Freshwater Ecology of Piped Streams in Wellington: Pilot Study Final Report

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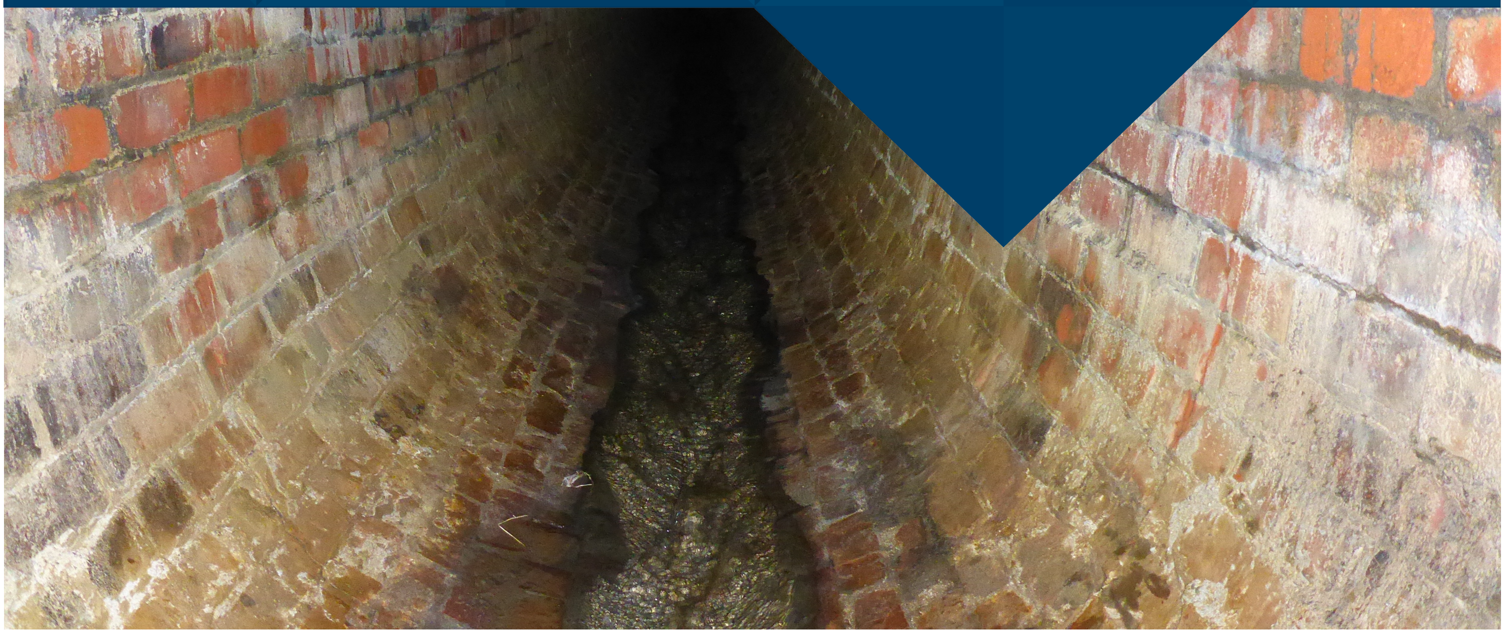
Prepared for Greater Wellington Regional Council

Prepared by EOS Ecology – Dr Alex James

Reviewed by Shelley McMurtrie (EOS Ecology) and Dr Evan Harrison (GWRC)



www.eosecology.co.nz
info@eosecology.co.nz

PO Box 4262, Christchurch 8140
P 03 389 0538

PO Box 8054, Palmerston North 4446
P 06 358 9566

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EXECUTIVE SUMMARY

The piping of natural stream channels is commonplace in many urban environments. Many catchments are extensively piped such that original open stream habitat only exists as isolated remnants among the pipe network. In Wellington city, with its steep topography and small coastal catchments, many small streams have undergone extensive piping as the landscape was urbanised. Because of the difficulty of sampling piped streams, most freshwater ecological information from these urban streams is derived from remnant open sections, even though these only account for a small proportion of total stream length. To address this knowledge gap, EOS Ecology and Greater Wellington Regional Council (with support from Wellington City Council) undertook a pilot study to investigate the habitat, fish communities, and macroinvertebrate assemblages of six piped stream sites across three predominantly urban catchments in Wellington.

In-pipe habitat ranged from fast, laminar flows over bare brick or concrete, to zones of slower water velocity with natural stony substrates. Organic material such as leaves, woody debris, and tree roots were present to some extent at all sites, while biofilms were prominent at five of the six sites. Water depths were generally very shallow (<10 cm) and fish cover lacking. Just as in natural stream channels, it is apparent piped streams have erosional and depositional zones.

Fish were found at five of the six sites, indicating fish, in particular eels (both longfin and shortfin), are relatively common and widespread in piped streams. A single young adult inanga was found at a tidally influenced site in Miramar, while two banded kokopu (live juvenile; dead, recently predated adult) were found further up the same catchment. Eels were often found hiding under whatever cover they could find (i.e., rubbish, rubble, tree roots, fine sediments), indicating that even in near complete darkness they prefer to spend some of their day concealed. A comparison of the fish assemblages of piped stream sites with open stream sites in the same catchments indicated strong habitat partitioning, with eels dominating piped sites and banded kokopu dominating open sites.

The macroinvertebrate community of piped streams was dominated by taxa known to be tolerant or to prefer degraded stream conditions (e.g., *Potamopyrgus* and *Physa* snails, oligochaete worms, Orthocladiinae and *Polypedilum* midge larvae, Collembola springtails, Psychodidae gnat larvae, mites, and *Ferrissia* limpets). All piped stream sites had mean MCI and QMCI values indicative of poor conditions. When compared to macroinvertebrate data collected by Greater Wellington Regional Council (GWRC) at open stream sites in the same catchments, piped stream sites had lower numbers of individuals, lower taxa richness, lower MCI and QMCI scores, and lower EPT abundance and richness. Piped stream macroinvertebrate communities were dominated by the most tolerant taxa that are capable of living in near complete darkness, with no riparian vegetation or benthic algae, and subject to a very flashy flow regime. In catchments with extensive piping, even small sections of remnant open channel are very important at maintaining catchment aquatic macroinvertebrate diversity, in particular EPT taxa.

Currently, piped streams are generally considered part of the stormwater network and are not recognised for their ecological values by the Proposed Natural Resources Plan. Should a piped stream be disturbed by some activity (e.g., construction or discharge), there is no requirement for ecological values to be taken into account or even for GWRC freshwater scientists to be notified. It is recommended that work be undertaken to allow for piped streams to be formally identified, their ecological values documented, and steps taken such that they are included in the next iteration of the Natural Resources Plan.

In-pipe habitats could be improved by the retrofit of various features such as flexible baffles in zones of laminar, high flow velocities to improve fish passage and cover for resident fish, installation of small structures to increase water depths (e.g., leaky weirs, vanes), and installation of secure artificial fish cover elements (e.g., small pipes and half pipes). Such features may also facilitate the retention of natural substrates and organic material, further improving habitat quality, including habitat for aquatic macroinvertebrates.

1 INTRODUCTION

In most cities urban streams have been extensively piped to provide land for development and alleviate flood and disease risk. In many catchments open stream habitat exists only as short remnant channels. To date ecological information on these highly modified catchments has primarily been derived from these remnant open sections for reasons of accessibility and safety, even though these sections make up a small percentage of total stream length. Further, the piped sections that join isolated open reaches are generally managed as part of the stormwater network and have typically been ignored from an ecological perspective.

Wellington, with its steep topography and coastal location, is a good example of a city where numerous small coastal stream catchments have been extensively piped, such that in several suburbs open stream channels are now only found as fragmented remnants. With the exception of some anecdotal reports of eels down stormwater grates, piped streams in Wellington have previously only been considered as migration pathways for some freshwater fishes that are known to be present in remnant open sections (e.g. banded kokopu, kōaro, eels). The fish and macroinvertebrates living within the piped sections are unknown and there has never been any attempt to characterise freshwater habitat condition in these highly modified stream environments.

EOS Ecology undertook a series of urban stream catchments investigations from 2015 to 2017 for Wellington Water Limited (WWL) to support Integrated Catchment Management Plan (ICMP) development, where the project brief was only to examine open sections of streams (James, 2016; James ,2017a; James, 2017b; James, 2018a; James, 2018b). It became apparent the ecological values of extensively piped catchments could not be fully determined without examining the piped sections (which were often the higher proportion of total stream length). Based on the catchment knowledge gained during the ICMP investigations, EOS Ecology then developed a plan to undertake a pilot study to survey piped stream ecology in Wellington. The lack of information on piped stream ecology was suggested to Greater Wellington Regional Council (GWRC) as a major knowledge gap and they agreed to fund (with assistance from Wellington City Council) a pilot study of six sites focussing on fish, macroinvertebrates, and habitat quality.

EOS Ecology was contracted by GWRC to design, implement, and report on this pilot study. Following on from an interim report completed in July 2019 (James, 2019), this final report incorporates analysis and interpretation of the quantitative Surber sampling macroinvertebrate data from the detailed survey. We examine habitat conditions, the fish community, and the macroinvertebrate assemblage. We compare piped site fish data with that from open stream sites in the same catchments. Analysis of the macroinvertebrate assemblage of the six sites based on the quantitative Surber sample information also includes comparison with data obtained earlier via modified long-handled kick nets deployed from the street surface, along with open stream standard kick net data from within the same catchments obtained from the GWRC urban stream sampling programme.

2 METHODS

2.1 Health and Safety

Underground pipes are classified as confined spaces, meaning only appropriately trained persons are able to enter and special procedures are required (e.g., operating a permitting system, use of gas detectors, use of a winch and rescue-tether system). As WWL manages the piped stream network as part of the stormwater system, a WWL-approved contractor was required to assist with the project. WWL put us in touch with Silver Linings Contracting, who were then contracted to assist with all piped stream fieldwork. They were in charge of site health and safety and supplied all equipment required for confined space entry. From EOS Ecology, the author (Alex James) was confined spaces entry certified.

2.2 Site Selection

2.2.1 Desktop Exercise

WWL provided GIS layers of the stormwater network, manhole locations, and remnant open channels. These were overlain with Google Earth imagery and used to select manholes within Wellington's inner suburbs where entry for an ecological survey appeared logistically realistic. Criteria for potential sites included:

» Pipe diameters of no less than 1200 mm.

» Manholes to be located on footpaths or berms to avoid the requirement for traffic management or entering of private property (Figure 1).

» The catchment would preferably have permanently flowing open stream remnants from which fish were known.

Based on these criteria, 36 candidate manholes were identified with the expectation some would be inaccessible in the field.

Miramar Stream manhole on grassed berm

Pae Kawakawa Stream manhole on footpath

Figure 1 Examples of berm and footpath locations of candidate manholes.

2.2.2 Manhole Lifting Exercise

Over 1–2 May 2018, a manhole lifting site visit was undertaken with Silver Linings Contracting to aid selection of the final survey sites. Overall, 20 manholes were opened, with the remaining 16 either being inaccessible (e.g., buried, car parked over, building on top) or being in close proximity to another opened manhole. We also took the opportunity to trial macroinvertebrate sampling from the surface utilising a modified sampling net.

Once each manhole was opened, a set procedure was undertaken:

» Lowering of a gas detector to check for unsafe concentrations of oxygen, hydrogen sulphide, carbon monoxide, and flammable gases (Figure 2).

» Measurement of surface to pipe bottom and pipe diameter using a Leica Disto laser measurement device.

» Visual estimation of water depth (dry/shallow/medium/deep), substrate type (brick, concrete, silt, cobbles, other), pipe shape/profile (circular/rectangular/arch/other), and pipe material (concrete/brick/other).

» Collection of macroinvertebrate samples using a brush and standard kick net with extendable handles (2.7–5 m). Such samples were collected from 16 sites (Figure 2). Samples were preserved with isopropyl alcohol (IPA) for later processing.

» The taking of photos of the manhole shaft and stream below.

» The taking of video footage from selected manholes using a GoPro video camera and torch attached to the extendable-handle kick net (Figure 2).

Using the extendable-handle kick net to collect a macroinvertebrate sample

Using the extendable-handle kick net in conjunction with a brush to collect a macroinvertebrate sample

Measuring the atmosphere using a gas detector

The GoPro video camera setup

Figure 2 Examples of manhole lifting exercise methodology.

2.2.3 Final Site Selection

Six sites were selected for detailed ecological survey: three in Pae Kawakawa Stream catchment (Island Bay), two in Miramar Stream (Miramar), and one in Waipapa Stream (Hataitai) (Figure 3). The Pae Kawakawa Stream and Miramar Stream sites were all vertical entries down manholes, while Waipapa Stream involved entry via the ocean outlet at low tide. It was originally planned to have a site in the Waitangi Stream catchment, however the only suitable site was deemed too dangerous to enter without using breathing apparatus, for which additional specialist training would have been required. One of the three Pae Kawakawa Stream sites was a substitute for this site.

Figure 3 Locations of the six detailed survey sites and the two GWRC open stream sites in the Pae Kawakawa, Miramar and Waipapa catchments. The GWRC site codes are shown in parentheses.

