Impacts of diquat herbicide and mechanical excavation on spring-fed drains in Marlborough, New Zealand

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ABSTRACT

Drainage is considered the primary function of many lowland waterways throughout New Zealand, but drains also provide habitat for many valued species. Aquatic plant growth and sediment accumulation can decrease drainage efficiency, making drain maintenance necessary. However, the importance of other functions provided by these waterways may be overlooked during drain maintenance. In this study we measured water levels, plant cover, water quality, and invertebrate community composition in spring-fed drains before and after mechanical excavation and herbicide (diquat) application. A control drain was also monitored. Many eels and other aquatic fauna were amongst the material removed from the drain by the excavator. Invertebrate densities recorded after excavation were half of those recorded shortly before clearance, but recovered within 1 month. Aquatic plant cover had returned to 80% of pre-excavation levels within 6 months. We observed no acute toxic effects of diquat application on aquatic invertebrates; however, survival of invertebrates living among overhanging vegetation was reduced. Aquatic invertebrate taxonomic richness decreased at the sprayed site after diquat application, probably due to an increase in detritus within the drain. We did not observe a decrease in oxygen concentration associated with the decay of aquatic plants after treatment. Plant cover returned to pre-treatment levels within 6 months of diquat treatment, but was dominated by aquatic plants rather than overhanging terrestrial vegetation. The use of weed rakes, rather than standard excavator buckets, should be encouraged to reduce the removal of eels and other aquatic organisms during mechanical excavation. Manual return of eels to drains following mechanical excavation could also be considered.

Keywords: drainage, management, drain ecology, aquatic plants, water quality, invertebrates, fish, excavation, diquat, oxygen.

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1. Introduction

Many waterways throughout New Zealand are managed for drainage purposes and often are referred to as drains. Although the primary function of drains is to provide for drainage of land, they also are important habitat for a wide range of freshwater fish, bird and invertebrate species (Hudson & Harding 2004). As well as their contribution to biodiversity, some of these species are important cultural, recreational and commercial resources. Drains filter out sediment and nutrients and thus limit transfer of these materials from the land to vulnerable freshwater or coastal areas downstream. Some drains also provide water supplies and some have aesthetic values that are treasured by local communities. In several areas of the country, drains are the last remaining remnants of formerly extensive lowland wetlands.

Traditional management of drains has focused on maintaining or improving drainage. However, a more holistic view, considering the many functions of drains, may result in changes in management practices to allow for multiple uses without compromising drainage. The main reasons for drain management are related to control of aquatic and streamside plants and accumulations of sediment, both of which have the potential to raise water levels and decrease drainage efficiency (Watson 1987; Pitlo & Dawson 1990; Wilcock et al. 1999; Champion & Tanner 2000). Aquatic plants are controlled using herbicide sprays, mechanical diggers, hand clearing, weed cutting and, occasionally, plant-eating fish (Edwards & Moore 1975; Pieterse & Murphy 1990; Wells et al. 2003). Natural or artificial shade can also be used in some situations to suppress aquatic plant growth (Dawson & Kern-Hansen 1979; Rutherford et al. 1999; Young et al. 2000). Mechanical clearance is the most common method for dealing with sediment accumulations, although alternative approaches include suction dredging, sediment flushing, and source control using soil conservation measures.

A variety of herbicides have been used to control aquatic plants in drains (Murphy & Barrett 1990). Herbicides may have direct environmental effects through toxicity to non-target organisms, and indirect effects associated with loss or decay of aquatic plant material. These effects include oxygen depletion due to decay of dead plant material, increases in detritus, toxin and nutrient release from decaying vegetation, and loss or changes to the habitat / cover / food that the plants provided (Murphy & Barrett 1990). However, highly toxic herbicides are no longer used in New Zealand because of concerns about their effects on the environment. Diquat is the only herbicide with aquatic registration permitting it to be broadcast onto water (for control of submerged aquatic plants and plants overhanging water) in New Zealand and usually requires consent from the relevant Regional Council. Glyphosate (Roundup®) is the only other herbicide registered for use on ditch banks (i.e. near waterways), but the spray must be directed onto vegetation with only limited over-spray (onto water) allowed. Regional Council consent is required for glyphosate usage, but it is a permitted activity in many areas. Diquat can be applied in both aqueous and gel formulations. Both formulations release diquat into the water column in similar concentrations, although the gel formulation releases diquat more slowly than the aqueous formulation, which can increase contact times and efficacy (Murphy & Barrett 1990). The gel formulation is advantageous in stratified water bodies, as the gel penetrates thermal barriers and gets down to the plants (this is important in static waters, but is of no consequence in flowing waters, Wells et al. 1995).

Several studies have been conducted in New Zealand to determine the ecological effects of drain maintenance using either diquat or mechanical excavation. These have reported a variety of impacts. Wilcock et al. (1998) assessed the effect of mechanical excavation on an 80-m reach of a Waikato drain. Short-term (3–4 hours) increases in turbidity and ammonia were observed, while dissolved reactive phosphorus and nitrate levels were reduced. Willow weed (*Persicaria* sp.) was still absent after 6 months but *Potamogeton* had recovered. Densities of the snail *Gyraulus* were reduced by 90%. Goldsmith (2000) sampled three mechanically cleared (digger), two sprayed (glyphosate and diquat) and four control sites in small Southland streams before and six weeks after treatment. Mechanical clearing removed plant material but did not lead to significant changes in aquatic plant species richness, water depth, water velocity or substrate size. Goldsmith (2000) also found no difference in fish species richness or density that could be attributed to drain treatment. However, differences in the efficiency of fish surveys before and after treatment make the interpretation of these results problematic (Hudson & Harding 2004). Young et al. (2000) surveyed a range of sites in the Spring Creek catchment near Blenheim and raised the likelihood that the lack of amphipods in some small tributaries could be related to herbicide toxicity and / or vegetation removal associated with drain maintenance. However, growth and mortality of freshwater shrimps housed in enclosures at sites around the catchment were not influenced by diquat application during the study.

This study was conducted as part of a multi-agency project coordinated by the Department of Conservation that arose from growing recognition around New Zealand that drains have a wide range of functions and thus more sustainable drain maintenance practices are required to maintain these functions. This study provided an assessment of the short- and medium-term effectiveness and impacts of diquat and mechanical (digger) clearance on water levels, water quality, nutrient and sediment retention, and biota (macroinvertebrates, eels and macrophytes) in drains. The recovery rates of invertebrates and macrophytes after drain treatment were also determined.

2. Site description and treatments

2.1 SITE SELECTION

Spring-fed drains are common on the Wairau Plain near Blenheim in the north of the South Island, and were chosen for the study because of their high potential ecological value. Sites were selected with the help of the drainage management staff of Marlborough District Council (MDC). A large network of drains on the Wairau Plain is managed by MDC staff to ensure that hydraulic efficiency and water level standards are maintained. The drains were selected to be as similar as possible in terms of flow, light exposure, connection to the coast, and weed bed composition. To minimise within-drain variation, the study reaches chosen were as uniform as possible. Each drain was also required to be located in a separate catchment (i.e. independent of the other drains), with a relatively restricted catchment upstream, so that the potential for unidentified upstream influences was limited. The sites chosen also had to fit within the MDC's drainage management programme and be deemed to require treatment and / or could be left alone during the study without causing major problems with water levels and associated complaints from adjacent landowners.

Despite the large drainage network in Marlborough, it was difficult to find drains that met all of the above criteria. Three roughly similar drains were eventually selected: Foots Drain, Pa Drain and Murrays Drain (Figs 1, 2, 3 and 4). All three drains are spring-fed from the Wairau Aquifer, are approximately 1–2 m wide, and are part of the network of waterways that the MDC manages

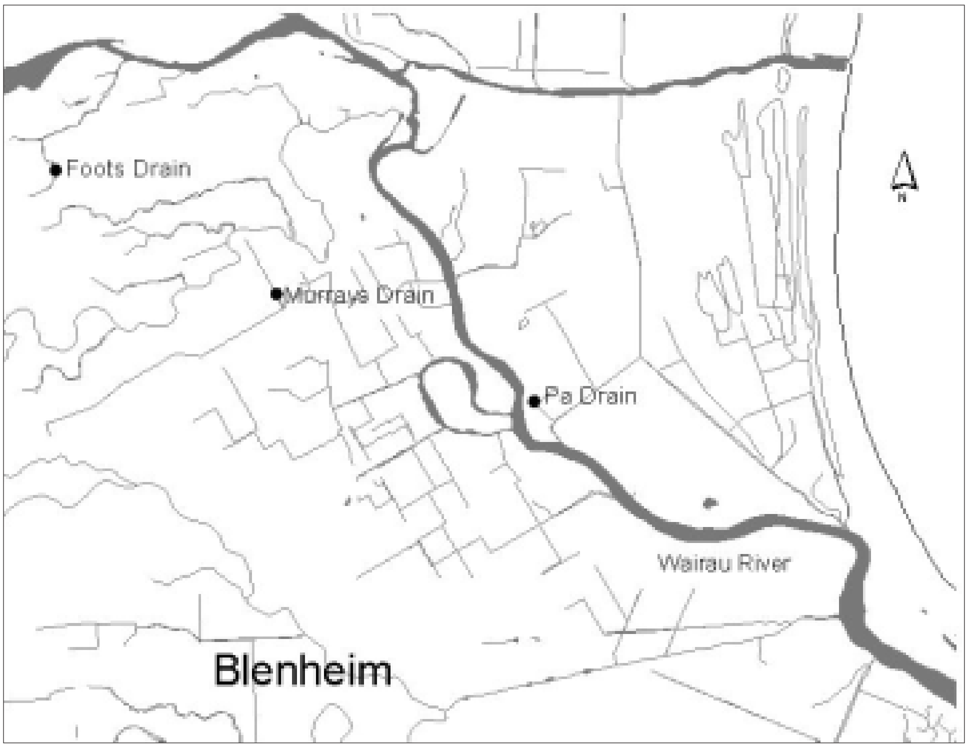


Figure 1. Location of the study sites on the Wairau Plain near Blenheim, northern South Island, New Zealand.

Figure 2. Application of diquat spray in Pa Drain.

Figure 3. Mechanical clearance in Foots Drain using an excavator.

Figure 4. Control site—Murrays Drain.

for drainage. All three drains had been sprayed in spring and / or autumn over the 5 years prior to the study. Mechanical clearance last occurred in Foots Drain in September 1995, Pa Drain in March 1998, and Murrays Drain in March 1985 (Steve Bezar, MDC, pers. comm.). Land use in the surrounding area is predominantly a mix of pastoral grazing (sheep and cattle) and horticulture (apples, grapes, vegetables). Access for fish and invertebrate migration to and from the lower Wairau River is via side-hung floodgates for Foots Drain and Murrays Drain and is thus relatively unrestricted. A pump-station discharges water from Pa Drain into the Wairau River but fish passage is still possible at low tide or during low river flows.

2.2 EXPERIMENTAL DESIGN AND TREATMENTS

The study was set up with a paired BACI (Before-After-Control-Impact) design with replicate measurements taken before and after treatment (Stewart-Oaten et al. 1986). Two of the three drains were cleared on January 16 2002 as per the MDC's drain maintenance programme; one by spraying (Pa Drain; Fig. 2) and the other mechanically with an excavator (Foots Drain; Fig. 3). The third drain (Murrays Drain; Fig. 4) was untreated and used as a control site. Prior to treatment, sampling took place on the same day in each drain on three separate occasions (15 November 2001, 27 November 2001 & 10 January 2002). Sampling was repeated in each drain 1 week (24 January 2002), one month (22 February 2002), three months (19 April 2002), and six months (25 July 2002) after treatment. We recognise that a study design involving replicate drains for each treatment would have been preferable. However, given the resources available we decided that it was more important to have a reasonable number of replicate sampling occasions (and samples) before and after the treatments at the sites that were studied.

In Pa Drain diquat spray was applied to the water surface and overhanging vegetation using a hand-held spray-gun connected to a motorised compressor on the back of a truck (Fig. 2), and achieved an estimated concentration of diquat in the water of 1.23 ppm (Bezar 2002). Mechanical clearing was carried out using a mechanical digger with a wide bucket that allowed water to drain out through holes (Fig. 3). The digger moved along the drain bank progressively scooping out the bottom of the drain, thus removing a layer of sediment (5–30 cm deep) and the associated macrophytes and fauna. Extracted material was placed in piles alongside the drain on the same side as the digger.

On each visit to the sites we measured water level, channel geometry, water quality, macroinvertebrate diversity and abundance, and aquatic plant diversity and cover over a 50–100 m study reach. Marked differences in the efficiency of fish surveys before and after treatment were expected (Goldsmith 2000), therefore only casual observations of fish presence at each site were conducted. Wetland birds were not surveyed.

2.3 SITE DESCRIPTIONS

2.3.1 Murrays Drain—control

Over the study period Murrays Drain flowed at between 0.029 and 0.069 m^3/s (Fig. 5). Water depth was typically between 40 and 50 cm and the drain bed comprised a mixture of soft sediment, gravel and rock. The dominant macrophyte was the introduced oxygen weed *Elodea canadensis*, with watercress (*Nasturtium* sp.) and starwort (*Callitriche stagnalis*) commonly fringing the waterway in some sections (Appendix 1.1, 1.2, 1.3). Macrophytes were generally absent in areas where gravel and rock were the dominant substrates. The stream banks remained unchanged and intact until the last sampling occasion when some portions had been collapsed by a hedge-trimming vehicle driving along the bank edge. Brown trout (*Salmo trutta*), shortfinned eels (*Anguilla australis*) and numerous koura (freshwater crayfish, *Paranephrops planifrons*) were observed in the drain.

2.3.2 Foots Drain—mechanical excavation

Prior to mechanical clearance, Foots Drain was an open, slow-flowing drain with a dense macrophyte bed dominated by *Nitella* sp. with patches of *Potamogeton crispus* interspersed (Appendix 1.4, 1.5, 1.6). The water depth was between 45 and 60 cm and the drain bed was composed of soft sediments between 20 and 30 cm deep. The north bank of the lower 25 m of the study reach was lined with large trees (> 5 m tall) which shaded all or part of the water body, and the south bank was lined with terrestrial grasses and weeds. The middle section of the study reach was fringed by terrestrial grasses on both sides, while the upper part was lined on the south bank by large trees and flaxes but was not shaded from the north side. Inanga (*Galaxias maculatus*), shortfinned eels (*Anguilla australis*) and brown trout (*Salmo trutta*) were observed during the study. Flows in

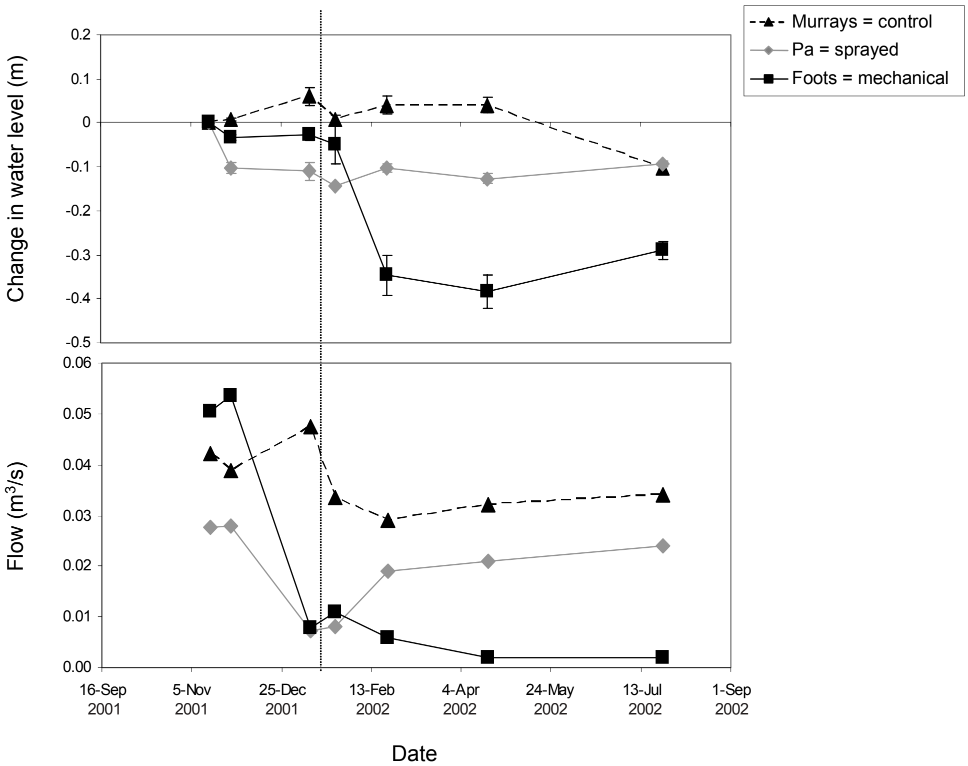
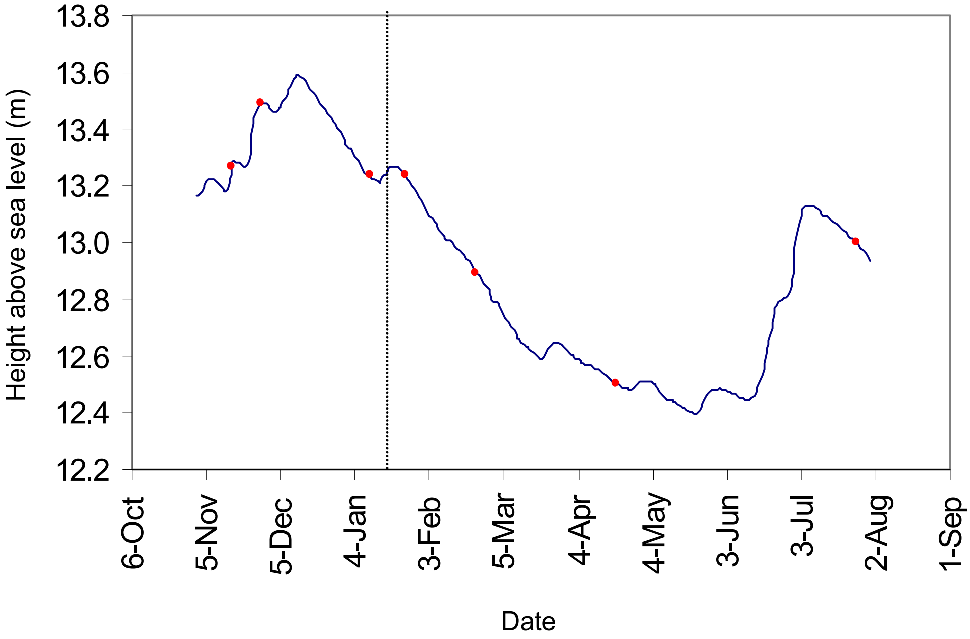


Figure 5. Average change in water level (from first survey: 15 November 2001) and flow during each of the sampling periods. The vertical dotted line indicates the timing of spraying and mechanical clearance.

