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A review of the ecological effects of macrophyte management in soft-bottomed waterways

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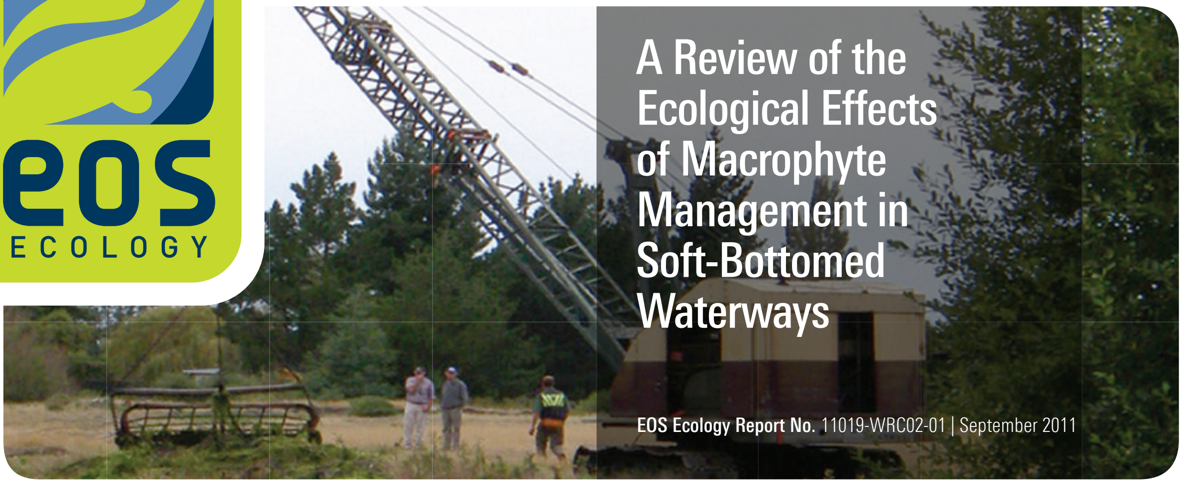
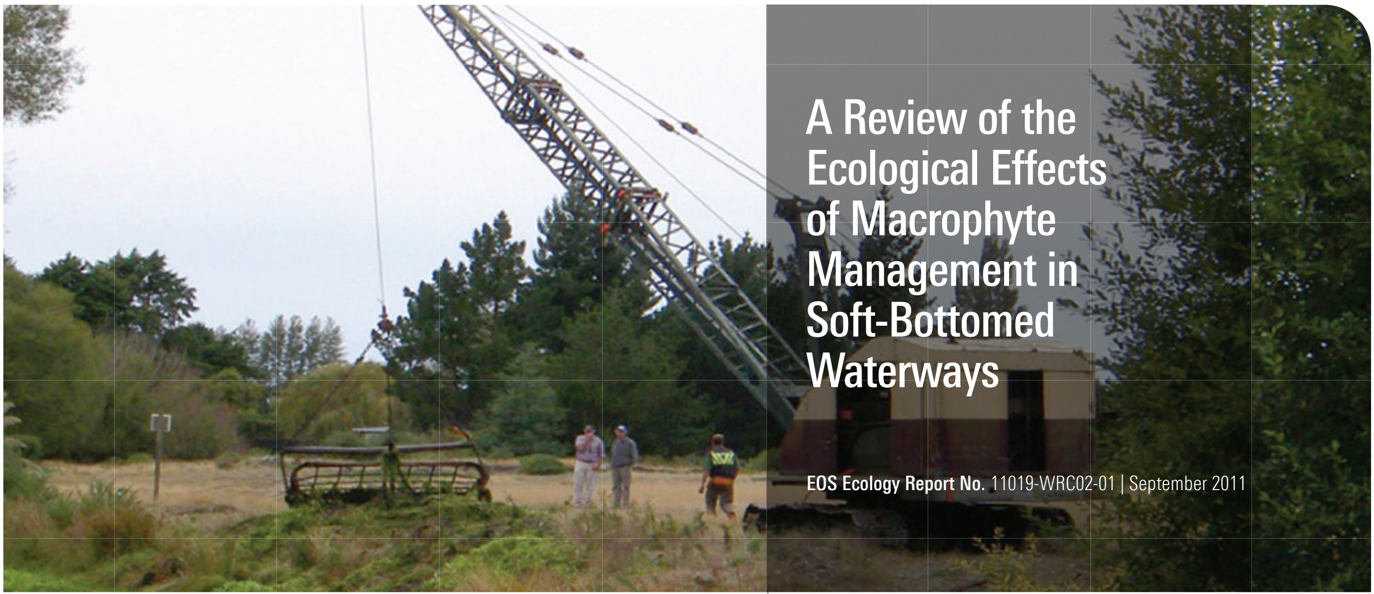


A Review of the Ecological Effects of Macrophyte Management in Soft-Bottomed Waterways

EOS Ecology Report No. 11019-WRC02-01 | September 2011

AQUATIC RESEARCH & SCIENCE COMMUNICATION CONSULTANTS



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REPORT

Prepared for
Waikato Regional Council

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EXECUTIVE SUMMARY

Aquatic plants (macrophytes) are an important component of many aquatic environments. However, in some environments, and especially those where introduced species are established, they can cause problems for various human endeavours and as a consequence a range of control techniques are in use around the world (e.g., biological control, chemical application, mechanical clearance). In New Zealand, large tracts of agricultural land are on former wetland areas and large-scale drainage schemes are required to maintain their productivity. As these drains are often the only remnant wetland habitat left they are home to many native freshwater species, some of which have high ecological and cultural value. This is especially the case in the Waikato, and the Waikato Regional Council consequently has an interest in the impacts of the macrophyte management techniques used in these schemes on native flora and fauna. EOS Ecology was contracted to compile a literature review on the ecological and physicochemical impacts of mechanical and chemical macrophyte management in soft-bottomed waterways and any best practice or guideline documents that have been produced to minimise any negative ecological impacts. A total of 42 documents that directly investigate some aspect of chemical or mechanical macrophyte management were reviewed, with eight from New Zealand and 34 from overseas.