2.3 Detailed Ecological Survey

The six sampling sites were visited on two occasions for the detailed survey (Stage 1: 6–7 March 2019 and Stage 2: 20–21 March 2019). Stage 1 involved installation of trail/game cameras, sticky traps, and collection of macroinvertebrate samples, while Stage 2 consisted of the recovering of cameras and sticky traps and undertaking a fish survey. In practice, fish were often sighted during Stage 1, so an informal fish survey (consisting of noting if fish were seen) was also undertaken at that time. Additionally, an equipment mishap required macroinvertebrates at one site to be collected on the Stage 2 visit. Details of the survey methodology are detailed below:

» **Trail/game cameras**: At each site, a single trail camera was installed near the manhole, with the lens facing towards the wetted channel in an attempt to obtain images of fish within the piped streams (Figure 4). Cameras were mounted on existing pipes or reinforcing steel rods where available, otherwise a steel extendable curtain rod was affixed across the width of the piped stream. Curtain rods were attached using cable ties to any available protrusions (e.g., ladder rungs, reinforcing steels) and/or appropriate concrete adhesives applied via caulking gun. Cameras were set to take time-lapse images every 10 minutes for the duration of deployment and also be triggered to take a photo by movement. The typical movement sensor of such cameras relies on a difference in temperature between the environment and the animal, hence, is unlikely to be triggered by fish. Where the camera model allowed (we used three different models), 10-second videos were also recorded every 10 minutes.

» **Sticky traps**: At each site, a single 24.5 cm wide by 40 cm high plastic yellow sticky trap was installed as near the roof of the piped stream as possible (Figure 4). These were sticky on both the upstream and downstream sides and installed to existing pipes or reinforcing steels at some sites or to the curtain rod described above at others.

» **Macroinvertebrates**: Twelve Surber samples (0.09 x 0.09 m^2) were collected from each site over a 40 to 100 m length of stream, depending on availability of habitat suitable for Surber sampling and access (Figure 4). Samples were preserved with isopropyl alcohol (IPA) for later processing. Macroinvertebrate samples were processed using a full-count method.

» **Fish survey**: At each site, a 200 m (100 m upstream and downstream of the manhole access point) reach was carefully searched for fish using a spotlight and hand netting technique (Figure 4). The exception was Waipapa Stream, where we entered via the ocean outlet. At this site, we searched for fish from the entrance all the way upstream to where the macroinvertebrate survey was undertaken. In practice, in Waipapa Stream, fish were only observed in the lower 90 m of pipe as above this point water became too shallow and cover lacking for the fish present. Any obvious fish cover elements (e.g., pieces of wood, brick, and assorted rubbish) were slowly lifted to determine if fish were underneath. Fish were identified to species, with the exception of those eels that were unable to be captured. Lengths were visually estimated.

» **Habitat characterisation**: At each Surber sample location (12 at each site), water depth, wetted width, substrate composition, and organic matter cover (leaves, CPOM, biofilms) was recorded. We recorded the "head" where water depth was recorded to enable an estimate of water velocity using the ruler methodology (cf. Harding et al., 2009 – Appendix 3). Biofilm colour and thickness was also recorded. Site photos were taken, including images of each Surber location prior to sampling (Figure 4). We also made site wide measurements of meso-habitat length (rapid, run, riffle, pool, fall) and made visual estimates of substrate composition and organic matter cover (leaves, roots, CPOM, biofilms). Any potential fish barriers were noted.

» **Water quality**: A YSI multiprobe supplied by GWRC was used to collect spot water quality records of temperature, dissolved oxygen, and conductivity.

Camera and sticky trap attached to reinforcing steel

Surber sampling

An eel captured via spotlighting and hand netting

Example of substrate sampled for macroinvertebrates

Figure 4 Images of detailed survey methodologies.

2.4 Data Analysis

Habitat data were summarised by calculating mean values for those parameters measured at each of the 12 Surber sampling locations (water depth, wetted width, water velocity, substrate composition, and organic matter cover). Fish data were summarised by total abundance, taxa richness, the density of fish captured per linear length of pipe sampled, and relative abundance.

Macroinvertebrate data were summarised by total density, taxa richness, the densities or abundance of the five most of abundant taxa, and non-metric multidimensional scaling ordination (NMS). Biotic indices calculated were the number of Ephemeroptera-Plecoptera-Trichoptera taxa (EPT richness), % EPT abundance (i.e., EPT abundance/total abundance ×100), the Macroinvertebrate Community Index (MCI), and its quantitative derivative (QMCI). The paragraphs below provide clarification on some of these metrics.

Total density refers to the number of macroinvertebrates in the sampled area for each 0.1 m^2 Surber sample. Taxa richness is the number of different taxa identified in each sample. 'Taxa' is generally a term for taxonomic groups, and in this case refers to the lowest level of classification that was obtained during the study. Taxa richness can be used as an indication of stream health or habitat type, where sites with greater taxa richness are usually healthier and/or have a more diverse habitat.

EPT refers to three Orders of invertebrates that are generally regarded as 'cleanwater' taxa. These Orders are Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), forming the acronym EPT. These taxa are relatively intolerant of organic enrichment or other pollutants and habitat degradation. The exceptions to the rule are hydroptilid caddisflies (e.g., Trichoptera: Hydroptilidae: *Oxyethira, Paroxyethira*), which are algal piercers and often found in high numbers in nutrient enriched waters. Hydroptilids were not found at the piped stream sites, nor at the GWRC open stream sites. EPT richness and % EPT scores can provide a good indication as to the health of a particular site. EPT taxa are generally more diverse in non-impacted, "pristine" stream systems.

The MCI score (and its quantitative variant, QMCI) can be used to determine the level of organic enrichment for stony-bottomed waterways in New Zealand (Stark, 1985). It calculates an overall score for each sample, which is based on pollution-tolerance values for each macroinvertebrate taxon that range from 1 (very pollution tolerant) to 10 (pollution-sensitive). MCI is calculated using presence/absence data, whereas the QMCI score incorporates abundance data and so gives a more accurate result by differentiating rare taxa from abundant taxa. According to the interpretative categories of Stark & Maxted (2007), excellent conditions are indicated by a QMCI of >5.99 and an MCI of >119; good conditions by a QMCI of 5.00–5.99 and an MCI of 100–119; fair conditions by a QMCI of 4.00–4.99 and an MCI of 80–99; and poor conditions by a QMCI of <4.00 and an MCI of <80. GWRC has classified streams in their region based on their physical characteristics and developed river class-specific "MCI ecological condition classes" (Clapcott & Goodwin, 2014). The sampled streams were all classified as "Class 6 – Lowland, small", which has MCI classes nearly identical to those of Stark & Maxted (2007) (i.e., <80 = poor, 80–100 = fair, 100–120 = good, and ≥120 = excellent).

NMS is non-metric statistical technique that condenses sample data (in this case macroinvertebrate community data) to a single point in low-dimensional ordination space using some measure of community dissimilarity (Bray-Curtis metric in this instance). Interpretation is straightforward such that points on an x-y plot that are close together represent samples that are more similar in community composition than those further apart (Clarke & Gorley, 2006). Significant differences in macroinvertebrate community composition between sites, catchments, Surber vs. kick net samples, and piped vs. open streams were tested using the analysis of similarities (ANOSIM) procedure, which is a non-parametric procedure, applied to the similarity matrix that underlies the NMS ordination. ANOSIM is an approximate analogue of the standard ANOVA (analysis of variance) and compares the similarity between groups (in this instance upstream control and downstream impact) using the R test statistic. R=0 where there is no difference in macroinvertebrate community between groups, while R=1 where the groups have completely different communities. Where ANOSIM results showed significant or near-significant differences in macroinvertebrate community compositions, the similarity percentages (SIMPER) procedure was used to determine which taxa where responsible. NMS, ANOSIM, and SIMPER were all carried out in PRIMER v6.1.5 (Clarke & Gorley, 2006). To determine which of the measured environmental variables (wetted width, water depth, water velocity, biofilm cover, substrate index) best explained the macroinvertebrate assemblages observed, the BEST procedure in PRIMER v6.1.5 was used (Clarke & Gorley, 2006).

3 RESULTS

3.1 Habitat

Water depths were generally very shallow, with only one site (the tidally influenced Waipapa Stream) having an average water depth greater than 0.1 m (Table 1). Two sites had relatively swift water velocities (The Parade – Dover St and Waipapa), which were a result of pipe gradient. The other sites had very low water velocity, with the 302 The Parade and Miramar – Shops sites having no detectable water velocity with the velocity head rod methodology used (Table 1). Two sites had virtually no mobile substrate, with the streambed being entirely bare concrete (The Parade – Dover St and) or bricks (Waipapa) (Table 1, Figure 5). These were also the two sites with the relatively high water velocities; hence it appears there are minimal depositional areas in these high gradient sections. The 302 The Parade site was also predominantly concrete but did have some areas of deposited substrate. The three remaining sites had a significant cover of a range of stony and sandy substrates (Table 1, Figure 5). Biofilms were prominent at all sites, with the exception of 348 The Parade where none were detected (Table 1). Other organic matter such as leaves and wood were relatively uncommon. Mesohabitat was predominantly runs, with the only riffle-type habitat present at 348 The Parade. Deeper pool habitat was only present at 302 The Parade and 348 The Parade (Table 1).

Spot water temperatures were in the 16.4–18.5 °C range across the sites, while specific conductivity was very high (28,440 μS/cm) at the Miramar – Shops site due to the influence of seawater (Table 1). The other five sites had relatively high specific conductivities (323–481 μS/cm) for freshwater systems. All sites had well oxygenated water, with only the tidally influenced Miramar – Shops site being less than 80% saturation at the time of measurement (Table 1).

Table 1 Habitat characteristics measured at each Surber sampling location (n=12 per site), mesohabitat percentages measured over the length of the macroinvertebrate sampling reaches, and water quality spot measures recorded at the entrance manholes (or start of macroinvertebrate sampling reach in Waipapa Stream).

Parameter	Pae Kawakawa Stream			Waipapa Stream	Miramar Stream	
	The Parade – Dover St	302 The Parade	348 The Parade	Waipapa*	Miramar Park	Miramar – Shops**
Mean wetted width (m)	1.17	0.63	1.14	0.52	1.25	1.38
Mean water depth (m)	0.07	0.05	0.05	0.07	0.04	0.16
Mean water velocity (m/s)	0.51	0	0.05	0.61	0.02	0
Mean substrate composition (%)	Concrete: 100	Concrete: 77 Cobble: 2 Pebble: 3 Gravel: 5 Sand: 13	Concrete: 12 Cobble: 3 Pebble: 4 Gravel: 40 Sand: 41	Brick: 100	Cobble: 5 Gravel: 13 Pebble: 80 Sand: 2	Concrete: 25 Cobble: 5 Pebble: 37 Gravel: 31 Sand: 2
Mean organic matter cover (%)	Biofilms: 100 Leaves: 0.1	Biofilms: 76 Wood: 0.2 Leaves: 0.7	Wood: 2 Leaves: 1	Biofilms: 90	Biofilms: 92.5 Wood: 0.2 Leaves: 0.6	Biofilms: 60
Mesohabitat lengths (%)	Run: 100	Run: 97 Pool: 3	Run: 51 Riffle: 44 Pool: 5	Run: 100	Run: 100	Mesohabitat varies with tide
Spot temperature	16.4 °C	18.5 °C	18.2 °C	17.4 °C	17.7 °C	17.8 °C
Spot specific conductivity	481 μS/cm	323 μS/cm	580 μS/cm	371 μS/cm	440 μS/cm	28,440 μS/cm
Spot dissolved oxygen	83.6% 8.27 mg/L	93.4% 8.86 mg/L	83.6% 7.95 mg/L	95.2% 9.22 mg/L	84.6% 8.16 mg/L	74.8% 6.49 mg/L
Spot water quality measurement time	10:30 am	4:15 pm	3:00 pm	12:20 pm	9:00 am	2:15 pm

*The Waipapa site data presented was collected in the reach where macroinvertebrates were sampled. All fish were observed in the lower, tidally influenced 90 m of pipe, which had a mostly bare concrete base.

**The Miramar – Shops site was tidally influenced, hence wetted width and depth will vary over tidal cycles.

The Parade – Dover St

302 The Parade

348 The Parade

Waipapa Stream

Miramar Park

Miramar - Shops

Figure 5 Images of each site within the macroinvertebrate sampling reach.

3.2 Fish

Fish were present at five of the six sites that underwent detailed ecological survey, with only The Parade – Dover St site not having any fish found over the 200 m survey reach (Figure 6). A total of 54 fish were found at the five piped sites. Fish abundance ranged from 6–14 individuals, with the 348 The Parade site having the highest number of fish (15 fish) and the 302 The Parade site having the least (six fish) (Figure 6). Species diversity was low with four species being found across the sites, which were (in order of abundance) longfin eel, shortfin eel, banded kokopu, and inanga (Figure 6). Longfin and shortfin eels were found at all sites where fish were found, whilst two banded kokopu (a recently dead adult and a post-whitebait juvenile) and one inanga were only found at one site each (Figure 6, Figure 7). The two kokopu were found at the Miramar Park site. One was a recently dead adult banded kokopu (150 mm long), which, based on the markings on the body, had been killed by a large eel (Figure 6). One banded kokopu post-whitebait juvenile (50 mm long) was also found at this site. The single inanga was a young adult (70 mm) found at the tidally influenced Miramar – Shops site (Figure 6, Figure 7).