Figure 6. Changes in groundwater level in the spring zone (Wratts Road) within the Wairau Aquifer over the course of the study (from October 2001 to August 2002). The dashed line indicates the timing of spraying and mechanical clearance. Dots indicate sampling occasions.



November 2001 were c. 0.05 m^3/s, but dropped considerably (to 0.008 m^3/s) just prior to clearing in January 2002 (Fig. 5). Water level, on the other hand, was relatively unchanged prior to clearing (Fig. 5). The drop in flow was presumably related to the declining groundwater level within the Wairau aquifer (Fig. 6) and hence discharges to spring-fed streams. Foots Drain is further up the Wairau Plain than the other sites and both flow ($r = 0.7$) and water level ($r = 0.89$) at this site were significantly correlated with groundwater levels.

2.3.3 Pa Drain—herbicide

Prior to spraying, the water surface of Pa Drain was almost completely closed over by a canopy of weeds and grasses (blackberry (*Rubus sp.*), *Carex* sp.; Appendix 1.7, 1.8, 1.9). Beneath the canopy the channel itself was relatively clear with only a few root systems and overhanging grasses obstructing flows. Flows prior to spraying were between 0.007 and 0.028 m^3/s (Fig. 5). Where the riparian cover did not completely cover the stream, there were small beds of *Nitella* sp. There were also pockets of watercress (*Nasturtium* sp.) along the stream edges. Freshwater shrimps (*Paratya curvirostris*), inanga (*Galaxias maculatus*), shortfinned eels (*Anguilla australis*) and common bullies (*Gobiomorphus cotidianus*) were observed in this drain on several occasions before and after spraying.

3. Methodology

3.1 WATER LEVEL, FLOW AND PLANT COVER

Stream bed profile, water level, and plant cover were monitored at three sites at set distances along the study reach at each drain (¼, ½ and ¾ marks). Water level, bed level and plant heights were measured from a taught horizontal measuring tape stretched across the drain, perpendicular to the direction of flow. A peg driven into the left bank during the first sampling occasion was used as the datum and the tape was leveled with a 1-m builder's level and a temporary stake in the right bank. The percentage of plant cover was also assessed at 0.5-m intervals across each cross section. Notes were taken describing the vegetation types in and on the banks of the drains. Flow was calculated using measurements of velocity (Marsh-McBirney current meter) and depth across the stream cross section.

3.2 WATER QUALITY

Water quality analyses included turbidity, indicator bacteria (*E. coli*), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), nitrate nitrogen (NO_3-N), ammoniacal nitrogen (NH_4-N), and dissolved reactive phosphorus (DRP). Water samples were collected at the downstream end of each study reach prior to any other in-stream work to avoid sampling disturbed water. Data loggers (YSI 6920, YSI 6000, and YSI 650) were also deployed on each sampling occasion to measure dissolved oxygen, temperature and conductivity every 15 minutes for at least 24 hours.

3.3 ASSESSMENT OF IMMEDIATE IMPACTS

At the site that was sprayed, three drift nets with 16-cm-diameter apertures were placed in the drain approximately 30 m apart for three periods of approximately 3 hours before, during and after spraying. All drift sampling was carried out during daylight. Water velocity was measured at the mouth of the nets at the beginning and end of each deployment using a Marsh McBirney flow meter so the volume of water filtered by each net could be calculated. To assess acute toxicity of diquat to invertebrates (i.e. were drifting invertebrates healthy or unhealthy / dead), the invertebrates caught within the nets were transferred to 500-mL containers filled with clean stream water. After transport back to the laboratory the containers were kept cool with the lids loosened to allow oxygen transfer. The composition, numbers and health (i.e. live v. dead) of the contents were then determined after 96 hours. This period was chosen because it corresponds with the period often used for acute toxicity tests (e.g. Hickey & Clements 1998).

At the site that was mechanically cleared, the digger spoil was examined for eels and other large aquatic fauna (e.g. koura, other fish species) over the entire length of cleared drain. Animals found were counted to provide an estimate of the number that were removed from the drain. After counting and measuring, all animals were returned to the drain.

3.4 CHANGES IN INVERTEBRATE ABUNDANCE AND COMMUNITY COMPOSITION

At each site, invertebrate abundance and diversity were assessed from three core samples (13 cm diameter) collected on each sampling occasion. The sampling positions along the study reach and across the channel on each sampling occasion were selected using random numbers. The core sampler was pushed vertically down into the stream bed (approximately 10 cm) to trap a 13-cm cylindrical column of water, mud and macrophytes. Before being lifted out of the sediment, a pull cord was tightened around the front opening of the core to seal it off. The contents were then sieved through a 0.5-mm mesh bag attached to the back of the core, transferred to a 1-L sample container and preserved in a 2% formalin, 70% ethanol solution. In the laboratory, samples were sieved, and macroinvertebrates were counted and identified (using a binocular microscope and standard keys) to the lowest possible taxonomic level. The dry-weight of live aquatic plant material and detritus in each invertebrate sample was measured (dried to constant weight for > 24 hours at 60°C) to help explain variability in invertebrate densities among samples. We recognise that larger samples would be required to accurately assess aquatic plant biomass over time in each drain.

Additional invertebrate information was obtained by sweep-netting (0.5 mm mesh size) the submerged plants along the side of both banks (Protocol C2; Stark et al. 2001). The sampling effort was standardised to one sweep of the net along a 1-m section of the bank on both sides of the drain at all three core sampling locations. Sweep net samples from the three core locations were pooled for analysis, and preserved in a 2% formalin, 70% ethanol solution. In the laboratory, samples were sieved, and macroinvertebrates were counted (using a fixed 200 animal count plus scan for rare taxa) and identified as for core samples (Protocol P2; Stark et al. 2001).

3.5 DATA ANALYSIS

The immediate effects of diquat application on drifting-invertebrate densities were assessed using one-way ANOVA, while any differences in survival rates of drifting invertebrates collected before, during and after spraying were detected using a G-test of independence (Sokal & Rohlf 1981). As mentioned earlier, the main part of the study had a paired BACI (Before-After-Control-Impact) design with samples collected three times before and four times after treatment at both the control and treatment sites. Any significant differences in water quality and invertebrate community density and composition between control-impact pairs before and after treatment were assessed using a paired t-test as recommended by Downes et al. (2002). This analysis assumes that sampling occasions before and after treatment were a random selection of possible sampling occasions, that sampling occasions were not temporally autocorrelated, and that the impact of the treatment was evident for all sampling occasions post treatment. Given that 6 months had elapsed between the treatment and the final sampling occasion, there was opportunity for some recovery of water quality and the invertebrate community from the treatment. Any significant effects identified using the paired BACI analysis can therefore be considered medium-term effects lasting up to 6 months. Any shorter-term changes in the invertebrate communities among individual sampling occasions at each site were assessed using one-way ANOVA for data that was normally distributed (taxonomic richness, log total density), or using the Kruskal-Wallis test for the densities of individual taxa which included a large number of zero values and thus precluded parametric analysis. Changes in invertebrate community composition at each of the sites over time were also assessed using detrended correspondence analysis (DECORANA). The impacts of changes in flow on water quality at each site were assessed using Pearson correlations between water quality parameter values and flow measurements. Pearson correlations were also used to determine the significance of any relationships between invertebrate taxonomic richness (and biomass) and the biomass of macrophytes and detritus collected within the core samples.

4. Results

4.1 EFFECTS OF MECHANICAL EXCAVATION ON WATER LEVELS, FLOW AND PLANT COVER

One week after mechanical clearing, Foots Drain was deeper by 10–20 cm and the bulk of the macrophyte beds were removed (Fig. 7). Some remnant strands of *Nitella* sp. and *P. crispus* remained, indicating that the root systems had not been completely removed (Appendix 1.4, 1.5, 1.6). The drain cross-section was asymmetrical, with the deepest point, and the steepest bank on one side (the opposite side from the digger). The removal of the weed beds and other obstructions (i.e. branches) allowed *Lemna minor* and *Azolla* sp. to drift freely. Eventually they backed up from a small culvert downstream and covered the entire water surface in the lower 25 m of the study reach (Appendix 1.4). Riparian grasses on the side where the digger operated were crushed. Water levels and flow rates had dropped only slightly one week after clearance (Fig. 5).

After 1 month, soft sediments had begun to re-accumulate in the bed of the drain and the macrophyte communities were re-establishing (Fig. 7). Water levels had dropped by approximately 30 cm in conjunction with declining groundwater levels, and flows were also slightly reduced (Fig. 5). The crushed riparian grasses were growing through the edges of the sediment piles (Appendix 1.4, 1.5, 1.6).

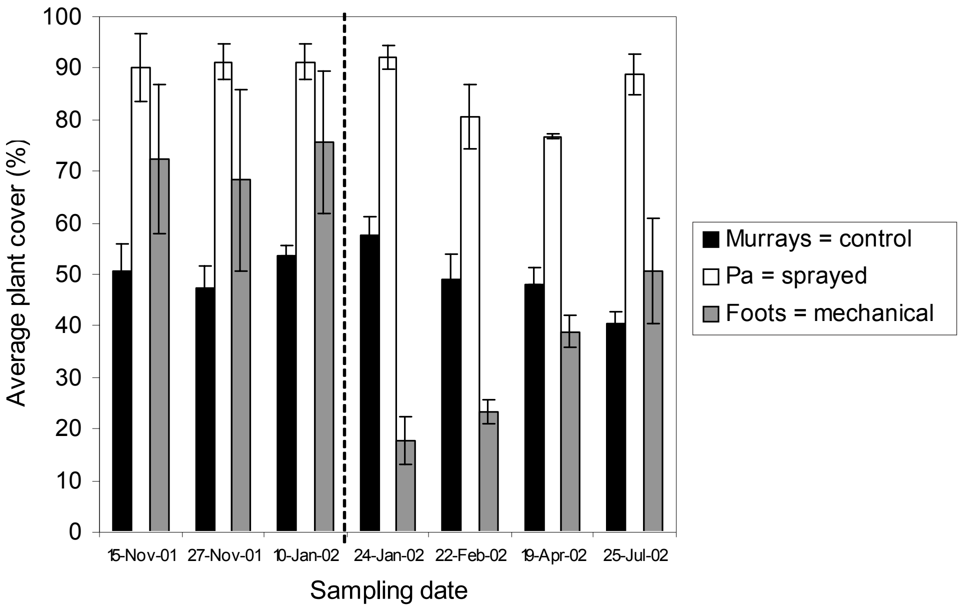


Figure 7. Changes in percentage coverage of aquatic plants at each site over the course of the study. The dashed line indicates the timing of spraying and mechanical clearance.

After 3 months the macrophyte beds had re-established (Fig. 7), but the water levels and flows were lower (Fig. 5). Riparian grasses had recovered and were covering the banks again (Appendix 1.4, 1.5, 1.6). After 6 months, more sediment had accumulated under the macrophyte beds and drain condition appeared similar to what it was prior to mechanical clearance, although average percent plant cover was still lower than prior to clearance (Fig. 7, Appendix 1.4, 1.5, 1.6). However, water levels and flows were still relatively low, reflecting the low groundwater levels within the aquifer (Fig. 5). Growth of macrophytes in the lower part of the study reach was apparently suppressed by the floating cover of *L. minor* and *Azolla* sp.—presumably because the floating plants restricted the amount of light penetrating below the water surface (Appendix 1.4).

4.2 EFFECTS OF DIQUAT ON WATER LEVELS, FLOW AND PLANT COVER

One week after spraying, vegetation in and overhanging Pa Drain appeared dessicated. The affected vegetation was still holding its shape and maintained a canopy over the water surface in some areas (Appendix 1.7, 1.8). Average water levels decreased slightly (0.03 cm), while flow showed a very slight increase (Fig. 5).

One month after spraying the 'die back' line was more pronounced. Overhanging plant material had collapsed into the waterway and was decaying. Average percent plant cover had declined (Fig. 7) and a gap had developed between the overhanging vegetation on either side of the drain, but the collapsed plants still covered the waterway in some places (Fig. 7, Appendix 1.7, 1.8, 1.9). Filamentous algae were common in areas that were exposed to light. Water levels had increased slightly (Fig. 5).

After 3 months most of the affected plants had collapsed into the stream and were decaying, and average plant cover had declined further (Fig. 7). Filamentous algae had proliferated in many areas of the drain (*Vaucheria* sp., *Spirogyra* sp.). Overhanging vegetation was starting to regrow, particularly the blackberry on the true right bank and terrestrial grasses on the true left bank. Watercress was also regrowing and spreading further out into the stream than had been observed prior to treatment (Appendix 1.7, 1.8, 1.9). Water levels remained unchanged (Fig. 5).

After 6 months the average plant cover had recovered to a level similar to that observed prior to treatment (Fig. 7). However, plant cover was dominated by aquatic vegetation rather than overhanging terrestrial vegetation. Watercress had proliferated and in places was restricting flow (Appendix 1.7, 1.8, 1.9). Water levels remained unchanged (Fig. 5).

4.3 WATER QUALITY

During mechanical excavation, water downstream of the digger became very turbid as sediment and fine organic matter were suspended into the water column. The only significant medium-term change in water quality variables that could be attributed to drain clearance was an increase in total phosphorus

(TP) concentrations at the mechanically-cleared site (Foots Drain) relative to that at the control site (Murrays Drain) ($t = 3.85$, $df = 5$, $p = 0.012$). Total phosphorus concentrations at these two sites were very similar prior to treatment, but concentrations were higher at Foots Drain after mechanical clearance (Fig. 8).

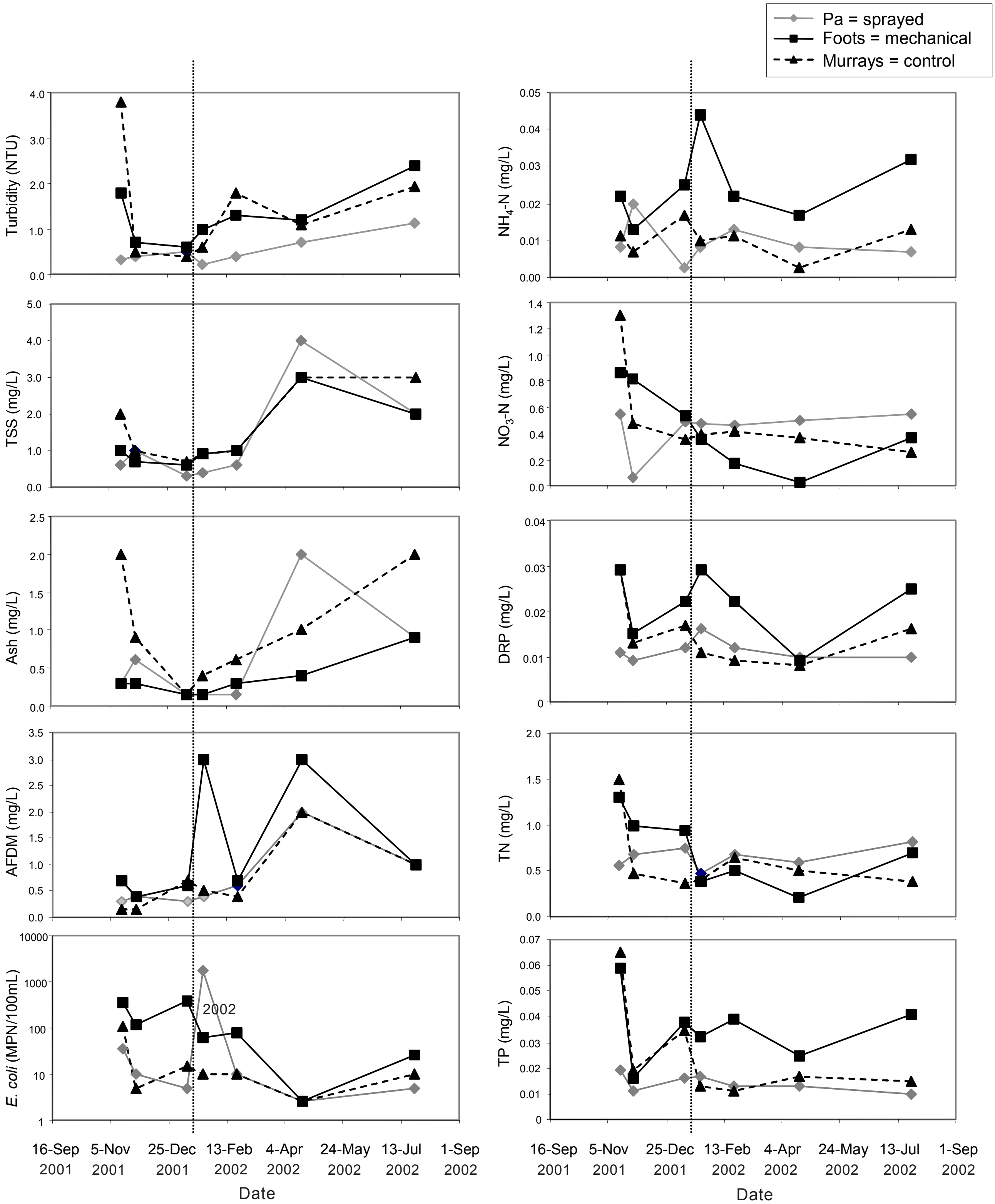


Figure 8. Changes in water quality variables over the study in the three drains. The vertical lines indicate the timing of the spraying and mechanical clearance.

Most of the water quality variables showed significant seasonal variations in all the drains, presumably in response to seasonal changes in flows, water temperatures and aquatic plant growth (Fig. 8). However, these changes were not necessarily consistent between sites. The concentration of nitrate nitrogen (NO_3-N) (r = 0.89) and total nitrogen (TN) (r = 0.76) were positively correlated with flow in Foots Drain, but were not correlated with flow in the other drains. Similarly, the concentration of dissolved reactive phosphorus (DRP) (r = -0.78) was negatively correlated with flow in Pa Drain, but not related to flow in the other drains. No other significant relationships between flow and water quality parameters were observed.

