Trichocerca similis	Trichocerca stylata	Trichocerca unknown?	Trichotria tetractis	Bosmina meridionalis	Chydoridae
Artificial	1	0.01	0.04	0.06		0.01	0.10	0.04
Natural	1		0.03	0.35		0.20	0.25	0.15
River	1	0.01	0.02	0.09		0.03	0.15	0.02
Artificial	2	0.01	0.01	0.03	0.02	0.01	0.08	0.02
Natural	2					0.49	1.94	
River	2	0.01	0.02	0.01		0.01	0.16	
Artificial	3	0.20	0.10	0.01		0.01	0.08	0.04
Natural	3	0.21	0.08	0.01		0.01	0.22	0.04
River	3	0.15	0.06	0.00		0.01	0.13	0.03

Habitat	Connectivity Phase	Daphnia	Ilyocryptus sordidus	Calanoid	Cyclopoid	Harpactacoid	Mesocyclops leuckarti
Artificial	1			0.03			0.01
Natural	1	0.02			0.64	0.02	
River	1	0.02			0.03	0.01	
Artificial	2				0.09	0.01	
Natural	2				18.55	0.49	
River	2			0.01			
Artificial	3	0.01	0.00	0.00	0.03	0.00	
Natural	3	0.04		0.01	0.03	0.00	
River	3	0.03	0.00	0.01	0.03		

A-3 Cont.

Habitat	Connectivity Phase	Total Abundance (individuals/ml)
Artificial	1	1.95
Natural	1	3.52
River	1	1.79
Artificial	2	0.12
Natural	2	177.49
River	2	0.28
Artificial	3	2.01
Natural	3	2.17
River	3	1.40

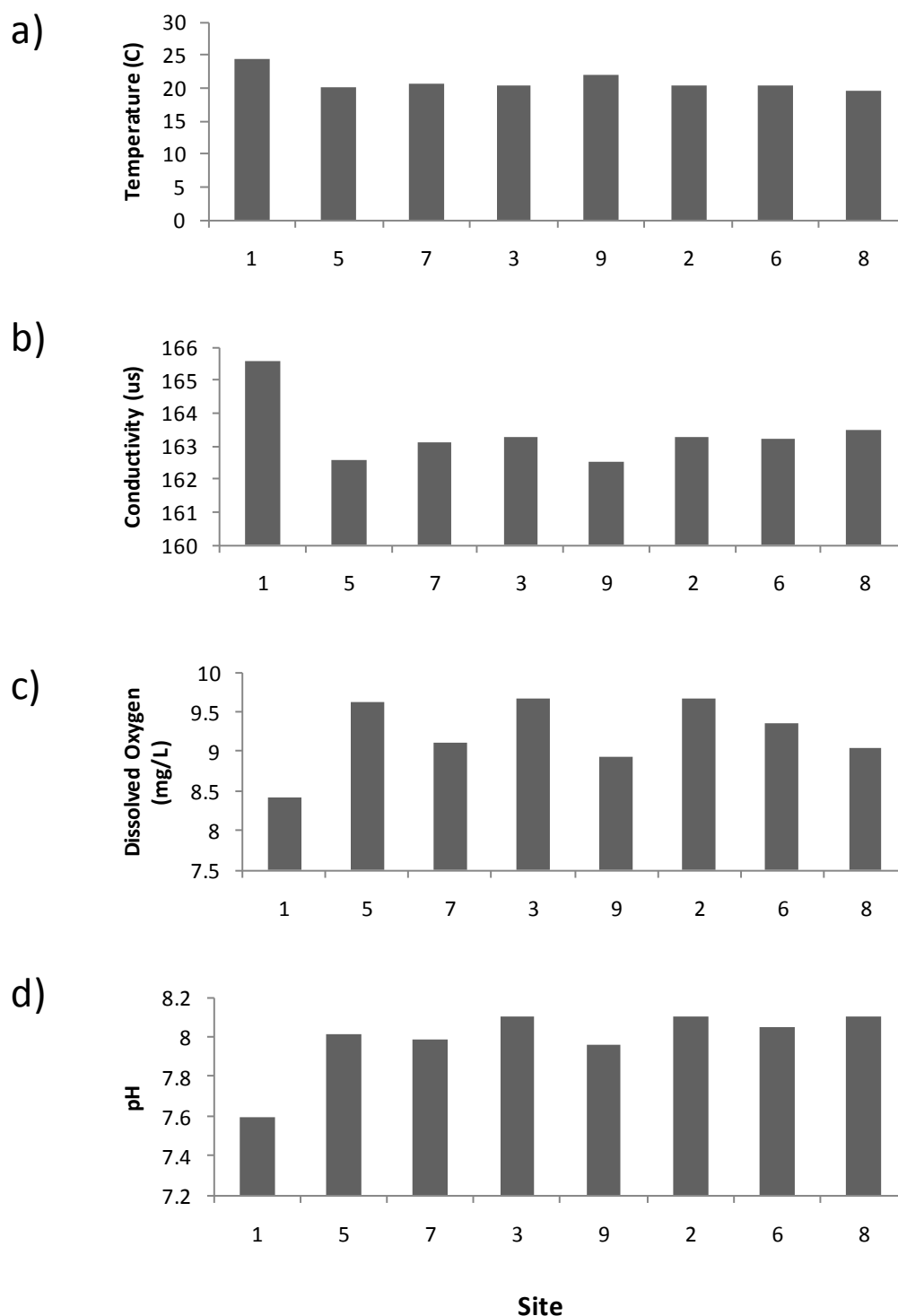## Appendix 4 – Spatial survey river data