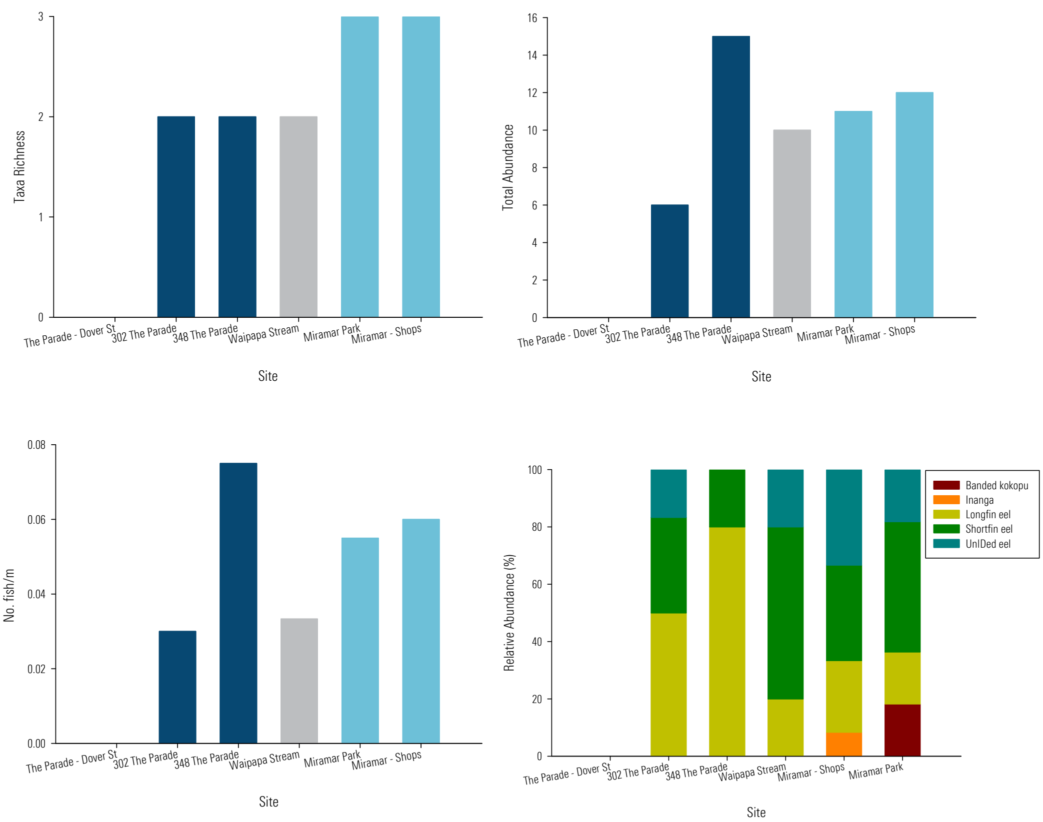

Figure 6 Fish community metrics and relative abundances from the six piped stream sites surveyed on 20–21 March 2019. 'UnIDed eel' = unidentified eels, and refers to those eels that were not able to be caught to allow for a definitive identification. Dark blue bars indicates the Pae Kawakawa catchment, grey bars Waipapa Stream, and light blue bars the Miramar catchment.

Longfin eel

Inanga young adult

Post-whitebait juvenile banded kokopu

Banded kokopu adult (dead)

Figure 7 **Fish species found during surveys of the six piped stream sites on 20–21 March 2019.**

Recent GWRC fish survey data were available from open stream sites in the Pae Kawakawa (two sites) and Miramar Stream (one site), allowing for comparison of fish assemblages between remnant open stream sections and piped stream sections (Figure 8). In the Pae Kawakawa catchment, no fish (or waikōura/freshwater crayfish) were found at one open and one piped survey site. At sites where fish were found, there was a distinct difference in composition between open and piped stream sections. Shortfin and longfin eel were found exclusively at the piped sites, while the one open site with fish had banded kokopu (Figure 8). In the Miramar Stream catchment, eels (shortfin and longfin) also dominated in the piped sites and longfin eels were only found at piped sites, while the single open stream site surveyed had mostly banded kokopu (Figure 8). Waikōura were only found in open stream sites in both catchments. Overall, the addition of the piped stream surveys has increased the known diversity of fish in both catchments by two species (longfin and shortfin eel for Pae Kawakawa Stream, and inanga and longfin eel for Miramar Stream).

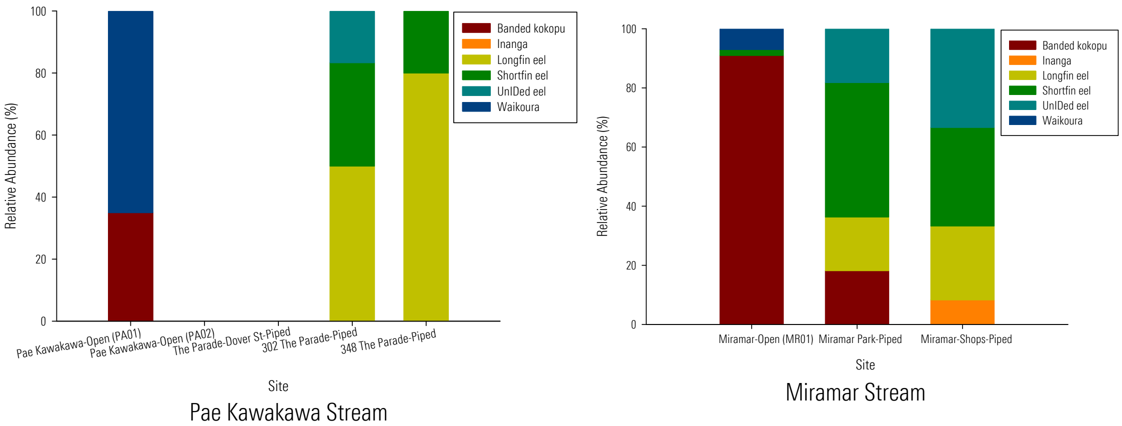

Figure 8 Relative abundance of fish species (including waikōura) at piped and open survey sites in the Pae Kawakawa Stream and Miramar Stream catchments. Open stream sites were surveyed by GWRC and their site codes are shown in parentheses.

Eels were also observed in trail camera footage, although it was impossible to determine species (Figure 9). Full consideration of the use of trail cameras in piped streams is given in Section 4.4.

Figure 9 Trail camera infrared night vision photo from the 348 The Parade site clearly showing an eel in midframe.

3.3 Benthic Macroinvertebrates – Surber Sampling

A total of 31 invertebrate taxa were recorded from the six sites that underwent detailed ecological survey. The most diverse groups were the two-winged flies (Diptera: 10 taxa), crustaceans (Crustacea: 5 taxa), molluscs (Mollusca: 4 taxa), caddisflies (Trichoptera: 3 taxa), and polychaete worms (Polychaeta: 2 taxa). Groups represented by one taxon included springtails (Hexapoda: Collembola), beetles (Coleoptera), mites (Arachnida: Acari), and four groups collectively called worms (Nematoda, Nemertea, Oligochaeta, Platyhelminthes).

The total number of taxa captured at each site ranged from nine (302 The Parade and Miramar – Shops) to 14 (The Parade – Dover St). Taxa unique to each site ranged from one (302 The Parade) to six (The Parade – Dover St) (Figure 10). Sites were dominated by non-insect taxa with oligochaete worms and *Potamopyrgus* snails being particularly common (most abundant taxa at three and two sites respectively) (Figure 10). Other common non-insect taxa included collembola, *Physa* snails, *Ferrissia* limpets, and mites. The only relatively common insect taxa at some sites were various Diptera (true flies) taxa (Orthocladiinae and *Polypedilum* midge larvae, Psychodidae gnat larvae). The only other relatively common insect were Scirtidae beetle larvae, which were only found at the The Parade – Dover St site (Figure 10). The Trichoptera captured were single individuals of *Hydropsyche (Aoteapsyche*), *Oeconesus* (both at 348 The Parade), and *Polyplectropus* (at Miramar Park). Based on such rarity, it is likely these individuals had been transported downstream from open sections upstream.

NMS ordination indicated samples from some sites were far more variable than others. For example, those samples from the Miramar catchment (Miramar Park and The Parade – Dover St) clustered fairly tightly together compared to the large spread of the 302 The Parade and Waipapa Stream sites (Figure 11). ANOSIM comparing sites indicated a moderately strong (Global R=0.63) and significant (p=0.01) difference among the sampling sites (Figure 11). SIMPER results showing the main taxa responsible for differences between each site pair are shown in Appendix Table 1. Between site differences often resulted from differences in the abundance of common, widespread taxa (e.g., Oligochaeta worms and *Potamopyrgus* snails). However, on several occasions taxa that are present in one site, but absent from another contribute to differences (often Psychodidae gnat larvae, *Physa* snails, or Scirtidae beetle larvae).

The BEST procedure indicated that of the measured environmental variables, a combination of wetted width and water velocity was the most correlated with the macroinvertebrate community data, although the correlation was not strong (0.36) (see Appendix Table 2 for full BEST results).

Pae Kawakawa Stream			Waipapa Stream	Miramar Stream	
The Parade – Dover St	302 The Parade	348 The Parade	Waipapa Stream	Miramar Park	Miramar - Shops
Total taxa: 14 Unique taxa: 6	Total taxa: 9 Unique taxa: 1	Total taxa: 13 Unique taxa: 4	Total taxa: 10 Unique taxa: 3	Total taxa: 10 Unique taxa: 2	Total taxa: 9 Unique taxa: 4
 Oligochaeta worms (MCI=1; 41%)	 *Potamopyrgus* snails (MCI=4; 46%)	 *Potamopyrgus* snails (MCI=4; 77%)	 Collembola springtails (MCI=6; 43%)	 Oligochaeta worms (MCI=1; 49%)	 Oligochaeta worms (MCI=1; 48%)
 Psychodidae gnat larvae (MCI=1; 18%)	 *Physa* snails (MCI=3; 28%)	 Oligochaeta worms (MCI=1; 15%)	 Oligochaeta worms (MCI=1; 23%)	 *Potamopyrgus* snails (MCI=4; 37%)	 *Polypedilum* midge larvae (MCI=3; 32%)
 Orthocladiinae midge larvae (MCI=2; 14%)	 Oligochaeta worms (MCI=1; 18%)	 *Physa* snails (MCI=3; 4%)	 Orthocladiinae midge larvae (MCI=2; 9%)	 *Physa* snails (MCI=3; 7%)	 Acarina mites (MCI=5; 7%)
 Collembola springtails (MCI=6; 14%)	 Ferrissia limpets (MCI=3; 3%)	 Ferrissia limpets (MCI=3; 2%)	 Psychodidae gnat larvae (MCI=1; 9)	 Ferrissia limpets (MCI=3; 3%)	 *Potamopyrgus* snails (MCI=4; 6%)
 Scirtidae beetle larvae (MCI=8; 5%)	 Acarina mites (MCI=5; 2%)	 Orthocladiinae midge larvae (MCI=2; 1%)	 Acarina mites (MCI=5; 3%)	 Empididae fly larvae (MCI=3; 1%)	 Platyhelminthes flatworms (MCI=3; 2%)

Figure 10 The total number of taxa captured at each site, the number of taxa that were unique to that site, and the five most abundant taxa at each of the six piped stream sampling sites. The relative abundance percentages and MCI-hb scores for each taxon are shown in parentheses. All images © EOS Ecology except *Ferrissia* (A. Mrkvicka), *Polypedilum* (Landcare Research), Psychodidae (MAF), and Scirtidae (Landcare Research).

When looking at the catchment scale, there is wide scatter among the samples with the ANOSIM comparing catchments, indicating a relatively weak (Global R=0.19) but significant difference (Figure 12). SIMPER results showing the main taxa responsible for differences between each catchment pair are displayed in Appendix Table 3. In terms of catchment pairs, the Miramar and Waipapa catchments were the most different (R=0.73), while the Pae Kawakawa and Miramar catchments were the least different (R=0.05), with the lack of Psychodidae gnat larvae in the Miramar samples being the most notable faunal difference.

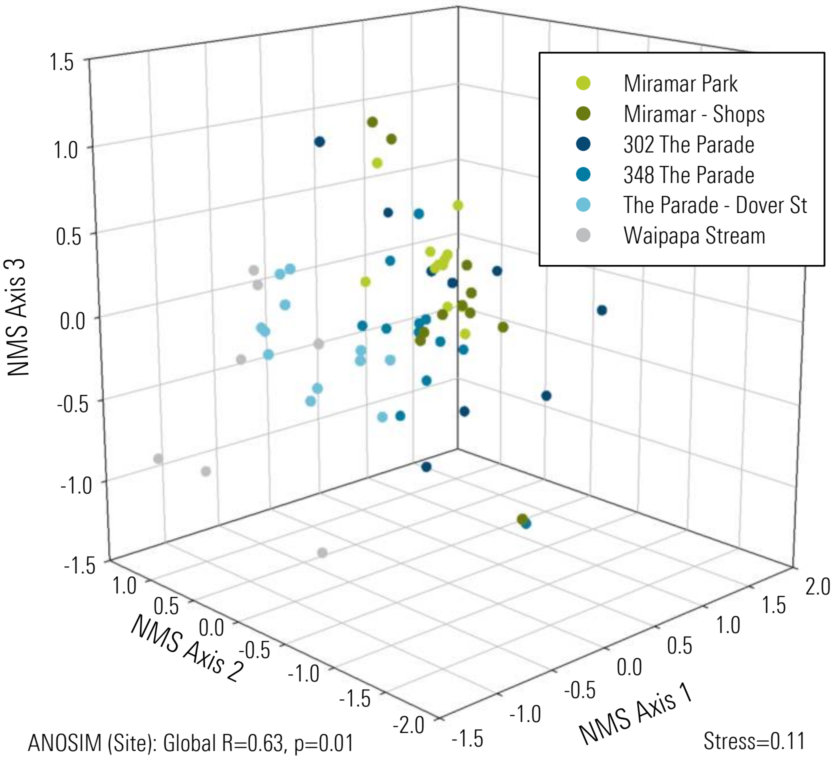

Figure 11 Non-metric multidimensional scaling (NMS) ordination of macroinvertebrate community data from the six piped stream sites with data divided by site. Each point represents a single Surber sample. The analysis was based on abundance data. Also shown is the ANOSIM site comparison result. A stress value of 0.11 is indicative of a fair ordination that can still correspond to a usable picture.