Turbidity and total suspended solids (TSS) concentrations tended to increase in all drains over the course of the study, apart from a peak in Murrays Drain in early November (Fig. 8). The increase in suspended sediment concentration was apparently due to increases in both the inorganic (ash) and organic (AFDM) fractions of suspended material (Fig. 8).

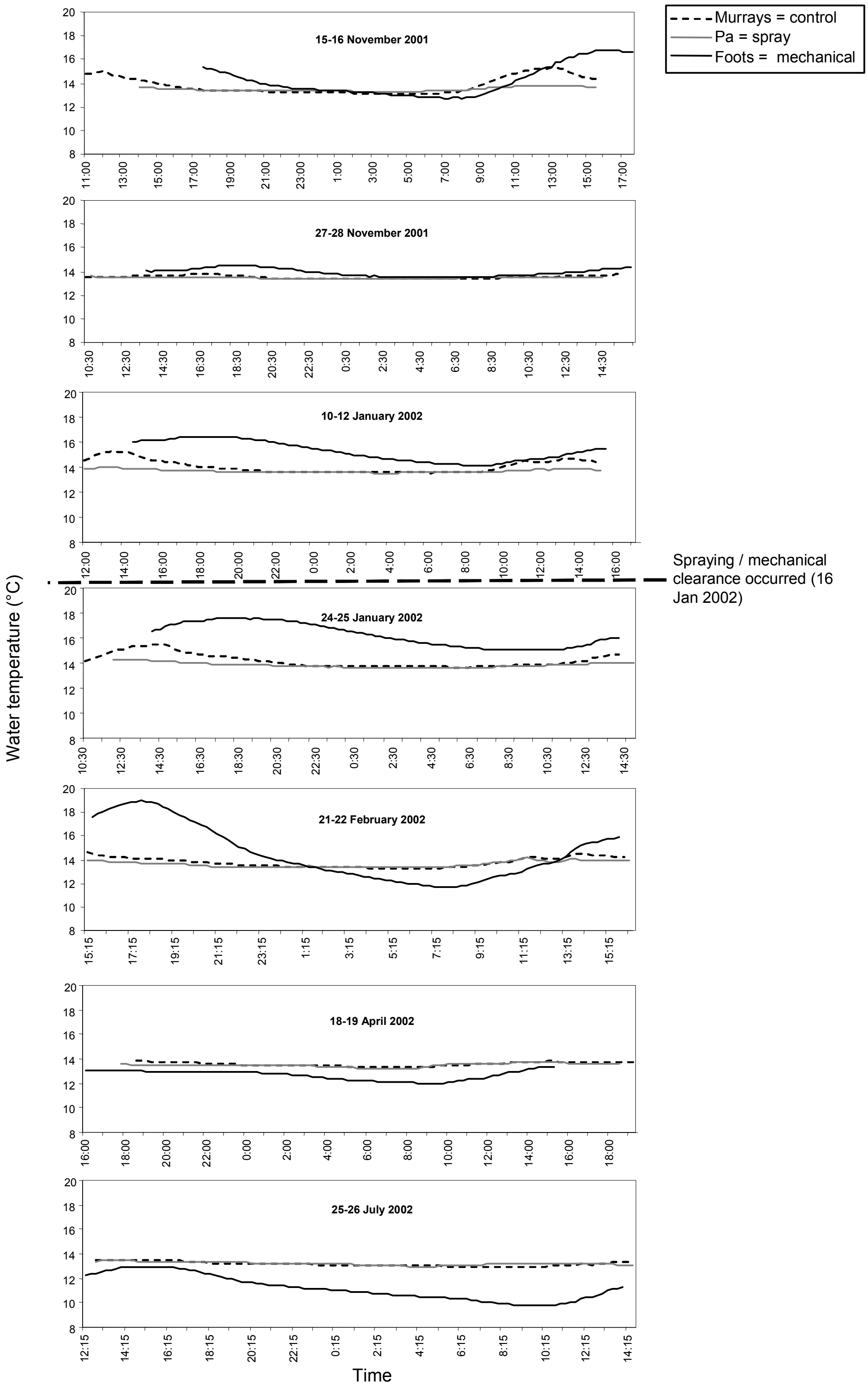
Indicator bacteria (*E. coli*) concentrations were highest at Foots Drain, apart from a sudden peak at Pa Drain in the week after spraying (Fig. 8). Apart from this peak, concentrations of indicator bacteria tended to decrease over the course of the study. Overall, concentrations were relatively low compared with other agricultural drains around the country, perhaps due to the small catchment areas and spring-fed nature of these systems.

Ammoniacal nitrogen concentrations (NH_4-N) also tended to be highest in Foots Drain, and this was particularly the case one week after mechanical clearance when levels jumped considerably. These elevated concentrations did not last long, however, and after one month were back to levels similar to those observed before drain clearance (Fig. 8). Nitrate nitrogen concentrations tended to be lower in Foots Drain after mechanical treatment (Fig. 8), probably reflecting the decreased input of nitrate-rich groundwater to this system rather than uptake during macrophyte re-establishment. Dissolved reactive phosphorus concentrations increased slightly at both Pa Drain and Foots Drain one week after spraying and mechanical clearance, but dropped back to more typical concentrations within one month. In contrast, total nitrogen concentrations at these two sites dipped slightly one week after treatment before rising again (Fig. 8).

4.4 DIURNAL PATTERNS IN TEMPERATURE AND DISSOLVED OXYGEN

The temperature of water discharging from the Wairau Aquifer is consistent at approximately 14°C (Young et al. 2000, 2002). Although water temperature can be affected by a wide range of variables, the deviation in measured temperatures from 14°C gives some indication of the strength of the connection between drain water and the aquifer. Diurnal changes in temperature were most pronounced at Foots Drain (Fig. 9), indicating that water in the drain was either not flowing directly from the aquifer into the drain, or had been in the drain for a sufficient period of time to more closely reflect variations in air temperature and solar radiation. In contrast,

Figure 9. Daily changes in water temperature at each of the sites on each sampling occasion.



temperatures at Pa Drain were consistently close to 14°C in both summer and winter, indicating a strong connection to the aquifer (Fig. 9). Water temperatures in Murrays Drain showed some daily variation until late January and then closely matched temperatures in Pa Drain (Fig. 9). It is possible that runoff and shallow groundwater made a contribution to flows until late January, after which drain flow was dominated by water coming directly from the aquifer.

Daily changes in dissolved oxygen concentration also indicated variation between drains in the strength of their connection with the aquifer. Water from the aquifer is depleted in dissolved oxygen—explaining the relatively low oxygen concentrations in Pa Drain—and is typical of spring-fed waterways throughout Marlborough (Young et al. 2002). During daytime, oxygen is released into the water by photosynthesising plants, while at night oxygen concentrations decline due to respiration by living organisms within the water. Therefore, daily changes in oxygen concentration can be used as an indicator of how much photosynthesis is occurring within waterways (Young & Huryn 1996). The daily changes in oxygen concentration in Pa Drain were very small prior to spraying and in the week after spraying. However, at the end of February there was an appreciable daily change (Fig. 10), which probably corresponded to the proliferation of algae that was observed at this site once more light was able to reach the water surface. We saw no decline in oxygen concentrations after spraying in Pa Drain that could be related to decomposition of plant material killed by the spray (Fig. 10). Daily oxygen changes in Murrays Drain were appreciable on most sampling occasions, but were largest during January (up to 25% saturation change). Of the three sites, Foots Drain had the largest daily oxygen fluctuations prior to treatment, and the fluctuations became even larger after mechanical clearance, despite the removal of considerable amounts of macrophyte biomass. This was especially the case one month after treatment when a daily change of 80% saturation was recorded. The combination of very low flow and abundant algae and macrophytes resulted in very low dissolved oxygen concentrations in Foots Drain in April, but these had recovered by July (Fig. 10).

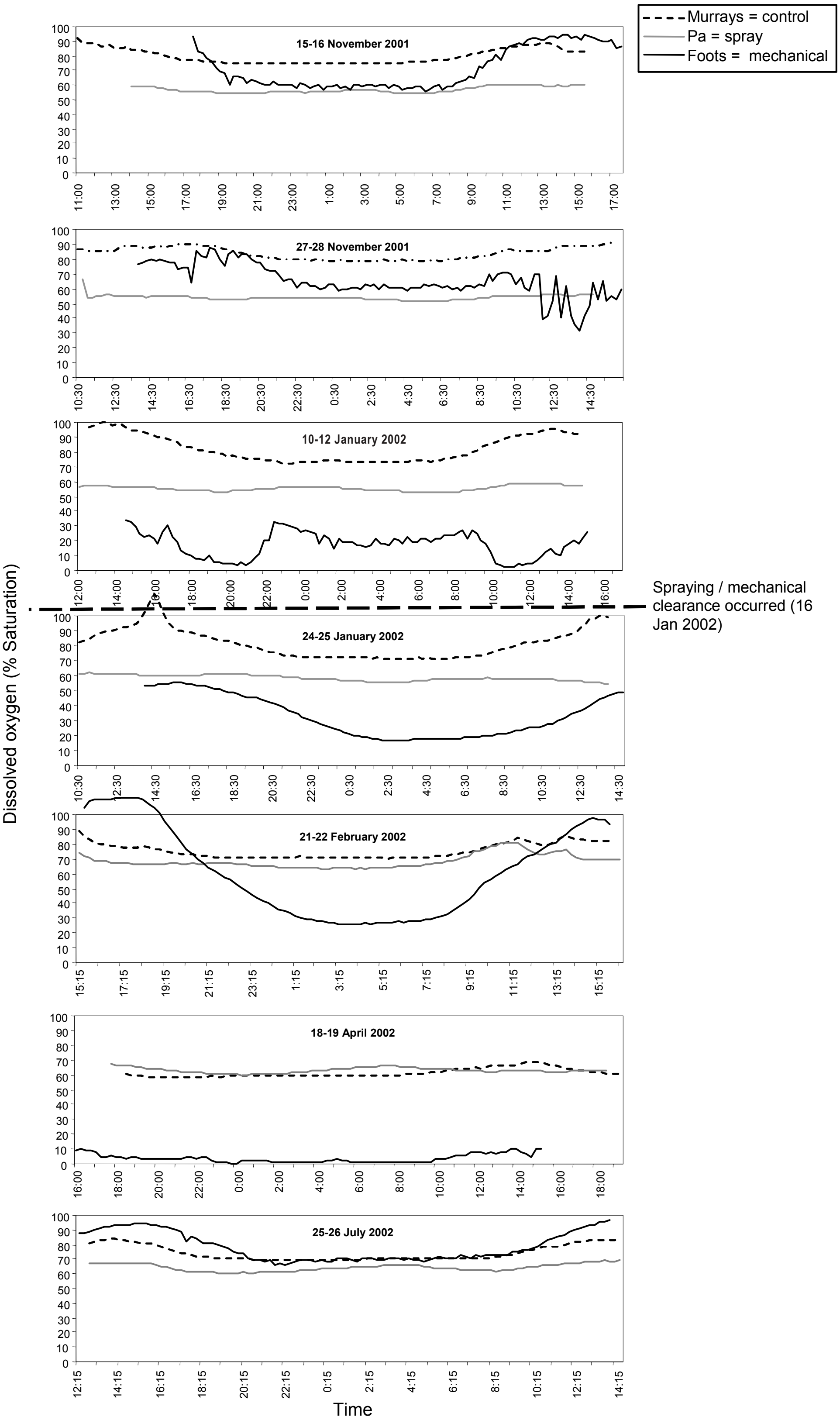
4.5 EFFECTS ON DRAIN FAUNA

4.5.1 Immediate effects of mechanical clearing

Shortfinned eels (*Anguilla australis*) were the only large aquatic fauna found in the digger spoil. Eels ranged from 9 to 60 cm in length with frequency peaks at 16–20 cm, 26–35 cm and, to a lesser degree, 41–45 cm, indicating a healthy population structure of juveniles and adults with at least 4 cohorts (Fig. 11). In total, 88 eels were found amongst the material extracted from the 290-m section of drain. Intensive sieving of a 20-m section of the spoil indicated that about 80% of eels present were evident on the surface and edges of the spoil. Therefore, assuming a discovery rate of 80% for the entire 290-m section of drain, this translates into an estimated density of 0.3–0.4 eels removed per metre of drain length. The average width of Foots Drain is about 2.5 m. Therefore, on an areal basis, the number of eels removed was between 0.12 and 0.16 eels/m^2.

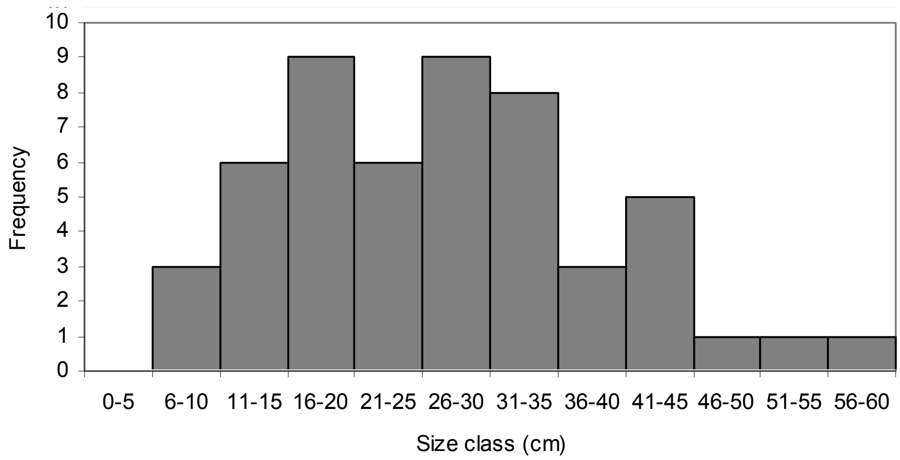
If these eels had not been collected from the digger spoil and returned to the drain, their chance of survival was likely to have been poor. Most of the eels were observed trying to make their way out of the sediments. However, unless they headed directly back to the drain they were very quickly dessicated in the hot sun. The likelihood of eels heading in the right direction was reduced by the fact that the land tended to slope away from drain rather than towards it, and most of the eels headed downhill with the water oozing out of the digger spoil, which resulted in them moving away from the drain. A few eels stayed within

Figure 10. Daily changes in dissolved oxygen at each of the sites on each sampling occasion. The abnormal oxygen record in Foots Drain on 10–12 January 2002 was probably due to sampling of still water among macrophyte beds, rather than free-flowing water.



the digger spoil, but this was likely to lead to their being starved of oxygen and cemented into the sediment as it dried out. Gulls and hawks quickly discovered the eels in and around the digger spoil and made the most of the opportunity for an easy meal. No koura were found amongst the digger spoil, but numerous small aquatic invertebrates were found. Given the limited mobility of most invertebrates, the majority of them would presumably also have perished.

Figure 11. Size-frequency plot of shortfinned eels (*Anguilla australis*) recovered from sediment piles after mechanical clearing of Foots Drain.



4.5.2 Immediate effects of diquat application

The mean density of drifting invertebrates during spraying tended to be higher than either before or after spraying (Fig. 12). However, there was considerable variation among the nets during spraying and therefore this difference was not statistically significant (ANOVA, $F = 1.395$ $p = 0.318$). Taxa that were particularly abundant in the drift during spraying included pond skaters (*Microvelia* sp.), terrestrial flies, and slugs, which live on or above the water surface and were probably hit directly with the herbicide. Drift densities of invertebrates that are truly aquatic, and thus would only experience the diluted herbicide, were very low on all occasions. Survival of drifting invertebrates collected in the nets was assessed after 96 hours and was significantly lower in samples that were collected during and after spraying than in samples collected prior to spraying (Fig. 12, G test of independence = 40.4, df = 2, $p < 0.001$). Inanga and eels were seen in the drain shortly after spraying and appeared to be behaving normally.

4.5.3 Medium-term effects on macroinvertebrates

Seventy-three invertebrate taxa were collected from the three drains over the course of the study. Fifty-eight of these were collected in core samples, with 10 found only in cores. Sixty-three taxa were collected in hand net samples, with 15 of these found only in hand nets. Foots Drain had the most diverse assemblage, with 45 invertebrate taxa, followed by Murrays Drain with 42 taxa and Pa Drain with only 38 taxa. Chironomids (*Chironomus*, Orthocladiinae, *Tanytarsus*), purse-cased caddis (*Oxyethira*), worms (Oligochaeta), snails (*Potamopyrgus, Gyraulus*), bivalves (Sphaeriidae), amphipods, and ostracods were the most abundant taxa overall.

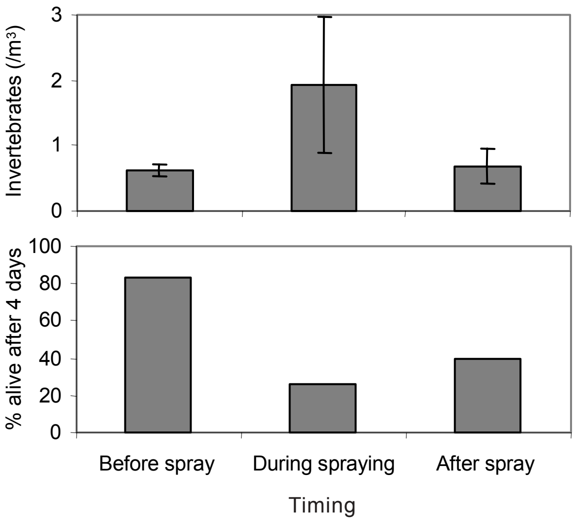


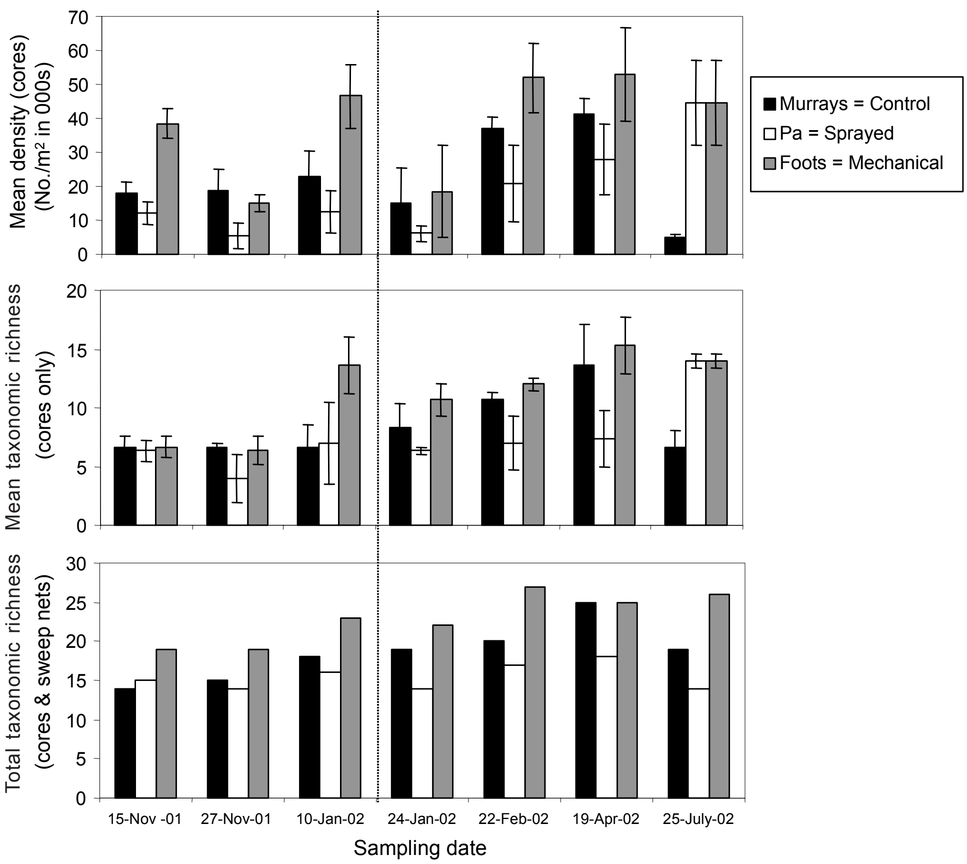
Figure 12. Mean density and survival of drifting invertebrates collected before (15 January 2002), during (16 January 2002) and after (16 January 2002) diquat spraying in Pa Drain.