Mechanical clearance of macrophytes has a range of potentially negative impacts on aquatic ecology including the release of suspended sediment and alteration of diurnal oxygen ranges. The greatest effect however, is probably the loss of the habitat macrophytes provide and the physical removal of aquatic fauna from the channel. Often the main concerns with chemical clearance relate to the toxicity of the herbicides used and the potential for the decaying plant material to cause a spike in oxygen demand that may depress oxygen to levels hazardous to aquatic biota. Most studies investigating chemical control find no direct impact of herbicides on aquatic fauna (e.g., toxicity or depressed oxygen levels) and observed effects (if any) are more related to habitat changes (e.g., death of macrophytes) which may also occur with mechanical methods (e.g., loss of habitat). The effects of macrophyte management on New Zealand fauna and whether management activities achieve their desired goals have rarely been studied.

A number of international and New Zealand best practice or guideline documents relating to drainage management contained information on minimising the negative ecological impacts of mechanical and chemical macrophyte control activities. Common to a number of these documents is the suggestion that a proportion of the macrophyte cover needed to be left undisturbed to provide a refuge for aquatic biota. Unfortunately there is a lack of quality empirical studies on the effectiveness of this (and other) suggested best practices, so it is unclear as to the proportion of macrophyte cover required to be retained to achieve such a goal.

A review of 16 New Zealand regional plans showed that the ecological impacts of the management of land drainage waterways are not usually considered in any great detail, as shown by the lack of suitable rules relating to this usually permitted activity.

We have provided some recommended best practices that should be adopted in New Zealand but acknowledge that a great deal more research into their efficacy is required before many of their details can be decided upon (e.g., the proportion of macrophyte cover retention required to maintain biodiversity values).

1 INTRODUCTION

Throughout the world in certain situations macrophytes cause problems for humans. To name but a few, they choke irrigation and drainage channels impeding water movement; hinder recreational activities such as angling, boating, and rowing; clog hydroelectric and irrigation scheme intakes; and some invasive species develop monocultures to the detriment of native flora and fauna. Thus a suite of usually invasive species requires often-intensive management around the world. New Zealand is no different and several introduced species are present that require management in lakes, rivers, and artificial or modified drainage waterways. A range of management techniques are in use around the world including biological control (e.g., stock grazing and grass carp introductions), chemical control (i.e., herbicide use), and mechanical control (e.g., physical removal or cutting of plants; Fig 1). All control methods inevitably have some level of ecological and physicochemical impact on the targeted waterway, which is often not desirable. Large tracts of Waikato's agricultural land are on former wetland areas and large-scale drainage schemes are required to maintain its productivity. As these drains are often the only remnant wetland habitat left they are home to many native freshwater species, some of which have high ecological and cultural value (e.g., eels and freshwater mussels; Fig 2). The Waikato Regional Council is investigating the impact of these macrophyte management techniques on the native flora and fauna. To assist the development of science-informed policy in this area, Waikato Regional Council contracted EOS Ecology to compile a literature review on the ecological and physicochemical impacts of mechanical and chemical macrophyte management in soft-bottomed waterways.

FIGURE 1 Some mechanical methods of macrophyte control used in New Zealand.

The first step in ensuring that the most appropriate low-impact methods are used is an understanding of the relative impacts of different macrophyte management techniques. This review collates and summarises research on the ecological and physicochemical impacts of mechanical clearance of macrophytes and silt, and chemical spraying for the management of macrophytes (these documents are outlined in Table 1). While predominantly aimed at soft-bottomed waterways, literature from lakes and reservoirs is included as these environments have similar characteristics to many drainage channels (e.g., low water velocities and macrophyte problems) and the effects of mechanical and chemical control would be similar. Also included are some laboratory and artificial pond bioassay experiments that give an indication of the relative toxicity of some common macrophyte herbicides.

The second step in identifying the best macrophyte management techniques for minimising ecological impacts is to examine any national or international best practice or guideline documents aimed to minimise the environmental impact of these activities. We have thus reviewed several such guidelines from New Zealand and abroad.

2 LITERATURE SUMMARY

A total of 42 documents that directly investigate some aspect of chemical or mechanical macrophyte management were reviewed (Table 1). Of these, eight were from New Zealand and 34 from overseas. Mechanical methods were the subject of 22 studies, chemical methods 17 studies, while the remaining three studies investigated both. Eleven studies examined the impacts on physicochemical or water quality parameters and 38 investigated aquatic fauna. Aquatic macroinvertebrates were the most common faunal group studied (21 studies) closely followed by vertebrates (mostly fish; 17 studies). In terms of age, the reviewed studies are spread over the last ca. 50 years with 18 being pre-1980 and 24 being post-1980. Eight are from the last 10 years. Table 1 summarises the reviewed studies and highlights their salient findings.

FIGURE 2 Eels and freshwater mussels are two native species that may be impacted by macrophyte control activities.

TABLE 1 **Summary of literature investigating the impacts of mechanical and/or chemical macrophyte management techniques.**