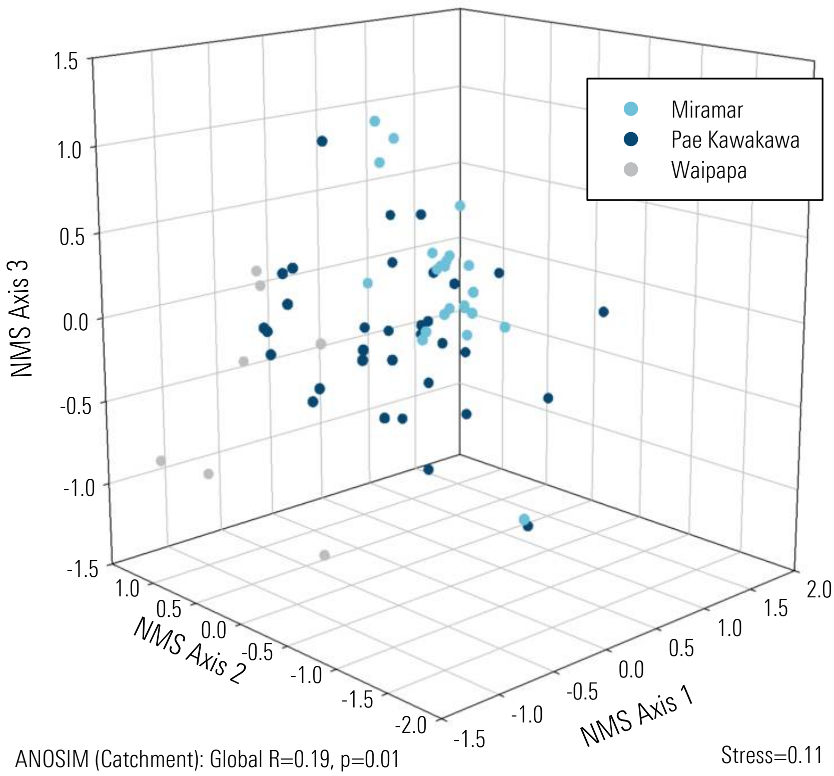

Figure 12 Non-metric multidimensional scaling (NMS) ordination of macroinvertebrate community data from the six piped stream sites with data divided by catchment. Each point represents a single Surber sample. The analysis was based on abundance data. Also shown is the ANOSIM catchment comparison result. A stress value of 0.11 is indicative of a fair ordination that can still correspond to a usable picture.

Mean macroinvertebrate densities were much greater at the 348 The Parade site than the other five sites (Figure 13). In general, macroinvertebrates were at very low densities in piped streams and Surber samples were sometimes lacking any animals at all (Waipapa Stream: 4 samples; 302 The Parade and Miramar - Shops: 1 sample each). The Waipapa Stream site had particularly low densities and was also the site with the highest water velocities and only site with a 100% brick bottom (Table 1, Figure 5). Mean taxa richness was greatest at the The Parade – Dover St site and least at the Waipapa Stream site (Figure 13). The Parade – Dover St also had the highest number of overall taxa captured (14), while 302 The Parade and Miramar - Shops had the least (nine taxa each) (Figure 10). Mean MCI tended to be slightly higher at the three Pae Kawakawa catchment sites (i.e., The Parade sites) but was well within the "poor" category (Figure 13). Likewise, QMCI scores all indicated "poor" conditions (Figure 13).

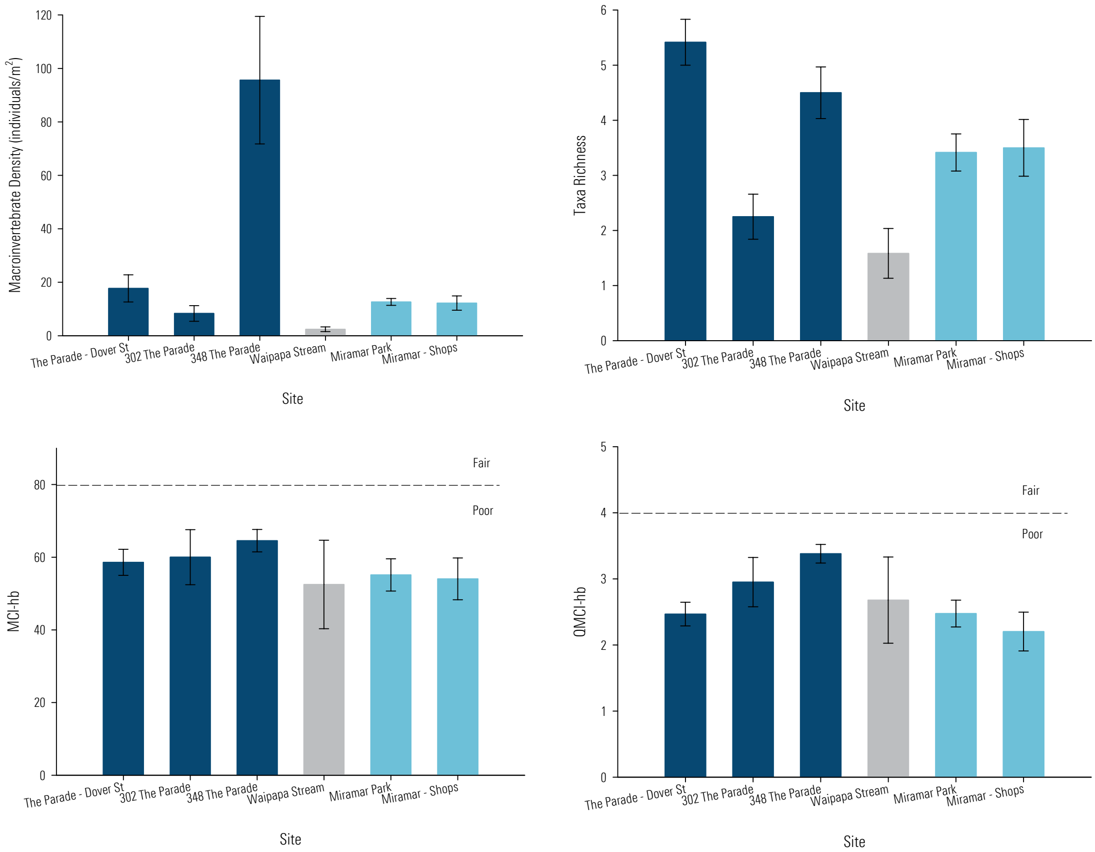

Figure 13 Mean macroinvertebrate community metrics from each of six piped streams sites. Twelve Surber samples were collected at each site. The interpretive categories of Clapcott & Goodwin (2014) and Stark & Maxted (2007) are shown on the MCI and QMCI graphs, respectively.

3.4 Macroinvertebrates – Sticky Traps

Several invertebrate taxa were captured on sticky traps hanging vertically at each piped stream site. The most common and abundant taxon was the fungus gnat family, Mycetophilidae, which were present at all sites, and do not have aquatic larvae (Table 2). They are commonly found in damp habitats where their preferred host fungi are abundant. Hence the dark, damp environment of piped streams likely suits the particular Mycetophilidae genera found. Other terrestrial taxa found included mites, beetles, and ants (Table 2). Along with the various spiders observed in the pipes, these indicate there is likely a significant terrestrial arthropod community living within piped streams.

Adults of aquatic taxa included mosquitos (four sites), non-biting Chironomids (two sites), and crane flies (one site) (Table 2). Larval mosquitos were found in Surber samples at one of the four sites where adult mosquitos were found indicating, the value of sticky trapping at detecting additional aquatic taxa that may be missed by benthic sampling. Chironomidae larvae were present at both the sites adult chironomids were found at (Table 2). These results confirm there are various insect taxa flying around in permanent darkness and terrestrial and aquatic taxa are present.

Table 2 **Invertebrates captured on single, double-sided sticky traps installed at each piped stream site for an approximately two week period. The sticky trap at the Waipapa Stream site was lost. For those taxa with aquatic larvae, the presence of potential larvae in Surber samples is indicated by "(larvae present)" in the Larval Habitat column.**

Site name	Taxa name	Common name	Sticky trap count	Larval Habitat
The Parade - Dover St	Diptera: Mycetophilidae	Fungus gnat	5	Terrestrial
	Diptera: Culicidae	Mosquito	2	Aquatic (larvae present)
302 The Parade	Diptera: Mycetophilidae	Fungus gnat	2	Terrestrial
	Diptera: - Sciariidae	Fungus gnat	1	Terrestrial
348 The Parade	Diptera: Chironomidae	Non-biting midges	1	Aquatic (larvae present)
	Diptera: Mycetophilidae	Fungus gnat	12	Terrestrial
	Diptera: Culicidae	Mosquito	1	Aquatic
Miramar Park	Acari	Mites	6	Terrestrial
	Diptera: Mycetophilidae	Fungus gnat	17	Terrestrial
	Coleoptera	Beetles	2	Terrestrial
	Formicidae	Ants	2	Terrestrial
	Diptera: Tipulidae	Crane flies	1	Possibly Aquatic
	Diptera: Culicidae	Mosquito	3	Aquatic
	Diptera: Chironomidae	Non-biting midges	1	Aquatic (larvae present)
Miramar - Shops	Diptera: Mycetophilidae	Fungus gnat	451	Terrestrial
	Diptera: Culicidae	Mosquito	3	Aquatic

3.5 Benthic Macroinvertebrates – Surber vs. Kick Net Samples

Surber sampling involved much more sampling effort with a greater area of habitat sampled compared to kick nets collected from the surface using the long-handled kick net illustrated in Figure 2. This resulted in Surber samples collecting higher numbers and a greater diversity of benthic macroinvertebrates than the kick nets (Figure 14, Figure 15, Figure 16). Consequently Surber sample data had between three and ten extra taxa per site that were not encountered by the single kick net sample (Figure 14, Figure 15). However, at three sites the kick net samples also contained two or three taxa that were not captured in any of the 12 Surber samples collected at each site (Figure 14, Figure 15). NMS ordination of presence-absence data showed the two methods aligned more closely at some sites than others. For example, Surber and kick net data plotted relatively close together for the 348 The Parade and Miramar – Shops sites, compared to the other two sites (Figure 17). ANOSIM comparing the two methods showed no significant difference.

Despite the disparity in sampling effort, the five most common taxa at each site were generally similar between Surber and kick net sampling. For the 348 The Parade site the four most abundant taxa, and at the Miramar Park site the two most abundant taxa, were the same for both sampling methods (Figure 14, Figure 15). Each sampling method was undertaken at a different time (Surber's: March 2019; Kick nets: May 2018), which may have played some role in the macroinvertebrates captured. However, piped streams are a more stable environment compared to open streams in terms of seasonal variables like temperature and daylight, so any seasonal variation in macroinvertebrate communities is likely to be minimal.

Overall, site MCI and QMCI scores based on a single sample (kick nets) or twelve pooled samples (Surbers) varied between the sampling methods. MCI scores for pooled Surbers were higher than those of kick net samples at three of the four sites, while pooled Surber QMCI was higher than kick net scores for two of the four sites (Figure 16). However, all scores remained well in the "poor" category, with the exception of the Surber data at the 348 The Parade site, which was slightly above the "poor"-"fair" boundary (Figure 16).

The Parade – Dover St Surber	The Parade – Dover St Kick	348 The Parade Surber	348 The Parade Kick
Total taxa: 14 Unique taxa: 10	Total taxa: 7 Unique taxa: 3	Total taxa: 13 Unique taxa: 6	Total taxa: 10 Unique taxa: 3
 Oligochaeta worms (MCI=1; 41%)	 *Potamopyrgus* snails (MCI=4; 29%)	 *Potamopyrgus* snails (MCI=4; 77%)	 *Potamopyrgus* snails (MCI=4; 35%)
 Psychodidae gnat larvae (MCI=1; 18%)	 Oligochaeta worms (MCI=1; 24%)	 Oligochaeta worms (MCI=1; 15%)	 Oligochaeta worms (MCI=1; 26%)
 Orthocladiinae midge larvae (MCI=2; 14%)	 *Polypedilum* midge larvae (MCI=3; 18%)	 *Physa* snails (MCI=3; 4%)	 *Physa* snails (MCI=3; 15%)
 Collembola springtails (MCI=6; 14%)	 *Physa* snails (MCI=3; 12%)	 Ferrissia limpets (MCI=3; 2%)	 Ferrissia limpets (MCI=3; 7%)
 Scirtidae beetle larvae (MCI=8; 5%)	 Talitridae amphipods (MCI=5; 6%)	 Orthocladiinae midge larvae (MCI=2; 1%)	 Collembola springtails (MCI=6; 6%)

Figure 14 Pae Kawakawa Stream catchment: The total number of taxa captured at each site with each method (Surbers and kick net), the number of taxa that were unique to each method at that site, and the five most abundant taxa of each method and site. The relative abundance percentages and MCI-hb scores for each taxon are shown in parentheses. All images © EOS Ecology except *Ferrissia* (A. Mrkvicka), Psychodidae (MAF), and Scirtidae (Landcare Research).