Despite our best efforts to find three drains with similar characteristics, there were some significant differences among the fauna of the drains. No amphipods, koura or shrimp were collected from Foots Drain, but this was the only site where dragonflies (*Procordulia*) and *Gyraulus* snails were found. Sphaeriidae bivalves were common in Foots Drain, but rare at the other sites. The absence of koura in the study reach at Foots Drain was surprising, since they were present in Cravens Creek just 200 m downstream (Young et al. 2002). Pa Drain was the only site where shrimps (*Paratya*) were collected. No shrimps, damselflies or *Physa* snails were found at Murrays Drain. However, this was the only site with mayflies (*Austroclima, Deleatidium, Zephlebia*), stoneflies (*Megaleptoperla, Zelandobius*) and the dobsonfly (*Archichauliodes*), although none of these taxa were common.

Using the paired BACI design, the only consistent difference in the invertebrate communities over the period of the study that could be attributed to drain clearance was a decrease in total taxonomic richness (cores plus hand nets) at the sprayed site (Pa Drain) relative to that at the control site (Murrays Drain) ($t = -3.61$, $df = 5$, $p = 0.018$). Total taxonomic richness at these two sites was similar prior to treatment, but was consistently lower at the sprayed site after treatment (Fig. 13).

Mean taxonomic richness from the cores tended to increase slightly throughout the study at Murrays Drain (ANOVA, $F = 2.33$, $p = 0.09$), and significantly at Foots Drain (ANOVA, $F = 5.48$, $p = 0.004$). However, the increases at Foots Drain did not appear to be linked to mechanical removal of aquatic plants, as the most marked increase in mean taxonomic richness occurred prior to drain clearance (on 10 January 2002), after which mean taxonomic richness remained relatively constant (Fig. 13). Significant changes over the study period were also observed in the mean density of invertebrates (log transformed) at both Murrays Drain (ANOVA, $F = 4.72$, $p = 0.008$) and Foots Drain (ANOVA, $F = 3.39$, $p = 0.028$). Densities of invertebrates at Foots Drain one week after mechanical clearance were approximately half of those recorded prior to treatment, or one

Figure 13. Mean density and number of taxa collected at each site on each sampling occasion. The dotted line indicates the timing of drain treatment.



month and three months after treatment (Fishers LSD posthoc test, $p < 0.05$; Fig. 13). The most significant change in mean density at Murrays Drain was a decline in density in late July compared with those in February and March (Fig. 12). The cause of this decline is unknown.

The densities of the most abundant taxa were highly variable among sites and over time (Fig. 14). This variability masked any significant changes in densities, although the number of Sphaeriidae and worms appeared to decline by approximately 70% after mechanical clearance in Foots Drain before recovering after one month (Fig. 14).

DECORANA ordinations of macroinvertebrate communities from core and hand net samples are presented in Figs. 15 and 16, respectively. The separation of points is proportional to the relative similarity of the macroinvertebrate communities among sites and over time. Characteristic taxa (from a taxon ordination which is not shown) are plotted near the sites where they were most commonly represented. Each site occupied a relatively separate part of both ordinations, reflecting the consistent differences in macroinvertebrate communities among sites. This was particularly the case for the hand net samples, where the community in Foots Drain was quite different from that in the other two drains (Fig. 16). There was no clear shift in macroinvertebrate communities over time that could be attributed to drain treatment. Samples collected from Pa and Foots Drains after the treatment had similar positions on the ordination as samples collected prior to treatment. Inherent between-site differences in the macroinvertebrate community appeared to be larger than any effects caused by drain maintenance.

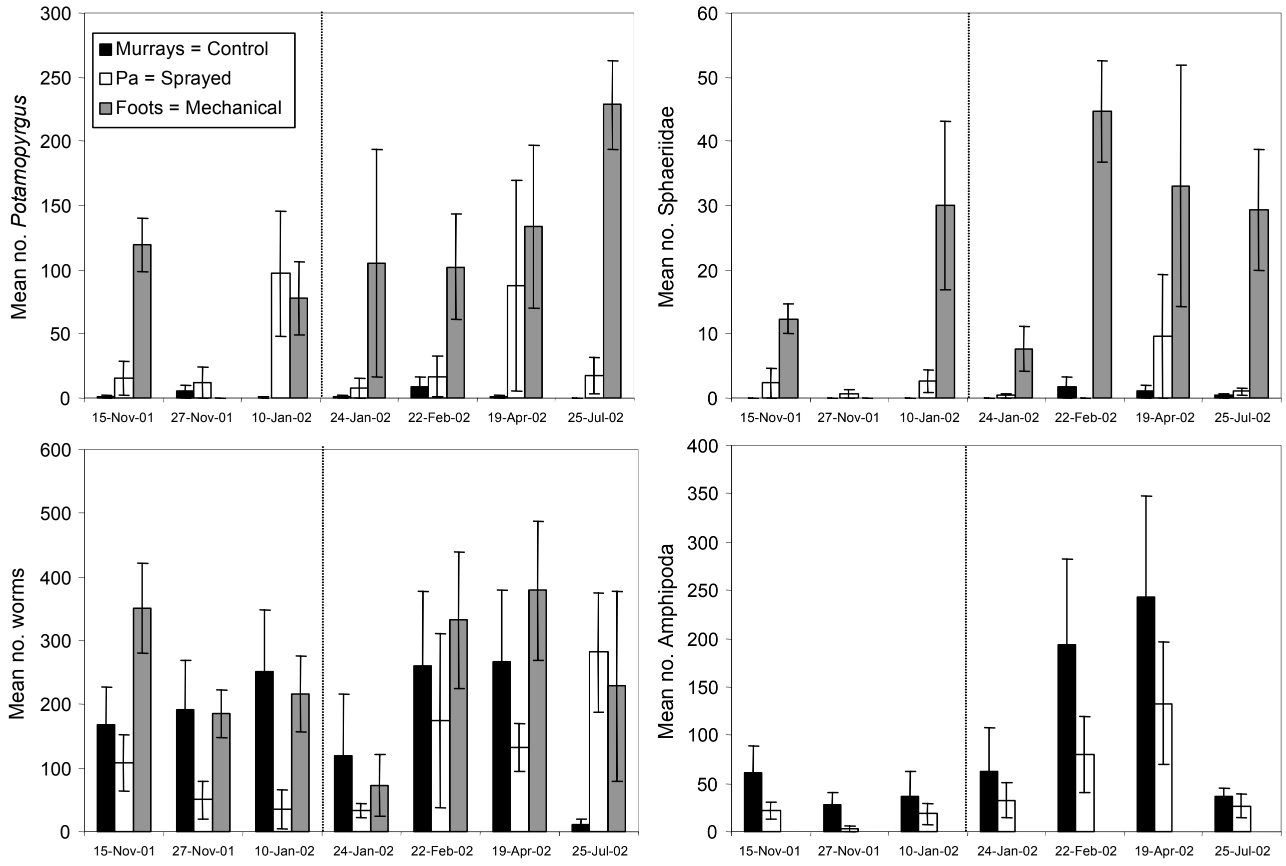


Figure 14. Mean densities of the main invertebrate groups collected in core samples at each site on each sampling occasion. The dotted line indicates the timing of drain treatment.

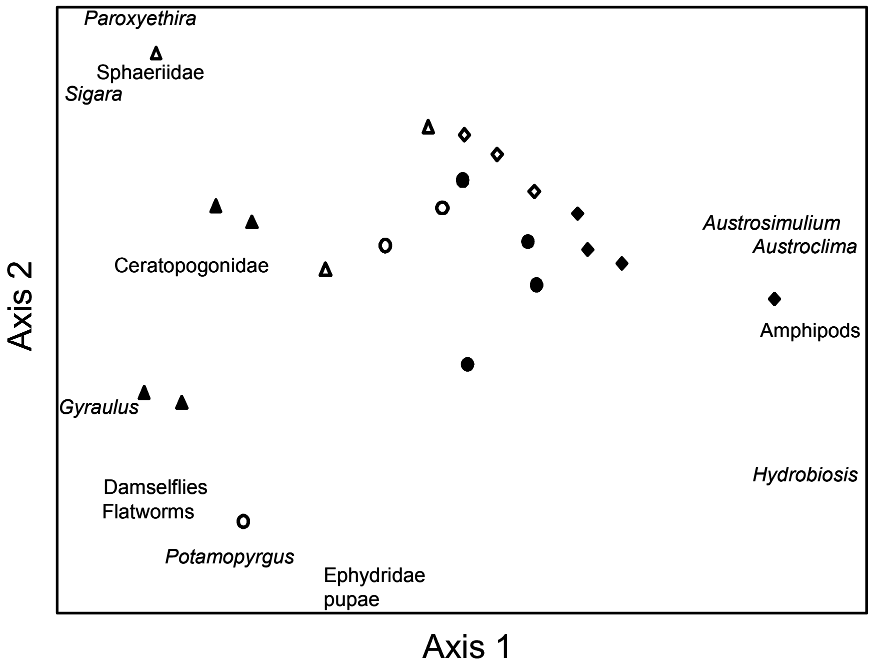


Figure 15. DECORANA ordination of invertebrate communities based on abundance from core samples at each site (▲ = mechanical. ● = spray, ◆ = control) on each occasion. Open symbols are samples taken prior to treatment, filled symbols are after treatment. Taxa shown are those that correlate most strongly with sites.

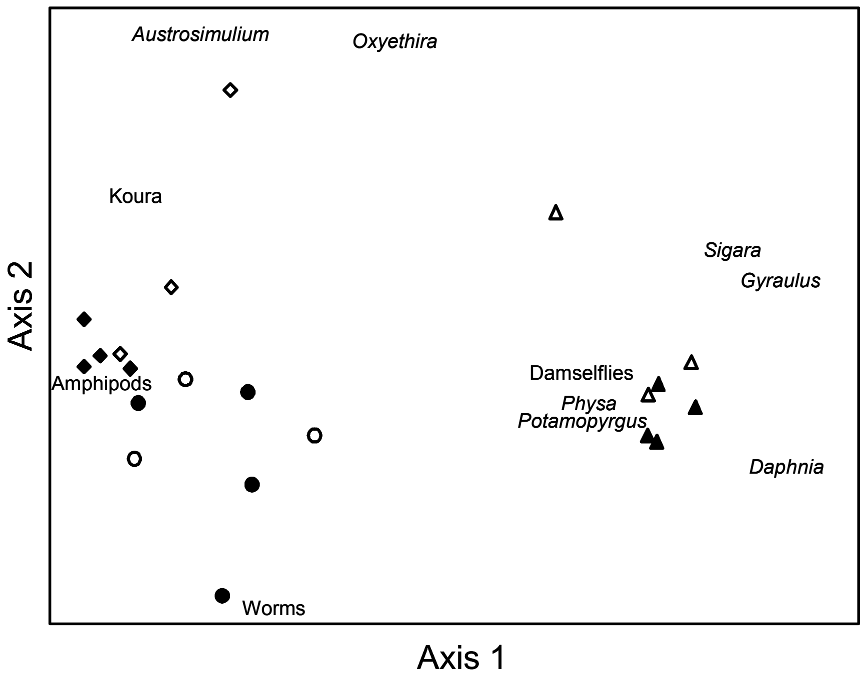


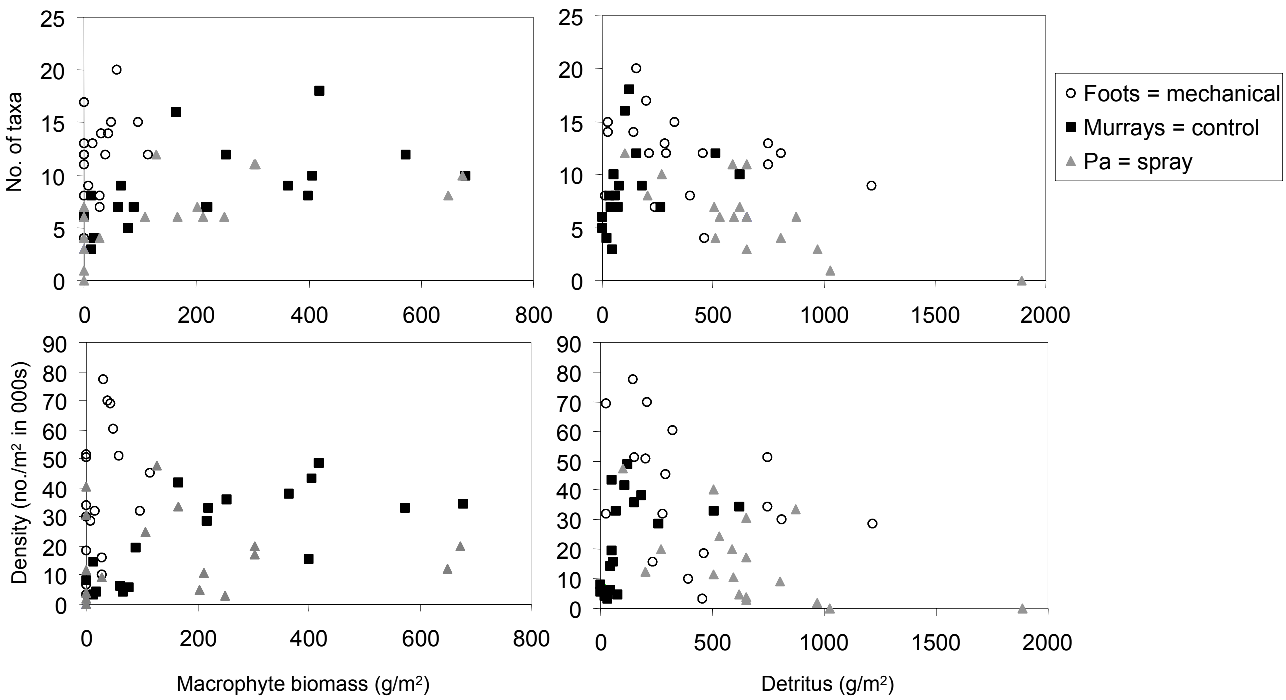
Figure 16. DECORANA ordination of invertebrate communities based on fixed counts from hand net samples. Rare taxa were entered as 0.5. Symbols correspond with those in Fig. 15. Taxa shown are those that correlate most strongly with sites.

4.5.4 Relationships between macrophyte biomass, organic detritus and invertebrates

Previous studies of lowland stream communities have shown strong relationships between aquatic plant biomass and invertebrate taxonomic richness and density (Collier et al. 1999). Similar significant correlations between aquatic plant biomass and invertebrate taxonomic richness ($r = 0.54$, $p < 0.05$) and density ($r = 0.71$, $p < 0.05$) were observed in Murrays Drain during this study (Fig. 17). There was also a significant positive relationship between aquatic plant biomass and taxonomic richness ($r = 0.61$, $p < 0.05$) in Pa Drain, but no relationship with invertebrate density (Fig. 17). No significant relationships between aquatic plant biomass and invertebrates were observed in Foots Drain (Fig. 17).

There was a considerable amount of dead plant material in some of the drains, and particularly in Pa Drain after spraying. There were strong negative correlations between detritus biomass and invertebrate taxonomic richness ($r = -0.74$, $p < 0.05$) and density ($r = -0.51$, $p < 0.05$) in Pa Drain (Fig. 17). The increase in detritus in Pa Drain after spraying may explain the significant reduction in taxonomic richness at this site compared with the control site (as discussed above).

Figure 17. Relationships between macrophyte and detritus biomass and macroinvertebrate diversity and density in each of the drains.



5. Discussion

5.1 IMMEDIATE IMPACTS OF MECHANICAL CLEARANCE

The removal of eels and invertebrates from Foots Drain was probably the most dramatic effect associated with mechanical excavation that we observed. Some eels that were removed would have returned to the drain by themselves, but the majority would not have survived. An excavator bucket was used in Foots Drain since the aim of the clearance was also to remove sediment. However, if weed clearance was the only aim, then a weed rake could be used, which may limit the removal of fauna associated with the sediment and plants (Hudson & Harding 2004).

Concern over the removal of fauna during mechanical clearance of drains has been expressed in the past (Pearson & Jones 1978; Wade 1990; Dawson et al. 1991; Serafy et al. 1994). Species that inhabit the substrate or are closely associated with aquatic plants are more likely to be affected than free-swimming species. It appears that eels are particularly susceptible to removal because of their habit of burrowing into the stream-bed sediments when disturbed. Other fish are more likely to swim away from the disturbance associated with an approaching excavator.

Large amounts of sediment and organic material were suspended in the water during mechanical clearance, making the water highly turbid downstream for several hours. The ecological effects of this sediment pulse are unknown, but presumably any effects are only temporary (Waters 1995).