Study	Location	Environment	Management Technique (Mechanical or Chemical)	Parameter Measured	Summary of Findings
Aldridge (2000)	Wicken Lode, Cambridgeshire, England	River	Mechanical (Bradshaw bucket on bank-based excavator; this device is 2.5 m wide, with elongate apertures 10 cm wide to enable water and small debris to fall through)	Freshwater mussels	Bradshaw bucket removes 3% of mussels.
Armitage *et al.* (1994)	England	Stream	Chemical & mechanical (cutting)	Aquatic macro-invertebrates	No statistically significant effect on biotic score, richness, or abundance. Weed-cut and herbicide treated sites could not be distinguished from control site based on their fauna.
Berry *et al.* (1975)	Chickahominy Reservoir, Virginia, USA	Reservoir	Chemical (combined diquat & endothall)	Aquatic macro-invertebrates	No direct harm to macroinvertebrate populations.
Booms (1999)	Lake Keesus, Wisconsin, USA	Spring-fed lake	Mechanical (Aquarius Systems model HM 420 weed harvester (2.43-m cutting bar, maximum cutting depth of 1.68 m))	Vertebrates (fish and turtles)	Mean of 38.7 vertebrates per 1 m^3 sample of removed macrophyte.
Brooker & Edwards (1973)	Glamorgan, Wales	Artificial reservoir	Chemical (paraquat)	Water chemistry	Generally no discernible effect on the concentrations of combined nitrogen, phosphorus, silica and organic carbon in the water or on the organic content of the sediments. pH decline by one unit. Diel dissolved oxygen amplitude declined.
Brooker & Edwards (1974)	Glamorgan, Wales	Artificial reservoir	Chemical (paraquat)	Fish & aquatic macroinvertebrates	Reductions in species associated with target submerged weeds. Generally no change to species associated with marginal emergent vegetation. Change in eel diet.
Burnet (1972)	Christchurch, NZ	River	Chemical (paraquat)	Aquatic macro-invertebrates	Severe rapid reduction in amphipods indicating toxicity effect. No effect on mayflies or caddisflies.
Carpenter & Gasith (1978)	Lake Wingra, Wisconsin, USA	Lake	Mechanical	Water chemistry & metabolism	Effects of cutting on concentrations of seston, dissolved organic carbon, biological oxygen demand of dissolved organic carbon, and particulate, dissolved unreactive, and dissolved reactive phosphorus were short lived or insignificant. In shallow areas, community photosynthesis and respiration were decreased by macrophyte removal.
Dawson *et al.* (1991)	Dorset, England	River	Mechanical (cutting)	Aquatic macro-invertebrates	Cutting and removal of weed removed ca. 4900 individuals/m^2. This was estimated to be ca. 20% of numbers and ca. 12% of biomass of the total population.
Engel (1990)	Halverson Lake, Wisconsin, USA	Artificial reservoir	Mechanical (harvesting)	Fish & aquatic macroinvertebrates	Harvesting removed an estimated 3 million invertebrates and 20–30 000 fish.
Garner *et al.* (1996)	River Great Ouse, UK	River	Mechanical	Fish & zooplankton	Rapid decline of planktonic cladocera and related decrease in fish (roach) growth rate.
Goldsmith (2000)	Southland, NZ	Drains	Mechanical	Fish & habitat	No changes to fish abundance or density. No significant changes to water depth, velocity, or median substrate size.
Haller *et al.* (1980)	Orange Lake, Florida, USA	Lake	Mechanical (harvesting)	Fish	Harvesting removed an estimated 32% of fish numbers and 18% of biomass. Most fish removed were juvenile sportfish and smaller species.
James *et al.* (2002)	Lake Champlain, Vermont-New York, USA	Lake	Mechanical (shredding)	Water chemistry	Increase in total nitrogen and phosphorus, and soluble reactive phosphorus coinciding with decomposition of weed. Increase in phytoplankton, turbidity, and dissolved oxygen.

Jewell (1971)	Laboratory	Experimental chambers	Simulate in situ decay of aquatic weeds (could be either chemical of mechanical)	Water chemistry	Increases in nitrogen and phosphorus and a decrease in dissolved oxygen.
Kaenel *et al.* (2000)	Swiss Plateau, Switzerland	Streams	Mechanical (cutting & dredging)	Community metabolism & oxygen balance	In one stream neither primary production nor ecosystem respiration were significantly affected. In a second stream gross primary production and ecosystem respiration were reduced by about 70%. The removal of plants coincided with only a moderate increase in nocturnal oxygen concentration (+1 mg L^{-1}).
Kaenel & Uehlinger (1999)	Swiss Plateau, Switzerland	Streams	Mechanical (cutting & dredging)	Aquatic macro-invertebrates	Plant removal decreased the total number of invertebrates by about 65%,
Kaenel *et al.* (1998)	Swiss Plateau, Switzerland	Streams	Mechanical (cutting & dredging)	Aquatic macro-invertebrates	Plant cutting affected mainly taxa that used macrophytes as habitat (e.g. Simuliidae, Chironomidae), while highly mobile taxa (e.g. Ephemeroptera) and benthic taxa (e.g. Trichoptera, Bivalvia) were less affected. Taxa that decreased after plant removal recovered within 4–6 months.
Kern-Hansen (1978)	Denmark	Streams	Mechanical (cutting)	Aquatic macro-invertebrate drift (specifically the amphipod *Gammarus pulex*)	Total cutting of plants resulted in great increase in drift density. Leaving 35% of plants along margins caused small increase in drift while retaining 50% of plants did not significantly increase drift density.
Lawrence *et al.* (1962)	Artificial ponds	Fish rearing ponds	Chemical (diquat & paraquat)	Fish	No indications of detrimental effects on fish or fish-food organisms.
McMurtrie (2001)	Avon River, Christchurch, NZ	River	Chemical (diquat)	Aquatic macro-invertebrates	A survey and in-stream bioassay indicated invertebrates were largely unaffected by diquat application.
Mikol (1985)	New York, USA	Lake	Mechanical (barge-type harvester with cutting bar 1.2 m wide & 1.5 m wide with a maximum cutting depth of 1.5 m).	Fish (juveniles)	2–8% if the total standing crop of juvenile fish were removed by harvesting.
Milisa *et al.* (2006)	Plitvice Lakes, Croatia	Streams (tufa barrage system)	Mechanical (chainsaw and manual removal)	Aquatic macroin-vertebrates & habitat	Removal of plants resulted in decreased flow velocity and increased sediment deposi-tion. Invertebrate density and diversity declined as rheophilic species presumably left the area.
Monahan & Caffrey (1996)	Ireland	Canals	Chemical (dichlobenil) & mechanical (boat-mounted and land-based cutting)	Aquatic macroin-vertebrates	Mechanical: Land-based mowing bucket resulted in greatest reduction in invertebrate abundance. Chemical: No significant change to invertebrate abundance. No adverse effects on fish life observed from either method.
Mortenson (1977)	Denmark	Streams	Mechanical (cutting)	Fish (fry)	Mortality of fry higher in reaches where weed-cutting and streambed cleaning had occurred compared to undisturbed reaches.
Nichols & Keeney (1973)	Laboratory	2 L contain-ers	Chemical (endothall)	Nutrient release (nitrogen & phosphorus) from decaying plants	Rapid release of phosphorus. No definite conclusion about nitrogen except that in appears to be released slower than phosphorus.
Paul *et al.* (1994)	Laboratory	2 L or 20 L jars	Chemical (diquat, endothall, & fluridone)	Fish (juvenile)	Diquat was more toxic to juvenile fish than endothall or fluridone.
Ryder (1997)	Southland, New Zealand	Spring-fed creeks	Mechanical (excavator)	Fish & aquatic macroinverte-brates	Difficult to assess effect on fish because of difficulties in fish sampling, but many fish were removed from waterways. Benthic invertebrates were resilient to weed clearance.