Miramar Park Surber	Miramar Park Kick	Miramar – Shops Surber	Miramar – Shops Kick
Total taxa: 10 Unique taxa: 6	Total taxa: 6 Unique taxa: 2	Total taxa: 9 Unique taxa: 3	Total taxa: 6 Unique taxa: 0
 Oligochaeta worms (MCI=1; 49%)	 Oligochaeta worms (MCI=1; 68%)	 Oligochaeta worms (MCI=1; 48%)	 *Polypedilum* midge larvae (MCI=3; 59%)
 *Potamopyrgus* snails (MCI=4; 37%)	 *Potamopyrgus* snails (MCI=4; 19%)	 *Polypedilum* midge larvae (MCI=3; 32%)	 Acarina mites (MCI=5; 9%)
 *Physa* snails (MCI=3; 7%)	 Collembola springtails (MCI=6; 8%)	 Acarina mites (MCI=5; 7%)	 Orthocladiinae midge larvae (MCI=2; 9%)
 Ferrissia limpets (MCI=3; 3%)	 Orthocladiinae midge larvae (MCI=2; 2%)	 *Potamopyrgus* snails (MCI=4; 6%)	 Oligochaeta worms (MCI=1; 9%)
 Empididae fly larvae (MCI=3; 1%)	 *Polypedilum* midge larvae (MCI=3; 2%)	 Platyhelminthes flatworms (MCI=3; 2%)	 Platyhelminthes flatworms (MCI=3; 9%)

Figure 15 **Miramar Stream catchment: The total number of taxa captured at each site with each method (Surbers and kick net), the number of taxa that were unique to each method at that site, and the five most abundant taxa of each method and site. The relative abundance percentages and MCI-hb scores for each taxon are shown in parentheses. All images © EOS Ecology except *Ferrissia* (A. Mrkvicka), *Polypedilum*, and Scirtidae (Landcare Research).**

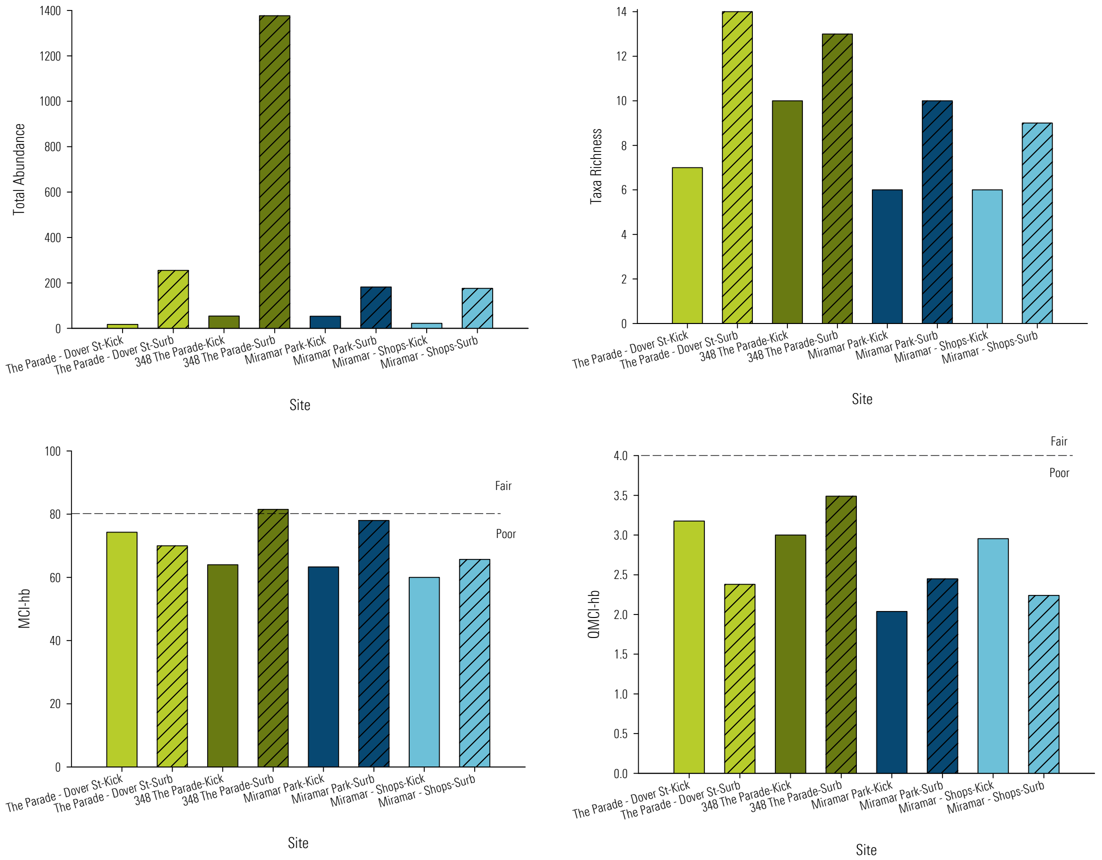

Figure 16 Mean macroinvertebrate community metrics from the four piped streams sites where Surber and kick net data was available. Stripped bars are Surber samples and plain bars are kick net samples. Data from the twelve Surber samples have been pooled. The interpretive categories of Clapcott & Goodwin (2014) and Stark & Maxted (2007) are shown on the MCI and QMCI graphs, respectively.

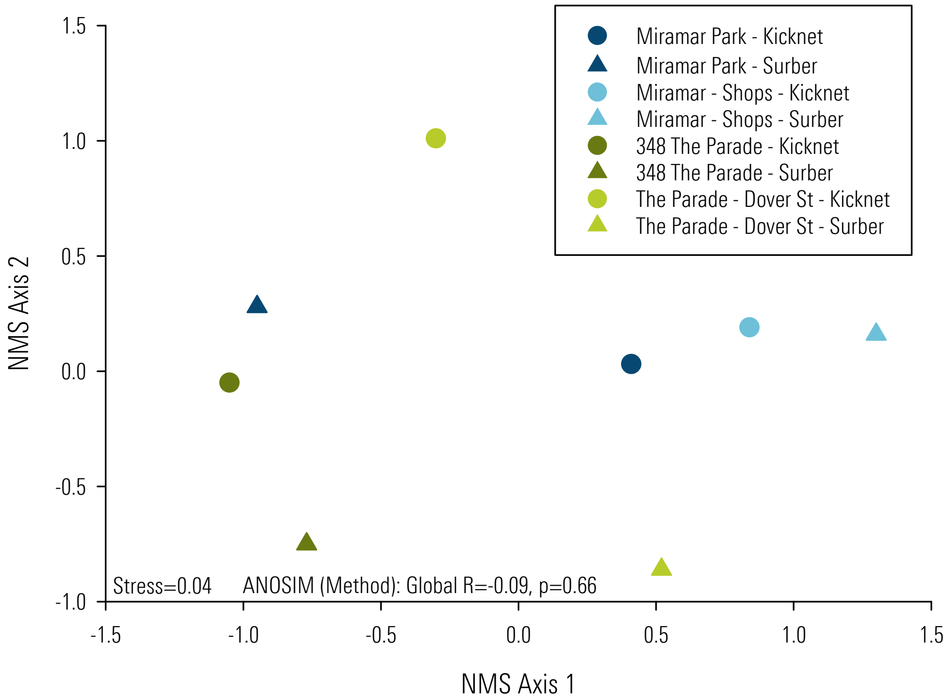

Figure 17 Non-metric multidimensional scaling (NMS) ordination of macroinvertebrate community data from the four piped stream sites where Surber (triangles) and kick net (circles) data was available. Kick nets were single samples whilst the 12 Surber samples per site were pooled to one sample per site, and all data transformed into presence-absence. Also shown is the ANOSIM method (Surber or kick net) comparison result. A stress value of 0.04 is indicative of an excellent representation of data with no prospect of misinterpretation.

3.6 Benthic Macroinvertebrates – Piped vs. Open Stream Sites

In the Pae Kawakawa (Island Bay) and Miramar catchments, GWRC had undertaken macroinvertebrate sampling from sections of remnant open stream in January 2019, with which we could directly compare the piped stream site data. It was considered the collection of twelve quantitative Surber samples per site would provide a better representation of the benthic macroinvertebrate community of piped stream sites than would the data obtained from a single, kick net sample collected down the manhole shaft with a modified, long-handled sampling net. Hence, we have used this piped stream Surber data for this piped vs. open stream comparison. GWRC sampled one open site in each catchment (Figure 3). A second open stream site in the Pae Kawakawa Stream catchment was found to be dry when visited. In the Pae Kawakawa Stream catchment a total of 22 taxa were found across three piped stream sites (7–14 taxa range at individual sites), while 29 taxa were found at the GWRC open stream site. In the Miramar catchment and total of 19 taxa were found at the two piped stream sites (nine or ten taxa at each site), while 26 taxa were found at the GWRC open stream site.

The main differences between open and piped sites in the Pae Kawakawa catchment in terms of the most abundant taxa were the dominance of chironomid midge larvae (*Polypedilum* and Orthocladiinae) and presence of relatively pollution-sensitive *Hydropsyche* (*Orthopsyche*) larvae at the open stream site (Figure 18). At the piped stream sites, while midge larvae were also among the more common taxa, oligochaete worms and snails (*Potamopyrgus* and *Physa*) tended to be the most abundant taxa (Figure 18). While also dominated numerically by *Potamopyrgus* snails, the macroinvertebrate community of the open stream site in the Miramar catchment differed from those of the two piped sites by having two pollution-sensitive taxa (*Hydropsyche* (*Orthopsyche*) caddisflies and *Zephlebia* mayflies) as the second and third most abundant taxa (Figure 19). The sampling of piped streams sites detected an additional ten taxa in the Pae Kawakawa catchment and an additional seven taxa in the Miramar catchment to the open stream site samples taken in each catchment.

Pae Kawakawa – Open (Island Bay Stream trib @ Farnham Street; PA01)	The Parade – Dover St	302 The Parade Surber	348 The Parade
Total taxa: 29 Unique taxa: 16	Total taxa: 14 Unique taxa: 7	Total taxa: 7 Unique taxa: 1	Total taxa: 13 Unique taxa: 2
 *Polypedilum* midge larvae (MCI=3; 25%)	 Oligochaeta worms (MCI=1; 41%)	 *Potamopyrgus* snails (MCI=4; 46%)	 *Potamopyrgus* snails (MCI=4; 77%)
 Orthocladiinae midge larvae (MCI=2; 24%)	 Psychodidae gnat larvae (MCI=1; 18%)	 *Physa* snails (MCI=3; 28%)	 Oligochaeta worms (MCI=1; 15%)
 *Hydropsyche* (*Orthopsyche*) caddisflies (MCI=9; 8%)	 Orthocladiinae midge larvae (MCI=2; 14%)	 Oligochaeta worms (MCI=1; 18%)	 *Physa* snails (MCI=3; 4%)
 Oligochaeta worms (MCI=1; 8%)	 Collembola springtails (MCI=6; 14%)	 Ferrissia limpets (MCI=3; 3%)	 Ferrissia limpets (MCI=3; 2%)
 *Hydropsyche* (early instar*) caddisflies (8%)	 Scirtidae beetle larvae (MCI=8; 5%)	 Acarina mites (MCI=5; 2%)	 Orthocladiinae midge larvae (MCI=2; 1%)

Figure 18 Pae Kawakawa Stream catchment: The number of unique taxa at each site and the five most abundant taxa of each piped stream site and the single GWRC open stream site. The relative abundance percentages and MCI-hb scores for each taxon are shown in parentheses. All images © EOS Ecology except *Ferrissia* (A. Mrkvicka), Psychodidae (MAF), *Polypedilum* and Scirtidae (both Landcare Research).

Miramar – Open (Maupuia Stream; MR01)	Miramar Park	Miramar – Shops
Total taxa: 26 Unique taxa: 16	Total taxa: 10 Unique taxa: 3	Total taxa: 9 Unique taxa: 4
 *Potamopyrgus* snails (MCI=4; 38%)	 Oligochaeta worms (MCI=1; 49%)	 Oligochaeta worms (MCI=1; 48%)
 *Hydropsyche* (*Orthopsyche*) caddisflies (MCI=9; 17%)	 *Potamopyrgus* snails (MCI=4; 37%)	 *Polypedilum* midge larvae (MCI=3; 32%)
 *Zephlebia* mayflies (MCI=7; 8%)	 *Physa* snails (MCI=3; 7%)	 Acarina mites (MCI=5; 7%)
 Talitridae amphipods (MCI=5; 5%)	 Ferrissia limpets (MCI=3; 3%)	 *Potamopyrgus* snails (MCI=4; 6%)
 *Polypedilum* midge larvae (MCI=3; 5%)	 Empididae fly larvae (MCI=3; 1%)	 Platyhelminthes flatworms (MCI=3; 2%)

Figure 19 Miramar Stream catchment: The number of unique taxa at each site and the five most abundant taxa of each piped stream site and the single GWRC open stream site. The relative abundance percentages and MCI-hb scores for each taxon are shown in parentheses. All images © EOS Ecology except *Ferrissia* (A. Mrkvicka) and *Polypedilum*, (Landcare Research).

Macroinvertebrate community metrics were all greater at the open stream sites than the piped stream sites in the Pae Kawakawa and Miramar catchments (Figure 20). While different sampling methods were used (single composite kick net at open sites; 12 Surber samples at piped sites), it is clear there were much higher numbers of macroinvertebrates and taxa at the open stream sites in both catchments. MCI and QMCI were higher at open sites, although only marginally for QMCI in the Pae Kawakawa catchment (Figure 20). EPT taxa richness and percentage EPT individuals were substantially higher at the open sites, with three of the five piped stream sites not having any EPT taxa at all (Figure 20). At those piped sites with EPT taxa, these were just single individuals that may well have been transported from upstream open sites during floods, rather than being permanent residents.