5.2 IMMEDIATE IMPACTS OF HERBICIDE APPLICATION

After dilution with drain water the concentration of diquat used in Pa Drain did not appear to be sufficient to have any immediate toxic effect on aquatic invertebrates. We did not observe the large increases in the numbers of drifting invertebrates that have been observed in the past after paraquat application (Burnet 1972). The main effect of diquat appeared to be on invertebrate species living on or above the water surface. These were directly exposed to the spray and thus tended to be more abundant in drift samples collected during spraying. The undiluted spray was sufficiently toxic to reduce the survival of these invertebrates by approximately 50% after 96 hours (Fig. 12). Application of diquat to overhanging vegetation is uncommon, since glyphosate is generally preferred for bankside plants. Therefore, the effect on terrestrial invertebrates that we observed in Pa Drain may not be a widespread phenomenon.

5.3 MEDIUM-TERM IMPACTS OF MECHANICAL EXCAVATION

Mechanical clearance was very effective at immediately reducing the coverage of aquatic plants in Foots Drain. Plant recovery was steady throughout the remainder of the study, but even after 6 months plant coverage was still only about 80% of that prior to treatment (Fig. 7). Rapid regrowth of aquatic plants after mechanical clearance is well known, with some species reaching pre-harvest levels within just a few months (Wade 1990; Kaenel & Uehlinger 1998; Schwarz & Snelder 1999). However, mechanical clearance can sometimes have long-lasting effects on the physical habitat and plant community of waterways (Wade 1994). For example, recolonisation of the Boro River in Botswana was still in its early stages 8 years after clearance (Lubke et al. 1984). Vegetation clearance can also result in changes to the composition of the macrophyte community present, since it provides an opportunity for new species to invade or previously rare species to dominate (Wade 1990; Howard-Williams et al. 1996). No major change in species composition was observed in Foots Drain, with *Nitella* sp. and *Potamogeton crispus* dominating the plant community before and after treatment. In a Waikato drain, the density of *Potamogeton* had recovered to pre-treatment levels six months after mechanical clearance, but willow weed (*Persicaria*) had not recovered (Wilcock et al. 1998).

After mechanical clearance, total phosphorus concentrations were significantly higher in Foots Drain relative to the control (Murrays Drain). The consistent difference in total phosphorus concentration may be due to reduced uptake by aquatic plants, and / or effects of physical disturbance by the excavator mobilising phosphorus-rich sediments (Wade 1990). It is also possible that the decline in groundwater input at Foots Drain may be responsible for this change. The short-term increases in ammoniacal nitrogen and dissolved reactive phosphorus concentrations seen one week after treatment in Foots Drain can be attributed to mechanical clearance and probably are also linked with reduced uptake by aquatic plants and / or mobilisation from the sediments.

Excessive growth of aquatic plants can lead to large diel fluctuations in dissolved oxygen concentrations and low oxygen minima around dawn (Simonsen & Harremoës 1978; Wilcock et al. 1995; Kaenel et al. 2000; Young et al. 2000). Consequently, macrophyte removal has been suggested as a technique to reduce these daily variations and increase daily oxygen minima. There are two potential mechanisms for improvement in dissolved oxygen concentrations with macrophyte removal: a reduction in the respiratory demands resulting from the removal of a large amount of plant biomass, and an increase in the transfer of oxygen through the stream surface due to decreased stream depth and increased velocity after macrophyte removal (Wilcock et al. 1999; Kaenel et al. 2000). However, the effectiveness of such a strategy appears to be limited. Wilcock et al. (1999) showed that there was some improvement in oxygen transfer through the surface of a Waikato stream after macrophyte removal due to a reduction in stream depth, but to some extent this improvement was offset by a reduction in small-scale turbulence around macrophyte beds. Kaenel et al. (2000) studied two Swiss streams and found that oxygen demand was unchanged after macrophyte removal in one stream, and reduced for only two weeks after clearance in the second stream. We observed a similar result in this study with high daily dissolved oxygen fluctuations in Foots Drain one month after mechanical clearance, although changes in flow, rather than changes in oxygen demand, may have been responsible for this observation.

Invertebrate density one week after mechanical clearance was approximately half of that recorded in Foots Drain prior to treatment. However, invertebrate densities had recovered to pre-treatment levels within one month. Similar results were found by Pearson & Jones (1978), who recorded decreased numbers of invertebrates three days after mechanical clearance in an English chalk stream, whereas Armitage et al. (1994) found no significant decrease in invertebrate densities two and seven weeks after macrophyte cutting in similar stream systems. Kaenel et al. (1998) found that invertebrate densities were reduced by approximately 65% after mechanical clearance in two Swiss streams, with recovery taking 4–6 months. They also considered that the effects of macrophyte removal on invertebrates may be seasonally dependent, with more substantial effects in the stream cleared in spring than in the one cleared in summer. A more marked effect of mechanical clearance was reported by Monahan & Caffrey (1996), who found considerable reductions in invertebrate densities after weed removal from an Irish canal and that recovery took 8–11 months.

We found that invertebrate taxa associated with sediments (Sphaeriidae and Oligochaeta) appeared to be most susceptible to mechanical clearance, although there was no apparent reduction in the density of snails (*Potamopyrgus*). In contrast, Kaenel et al. (1998) found that invertebrates associated with plants were more susceptible than either highly mobile taxa or taxa living within the sediments. However, their results presumably are related to the fact that macrophytes were removed by cutting in their study so that the sediments were not disturbed to the same extent as in our study. Taxonomic richness was not reduced by mechanical clearance in our study, and to our knowledge effects on taxonomic richness have not been reported elsewhere.

5.4 MEDIUM-TERM IMPACTS OF DIQUAT APPLICATION

The effects of the herbicide spray on aquatic and overhanging bank-side plants were obvious in Pa Drain one week after treatment. However, the coverage of water that these plants provided was not reduced until one month after treatment when they began to collapse into the drain, letting more light onto the water surface. From then on, filamentous algae and watercress proliferated, resulting in an increase in plant cover back to pre-treatment levels within six months. The plant species providing this cover, however, were substantially different from those providing it prior to herbicide application.

An increase in oxygen demand associated with decaying vegetation is regarded as the main indirect effect of herbicide application, potentially leading to death of fauna from the resulting low oxygen concentrations (Brooker & Edwards 1975; Murphy & Barrett 1990). However, a decrease in oxygen concentration was not observed in Pa Drain in the six-month period following spraying. The magnitude of any deoxygenation after herbicide application depends on water temperature, turnover rate of the water column, macrophyte biomass and nitrogen content, and rates of external oxygen inputs (Murphy & Barrett 1990). The water temperature in Pa Drain was consistently cool because of substantial groundwater input, thus restricting decay rates. Turnover of the water column and diffusion of oxygen through the water surface was also relatively high in Pa Drain because of its moderate flow and shallow depth in comparison with lakes and large deep canals where deoxygenation has been observed previously (Brooker & Edwards 1973; Murphy et al. 1981). The heavy cover of riparian weeds and grasses prior to spraying in Pa Drain also resulted in a relatively low biomass of the soft aquatic plants that have the potential to decay quickly.

A slight increase in dissolved reactive phosphorus concentration was observed one week after spraying in Pa Drain, and along with the increased light getting to the water surface, may explain the filamentous algae proliferation after spraying. Stimulation of surface-floating macrophytes like *Lemna* by release of nutrients from decaying plant material has been reported previously and growth of these can lead to shading of any remaining submerged macrophytes, thus minimising oxygen production in the water beneath the mat for a considerable period after treatment (Murphy et al. 1981).

A multitude of laboratory studies have been conducted on the toxicity of a variety of herbicides for different species of invertebrates and fish (Murphy & Barrett 1990; ANZECC 2000). However, field studies have shown that medium-term changes in invertebrate communities following herbicide application at approved concentrations are generally the result of indirect effects associated with the death and destruction of aquatic plants, rather than direct toxic effects (Brooker & Edwards 1974). We found a thick coverage of organic detritus in Pa

Drain, particularly after herbicide application. There was also a significant negative relationship between detritus biomass and species richness in the core samples from Pa Drain. Therefore, the increase in detritus after spraying may have been responsible for the significant decline in species richness, relative to the control, that we observed in Pa Drain after spraying.

5.5 ARE THESE RESULTS APPLICABLE TO OTHER DRAINS?

This study concentrated on just three spring-fed drains in Marlborough. Recent data from a survey of water quality and ecological values of 34 spring-fed drains in Marlborough (Young et al. 2002) indicated that the three sites used in this study are typical of many spring-fed waterways found in that region. However, spring-fed drains are quite different from other types of drains and are uncommon in many areas of the country. Therefore, results from this study will not necessarily apply in other regions, or in other types of drains. Many replicates of different types of drains from throughout the country would be required to fully assess the relative efficacy and impacts of herbicides and mechanical clearance. Nevertheless, the results of this study, combined with the findings of earlier work in New Zealand and elsewhere, cover many of the effects that are likely to occur in any type of drain. Any future studies of the impacts of drain maintenance activities could use similar methods to those described here, so that the validity of extrapolating these results to other areas of the country and other types of drains could be determined.

5.6 CONSIDERATIONS FOR DRAIN MANAGEMENT ARISING FROM THIS STUDY

1. Significant numbers of eels living within drains are likely to be removed by mechanical clearance using buckets. The use of weed rakes, rather than buckets, has the potential to limit this effect and rakes should be used wherever possible. Placement of digger spoil close to the waterway (and preferably on an area sloping towards the drain) may assist eels and other aquatic organisms to return to the drain. However, some investigation of the feasibility of manually returning eels (and other large fauna such as koura) to drains following mechanical removal of aquatic plants and sediment could be carried out. It cannot be assumed that eels and other animals will make their own way back to the drain. A substantial number of eels can be collected from digger spoil in a short time and returned to the drain. Unfortunately, dealing with the small invertebrates removed with the digger spoil in this way is impractical.
2. Although we did not observe low oxygen concentrations in this study, oxygen depletion associated with the decay of sprayed vegetation can occur and has the potential to kill organisms living within drains. However, this will only be a problem in drains that are particularly deep and slow flowing, relatively warm, and have a large biomass of aquatic plants. Biota present in such drains may be tolerant of large daily changes in oxygen concentrations resulting from

daily fluctuations in photosynthesis and thus be relatively tolerant of low oxygen levels. Nevertheless, if oxygen depletion is likely to occur, then it would be advisable to only apply herbicides to small sections or a portion of a drain at a time.

3. Recovery of fish and invertebrate populations from mechanical clearance is dependent on the amount of habitat disturbance, but will occur more quickly if sources for recolonisation are available nearby. Clearance of small sections or a portion of a drain at any one time would ensure that recovery takes place as fast as possible. However, partial drain clearance may also allow rapid recovery of aquatic plants, thus requiring more regular drain maintenance. An assessment of the costs and benefits of partial clearance is required to determine if any ecological benefits of partial clearance are outweighed by economic costs associated with more regular clearance.
4. Removal of one type of vegetation may result in the proliferation of other types that may be equal or more serious threats to drainage. In this study, the dense canopy of bankside plants in some parts of Pa Drain before diquat application was actually controlling aquatic plant growth in some sections of the drain and maintaining a relatively clear waterway. However, once the overhanging vegetation was removed, in-stream plants such as watercress and filamentous algae flourished. This response could be a particular problem if the aim of drain clearance is to reduce water levels.

5.7 COSTS AND BENEFITS OF DRAIN MANAGEMENT

By maintaining hydraulic efficiency and lowering water levels, drain maintenance potentially enables considerable economic benefits associated with improved production on surrounding land. There may also be ecological benefits associated with control of noxious plant species and habitat modification that may increase habitat suitability for some species (Hudson & Harding 2004). However, drain maintenance also has economic and environmental costs that need to be balanced against the benefits. Herbicide application is generally the cheapest option for drain maintenance (Hudson & Harding 2004), with the cost per linear metre of treated drain in Marlborough estimated to average $0.22 (Bezar 2002). Mechanical excavation of drains is generally more expensive, with an average cost in Marlborough of $2.01 per linear metre of treated drain (Bezar 2002), although the cost is highly dependent on any need for disposal of spoil if it is not left along the drain margin. Ecological costs are more difficult to quantify, but this study suggests that one of the main concerns related to drain maintenance is eel removal during mechanical clearance. Drains often have high densities of eels and may contribute a significant proportion of New Zealand's eel stocks. Concerns have recently been raised about declines in New Zealand's eel stocks, and particularly of longfinned eels (*Anguilla dieffenbachii*) (Jellyman et al. 2000). Rare fish, such as giant kokopu (*Galaxias argenteus*), are also found in drains. Therefore, efforts to avoid losses of eels and other fish during drain maintenance could potentially improve eel fisheries, increase the number of eels that reach maturity and maintain populations of rare fish. These efforts would, however, add some extra economic costs to drain maintenance. The decline in invertebrate density related to mechanical excavation that we observed appeared to be a relatively short-term effect, although the reduction in invertebrate diversity related to diquat application was more persistent. The invertebrate taxa that we found in the drains are commonly found elsewhere. Therefore, any decline in their densities does not constitute a direct threat to biodiversity. Nevertheless, invertebrates constitute an important part of the food chain and have intrinsic values themselves. The balance between the costs and benefits of drain maintenance will probably differ among drains depending on the ecological values and hydraulic efficiency requirements at each site. Many councils already classify their drains according to the ecological values present, and future efforts at classifying the different types of drains found throughout the country may further help this balancing process.

6. Acknowledgements

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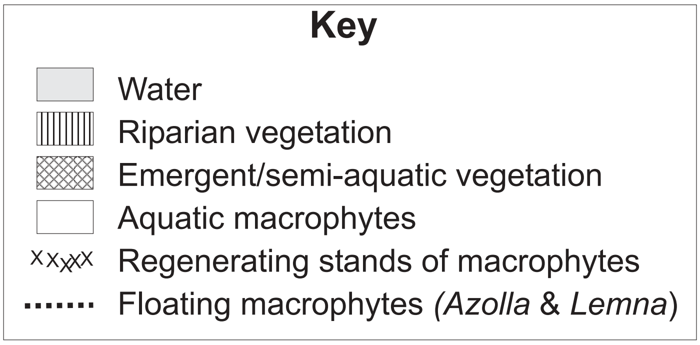
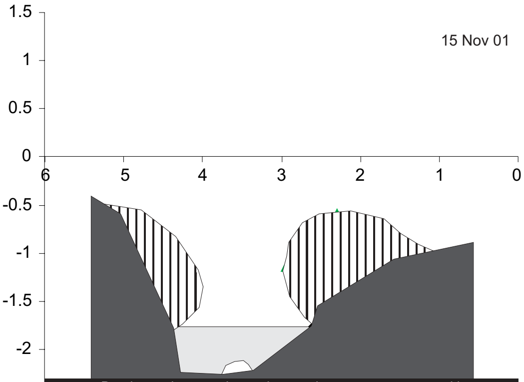
Appendix 1

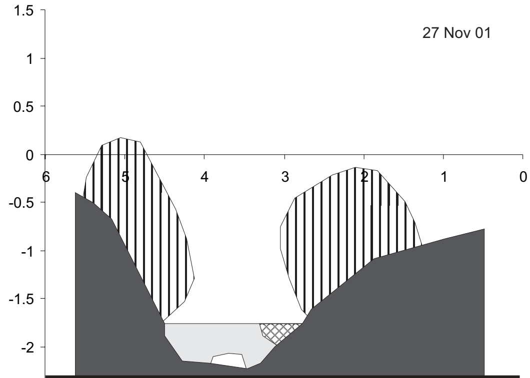
CROSS SECTION AND COVER CLASS PLOTS AT EACH SITE ON EACH SAMPLING OCCASION



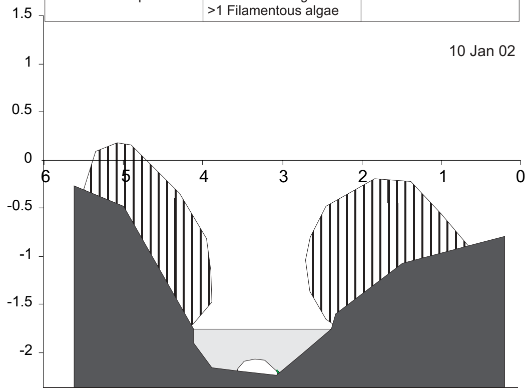
Appendix 1.1—Murrays Drain 12.5 m



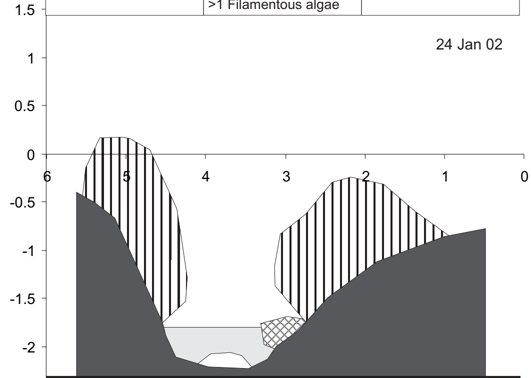
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	95 *Elodea canadensis* 4 *Callitriche stagnalis* >1 Filamentous algae	95 Terrestrial grasses



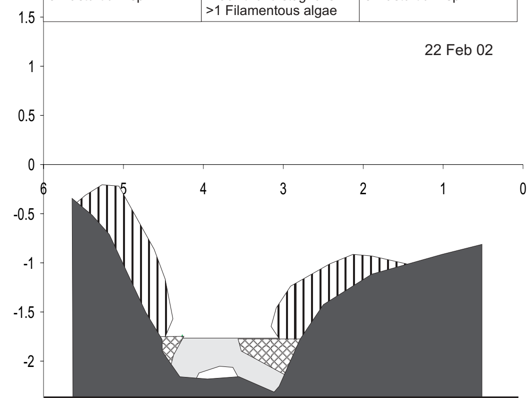
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Terrestrial grasses	94 *Elodea canadensis* 5 *Callitriche stagnalis* >1 Filamentous algae	95 Terrestrial grasses



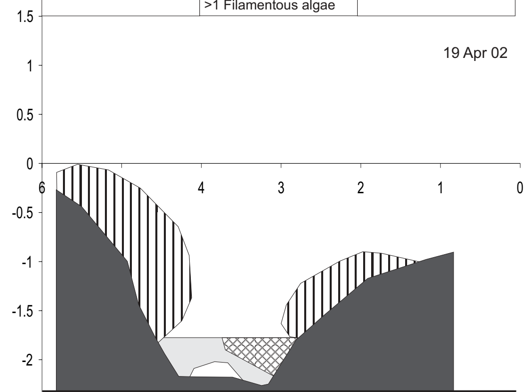
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	95 *Elodea canadensis* 4 *Callitriche stagnalis* >1 Filamentous algae	95 Terrestrial grasses 5 *Nasturtium* sp.