a)


b)

c)

d)

Site

Figure A-1 Physico-chemical concentrations from the one-off spatial survey (corresponding river sites 1-9). a) Temperature, b) specific conductivity, c) dissolved oxygen, and d) pH. Order that sites are presented along the x-axis relates to order of corresponding side-arm sites which is based on connectivity with the river (high connection towards the left of the x-axis, low connection towards the right). Values represent means.
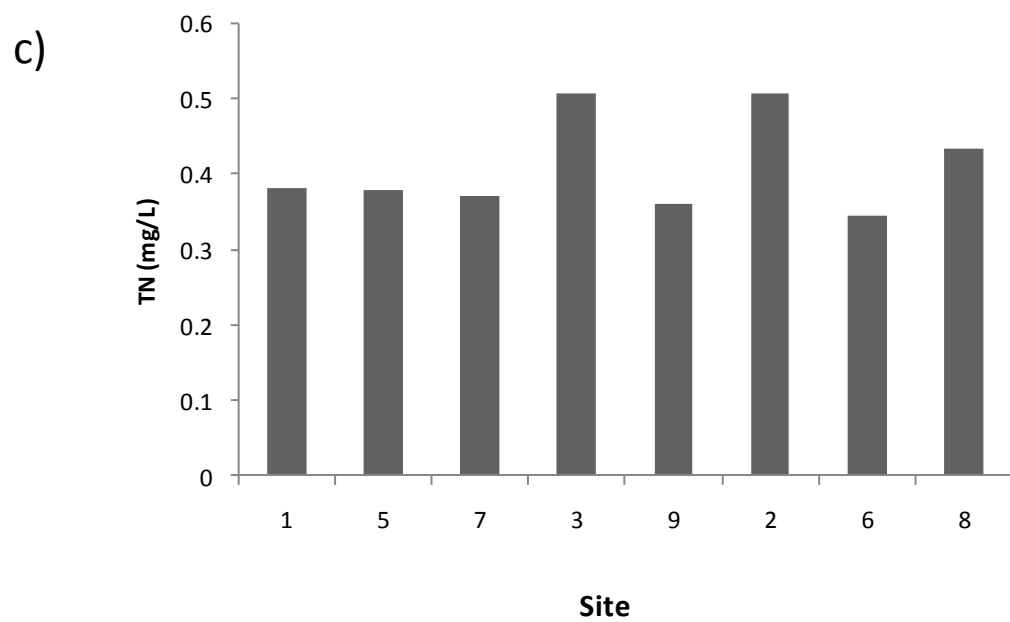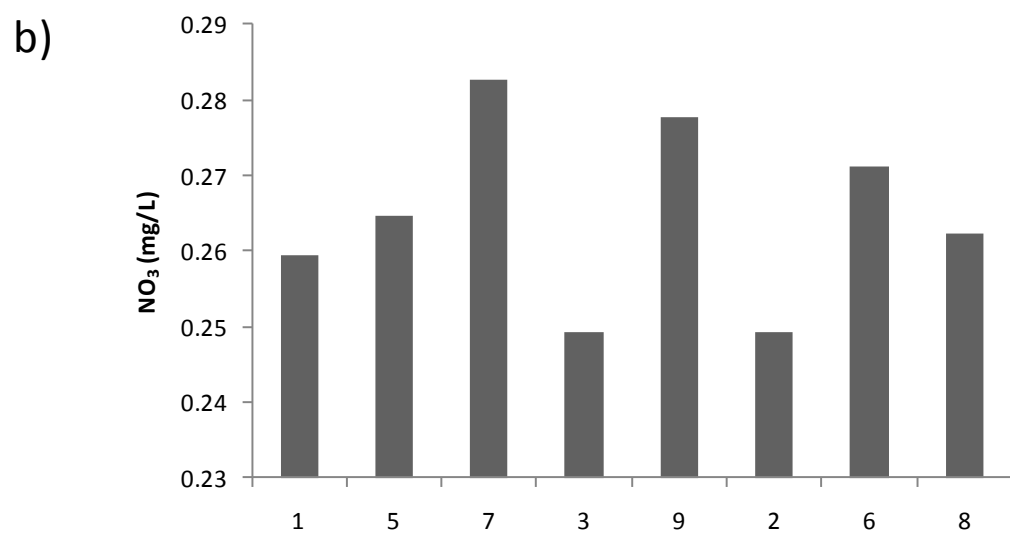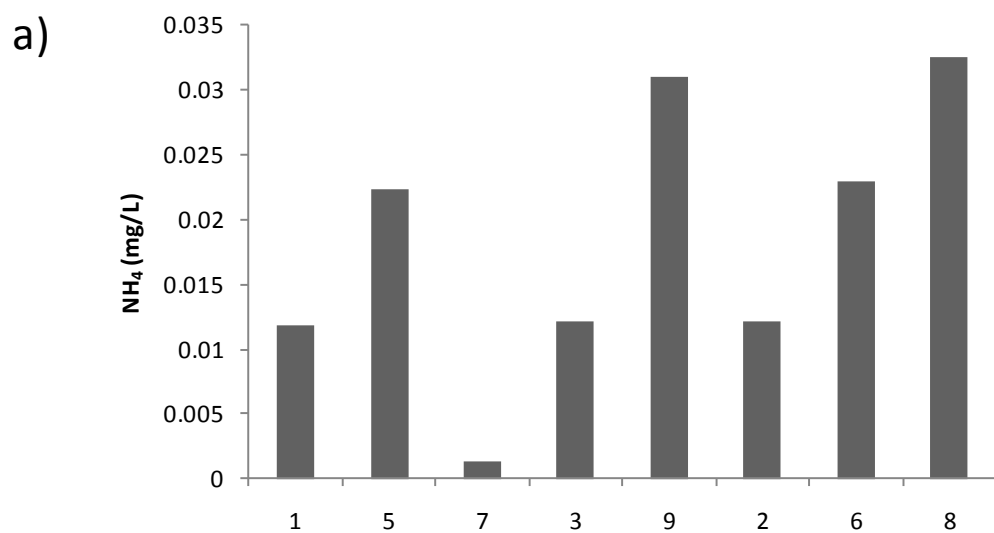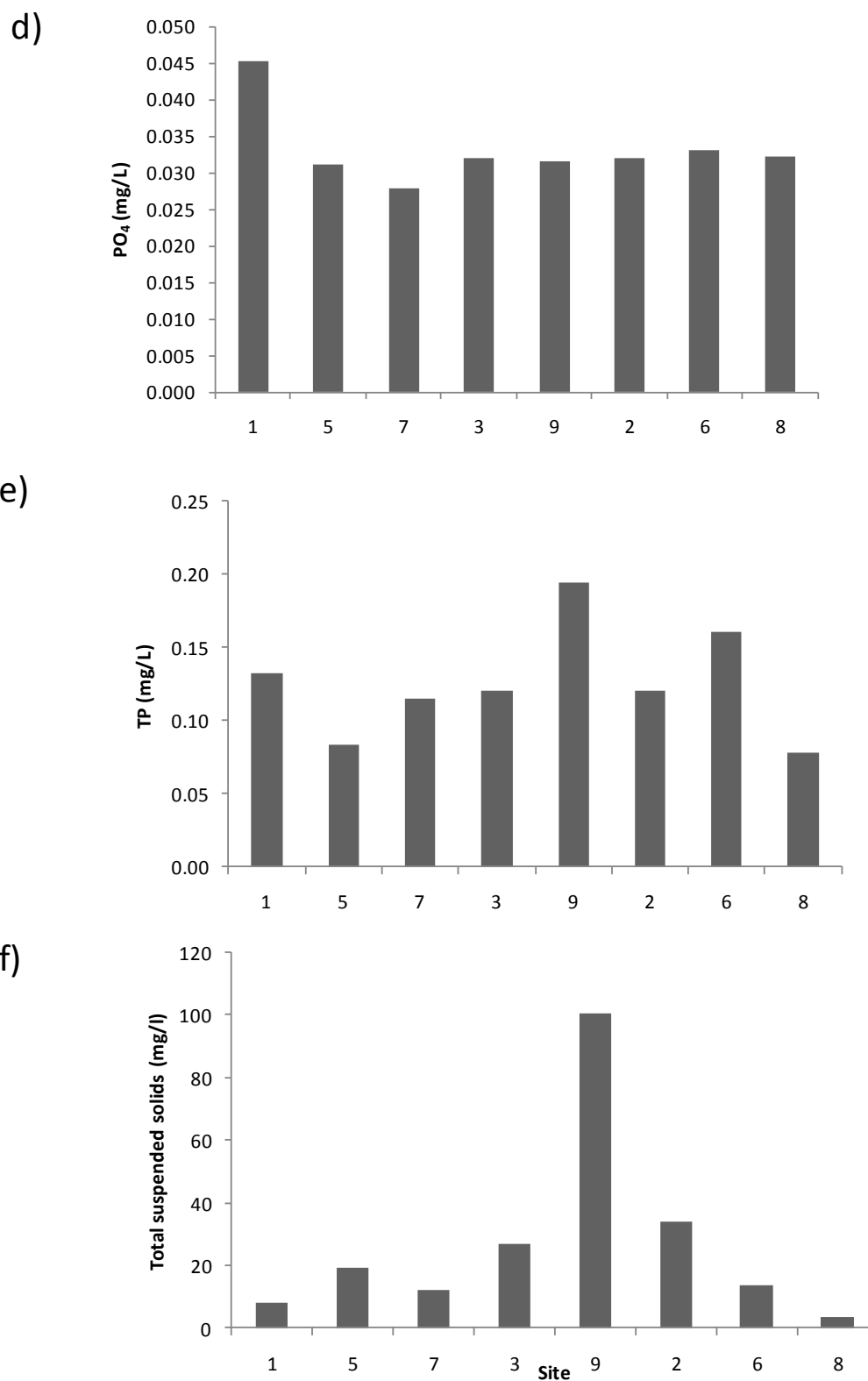
Figure A-2a-f Ammonium (NH$_4$-N), Nitrate (NO$_3$-N), Total nitrogen (TN), Phosphate (PO$_4$-P), Total phosphorus (TP), and total suspended solid concentrations from the one-off spatial survey (corresponding river sites 1-9) Order that sites are presented along the x-axis relates to order of corresponding side-arm sites which is based on connectivity with the river (high connection towards the left of the x-axis, low connection towards the right) Values represent means.

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