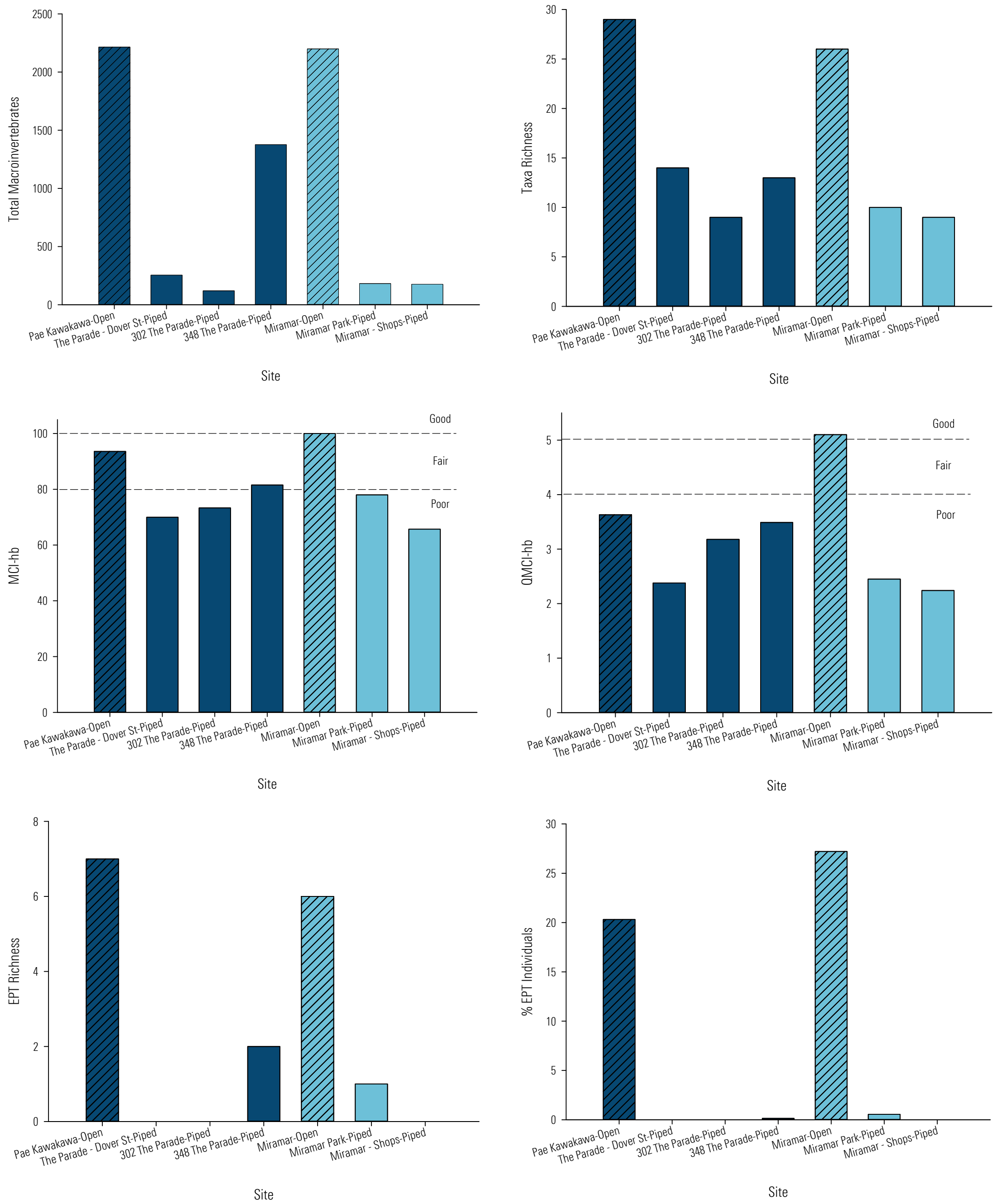

Figure 20 Macroinvertebrate community metrics from open and piped stream sites in the Pae Kawakawa (dark blue bars) and Miramar (light blue bars) catchments. Open stream data were derived from a single composite kick net sample and piped stream data from pooling 12 Surber samples. Striped bars indicate open stream sites. The interpretive categories of Clapcott & Goodwin (2014) and Stark & Maxted (2007) are shown on the MCI and QMCI graphs, respectively.

NMS ordination showed open stream sites were clearly separated from piped sites along Axis 2, although all sites (both open and piped sites) were quite separated from one another along Axis 1 (Figure 21). ANOSIM indicated a marginally significant difference between open and piped sites (p=0.048), while a R value of 0.56 is indicative of moderate differences in macroinvertebrate composition among site type (open and piped) (Figure 21). SIMPER results indicating the taxa most responsible for this open-piped difference are shown in Appendix Table 4. Non-insect taxa (oligochaete worms, *Potamopyrgus* snails, and *Physa* snails) tended to have higher relative abundances at piped sites, while insect taxa (*Polypedilum* and Orthocladiinae midge larvae and *Hydropsyche* (*Orthopsyche*) caddisfly larvae) had higher relative abundances at the open stream site (Appendix Table 4). Given the analysis is based on relative abundances, it is important the remember that at the open stream sites benthic macroinvertebrates were generally more abundant overall (Figure 20).

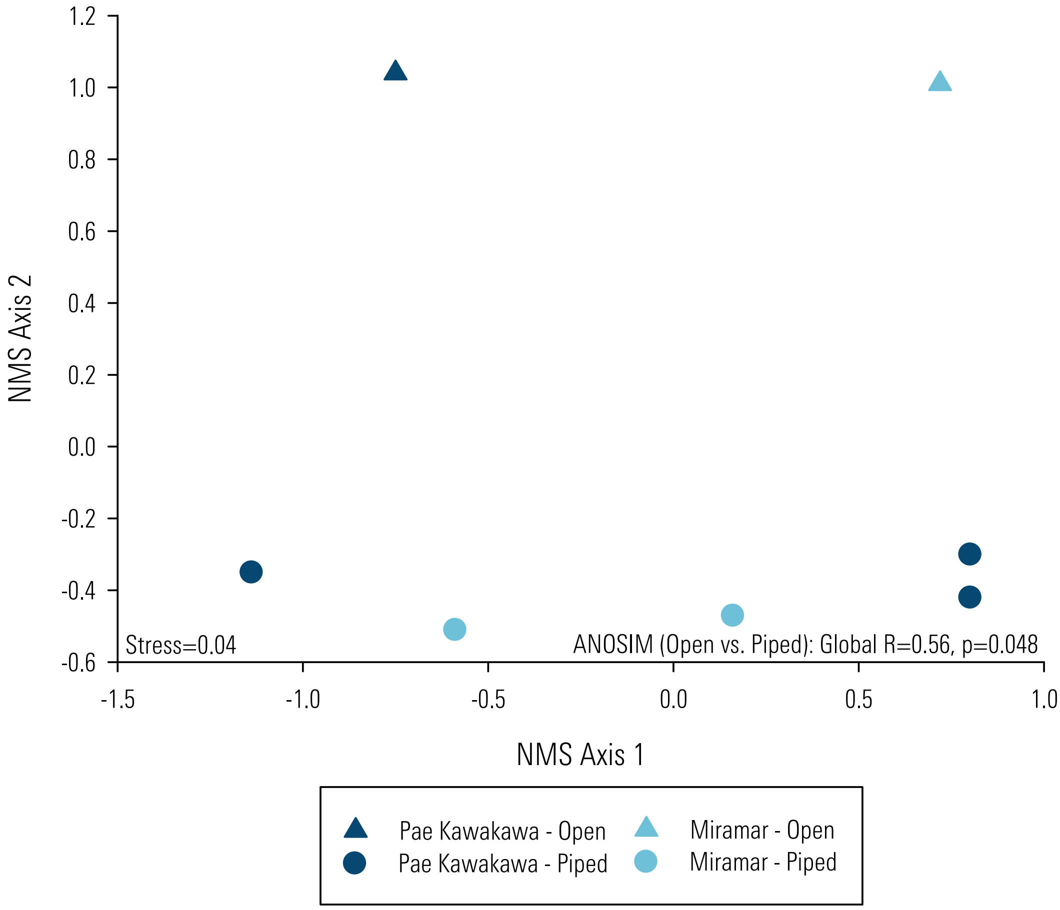

Figure 21 Non-metric multidimensional scaling (NMS) ordination of macroinvertebrate community data from open and piped stream sites in the Pae Kawakawa (dark blue symbols) and Miramar (light blue symbols) catchments. Open stream data is derived from a single composite kick net sample and piped stream data from pooling 12 Surber samples. Data was converted to relative abundance prior to analysis. Also shown is the ANOSIM open vs. piped comparison result. A stress value of 0.04 is indicative of an excellent representation of data with no prospect of misinterpretation.

4 CONCLUSIONS

4.1 Habitat

Zones of cobble and gravel substrate are present within piped streams and provide a stream bed in such areas that at least appears natural, although it will usually be underlain by concrete or sealed brick. Organic material (leaves, woody debris, tree roots) were also present. Stony substrates, leaves, and wood debris have presumably been transported from upstream remnant open stream sections and stormwater inputs. Some sites had minimal or no loose rocky substrates. It is likely that piped streams have depositional and erosional zones based on gradient and water velocity as in natural stream channels, with the difference that erosional zones will generally be bare concrete or whatever material the pipe is constructed from. Water depths at the surveyed sites were generally very shallow (<10 cm) and deeper pool habitat appeared to be very limited or absent. Brown-orange biofilms were prominent at five of the six sites and presumably are a food source for some macroinvertebrates. Spot measures of dissolved oxygen indicated relatively well oxygenated water.

From an ecological perspective, piped stream habitat could be improved from measures that increase water depths, increase the abundance of pool habitat, slow water velocities, trap natural substrates and organic material, and provide cover for fish. This is especially the case in higher gradient pipes such as observed at the Waipapa Stream and The Parade – Dover St sites, where long reaches of continuous high velocities over bare concrete or brick meant there was very limited habitat for fish and invertebrates (Figure 22). Proven technologies such as flexible plastic baffles are available to retrofit such zones to improve fish passage and provide slower velocity habitat for resident fish. Such baffles may also facilitate the retention of natural substrates and organic material, further improving habitat quality, including habitat for aquatic macroinvertebrates.

In terms of deeper pool habitat, more substantial structures such as leaky rock weirs could be used in appropriate locations to create such habitat in existing pipes. Some manholes, such as that at the Miramar Park site, were designed such that below the manhole was a pool-like zone of deeper water compared to the habitat directly upstream and downstream (Figure 23). There is the potential where pipes are being replaced or new ones laid that special pipe sections that create deeper pool habitat could be incorporated into the design.

Figure 22 Long, homogenous zones of high water velocities at the Waipapa Stream site (left) and The Parade – Dover St site in the Pae Kawakawa catchment (right).

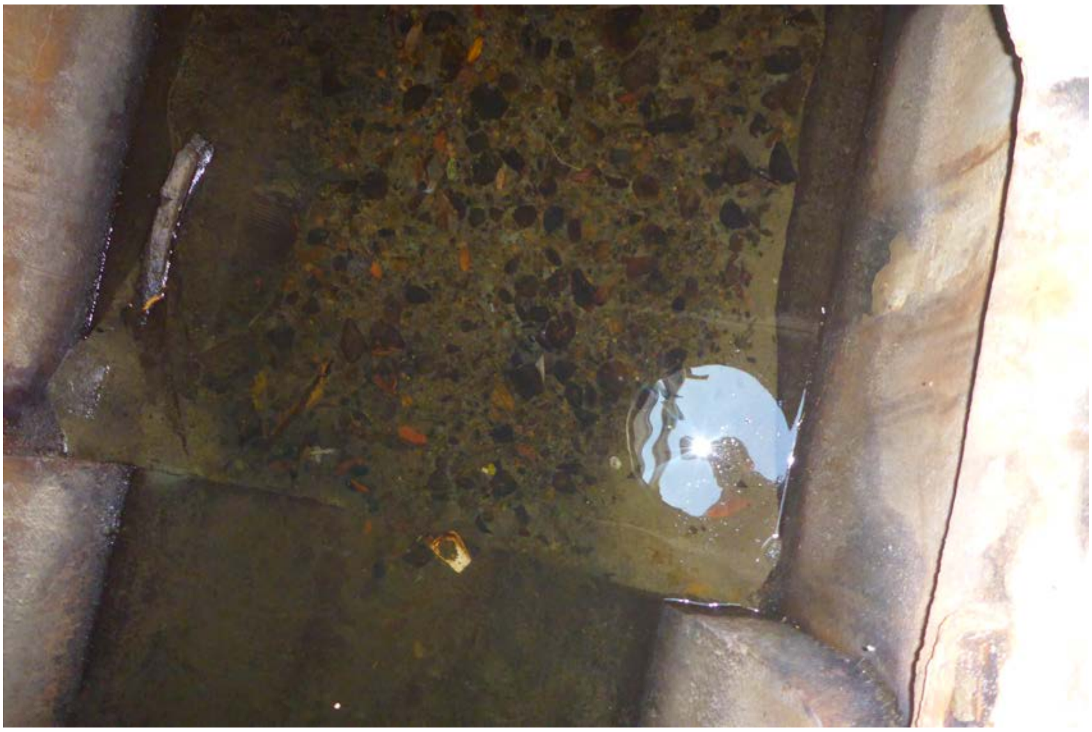

Figure 23 Pipe design at the Miramar Park site allowed the development of deeper pool-like habitat.

4.2 Fish Assemblages

Fish were present at five of the six detailed survey sites, hence appear to be widespread in the piped stream network. Fish diversity of piped stream sites was low and dominated by eels, with both longfin and shortfin eels present. Inanga appear to have the ability to live within piped streams. However, in catchments that are piped to the ocean it is highly unlikely they could ever successfully spawn due to a lack of spawning habitat. Additionally, it is highly likely they would be at low densities, would have limited ability to get beyond velocity and physical barriers due being relatively weak swimmers, and at high risk of eel predation given the lack of cover. There appears to be clear habitat partitioning of the fish fauna (and waikōura) in catchments that have extensive piped sections and remnant open headwater sections. Eels dominate the pipes while banded kokopu (and also waikōura) dominate the open sections, hence even relatively short sections of remnant open streams are crucial to maintaining catchment fish diversity.