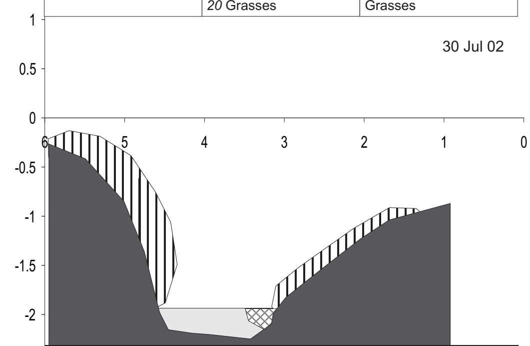
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	95 *Elodea canadensis* 4 *Callitriche stagnalis* >1 Filamentous algae	95 Terrestrial grasses



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	45 *Elodea canadensis* *35 Nasturtium* sp. *20* Grasses	95 Terrestrial grasses 5 *Nasturtium* sp. Grasses

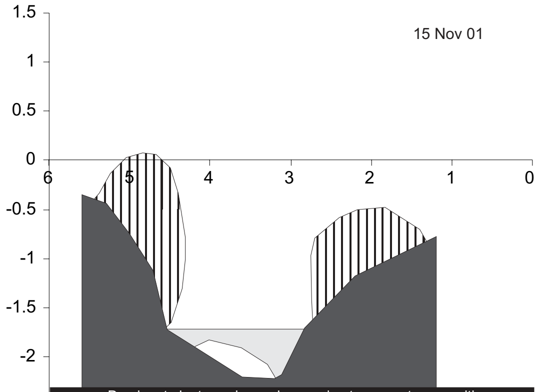


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	45 *Elodea canadensis* *35 Nasturtium* sp. *20* Grasses	95 Terrestrial grasses

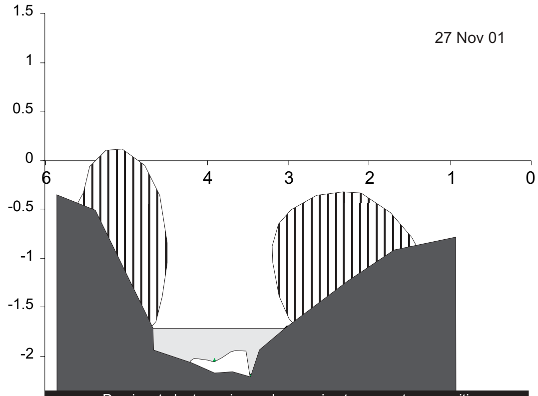


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
95 Terrestrial grasses 5 *Nasturtium* sp.	10 *Elodea canadensis* 2 *Callitriche stagnalis*	90 Dry leaf litter 5 Terrestrial grasses

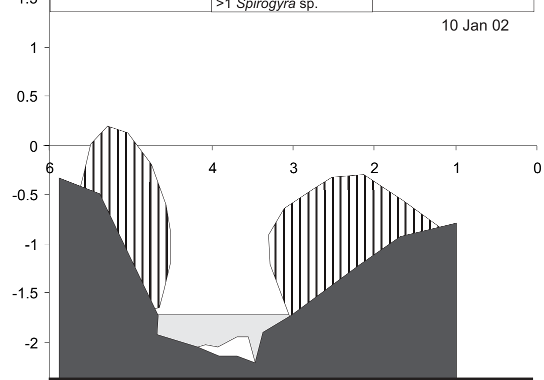
Appendix 1.2—Murrays Drain 25 m



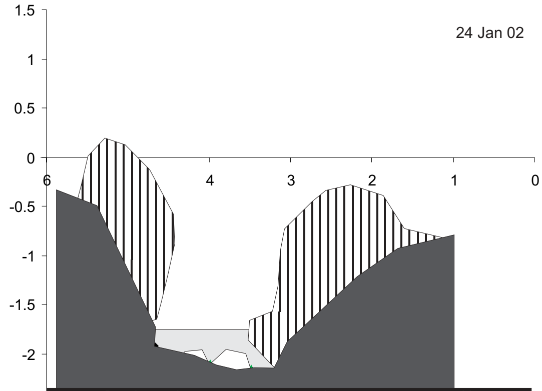
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses 5 *A. sanguisorbae* Sweet pea	80 *Elodea canadensis* 10 *Nasturtium* sp. 5 *Callitriche stagnalis* >1 *Spirogyra* sp.	95 Terrestrial grasses



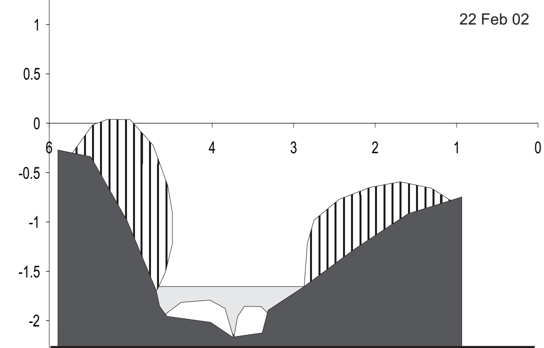
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



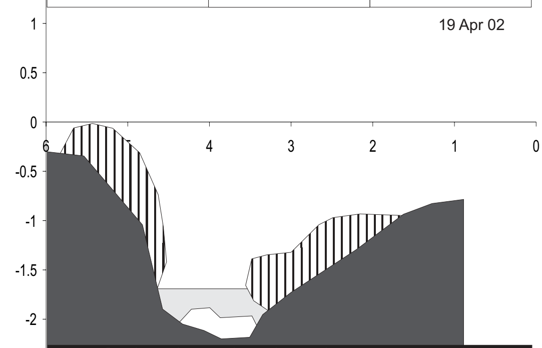
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



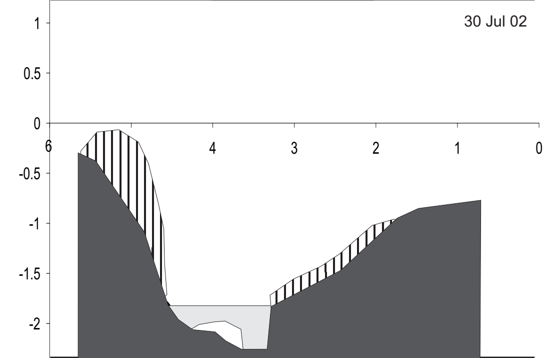
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Largely unchanged *Nasturtium* spreading	Largely unchanged,



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	*Elodea* thickening	Largely unchanged, grasses dying back

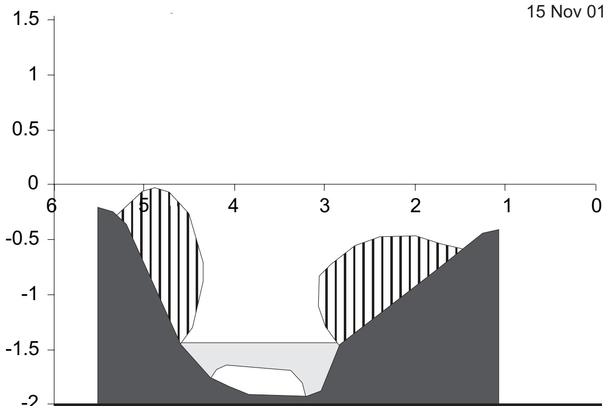


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Tall grasses dying back	Largely unchanged *Nasturtium* spreading	Grasses dying back

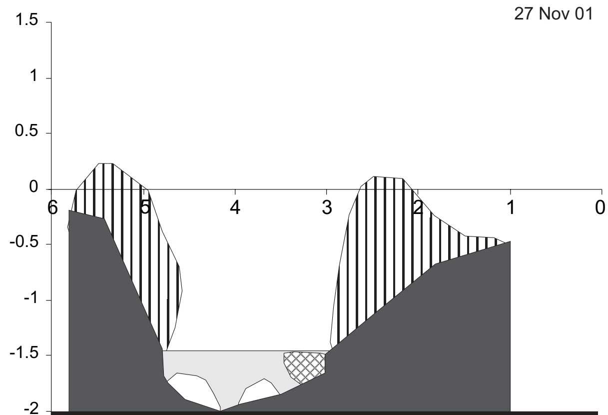


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Grasses died back	*Elodea* bed less dense and smaller	Grasses covered with layer of dry leaves

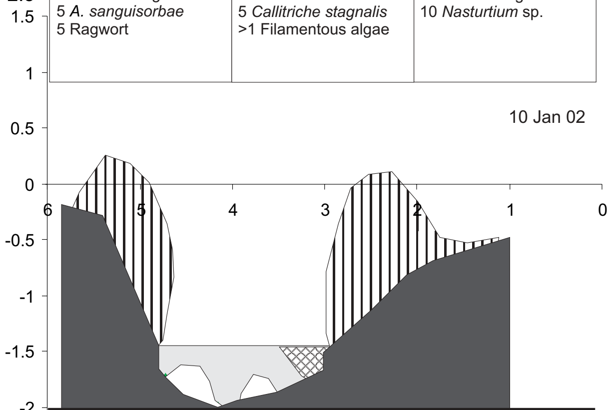
Appendix 1.3—Murrays Drain 37.5 m



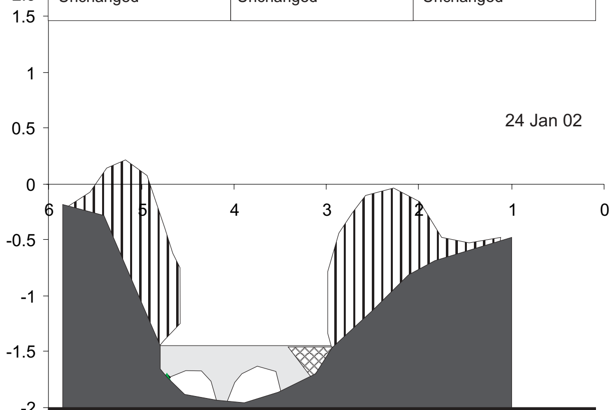
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
80 Terrestrial grasses 5 *A. sanguisorbae* 5 Ragwort	95 *Elodea canadensis* 5 *Callitriche stagnalis* >1 Filamentous algae	90 Terrestrial grasses 10 *Nasturtium* sp.



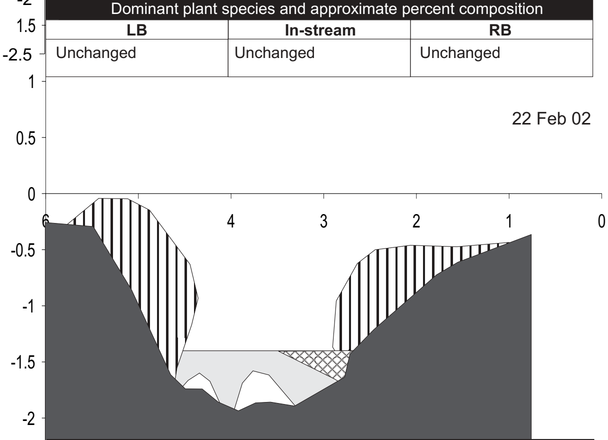
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



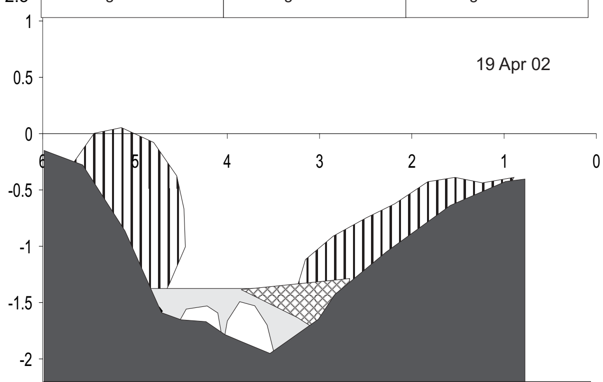
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



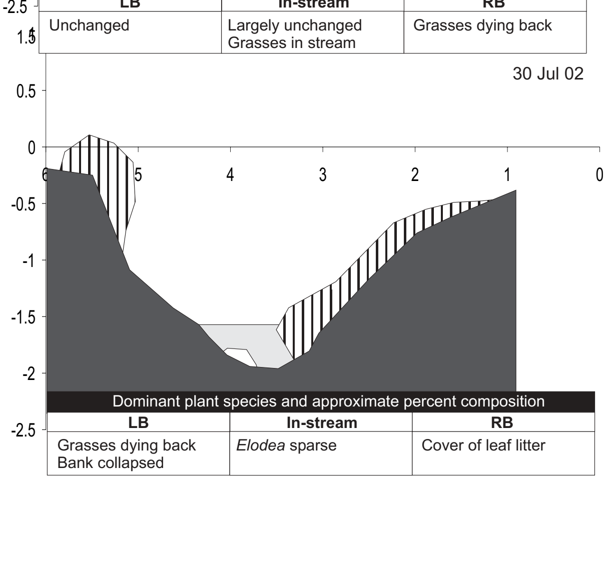
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Largely unchanged Grasses in stream	Grasses dying back

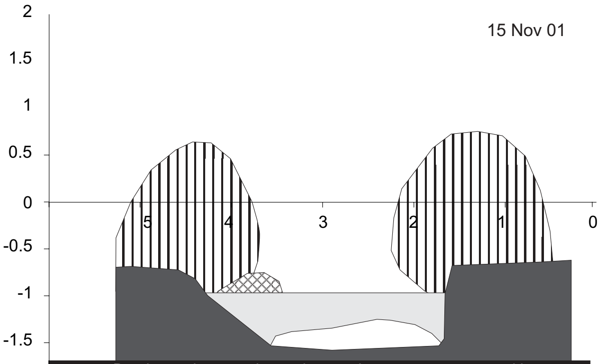


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Grasses & *Nasturtium* continuing to encroach	More die back

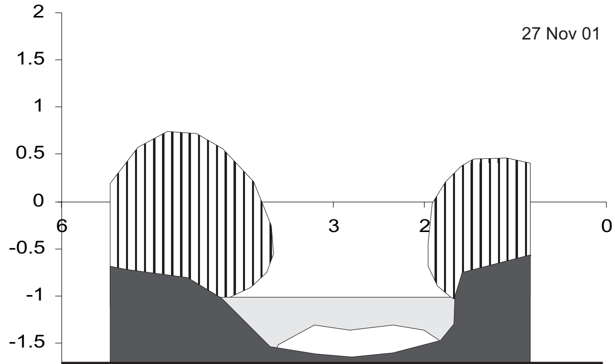


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Grasses dying back Bank collapsed	*Elodea* sparse	Cover of leaf litter

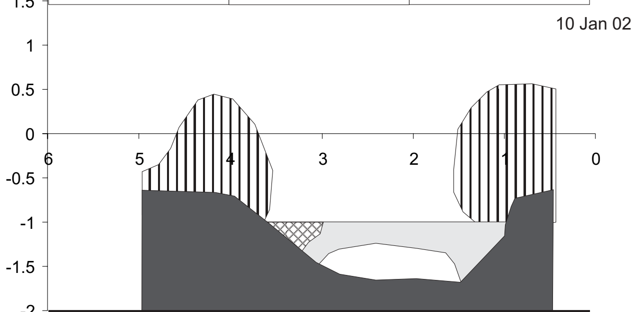
Appendix 1.4—Foots Drain 25 m



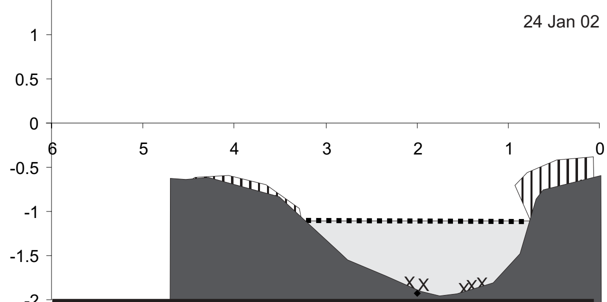
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses Cutty grass Clover *A. sanguisorbae*	95 *Nitella* sp. 5 *Vauscheria* sp. >1 *Lemna minor*	95 Terrestrial grasses 5 Thistle *A. Sanguisorbae*



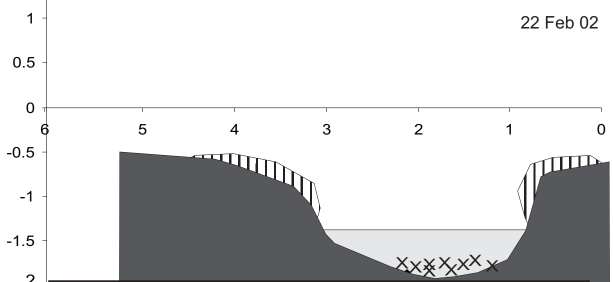
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses Cutty grass Clover *A. sanguisorbae*	95 *Nitella* sp. 5 *Vauscheria* sp. >1 *Lemna minor*	95 Terrestrial grasses 5 Thistle *A. sanguisorbae*



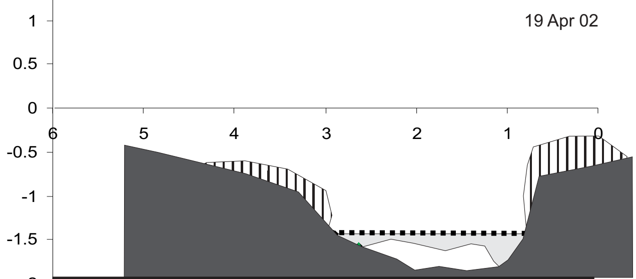
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	*Lemna* sparse Otherwise unchanged	Unchanged



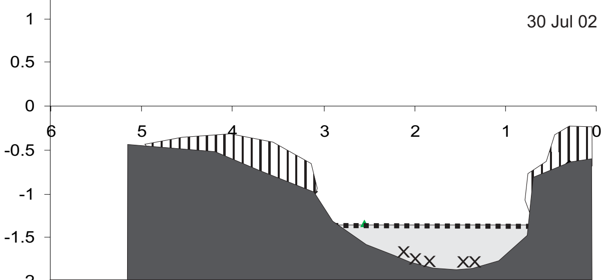
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses Cutty grass Clover *A. sanguisorbae*	20 *Nitella* sp. (sparse) 0-100 *Lemna minor*	95 Terrestrial grasses 5 Thistle *A. sanguisorbae*