TABLE 1 **Continued**

Study	Location	Environment	Management Technique (Mechanical or Chemical)	Parameter Measured	Summary of Findings
Serafy *et al.* (1994)	Potomac River, USA	River	Mechanical (harvesting)	Fish	Significantly lower mean fish density and biomass at the harvested vs. the control site. Species specific differences suggested harvesting improved habitat for pelagic species but negatively affected species preferring cover. Ten species were killed in the harvesting process representing an estimated 11–22% of numbers and 4–23% of biomass.
Statzner & Stechman (1977)	Schierenseebrook, Germany	Stream	Mechanical (cutting)	Aquatic macro-invertebrate drift	Cutting increased invertebrate drift, especially for species that were poor swimmers (e.g., cased-caddisflies, mites, bryozoans, some diptera larvae).
Strange (1976)	Laboratory	Experimental pools	Chemical (diquat-endothall mixture)	Nutrient release (nitrogen & phosphorus) from decaying plants	Slight increase in nitrogen & phosphorus but less than was taken up by plants after they were introduced to pools indicating much nitrogen & phosphorus stayed in the decayed plant remains.
Strange & Schreck (1976)	Chickahominy Reservoir, Virginia, USA	Reservoir	Chemical (diquat-endothall mixture)	Community metabolism	Herbicide treatment resulted in daily oxygen deficits at sites with moderate and heavy macrophyte density but not sites with low plant densities.
Swales (1982)	River Perry, England	River	Mechanical (cutting)	Fish	Fish distributions strongly associated with weed cover implying macrophyte removal decreases preferred fish habitat.
Tremblay (2004)	Avon River, Christchurch, NZ	River	Chemical (diquat)	Fish (eel biomarkers)	Diquat treatment caused no observable signs of acute toxicity and did not significantly alter biomarker responses.
Walker (1963)	Laboratory	Ponds & plastic enclosures	Chemical (endothall)	Water chemistry	Decay of macrophytes and algae lead to increases in a range of plant nutrients.
Way *et al.* (1971)	Nottinghamshire, England	Lakes	Chemical (paraquat)	Fish & aquatic macroinvertebrates	Fish appeared distressed in the days following application with some dead individuals observed. No significant changes to invertebrate communities observed.
Wells & Clayton (1996)	Lake Rotorua, NZ	Lake	Chemical (diquat)	Freshwater mussels	No evidence that regular diquat use has affected mussel abundance. Acute toxicity test indicated a large safety margin between weed control and lethal concentrations.
Wilcock *et al.* (1998)	Waikato, NZ	Drain	Mechanical (excavator)	Water chemistry & aquatic macroinvertebrates	Short-term (3–4 hrs) increases in turbidity and ammonia, and decreased levels of dissolved reactive phosphate and nitrate. Invertebrates decreased in density.
Wile (1978)	Ontario, Canada	Lake	Mechanical (harvesting)	Fish	No effect on fish populations.
Wilson & Bond (1969)	Laboratory	3 L jars or 6 L aquaria	Chemical (diquat & dichlobenil)	Aquatic macroinvertebrates	Diquat: amphipod very sensitive relative to mayfly, dragonfly, damselfly, & caddisfly. Dichlobenil: less toxic than diquat to amphipod but more toxic to insects.
Yeo (1967)	California, USA	Reservoirs and experimental pools	Chemical (diquat & paraquat)	Fish	Diquat in reservoir: No effect on fish. Paraquat and diquat in pools: some mortality of mosquito fish.
Young *et al.* (2004)	Marlborough, NZ	Spring-fed drains	Chemical (diquat) & mechanical (excavator)	Water chemistry, fish (eels), & aquatic macroinvertebrates	Mechanical: 50% reduction in invertebrate densities. Removal of many eels. Chemical: no acute toxic effect observed on invertebrates. No decrease in dissolved oxygen observed.

3 MECHANICAL MANAGEMENT

3.1 Types

Mechanical management typically involves using machinery to remove macrophytes and so alter the biomass and/or growth form of the plants. The purpose of this removal varies but in drainage channels it is primarily undertaken to facilitate the free movement of water downstream. Methods range in complexity from simple hand raking in smaller waterway or bank-based hydraulic excavators to speed up the process; to harvester and cutting boats of various sizes and designs that can work in deeper waterways and lakes. Most mechanical techniques actively remove macrophyte material from the waterways for disposal elsewhere, although in some circumstances cut material may be left to float downstream. The review by Hudson & Harding (2004) describes the most common mechanical macrophyte control methodologies used in New Zealand for drainage channels.

3.2 Environmental Effects

3.2.1 Water Quality

Sediment

Perhaps the most obvious immediate physicochemical effect of mechanical macrophyte management techniques is the mobilisation of sediment. In situations where either hand raking or excavators are used bed sediment is almost invariably disturbed. However, in many instances the removal of sediment is intentionally undertaken in conjunction with the removal of macrophytes. Where a harvester or cutter boat is used the volume of sediment disturbance will depend on the depth of the waterway, the depth at which plants are cut, and the amount of sediment trapped among the plant material.