Based on previous open stream fish survey data, it is clear the whitebait of at least banded kokopu and kōaro travel through the piped stream network to reach open sections with suitable habitat. Eels resident in the pipes likely feed extensively on upstream migrating whitebait and elvers at certain times of the year. The piped stream sites generally lacked fish cover and it was observed that even in near complete darkness, eels preferred to spend some of their time hiding under whatever cover was available, including tree roots, rubbish, concrete rubble, fine sediment accumulations, and woody debris (Figure 24). There is the potential that habitat improvement features could be added to piped streams to both provide cover for resident fish and improve conditions for migrating whitebait (e.g. fitting flexible baffles to sections with high velocity, laminar flows; increasing water depths/creating pools using leaky weirs; installing artificial fish cover elements such as securely attached small lengths of pipe) .

Figure 24 Eel attempting to use tree roots as cover.

4.3 Benthic Macroinvertebrate Assemblages

Piped stream sites were dominated by oligochaete worms, snails (*Potamopyrgus* and *Physa*), and midge larvae (Orthocladiinae and *Polypedilum*). Collembola springtails, Psychodidae gnat larvae, mites, and *Ferrissia* limpets were prominent at some sites. These are taxa known to be tolerant of or that prefer degraded stream habitats, hence it is no surprise they are able to persist in piped streams. It is notable that some of these taxa typically graze on algae or plant material in open streams (e.g. snails and limpets), hence they must be able to survive on the biofilms that grow in near complete darkness and/or organic material (e.g., leaves) that enter and are retained in the piped streams. There were some between-site differences in macroinvertebrate communities, often driven by differences in the abundance of the most common and widespread taxa (e.g., oligochaete worms and *Potamopyrgus* snails). However, on several occasions taxa that were present in one site, but absent from another, contributed to differences (often Psychodidae gnat larvae, *Physa* snails, or Scirtidae beetle larvae). Of the measured environmental variables, a combination of wetted width and water velocity showed the strongest correlation with macroinvertebrate data, although this was fairly weak (0.36). Water velocity appeared to have some effect on the community composition, with the two sites with the highest water velocities and a general lack of natural substrates (Waipapa Stream and The Parade – Dover St) being the only sites not to have *Potamopyrgus* snails among the five most abundant taxa. Additionally, both these sites were also the only ones to have collembola springtails, Psychodidae gnat larvae, and Orthocladiinae midge larvae among the top five most abundant taxa. The only other known published aquatic macroinvertebrate data from New Zealand piped streams are that of Neale & Moffett (2016), who collected samples from two piped sites as they were being removed as part of a daylighting project in Auckland. One of their sites was strongly dominated by oligochaete worms followed by mollusca and Diptera larvae, while the other was dominated by Diptera larvae. Three of our six sites were also dominated by oligochaete worms, however none were by Diptera larvae, although they were present at all sites. Neale & Moffett's (2016) study catchment had far more open channel length remaining than the catchments of this pilot study, and this may have some effect on the macroinvertebrate assemblages they encountered.

Mean invertebrate densities and taxa richness were low at all piped stream sites and MCI and QMCI were well within the "poor" quality class, although it is worth noting MCI was never intended for use in artificially piped streams, hence scores may not be overly applicable to such environments. It is clear that extensive piping of the stream channel has resulted in a macroinvertebrate community being limited to those species able to persist in a totally enclosed stream with near total darkness, no riparian vegetation or benthic algae, and subject to very flashy flow conditions. Additionally, given the predominantly urban catchment, they are further subjected to the various contaminants that are common with such a land use (e.g., heavy metals, hydrocarbons, detergents, paint wash water, etc.).

A comparison of macroinvertebrate communities between open and piped stream sites in the same catchments indicated open stream sites have a greater abundance of macroinvertebrates, greater taxa richness, and more pollution-sensitive EPT taxa than piped sites. It is likely the more natural conditions of the open sites (e.g., riparian vegetation, benthic algae, day-night cycle, greater instream habitat variability and likely a more stable habitat under flood conditions) supports higher densities and a greater diversity of macroinvertebrate taxa. Longitudinal studies centred on natural cave stream entrances have shown similar results with lower invertebrate richness and diversity within cave streams (e.g. Watson, 2010). The main macroinvertebrate community differences between open and piped stream sites in the Pae Kawakawa catchment were *Polypedilum* and Orthocladiinae midge larvae being the two most abundant taxa and the relatively pollution-sensitive *Hydropsyche* (*Orthopsyche*) being the third most abundant taxa at the open site. Similarly, the main macroinvertebrate community differences in the Miramar catchment are the presence of *Hydropsyche* (*Orthopsyche*) caddisfly larvae and *Zephlebia* mayfly larvae as the second and third most abundant taxa at the open site. The open-piped site comparison in the Miramar catchment is confounded somewhat as the open site was in a headwater stream in a vegetated reserve with minimal urban inputs, while the piped sites were further downstream and subject to substantial urban stormwater inputs. This was not the case in the Pae Kawakawa catchment as the open site was in a short section with pipes upstream and downstream and thus received urban stormwater runoff. Based on this limited data, it would appear that within extensively piped catchments, remnant sections of open stream are extremely important in maintaining catchment aquatic macroinvertebrate diversity. As such, the piping of even short sections of remnant open stream in urban catchments should be resisted. Additionally, it is evident the daylighting of piped streams, even relatively short sections, could have positive effects on catchment macroinvertebrate diversity.

For short sections of remnant open stream that have piped sections upstream and downstream (such as the GWRC Pae Kawakawa Stream site), the source of aquatic insects with flying adults (e.g., *Hydropsyche* (*Orthopsyche*)) pose several questions. Do adults fly up or down pipes to reach the site? Do adults fly across the heavily urbanised catchment to reach the site? Is the population sustained predominantly by emergence and oviposition of local individuals? Are some larvae transported to the site through the pipe network from upstream open stream habitat? Additionally, are some macroinvertebrate taxa that prefer open stream habitat able to persist in the pipes for some distance directly downstream of remnant open sections? This final question could be addressed by finding accessible pipe sites with open habitat directly upstream so you could collect samples from open habitats and at increasing distances downstream in the pipe network, utilising a combination of benthic and drift sampling methodologies.

4.4 Sampling Methodologies

For future piped stream macroinvertebrate surveys, the selection of methods would primarily depend on the overall aim of the study. Collecting a kick net sample from the surface is relatively quick and does not require confined space entry so many sites could theoretically be done in a single day. We have shown such a method can also yield macroinvertebrate community data at some sites that is fairly similar to that collected by Surber samples, at least in terms of presence/absence of more abundant taxa. There was some within-site variation in MCI and QMCI values between the two sampling techniques, although these were not great enough to change quality class interpretation with all sites being "poor", with the exception of MCI at one site (348 The Parade) where the Surber MCI was just above the "fair" threshold. Additionally, surface kick net sampling can be used at sites that are either too small or deemed too hazardous for people to enter (i.e., smaller dimension pipes, deep pipes, pipes with inflows from former landfill sites). Further, improvements to sampling equipment, such as a curved net frame for round pipe sites and a long handled stiff brush to scrub the stream bed, could improve sampling efficiency. However, the efficiency of sampling will never match that of standard open stream kick net sampling, such that a single manhole site sampled from the surface is not directly comparable to a single open stream site. To characterise the piped stream macroinvertebrate assemblage of a catchment surface kick net samples from several separate manholes would be required.

If a more detailed and accurate representative sample of the macroinvertebrate community is desired, then full pipe entry to undertake quantitative Surber sampling is recommended. Such sampling is less awkward, enables a larger area of stream bed and differing habitats/substrates to be sampled, but it is more time consuming/expensive. However, it is evident piped stream macroinvertebrates are very sparse, so it is recommended a greater area of stream bed is sampled than this pilot study for any future in-pipe Surber sampling. Twelve samples would still be reasonable, but samples could be obtained by pooling four standard Surber areas (i.e., sample four locations for each sample), which would result in four times the area being sampled as the current study. In-pipe Surber sampling also allows direct access to measure habitat variables and undertake spotlighting fish surveys.

The use of trail cameras to detect fish was trialled. While it did not appear eel movement was sufficient to trigger their operation, footage obtained through time lapse still and video imagery clearly was able to show eels moving around in the piped stream, although the species could not be identified (Figure 9). Hence, well installed trail cameras could be used to detect the presence of eels in piped streams, and could be especially useful in areas where the pipes are too small to be entered. It would be key to install cameras in such a way that they are well above any likely high flow events and positioned to provide the best footage possible as the confined space of piped streams can result in overexposed imagery if the infrared flash is reflected off the walls. There is the potential some kind of rig could be constructed so that cameras could be installed without the need for confined space entry. However, the use of cameras will not be sufficient to identify the species of eel, and nor would it be sufficient to see other fish, which would be too small and/or too cryptic to be seen from the cameras. Concomitantly, observations down manhole shafts without entering the piped streams can detect the presence of larger eels if they happen to be present at that particular time in the small section of stream that is visible, but are unlikely to reliably determine the species of eel or detect smaller and more cryptic fish species (e.g., banded kokopu, inanga). Thus if the aim of the study was to identify/detect all fish that may be found in a piped network, then accessing the stream to walk the piped channel would be required.

Given that the greatest expense in any pipe survey is the entering of the pipe (as this requires more personnel and specialist training and certification), then if a pipe was being entered to survey fish, then it would make sense to also collect invertebrate samples at the same time, or vice versa.

The sticky traps trialled captured relatively small numbers of flying insects, with taxa with terrestrial larvae being the most commonly trapped taxa at all sites. Despite this, they did capture taxa with an aquatic larval stage that were additional to those captured in benthic Surber samples (i.e., adult mosquitoes), although these flying adults did not necessarily originate from the surveyed section of piped stream. If sticky trapping was to be used it is recommended that several replicate traps are set along a 200 m survey reach. This would, however, require return entry to the sites after some period of time to retrieve the traps and would not be worthwhile if single-visit fish and macroinvertebrate sampling visits were being undertaken, given the expense of piped stream entry. It could be possible to design an active light trapping setup that could be suspended from manholes and thus not require piped stream entry to install and retrieve. Such a setup would require design and testing.

4.5 Recognition and Protection

There are various stormwater pipe management and construction practices that could have negative impacts on the biota that exist there:

» The removal of accumulated sediment and detritus via suction truck will remove habitat and likely lead to fish and macroinvertebrate mortality.

» Pipe repairs or alterations using mortars and grouts have the potential to negatively impact water quality and harm biota.

» Locations where pipe diameter changes have the potential to create fish barriers, as observed in Pae Kawakawa Stream under The Parade in Island Bay (Figure 25).

» The use of smooth, circular pipes may reduce the accumulation of natural gravels and detritus that provide habitat and cover for piped stream biota compared to older box culvert designs.

The permanent piping of existing remnant open stream sections will permanently alter the ecological function and fauna of those sections. There can be pressure to allow piping of such sections given that the majority of stream length in that catchment are already piped. However, this should be resisted from an ecological perspective given that these open remnant sections represent biodiversity 'hotspots' compared to piped sections for fish, macroinvertebrates, and likely algal species.

Currently, piped streams in Wellington are generally considered part of the stormwater system and managed as such. The Proposed Natural Resources Plan and the previous Regional Freshwater Plan do not provide any specific protection of piped stream habitats, the biota that inhabit them, or formally recognise them as migration pathways for freshwater fish. For example, if a section of piped stream was to be disturbed or replaced, there are no planning rules that would trigger the consideration of any ecological values or even alert GWRC freshwater scientists that the work was planned, even if the pipe in question is a fish migration pathway or has a permanent fish community within it. It would be sensible to work towards having piped stream recognised for their ecological values and be managed as such in the next iteration of the Natural Resources Plan.

Figure 25 A change in circular, concrete pipe dimensions in Pae Kawakawa Stream under The Parade in Island Bay in a high velocity section of piped stream has created a small, undercut drop that may impede fish passage.

5 RECOMMENDATIONS

5.1 Sampling Methodologies

» Develop a rapid piped stream ecological assessment protocol that can be done from manholes without the need for a confined space entry. This would allow multiple sites to be covered in a day and sampling of pipes too small and/or too hazardous for entry. This could include:

  – Sampling of macroinvertebrates using a modified, long-handled kick net and multiple manhole entry points (more entry points will be needed to obtain sufficient representative samples).

  – Habitat assessment of visible section of piped stream including measurement or visual estimation of water depth, wetted width, water velocity, substrate composition, and organic matter type and abundance. This can be improved by lowering of a GoPro camera or similar on a pole to obtain footage of general habitat upstream and downstream of the manhole.

  – Observation of any eels that happen to be present and visible down manhole shafts.

» Undertake detailed surveys that require pipe entry at key locations in main catchments. In practice this would likely only be in the middle to lower parts of larger catchments due to pipe size constraints. Any future detailed surveys should increase the area sampled for macroinvertebrates (e.g., collect pooled Surber samples rather than single samples) and include a fish survey via spotlighting and hand netting of at least 200 m of channel (so that actual fish species can be determined).

5.2 Habitat Improvements

» Investigate the viability of undertaking various in-pipe habitat improvement retrofits including:

  – Installation of flexible baffles (or similar) in zones of high velocity, laminar flows to slow water velocities, increase water depths, and provide resting areas for resident and migrating fish.

  – Installation of artificial elements such as small pipes or half pipes securely attached to the pipe base to provide fish cover for resident and migrating fish.

  – Installation of structures to increase water depths, create pool habitat, and increase retention of organic and stony substrate material. These could take the form of leaky weirs constructed of small boulders at appropriate locations to create pools and small wood or rock vanes across the low flow channel.

» Some locations have *in situ* materials from which fish cover can be constructed, however such improvised features are unlikely to withstand high flow events (Figure 26).