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Terrestrial grasses growing through mud	50 *Nitella* sp. 20 *Lemna minor*	Terrestrial grasses growing through mud

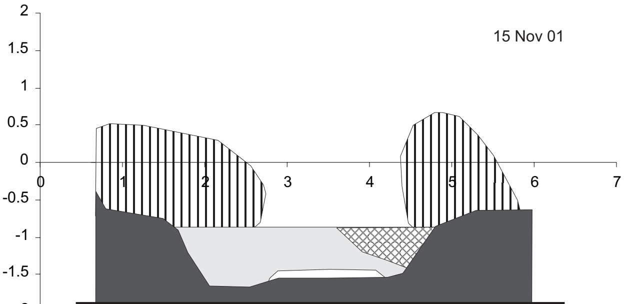


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Terrestrial grasses regrowing	70 *Nitella* sp. (re-established) 80-100 *Lemna minor*	Terrestrial grasses regrowing

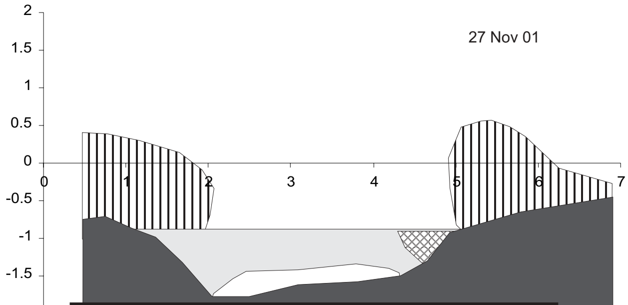


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses Cutty grass Clover *A. sanguisorbae*	0-20 *Nitella* sp. (Sparse) 100 *Lemna minor*	Terrestrial grasses (re-established)

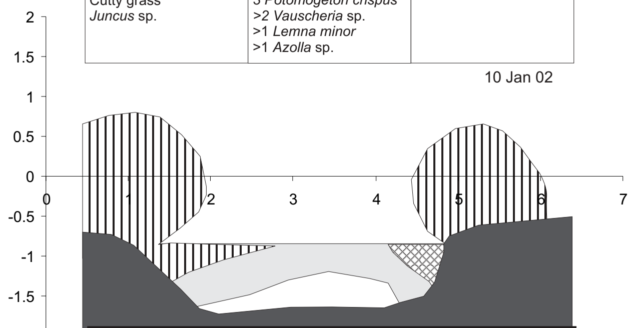
Appendix 1.5—Foots Drain 50 m



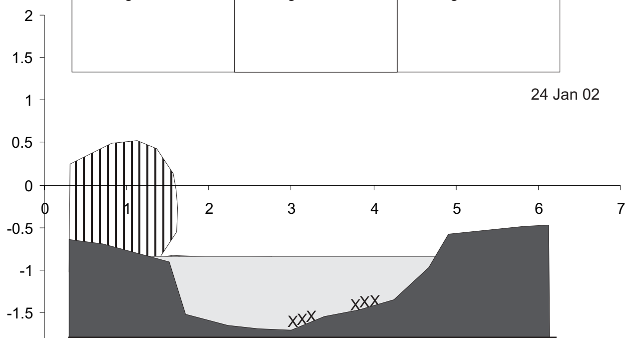
Dominant plant species and approximate percent composition		
LB	In-stream	RB
90 Terrestrial grasses Cutty grass *Juncus* sp.	95 *Nitella* sp. *3 Potomogeton crispus* >2 *Vauscheria* sp. >1 *Lemna minor* >1 *Azolla* sp.	95 Terrestrial grasses



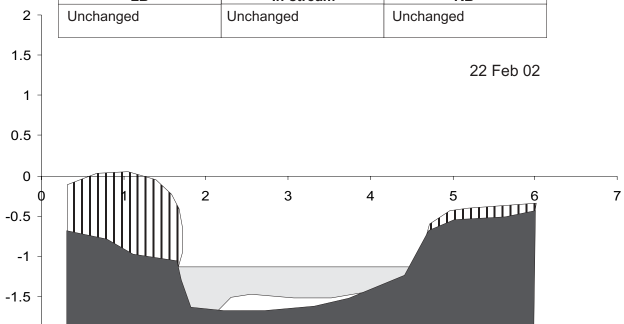
Dominant plant species and approximate percent composition		
LB	In-stream	RB
Unchanged	Unchanged	Unchanged



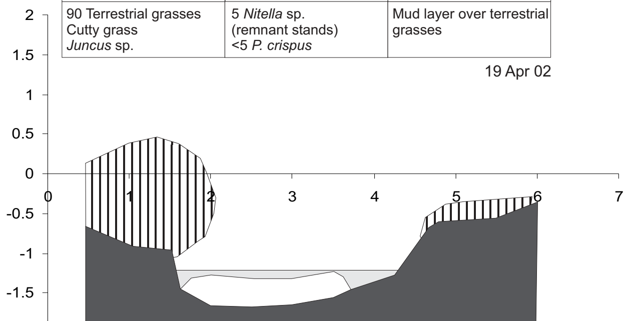
Dominant plant species and approximate percent composition		
LB	In-stream	RB
Unchanged	Unchanged	Unchanged



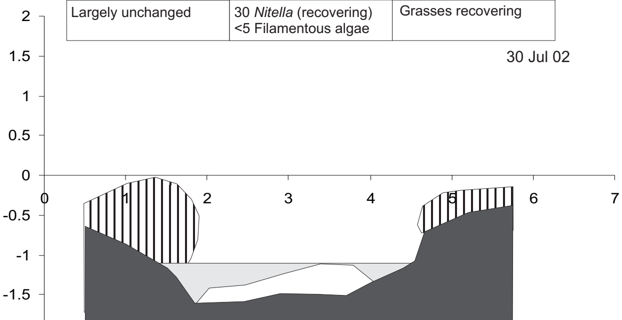
Dominant plant species and approximate percent composition		
LB	In-stream	RB
90 Terrestrial grasses Cutty grass *Juncus* sp.	5 *Nitella* sp. (remnant stands) <5 *P. crispus*	Mud layer over terrestrial grasses



Dominant plant species and approximate percent composition		
LB	In-stream	RB
Largely unchanged	30 *Nitella* (recovering) <5 Filamentous algae	Grasses recovering

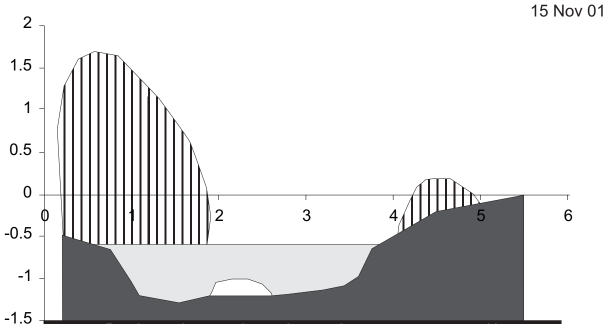


Dominant plant species and approximate percent composition		
LB	In-stream	RB
Unchanged	40 *Nitella* sp. *<5 P. crispus*	Grasses re-establishing

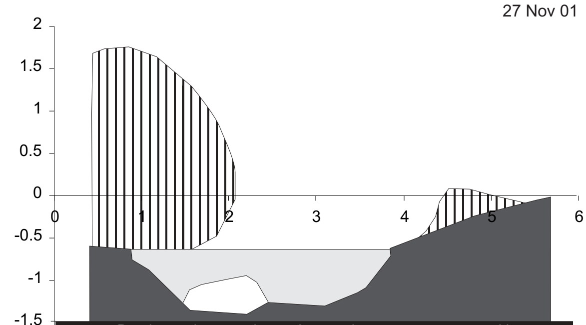


Dominant plant species and approximate percent composition		
LB	In-stream	RB
Largely unchanged	80 *Nitella* sp. 5-10 *P. crispus*	Grasses established

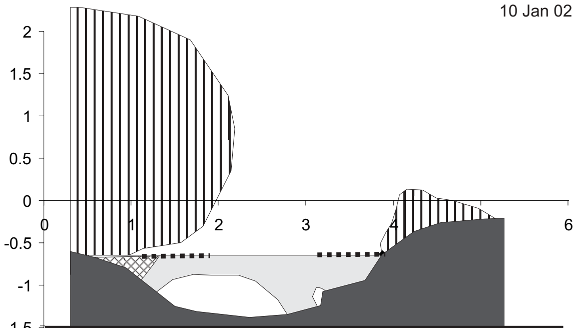
Appendix 1.6—Foots Drain 75 m



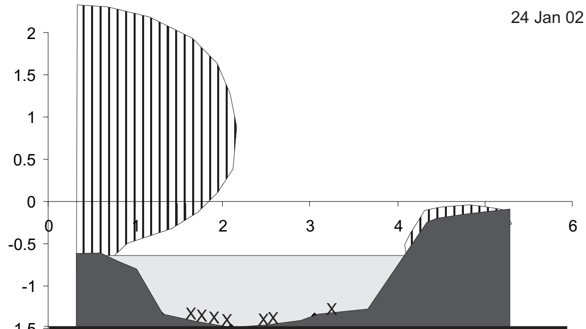
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Large trees 90 *Phormium tenax* 5 Cutty grass <5 *Juncus* sp.	95 *Nitella* sp. >2 *Vauscheria* sp. >1 *Lemna minor* >1 *Azolla* sp.	95 Terrestrial grasses



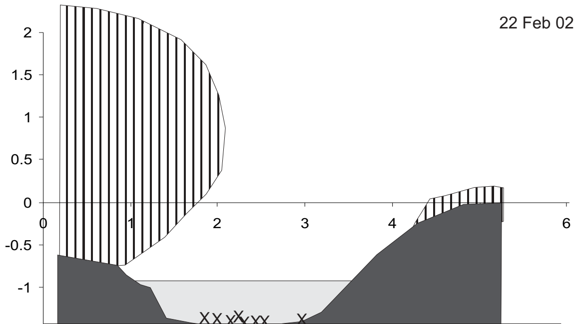
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



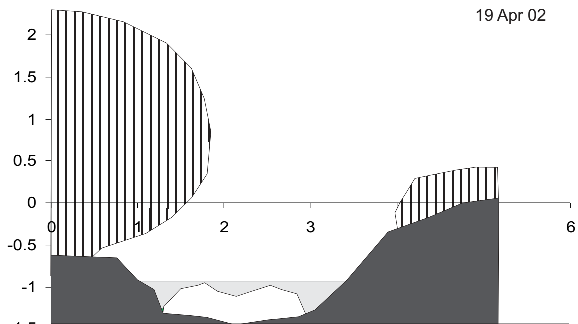
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	85 *Nitella* *10 P. crispus* Increased periphyton Increased *L. minor* & *Azolla* sp. cover	Unchanged



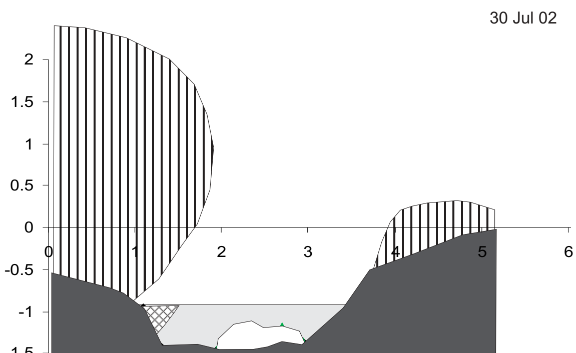
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Weed bed removed Sparse strands of *Nitella & Potomogeton* Firm bottom	Terrestrial grasses crushed by bucket & mud



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Largely unchanged	*Nitella* (recovering) Filamentous algae bloom	Grasses recovering

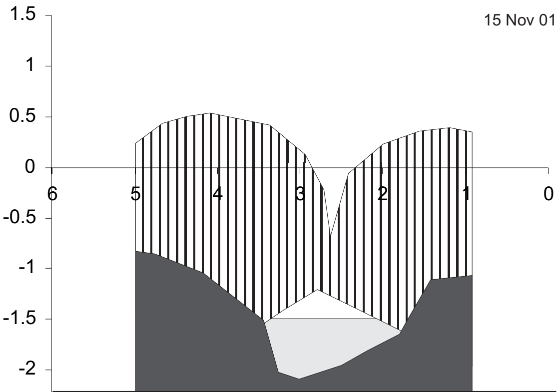


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged.	*Nitella* & *P. crispus* partially re-established *Lemna/Azolla* cover Periphyton com.	Grasses re-establishing

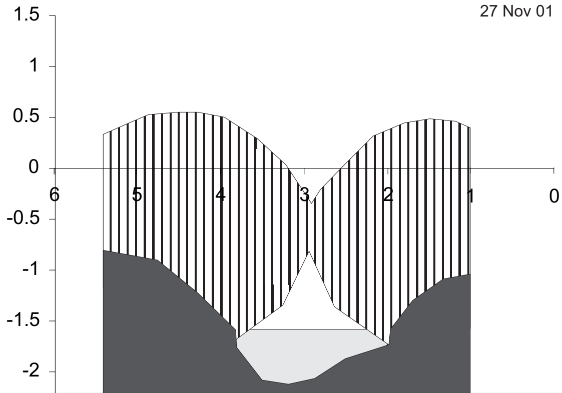


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Largely unchanged	90 *Nitella* sp. <10 *P. crispus* *Lemna/Azolla* on edges	Grasses established

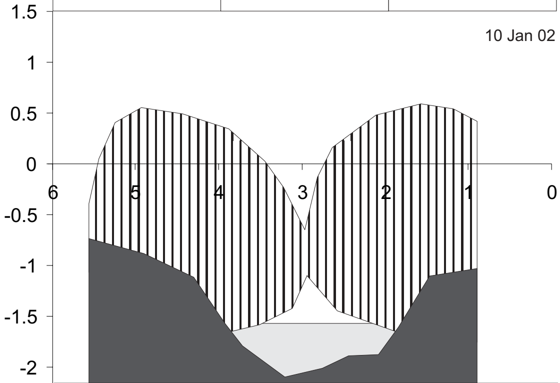
Appendix 1.7—Pa Drain 25 m



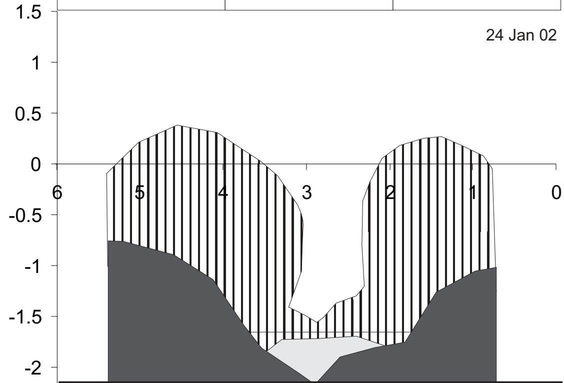
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Cutty grass 10 Terrestrial grasses	Grass roots	90 Cutty grass 10 Terrestrial grasses



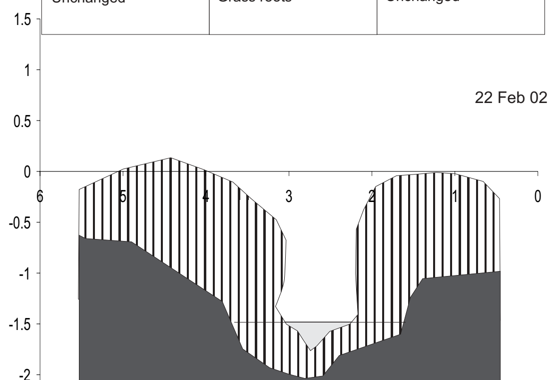
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



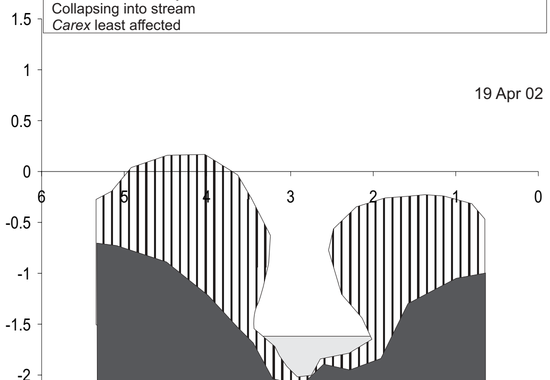
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Grass roots	Unchanged



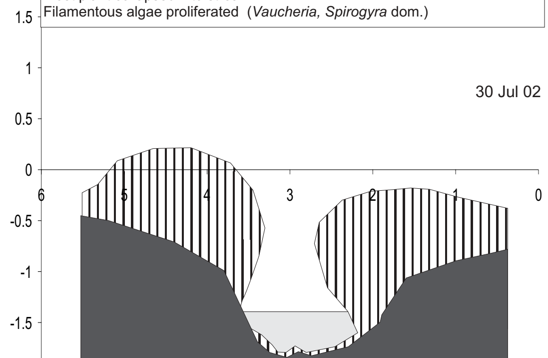
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Grasses, Blackberry dessicated Collapsing into stream *Carex* least affected		



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Obvious die back line Most plant collapsed into stream Filamentous algae proliferated (*Vaucheria, Spirogyra* dom.)		