Despite the fact that sediment release is one the most obvious effects of mechanical removal there are few studies that have assessed this. Wilcock *et al.* (1998) observed short-term (3–4 hours) increases in turbidity when assessing the effect of mechanical excavation on an 80 m Waikato drain reach. Young *et al.* (2004) noted high turbidity downstream of mechanical macrophyte removal in Marlborough spring-fed drains at the time the excavator was operating but only measured it a week afterward when levels were found to be similar to a control site. I have similarly observed substantial decreases in water clarity downstream of macrophyte removal using a dragline in a spring-fed Canterbury stream, but was not able to quantify the amount and duration. Few other studies have specifically measured sediment mobilisation and deposition as a result of mechanical macrophyte management techniques, but some papers have investigated the effects of sediment (suspended and settled) on aquatic habitats (e.g., see reviews by Ryan, 1991; Wood & Armitage, 1997). It would be expected that sediment mobilised and subsequently deposited via the mechanical management/removal of macrophytes would have the same effects as sediment disturbed by other activities. Suspended sediment limits light penetration potentially reducing primary production, and may impede the feeding activity of some fish species. However, suspended sediment resulting from the mechanical removal of macrophytes at any one location is usually short-lived (hours) and infrequent meaning the impact of feeding would be limited. Suspended material will settle out of the water column relatively quickly because of the low gradient, low velocity characteristics of most farmland drainage channels. This deposited material may smother the substrate and clog interstitial spaces rendering benthic habitat unsuitable for some aquatic fauna. It is therefore likely that in some situations sediments released by mechanical macrophyte management activities will have negative impacts on downstream receiving environments, especially if those receiving environments have a coarse clean substrate.

Nutrients

Another immediate effect of many mechanical management techniques is the release of solutes from the cutting or maceration of plant material. At sites where a significant biomass and/or area of macrophytes are cut and where water velocity is minimal, the release of such solutes could theoretically result in changes to water chemistry. This was shown to be the case in a New Zealand study where in a Waikato Drain, along with a short-term increase in turbidity, Wilcock *et al.* (1998) observed an increase in ammonia and decreases in dissolved reactive phosphorus and nitrate levels. Carpenter & Gasith (1978) investigated the effects of cutting in a shallow, eutrophic, Wisconsin USA lake on concentrations of seston, dissolved organic carbon, biological oxygen demand of dissolved organic carbon, and phosphorus (particulate, dissolved unreactive, and dissolved reactive phosphorus). In contrast to the New Zealand waterway study, they found that there were no significant changes to any of these parameters.

A few studies have investigated the impacts of leaving cut plant material left in situ to decay (i.e., no plant material removed from the water). James *et al.* (2002) found that over a two-week period following shredding of water chestnut (*Trapa natans*) in Lake Champlain (large $>1{,}000$ km^2 lake bordering New York, Vermont, and Canada), concentrations of total nitrogen and phosphorus, and soluble reactive phosphorus increased in a 1 ha experimental plot coinciding with the decomposition of plant material. In an experimental chamber experiment to determine the effect of decaying plant material on water quality, Jewell (1971) similarly found an increase in nitrogen and phosphorus, and a decline in dissolved oxygen (DO) as the plant tissue decomposed.

Dissolved Oxygen

Macrophytes and green algae produce oxygen during the day and consume it at night, resulting in a diurnal DO fluctuation pattern with maximum levels during daylight and minimum levels at night. Excessive macrophyte growths may lead to daily minimum levels that may harm aquatic fauna, and subsequently plant removal has been suggested as a technique to increase daily oxygen minima and reduce daily variation (Young *et al.* 2004). As dissolved oxygen fluctuation in waterways is influenced heavily by photosynthetic activity, the sudden removal of macrophytes can have an immediate effect on community photosynthesis and respiration. For example, Carpenter & Gasith (1978) found community photosynthesis and respiration was decreased by macrophyte removal in 0.2 ha plots in a shallow eutrophic lake but DO always remained above 80% saturation. James *et al.* (2002) found DO to increase from near zero to >2 mg/L in a 1 ha plot of a large (>1000 km^2) lake after the removal of the floating macrophyte, water chestnut, allowed better mixing and agitation of the water surface. Kaenel *et al.* (2000) observed contrasting effects of macrophyte removal on two similar Swiss streams. In one stream mechanical removal resulted in no significant changes to primary production or community respiration, while in the other these were reduced by around 70% immediately after macrophyte removal indicating the high contribution of macrophytes to primary production in that particular stream. In the second stream gross primary production did start to recover during the two weeks following plant removal, but never recovered to pre-removal levels. Kaenal *et al.* (2000) also noted that the removal of plants led to only a small increase (+1 mg/L) in nocturnal oxygen concentration. In a German stream Statzner & Stechman (1977) found mechanical cutting to have no effect on oxygen saturation (or conductivity, pH, and alkalinity). In a New Zealand spring-fed drain, Young *et al.* (2004) found daily DO fluctuations to increase following removal of macrophytes but thought changes to flow may have been responsible rather than changes in oxygen demand.

Conclusion

Overall the effects of mechanical macrophyte control on water quality is unclear as the few studies available on the topic have been conducted in vastly different aquatic environments, with different types of aquatic vegetation and using various mechanical techniques and only two studies conducted in New Zealand. Specific studies are therefore required in New Zealand land drainage waterways so as to determine the effects of common mechanical techniques on water quality.

3.2.2 Aquatic Fauna

Removal of Fauna from Channel

One of the major concerns with mechanical macrophyte management methods is the unintended physical removal of fauna from a water body. Numerous invertebrate species live on macrophytes utilising them as both a food source and as habitat. Many fish species use macrophytes as cover and feed on the associated invertebrates. Both fish and invertebrates are therefore easily entrained among the plant material as it is removed from the channel. Additionally some animals maybe injured or killed directly by the action of the excavator bucket or weed-harvester's cutting blade.

A few studies have investigated the level of aquatic invertebrate removal associated with different plant management techniques. Aldridge (2000) found plant removal using a weed-bucket in a UK river removed up to 3% of any of four unionid mussel species. Dawson *et al.* (1991) found around 4900 invertebrates per m^2 of river bed were removed by weed cutting in an English river, and estimated these accounted for 20% by number and 12% by biomass of the total population. Engel (1990) estimated that weed harvesting in a USA lake removed 11–22% of plant-dwelling invertebrates. In Marlborough spring-fed drains Young *et al.* (2004) observed 'large numbers' of aquatic invertebrates on excavated plant matter but did not quantify this further. It is thus clear that significant numbers of aquatic invertebrate fauna may be removed as 'by-catch' during mechanical removal of macrophytes.