» Where old pipes are being replaced or new piped sections constructed, investigate integrating in-pipe habitat features into the design rather than just using the standard, smooth bottomed concrete pipe design. This could include constructed pools, and designed low flow channels that incorporate fish cover elements and an irregular, rough pipe bottom to facilitate retention of stony bed substrates and organic matter.

Figure 26 Improvised fish cover feature constructed from rubble found at one piped stream site.

5.3 Recognition and Protection

» Undertake a formal programme to identify sections of the stormwater pipe network that can be considered to be "piped streams" in that they are permanently flowing and close to where a natural, open stream was known to be or highly likely to have been located historically. This would involve extensive examination of WWL stormwater pipe GIS layers, waterway GIS layers, historical information on streams and urban development, and institutional knowledge at WWL, local councils, and the contractors who regularly work with the stormwater pipe network. The ultimate goal would be to create a detailed and accurate "piped stream" GIS layer.

» After an accurate "piped stream" GIS layer has been created, initiate work to populate it with relevant metadata including presence or absence of permanent fish population, importance as a migratory fish pathway, in-pipe habitat quality, and macroinvertebrate community metrics. This would require a mix of GIS analyses and field investigations.

» Aim to include provisions around maintaining and improving piped stream ecological values in the next iteration of the regional plan.

5.4 Further Research

» A more widespread general survey of piped streams in the region, which should include smaller diameter pipes that would be unsuitable for human entry. This would feed into the recognition and protection recommendations above.

» Initiate research into the length of piping that results in permanent changes to fish and macroinvertebrate assemblages. Unpublished data held by EOS Ecology from a 220 m pipe in Wellington indicates a macroinvertebrate and fish community in the pipe largely similar to that of natural open stream habitat upstream (i.e., abundant EPT taxa and a relatively diverse fish fauna (eels, banded kokopu, kōaro) resident in the pipe). There could be some pipe length threshold at which there is a shift towards only those fauna that can cope with piped stream conditions, such as those found in this pilot study. Because of its topography, the greater Wellington region is a good candidate to find sampleable pipes of different lengths with open channels upstream or downstream.

» Initiate research into the importance of remnant open stream channels at maintaining catchment biodiversity, including the length of open habitat required for a macroinvertebrate and fish assemblage comprised of open stream habitat preferring taxa to be self-sustaining. This could help inform the minimum length of pipe daylighting required to attract open habitat preferring taxa. Part of such a study could involve determining how far downstream open habitat preferring taxa can persist in the pipe network and a comparison with longitudinal studies of natural cave systems (e.g., Watson, 2010).

» A test of the effectiveness of in-pipe habitat improvements at suitable locations. This would include the design and installation of baffles at some locations and structures to increase water depths at others. Before-after, control-impact sampling of fish and macroinvertebrates could be used to determine if such features are worthwhile to install in piped streams.

6 MEDIA

» Ecological work in piped streams has the ability to capture the imagination of journalists as a press release by GWRC prior to the fieldwork resulted in stories by TVNZ's One News and Radio New Zealand:

- www.tvnz.co.nz/one-news/new-zealand/whitebait-eels-found-in-wellingtons-stormwater-system
- www.rnz.co.nz/national/programmes/ourchangingworld/audio/2018697287/the-streams-beneath-the-streets

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9 APPENDICES

9.1 Appendix 1 – SIMPER Results Comparing Sites

Appendix Table 1 SIMPER results showing those taxa that contribute >5% of the differences between stream sites. Abundances shown are forth root transformed values. Also shown in parentheses are ANOSIM R-values for each pairwise comparison.

Taxon	Average Abundance	Average Abundance	% Contribution
The Parade–Dover St & Waipapa Stream (R=0.64, p=0.001)	**The Parade–Dover St**	**Waipapa Stream**	
Orthocladiinae midge larvae	1.26	0.19	18.02
Psychodidae gnat larvae	1.25	0.31	16.65
Oligochaeta worms	1.43	0.53	15.39
Collembola springtails	0.73	1.13	12.66
Scirtidae beetle larvae	0.58	0	8.82
Polypedilum midge larvae	0.43	0.14	6.31
Acarina mites	0.33	0.14	5.01
The Parade–Dover St & 302 The Parade (R=0.82, p=0.001)	**The Parade–Dover St**	**302 The Parade**	
Psychodidae gnat larvae	1.25	0	15.73
Orthocladiinae midge larvae	1.26	0	15.3
Oligochaeta worms	1.43	0.52	13.05
Potamopyrgus snails	0.17	1.16	12.43
Physa snails	0	0.8	8.53
Collembola springtails	0.73	0.09	8.38
Scirtidae beetle larvae	0.58	0	6.82
Waipapa Stream & 302 The Parade (R=0.69, p=0.001)	**Waipapa Stream**	**302 The Parade**	
Collembola springtails	1.13	0.09	23
Potamopyrgus snails	0	1.16	21.87
Physa snails	0.14	0.8	13.36
Oligochaeta worms	0.53	0.52	13.11
Psychodidae gnat larvae	0.31	0	5.1
Ferrissia limpets	0	0.29	5.08
The Parade–Dover St & 348 The Parade (R=0.93, p=0.001)	**The Parade–Dover St**	**348 The Parade**	
Potamopyrgus snails	0.17	2.66	21.48
Psychodidae gnat larvae	1.25	0	11.23
Orthocladiinae midge larvae	1.26	0.16	10.66
Ferrissia limpets	0	0.95	8.91
Oligochaeta worms	1.43	1.46	8.75
Physa snails	0	1.05	8.48
Collembola springtails	0.73	0.1	6.18
Scirtidae beetle larvae	0.58	0	5.02
Waipapa Stream & 348 The Parade (R=0.92, p=0.001)	**Waipapa Stream**	**348 The Parade**	

Potamopyrgus snails	0	2.66	28.11
Oligochaeta worms	0.53	1.46	12.99
Collembola springtails	1.13	0.1	12.71
Acarina mites	0	0.95	11.79
Physa snails	0.14	1.05	9.91
302 The Parade & 348 The Parade (R=0.27, p=0.002)	**302 The Parade**	**348 The Parade**	
Potamopyrgus snails	1.16	2.66	27.21
Oligochaeta worms	0.52	1.46	18.6
Ferrissia limpets	0.29	0.95	14.31
Physa snails	0.8	1.05	12.88
Acarina mites	0.11	0.3	5.86
The Parade–Dover St & Miramar-Shops (R=0.68, p=0.001)	**The Parade–Dover St**	**Miramar-Shops**	
Psychodidae gnat larvae	1.25	0	16.99
Orthocladiinae midge larvae	1.26	0.27	13.32
Polypedilum midge larvae	0.43	1.07	11.85
Collembola springtails	0.73	0	9.16
Oligochaeta worms	1.43	1.42	8.56
Acarina mites	0.33	0.79	8.54
Scirtidae beetle larvae	0.58	0	7.51
Potamopyrgus snails	0.17	0.53	6.68
Waipapa Stream & Miramar-Shops (R=0.74, p=0.001)	**Waipapa Stream**	**Miramar-Shops**	
Collembola springtails	1.13	0	19.22
Oligochaeta worms	0.53	1.42	17.34
Polypedilum midge larvae	0.14	1.07	15.58
Acarina mites	0.14	0.79	11.03
Potamopyrgus snails	0	0.53	7.32
Platyhelminthes flatworms	0	0.29	5.61
Orthocladiinae midge larvae	0.19	0.27	5.17
302 The Parade & Miramar-Shops (R=0.51, p=0.001)	**302 The Parade**	**Miramar-Shops**	
Oligochaeta worms	0.52	1.42	19.04
Polypedilum midge larvae	0.09	1.07	16.64
Potamopyrgus snails	1.16	0.53	14.7
Acarina mites	0.11	0.79	11.86
Physa snails	0.8	0	11.45
Platyhelminthes flatworms	0	0.29	5.89
348 The Parade & Miramar-Shops (R=0.70, p=0.001)	**348 The Parade**	**Miramar-Shops**	
Potamopyrgus snails	2.66	0.53	24.3
Polypedilum midge larvae	0	1.07	11.57
Oligochaeta worms	1.46	1.42	11.54
Ferrissia limpets	0.95	0	11.47
Physa snails	1.05	0	10.62
Acarina mites	0.3	0.79	7.71

The Parade–Dover St & Miramar Park (R=0.98, p=0.001)	The Parade–Dover St	Miramar Park	
Potamopyrgus snails	0.17	1.41	15.74
Psychodidae gnat larvae	1.25	0	15.63
Orthocladiinae midge larvae	1.26	0	15.28
Physa snails	0	0.73	9.03
Collembola springtails	0.73	0.08	8.45
Scirtidae beetle larvae	0.58	0	6.9
Oligochaeta worms	1.43	1.57	6.65
Waipapa Stream & Miramar Park (R=0.94, p=0.001)	**Waipapa Stream**	**Miramar Park**	
Potamopyrgus snails	0	1.41	23.19
Oligochaeta worms	0.53	1.57	19.67
Collembola springtails	1.13	0.08	18.73
Physa snails	0.14	0.73	11.64
302 The Parade & Miramar Park (R=0.20, p=0.004)	**302 The Parade**	**Miramar Park**	
Oligochaeta worms	0.52	1.57	31.38
Physa snails	0.8	0.73	18.9
Potamopyrgus snails	1.16	1.41	18.26
Ferrissia limpets	0.29	0.28	10.27
348 The Parade & Miramar Park (R=0.35, p=0.001)	**348 The Parade**	**Miramar Park**	
Potamopyrgus snails	2.66	1.41	25.42
Oligochaeta worms	1.46	1.57	16.77
Ferrissia limpets	0.95	0.28	14.99
Physa snails	1.05	0.73	12.01
Sphaeridae pea clams	0.35	0.08	5.44
Acarina mites	0.3	0	5.37
Miramar-Shops & Miramar Park (R=0.60, p=0.001)	**Miramar-Shops**	**Miramar Park**	
Potamopyrgus snails	0.53	1.41	17.9
Polypedilum midge larvae	1.07	0.08	17.18
Physa snails	0	0.73	12.79
Acarina mites	0.79	0	12.66
Oligochaeta worms	1.42	1.57	9.7
Platyhelminthes flatworms	0.29	0	5.73

9.2 Appendix 2 - BEST (Biota and Environment Matching) Results

Appendix Table 2 BEST results from piped stream sites showing those measured habitat parameters that best matched the observed macroinvertebrate community composition. Habitat variables included in the analysis were water depth, wetted width, water velocity, biofilm cover, and substrate index.

Variables	Correlation
Wetted width, Water velocity	0.356
Water velocity	0.320
Wetted width, Water velocity, Biofilm cover	0.312
Wetted width, Water velocity, Substrate index	0.287
Water velocity, Biofilm cover	0.282
Wetted width, Water velocity, Biofilm cover, Substrate index	0.281
Water velocity, Substrate index	0.271
Water velocity, Biofilm cover, Substrate index	0.256
Water depth, Wetted width, Water velocity	0.248
Water depth, Water velocity	0.233

9.3 Appendix 3 – SIMPER Results Comparing Catchments

Appendix Table 3 SIMPER results showing those taxa that contribute >5% of the differences between catchments (Pae Kawakawa, Waipapa, and Miramar). Abundances shown are forth root transformed values. Also shown in parentheses are ANOSIM R-values and significance level for each pairwise comparison.

Taxon	Average Abundance	Average Abundance	% Contribution
Pae Kawakawa & Waipapa (R=0.35, p=0.001)	**Pae Kawakawa**	**Waipapa Stream**	
Potamopyrgus snails	1.33	0	18.54
Collembola springtails	0.31	1.13	16.19
Oligochaeta worms	1.15	0.53	13.72
Physa snails	0.61	0.14	8.87
Psychodidae gnat larvae	0.43	0.31	7.67
Orthocladiinae midge larvae	0.49	0.19	7.21
Ferrissia limpets	0.42	0	6.13
Pae Kawakawa & Miramar (R=0.05, p=0.096)	**Pae Kawakawa**	**Miramar**	
Potamopyrgus snails	1.33	0.99	17.29
Oligochaeta worms	1.15	1.5	14.74
Physa snails	0.61	0.38	9.96
Polypedilum midge larvae	0.18	0.56	8.68
Orthocladiinae midge	0.49	0.13	7.17
Ferrissia limpets	0.42	0.14	6.98
Acarina mites	0.25	0.38	6.62
Psychodidae gnat larvae	0.43	0	5.96
Waipapa & Miramar (R=0.73, p=0.001)	**Waipapa**	**Miramar**	
Collembola springtails	1.13	0.04	18.96
Oligochaeta worms	0.53	1.5	18.55
Potamopyrgus snails	0	0.99	15.54
Polypedilum midge larvae	0.14	0.56	9.2
Physa snails	0.14	0.38	7.1
Acarina mites	0.14	0.38	6.2

9.4 Appendix 4 – SIMPER Results Comparing Open and Piped Stream Sites

Appendix Table 4 **SIMPER results showing those taxa that contribute >5% of the differences between open and piped stream sites in the Pae Kawakawa and Miramar catchments. Abundances shown are relative abundances. Also shown in parentheses are ANOSIM R-values and significance level.**

Taxon	Average Abundance	Average Abundance	% Contribution
Open & Piped (R=0.56, p=0.048)	**Open**	**Piped**	
Oligochaeta worms	4.59	33.92	20.04
Potamopyrgus snails	21.27	33.3	18.38
Polypedilum midge larvae	14.98	7.22	10.05
Hydropsyche (*Orthopsyche*) caddisfly larvae	12.42	0.01	8.48
Orthocladiinae midge larvae	13.52	3.38	8.39
Physa snails	0.02	7.65	5.23

www.eosecology.co.nz
info@eosecology.co.nz

PO Box 4262, Christchurch 8140
P 03 389 0538

PO Box 8054, Palmerston North 4446
P 06 358 9566

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