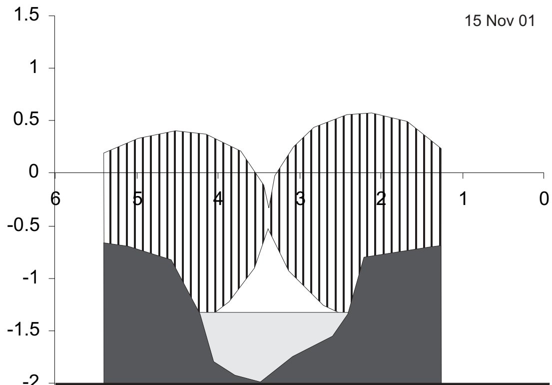


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Further die back *Carex* still decaying in stream Filamentous algae common. New grass growing through on banks		

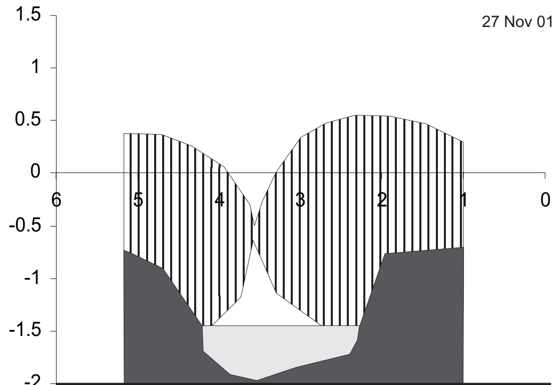


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Die back complete Decaying matter on bottom = detritus Sparse cover of *Nitella* on stream bed		

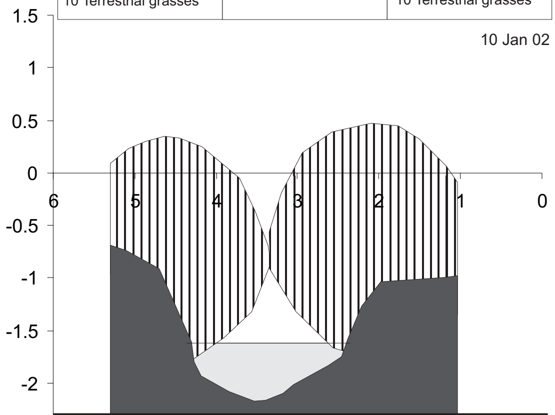
Appendix 1.8—Pa Drain 50 m



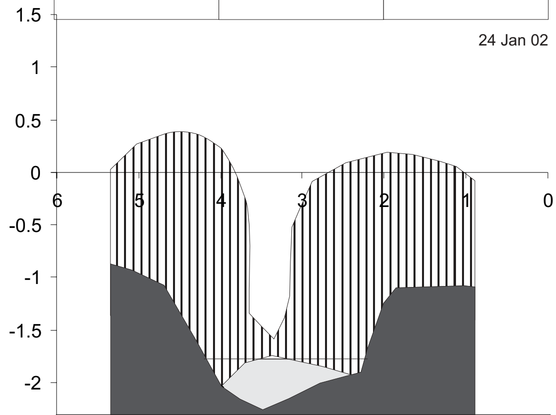
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 *Carex* 10 Terrestrial grasses	*Nasturtium*(Trace)	90 *Carex* 10 Terrestrial grasses



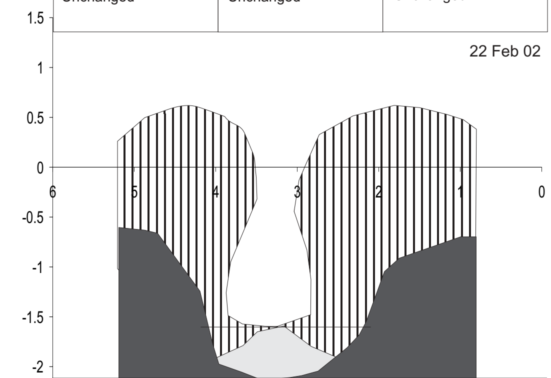
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



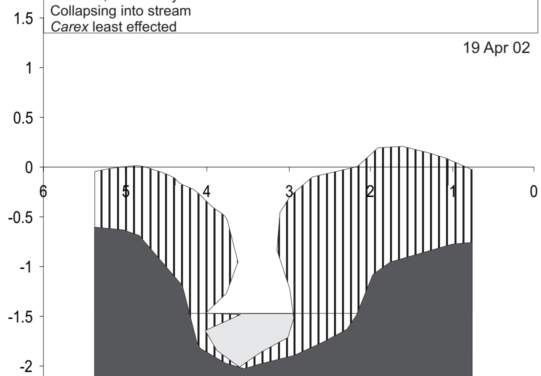
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Unchanged	Unchanged	Unchanged



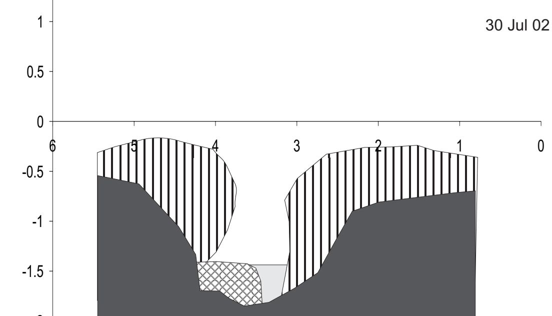
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Grasses, Blackberry dessicated Collapsing into stream *Carex* least effected		



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Most plant collapsed in sprayed area Plant beginning decay in stream Filamentous algae proliferated (*Vaucheria, Spirogyra* dom.)		

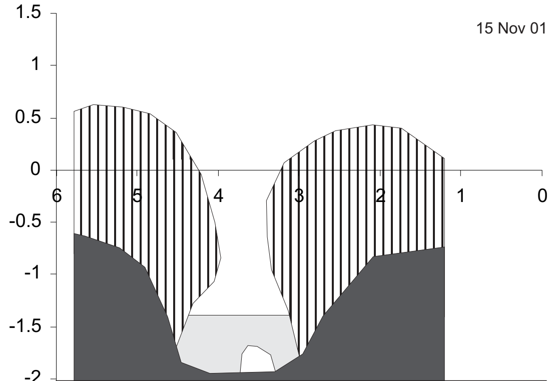


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Further die back, *Carex* still decaying in stream Filamentous algae common, *Nasturtium* recovering *Callitriche stagnalis* developing. New grass growing through on banks		

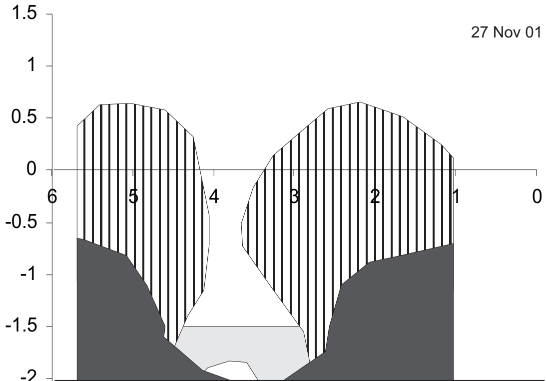


Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Terrestrial grasses recovering *Nasturtium* filling 75% of stream profile Traces of *L. minor* *Cutty grass recovering on RB*		

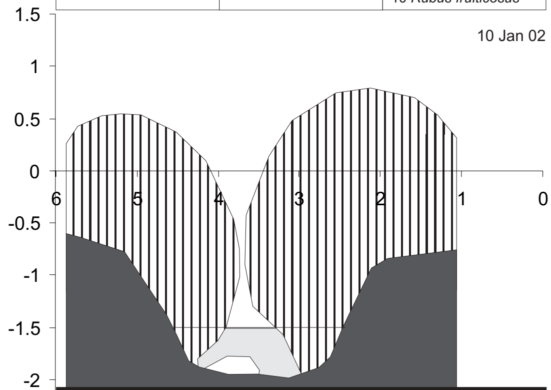
Appendix 1.9—Pa Drain 75 m



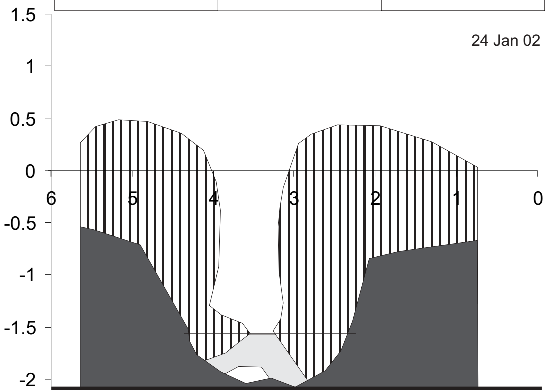
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
90 Terrestrial grasses 10 *Carex sp.*	90 *Nitella* sp. 10 *Nasturtium*	80 *Carex* sp. 10 Terrestrial grasses 10 *Rubus fruiticosus*



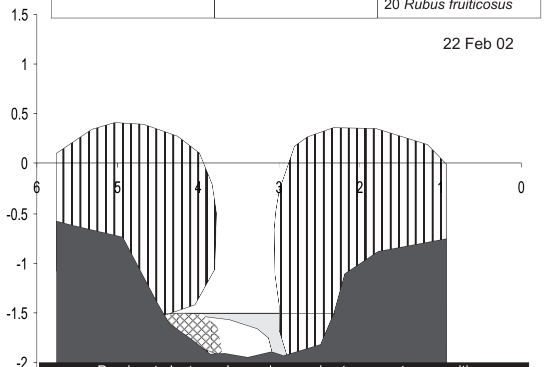
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Largely unchanged	Largely unchanged	Largely unchanged



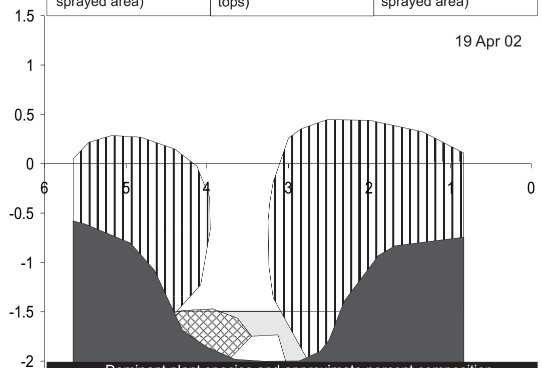
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
More growth Largely unchanged	80 *Nitella* sp. *20 Nasturtium*	70 *Carex* sp. 10 Terrestrial grasses 20 *Rubus fruiticosus*



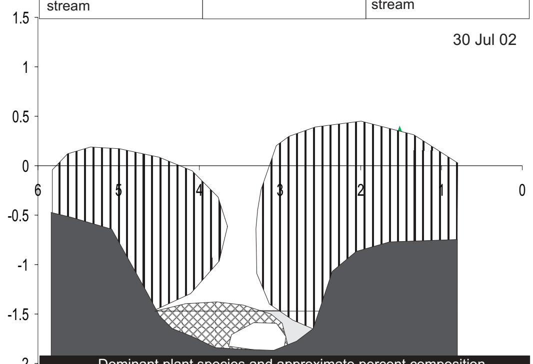
Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Largely unchanged (Browning off on sprayed area)	90 *Nitella* sp. 10 *Nasturtium*(burnt on tops)	Largely unchanged (Browning off on sprayed area)



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
Continued dieback Plants collapsing into stream	40 *Nitella* sp. 60 *Nasturtium*	Continued dieback Plants collapsing into stream



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
20 Cutty grass 30 Terrestrial grasses 40 *Rubus fruiticosus*	<20 *Nitella* sp. 80 *Nasturtium*	10 *Carex* sp. 20 Terrestrial grasses 70 *Rubus fruiticosus*



Dominant plant species and approximate percent composition		
LB	**In-stream**	**RB**
20 Cutty grass 30 Terrestrial grasses 40 *Rubus fruiticosus*	<10 *Nitella* sp. 90 *Nasturtium*	20 Terrestrial grasses 80 *Rubus fruiticosus*

Appendix 2

AVERAGE DENSITY OF MACROINVERTEBRATES IN CORE SAMPLES FROM EACH DRAIN ON EACH SAMPLING OCCASION

	MURRAYS DRAIN							PA DRAIN[1]							FOOTS DRAIN						
SAMPLING PERIOD[2]	1	2	3	4	5	6	7	**1**	**2**	**3**	**4**	**5**	**6**	**7**	1	2	3	4	5	6	7
Taxon																					
Mayflies																					
Austroclima jollyae	0.0	0.0	0.0	1.7	0.7	6.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Austroclima sepia	0.0	0.0	0.0	0.0	0.0	0.0	13.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Austroclima sp.	0.3	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Deleatidium spp.	0.0	0.0	0.0	3.0	1.0	0.3	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zephlebia sp.	0.0	0.0	0.0	0.0	0.0	0.7	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zephlebia versicolor	0.0	0.0	0.7	0.0	0.0	0.0	0.7	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Stoneflies																					
Megaleptoperla diminuta	0.0	0.0	0.0	0.0	0.0	0.7	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Megaleptoperla sp.	0.0	0.0	0.0	0.3	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zelandobius furcillatus	0.0	0.0	0.0	1.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dobsonflies																					
Archichauliodes diversus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Damselflies (tail-less)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.3**	**0.0**	0.0	0.0	0.3	2.0	0.7	1.0	3.3
Austrolestes colensis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.3	0.3	0.3
Xanthocnemis zealandica	0.0	0.0	0.3	0.0	0.0	0.0	0.0	**0.7**	**1.3**	**2.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	4.3	2.3	0.7	0.0	1.0	2.0
Dragonflies																					
Procordulia sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water bugs																					
Microvelia sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.3**	**0.0**	**0.3**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sigara sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.7	1.3	3.3	4.3	1.0	6.0	0.3
Beetles																					
Dytiscidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Elmidae	0.0	0.0	0.0	0.0	0.0	0.3	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Enochrus tritus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
True flies																					
Anthomyiidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Austrosimulium spp.	0.0	0.0	0.3	5.3	4.7	5.7	0.7	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.3**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ceratopogonidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.3	0.3	0.0	1.0	0.3
Chironomidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.3**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Chironomus sp. A	0.0	0.0	0.0	0.0	0.0	0.3	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	2.3	0.0	0.7	57.3	26.3	11.0
Chironomus zealandicus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.3	11.0	2.7	90.3	43.3	5.7
Corynoneura sp.	0.0	0.0	0.0	0.3	0.0	0.0	0.0	**0.0**	**0.0**	**1.0**	**0.0**	**0.3**	**0.0**	**0.0**	0.0	0.0	1.3	0.0	0.0	0.0	0.0
Culex sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.3	0.0	0.0	0.0	0.0
Empididae	0.0	0.0	0.0	0.0	0.0	0.3	0.0	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	**0.3**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ephydridae pupae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**1.3**	**2.7**	**1.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maoridiamesa sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Neolimnia sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Orthocladiinae	6.0	10.7	1.7	4.0	2.3	3.0	2.7	**3.3**	**1.7**	**3.3**	**5.3**	**5.0**	**5.0**	**0.0**	2.0	1.3	107	0.3	0.3	15.0	0.0
Paralimnophila skusei	0.7	2.3	0.7	0.3	0.0	2.7	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Polypedilum sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	1.0	1.7	0.0	0.0	0.0	0.0	1.3
Stratiomyidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Tanypodinae	0.0	0.0	2.3	1.0	6.3	4.7	0.0	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	1.7	0.0	2.7	2.7	0.7
Tanytarsus sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	0.0	0.0	71.7	3.0	0.0	3.7	0.0
Caddisflies																					
Costachorema sp.	0.0	0.0	0.0	0.3	0.0	0.3	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hudsonema amabile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrobiosis copis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrobiosis parumbripennis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrobiosis sp.	0.0	0.0	0.0	0.0	0.0	0.3	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydroptilidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Leptoceridae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxyethira albiceps	2.7	10.0	0.0	0.3	3.0	3.3	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**3.7**	**0.0**	0.3	3.3	33.0	10.7	7.0	3.0	2.0
Paroxyethira hendersoni	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	7.0	4.3	2.0	3.7	0.3
Polyplectropus puerilis	0.0	1.0	0.3	2.0	5.3	7.3	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psilochorema bidens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psilochorema macroharpax	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psilochorema sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.3	**0.0**	**0.0**	**0.0**	**0.0**	**1.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psilochorema tautoru	0.0	0.0	0.0	0.0	0.0	0.7	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.7**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pycnocentrodes sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Triplectides cephalotes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.7	1.0
Triplectides obsoleta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.7**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Triplectides sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0

	MURRAYS DRAIN							**PA DRAIN**							FOOTS DRAIN						
SAMPLING PERIOD	1	2	3	4	5	6	7	**1**	**2**	**3**	**4**	**5**	**6**	**7**	1	2	3	4	5	6	7
Flatworms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.7	0.7	0.0	0.7	0.0	2.0
Roundworms	0.0	2.0	0.0	0.0	0.3	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	0.0	0.3	0.3	0.3	0.0	0.3	0.0
Worms	169	192	251	118	260	268	11.3	**108**	**50.7**	**35.0**	**34.0**	**175**	**132**	**282**	350	185	217	72.3	332	379	228
Peanut worms	0.0	0.0	0.0	0.0	0.3	4.3	0.0	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Snails/Bivalves																					
Ferrissia sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Gyraulus sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	22.3	0.0	60.3	33.7	41.7	32.3	78.0
Hyridella sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Physa sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**1.3**	**0.0**	**0.3**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	1.0	1.3	5.3
Potamopyrgus antipodarum	1.0	5.3	0.3	1.0	9.0	1.0	0.0	**15.0**	**12.0**	**97.0**	**8.0**	**16.7**	**87.7**	**17.7**	119	0.0	77.7	105	102	134	228
Sphaeriidae	0.0	0.0	0.0	0.0	1.7	1.0	0.3	**2.3**	**0.7**	**2.7**	**0.3**	**0.0**	**9.7**	**1.0**	12.3	0.0	30.0	7.7	44.7	33.0	29.3
Crustaceans																					
Amphipoda	60.7	27.7	36.3	62.0	194	243	37.0	**21.7**	**3.3**	**18.7**	**32.7**	**80.3**	**133.**	**26.3**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Copepoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Daphnia carinata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	12.7	0.0
Ostracoda	0.0	1.3	10.7	1.3	8.0	0.7	0.0	**12.3**	**1.7**	**1.0**	**0.0**	**0.7**	**2.7**	**0.3**	11.3	0.0	4.7	1.7	16.7	15.3	0.7
Paranephrops planifrons	3.7	2.0	3.3	0.7	2.0	1.0	0.3	**0.0**	**0.0**	**0.0**	**1.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Paratya curvirostris	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.3**	**0.0**	**0.0**	**0.0**	**0.0**	**0.7**	**1.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mites	0.0	0.0	0.0	0.0	0.0	0.3	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Springtails	0.7	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.3**	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total taxa	6.7	6.7	6.7	8.3	10.7	13.7	6.7	**6.3**	**4.0**	**7.0**	**6.3**	**7.0**	**7.3**	**14.0**	6.7	6.3	13.7	10.7	12.0	15.3	14.0
Total individuals	244	254	308	203	499	556	68.3	**164**	**72.7**	**167**	**83.3**	**281**	**377**	**602**	519	200	630	250	700	715	602
Density (m^{-2})	18099	18840	22790	15037	36938	41161	5062	**12173**	**5383**	**12346**	**6173**	**20815**	**27926**	**44568**	38444	14840	46642	18519	51877	52963	44568

1. Bold type in columns used to distinguish Pa Drain entries from Murrays Drain and Foots Drain entries.
2. Sampling periods are as follows:
   1 = 15 Nov 2001
   2 = 27 Nov 2001
   3 = 10 Jan 2002
   4 = 24 Jan 2002
   5 = 22 Feb 2002
   6 = 19 Apr 2002
   7 = 02 Aug 2002