A number of studies have also assessed fish removal as a consequence of various macrophyte management techniques, particularly in lakes. Usually it is small fish (i.e., either juveniles or small-bodied species) that are entrained in the macrophytes. In a Wisconsin USA lake Booms (1999) calculated that a weed harvester captured 38.7 vertebrates per one m^3 sample of macrophytes. Most (77%) were fish of 2–8 cm length. Engel (1990) calculated weed harvesting removed about a quarter of fry from a USA lake and over 90% of the catch was young-of-the-year fish of 1.5–6 cm in length. Mikol (1985) specifically investigated removal of juvenile fish by macrophyte harvesting in a USA lake and estimated 2–8% of the total standing crop of such fish were removed by harvesting. In a Florida USA lake Haller *et al.* (1980) found that juvenile sportsfish and smaller species were most susceptible to mechanical removal with macrophytes and estimated 32% of fish numbers and 18% of fish biomass were removed by mechanical harvesting. In a large Canadian lake, Wile (1978) found around 8.9 kg of fish to be removed per hectare of macrophytes harvested and as in other studies these tended to be smaller individuals 12–190 mm in length. Similar results were found in waterways. Serafy *et al.* (1994) in the USA Potomac River observed that 10 fish species were killed in the mechanical harvesting process, representing 11–22% of fish numbers and 4–23% of fish biomass. In the New Zealand context, Young *et al.* (2004) found that shortfinned eels were the only fish to be captured during mechanical clearance of sediment and macrophytes in Marlborough spring-fed drains. It was hypothesised that this was because of their habit of burrowing into the sediment while other species would actively swim away from the disturbance of the excavator. Young *et al.* (2004)

estimated that 0.12–0.16 eels per m^2 were removed. It was also observed that most eels would have likely died had they not been collected from the removed material; in their efforts to escape the eels would move downslope, and as the land sloped away from the drain most eels moved away from the drain (Young *et al.* 2004). Ryder (1997) also noted the removal of roundhead galaxias (*Galaxias anomalus*; note that this may be a misidentification since this species is only known from Otago's Taieri and Clutha catchments) during mechanical vegetation clearance in two Southland spring-fed creeks, but did not quantify this.

As with aquatic invertebrates, fish (especially juveniles or small-bodied species) are removed as 'by-catch' along with macrophytes during mechanical removal operations. Because of New Zealand's unique freshwater fish fauna, overseas studies are not particularly useful in predicting the effects of mechanical macrophyte management in New Zealand drains. As far as I can determine Young *et al.* (2004) is the only study to quantify fish removal during mechanical drain management in New Zealand. His findings are supported by my own anecdotal observations in water races and lowland rivers (Alex James, pers. obs.), where numerous eels often require returning to the channel following the removal of macrophytes and silt. Beentjes *et al.* (2005) similarly found few published studies on eel mortality from mechanical drain clearing but notes that anecdotal reports indicate that eels are frequently removed from drains by excavators and dumped on the bank where they die if they are unable to return to the watercourse (which was confirmed by Young *et al.* (2004)). Given the broader habitat preference of shortfin eels, and their ability to burrow into soft silt beds, I would suspect they would be the main native freshwater fish to be removed from drains throughout New Zealand. Large invertebrates such as freshwater mussels are also susceptible and in Christchurch there is anecdotal evidence of their removal during mechanical weed management activities (Shelley McMurtrie, EOS Ecology, pers. com.). Furthermore we have observed that macrophyte beds often support large numbers of young of the year freshwater crayfish that would inevitably be removed with macrophytes and be unable to find their way back to the waterway (Shelley McMurtrie, EOS Ecology, pers. com.).

Changes to Density and Behaviour

The removal of macrophytes can have impacts on the abundance and behaviour of the aquatic fauna which rely on them for habitat and nutrition. For freshwater mussels, many species of which are largely sedentary, the mechanical removal of macrophytes (and sediment) can alter their distribution. Aldridge (2000), using marked stones as proxies for mussels found the excavator dragged them across the channel, leaving higher densities of mussels closest to the bank the excavator operated from. Monahan & Caffery (1996) in Irish canals found mechanical removal by a land-based mowing bucket to cause the greatest reduction in invertebrate numbers (compared to control and herbicide sites), reflecting the capacity of the machine to cut vegetation to bed level and in so doing, removing any substrate for colonisation. However, invertebrate numbers recovered relatively rapidly following treatment and no adverse effect on fish life was found. In Marlbourgh spring-fed drains Young *et al.* (2004) similarly observed that while invertebrate densities recorded after excavation were half of those recorded shortly before clearance, they recovered within one month.

Not surprisingly, habitat preferences of invertebrate taxa can have a strong influence on the relative impacts of mechanical macrophyte clearance. In two Swiss Streams, Kaenel *et al.* (1998) found plant removal decreased the total number of invertebrates by ca. 65%, with taxa that used macrophytes as habitat the most affected. Benthic and highly mobile taxa were less affected and invertebrate densities for these communities recovered within 4–6 months. In a Croatian stream Milisa *et al.* (2006) observed a decrease in macroinvertebrate density after the removal of macrophytes reduced current velocity, causing the mostly rheophilic (prefers to live in fast moving water) taxa to leave the reach.

The removal of macrophytes may also have effects along food chains, as shown by Garner *et al.* (1996). Prior to mechanical weed cutting in an English river zooplankton and fish (roach) were significantly associated with macrophytes, suggesting that they provide high food densities and refuge during floods. Removal of all but a two metre marginal strip of macrophytes led to a decline in mean densities of planktonic cladocera and a decline in the growth rate of roach.

The removal of macrophytes can affect invertebrate drift behaviour. In a German stream Statzner & Stechman (1977) found taxa richness and the number of individuals in the drift to increase during and after mechanical cutting of macrophytes. They observed that species that were good swimmers could settle out of the water column faster (e.g., amphipods) and thus were less affected because they could stop drifting quicker than those that were poor swimmers (e.g., diptera larvae and cased caddisflies). Invertebrate drift caused by macrophyte removal can, however, be regulated. For example, in four lowland Danish streams Kern-Hansen (1978) found the total cutting of macrophytes resulted in a great increase in the drift density of the amphipod *Gammarus pulex*, whereas leaving either 50% (as bars across streams) or 35% (as strips along margins) of macrophytes did not significantly increase drift density or resulted in only a small increase respectively.

In some instances the mechanical removal of macrophytes may have no measurable effect on invertebrate communities. For example, Armitage *et al.* (1994) found no statistically significant effects of mechanical removal of macrophytes in an English stream on invertebrate metrics such as biotic score, richness, or abundance, and multivariate analysis did not distinguish impact from control sites. In spring-fed Southland drains Ryder (1997) found the benthic invertebrate community to be resilient to the effects of mechanical clearance, meaning that while they were initially impacted the community was able to recover over time.

Studies show that mechanical macrophyte clearance generally has a negative effect on fish densities although this can be species and life stage specific. Serafy *et al.* (1994) found that fish density in the Potomac River (USA) three weeks following mechanical plant harvesting was significantly lower at the harvested site compared to an undisturbed site. However, after 43 days fish density was significantly higher at the harvested site and changes to species relative abundances indicated harvesting improved habitat for pelagic species but negatively affected species that prefer cover. Serafy *et al.* (1994) concluded that mechanical harvesting effects on the fish community were short-term and minor as it did not affect species composition or mean species richness and the survey site had large and extensive macrophyte beds that remained intact. However, Serafy *et al.* (1994) suggests that where macrophyte habitats are scarce (or presumably where large areas are being harvested at one time) mechanical harvesting removes considerable numbers of ecologically and recreationally valuable species and should be discouraged. The life stage of fish may also influence the impact of mechanical removal. For example, in Danish streams, Mortenson (1977) found the mortality of brown trout fry to be greater in reaches where weed cutting had occurred compared to those left undisturbed; presumably because the macrophytes provided cover for the young.

Little work has been done on the comparison of different mechanical methods of macrophyte removal on affecting aquatic fauna. One study (Swales (1982)) however, did investigate the impacts of different methods of weed cutting in a small lowland English river. He observed that fish distribution was strongly associated with macrophyte cover and that increased fish movements occurred during the operation of a weed-cutting boat compared to manual weed control (operators wading in the river using scythes). This suggests the use of a boat results in more disturbance to the fish community than manual methods to control macrophytes.

As with studies on invertebrate communities, there are some that have found no measurable effect on fish from mechanical macrophyte control. For example, in a large (24 km long, 1.3 km wide) Canadian lake Wile (1978) found no measurable effect of mechanical harvesting on fish populations, although the sheer size of the lake meant there was a large area for fish to escape to and recolonise from. In New Zealand, Goldsmith (2000) sampled Southland drains before and six weeks after mechanical macrophyte clearance and found no difference in fish species richness or density, although any effect may have been masked by subsequent recolonisation in the period between the clearance activities and re-sampling. Fish are also generally more mobile than aquatic invertebrates so have a greater capacity to both avoid and recolonise after mechanical macrophyte clearance activities. This however depends on habitat being available for them to escape to and to recolonise from.

3.2.3 Habitat Alteration

The primary aim of the mechanical removal of macrophytes in drainage channels is to improve the area of open water to increase channel capacity and facilitate drainage, meaning that invariably the instream habitat is altered in order to achieve this. Theoretically, the removal of macrophytes will decrease water depth and increase current velocity and where sediment is also removed, channel depth will increase. Unfortunately only a few studies have actually measured the physical habitat changes resulting from the mechanical clearance of macrophytes. Aldridge (2000) not surprisingly found that dredging to remove macrophytes and sediment resulted in an increase in channel depth, while Kaenal *et al.* (2000) observed the removal of ca. 90% of macrophytes in two streams to increase mean current velocity by around a third and decrease water depth by around 50%. However, in some instances where macrophytes have been concentrating flow in a discrete channel, their removal may actually decrease current velocity and water depth. Milisa *et al.* (2006) observed this, as well as an associated increase in particulate organic matter deposition, after the removal of aquatic vegetation in a Croatian stream.

Where drains are spring-fed, water depth and current velocity may have very little to do with macrophyte growth. This is indeed what Young *et al.* (2004) observed in Marlborough drains where one week after mechanical clearance of macrophytes water levels and flow rates had dropped only slightly. After one month water levels had dropped by 30 cm, in conjunction with declining groundwater levels and flows had reduced slightly more. After three months the macrophytes had re-established to pre-control levels, but water levels and flows remained relatively low, indicating how water levels in this particular drain were more related to groundwater levels than macrophyte growth.

An overlooked and apparently unquantified effect of macrophyte removal is the loss of the shade provided by emergent species. Such shading inhibits the growth of potentially nuisance algae and other macrophytes, reduces the effect of sunlight on water temperature, and provides cover for aquatic fauna from aerial predators. Also unquantified is the potential for dense macrophyte growth to impede fish passage, which if it does, would be a positive effect of removal.

Given the vast amount of macrophyte removal that occurs with the aim of increasing channel capacity, decreasing water levels, and facilitating land drainage, there is a lack of quantitative work to determine if these goals are met for different waterways (e.g., spring-fed vs. non spring-fed) and for how long. Thus it would appear that the benefits of macrophyte removal are often assumed and the efficacy of such activities is rarely, if ever, critically examined.

4 CHEMICAL MANAGEMENT

4.1 Types

Chemical management involves the application of an herbicide to kill macrophytes in situ, thus avoiding the direct physical impacts of mechanical removal. Herbicide may be applied by various methods ranging from simple bank-based backpack and vehicle spraying, to spray boats and helicopters in lakes and larger waterways. In New Zealand, the herbicide diquat dibromide (e.g., Reglone® and Reward®) has been used for decades and at one time was the only one registered for use on submerged macrophytes. In the past paraquat was also used to control submerged macrophytes but is no longer approved for use in New Zealand waters (Hudson & Harding, 2004). In 2004 the herbicide endothall (e.g., Aquathol® and Aquathol Super K®) was approved for use on submerged macrophytes in New Zealand. All three (paraquat, diquat, and endothall) have a label hazard classification of being "very toxic to aquatic organisms". The Waikato Regional Council formerly used diquat to control submerged macrophytes in drains but now use endothall (Keri Neilson, WRC, pers. com.). Herbicides used for submerged macrophytes typically have gelling agents added that enable them to sink and adhere to submerged plants and improve their effectiveness. Glyphosate (e.g., Roundup) is used extensively around New Zealand (and the world) to control marginal and emergent aquatic vegetation but is not allowed to be directly discharged to waterways.

4.2 Environmental Effects

4.2.1 Water Quality

The most commonly noted potential effect of aquatic herbicides on water chemistry is the rapid decay of dead plant material creating a sudden oxygen demand that could decrease DO to levels that may be hazardous to aquatic fauna. In a laboratory experiment Jewell (1971) found the decay of macrophytes would use one milligram of oxygen per milligram of ignitable suspended solids of plant material. He further calculated that if the all plants were killed and remained in situ to decay in a hypothetical one km section of stream 10 m wide, then with an average macrophyte accumulation of 500 g of ignitable suspended solids per square metre, the initial rate of DO demand would be equivalent to the discharge of untreated domestic wastewater from 24,000 people (Jewell, 1971).

Unfortunately only a few studies appear to have actually logged DO concentration fluctuation before and after and/or upstream and downstream of macrophyte herbicide treatments. Brooker & Edwards (1973) recorded diurnal DO concentration fluctuation in a reservoir before and after paraquat application. Prior to application DO fluctuated daily between 70–150% saturation, but afterwards within the range 70–100% indicating a reduction in photosynthetic activity after the death of the plants. With the subsequent growth of filamentous algae and the stonewort *Chara globularis* the amplitude of DO fluctuation increased towards pre-herbicide levels until another paraquat application decreased DO saturations to within a 60–100% range. While the death and decay of macrophytes clearly had an effect on DO, in this instance it did not result in a surge in oxygen demand leading to particularly low DO concentrations, possibly because the shallowness (0.25–0.8 m) of the reservoir allowed sufficient DO diffusion across the water surface. Similarly, in Marlborough spring-fed drains Young *et al.* (2004) did not observe a decrease in DO concentration associated with the decay of macrophytes after treatment with diquat. Only two studies provided evidence of a short-term decline in DO resulting from the rapid decay of plant material. Way *et al.* (1971) observed fish gasping for air shortly after the treatment of an English lake with paraquat, although actual DO levels were not measured. Following treatment of *Egeria densa* with a diquat-endothall mixture in a large reservoir (1,100 ha), Strange & Schreck (1976) found that daily oxygen consumption by the aquatic community regularly exceeded daily community oxygen production in areas of moderate to heavy macrophyte density. In areas of light macrophyte densities treatment with herbicide did not alter the pattern of community respiration. They concluded that the consistently negative oxygen budgets at their 'heavy' and 'moderate' growth sites after treatment were probably due to the cessation of macrophyte photosynthesis and beginning of microbial decay.

Another effect of decaying plant material is the release of nutrients. Nichols & Keeney (1973) investigated the nitrogen and phosphorus release from endothall-treated *Myriophyllum exalbescen* beds, finding that following herbicide application rapid phosphorus release can occur. They were unable to reach definite conclusions about nitrogen except that its release from decaying weeds is slower than phosphorus. Walker (1963) examined the impacts of endothall derivatives on fishery habitats and found its use to control a range of algae and macrophyte species in ponds and plastic enclosures increased concentrations of various nutrients including calcium, magnesium, potassium, ammonium-nitrogen, nitrate-nitrogen, and organic-phosphorus. In a laboratory experiment Strange (1976) measured the nutrient release of *Egeria densa* treated with a diquat-endothall mixture. He found that nitrogen and phosphorus concentrations in the water increased slightly after treatment but this was less than the amount removed by plants after introduction to the experimental pools, indicating much of these nutrients remained in the decayed plant sediments and was not lost to the water. Such retention of nutrients may explain why Brooker & Edwards (1973) observed some water chemistry changes water after paraquat application in a reservoir that were consistent with the death of the plants (e.g. alkalinity), but found no evidence that plant decay produced large increases in nutrient concentrations in the water.

4.2.2 Toxicity to Aquatic Fauna

Perhaps the best studied aspect of chemical macrophyte control is the toxicity of the herbicides to aquatic invertebrates and fish. Determining the toxicity of herbicides to aquatic fauna is complicated by sometimes vast interspecific variation. For example, in a laboratory experiment testing the toxicity of diquat and dichlobenil Wilson & Bond (1969) found diquat to be more than 300 times more toxic to an amphipod than to several aquatic insect taxa (a mayfly, caddisfly, midge larvae, dragonfly, and damselfly). In contrast dichlobenil was less toxic than diquat to the amphipod but more toxic to the aquatic insects. In a Canterbury stream Burnet (1972) similarly found amphipods to be greatly susceptible to a herbicide application (in this instance paraquat), where after a heavy initial kill the treatment reduced the number of amphipods caught in the drift to 5% of the pre-treatment level, while in comparison there was only a slight reduction in the numbers of hemipterans. The total invertebrate numbers in benthic Surber samples increased markedly a year after treatments ended, mainly due to increased numbers of trichopterans. He concluded that the use of paraquat for aquatic weed control will severely reduce the amphipod fauna, probably because of a direct toxic effect, while there were indications of only slight effects on hemipterans and molluscs (Burnet, 1972).

The actual toxicity of herbicides depends greatly on the safety margin between the label application concentrations and those which are hazardous to animals. For example, Paul *et al.* (1994) observed in a study of the toxicity of diquat, endothall, and fluridone on the early life stages of three USA fish species that the LC_{50} for diquat was very close to the predicted application concentrations, meaning the safety margin for using diquat appears to be small. In contrast, the LC_{50} of fluridone and endothall were at least one order of magnitude greater than labelled application concentrations. For more mature fish, Lawrence *et al.* (1962) reports that the minimum herbicidally active concentration of diquat and paraquat compared to the threshold toxicity to fish indicates an at least 10-fold safety margin. This is probably why many studies have shown no adverse effects of herbicides (i.e. the concentrations used do not result in toxic concentrations in the environment of interest). For example, in an English stream Armitage (1994) found no statistically significant effects of diquat on invertebrate metrics such as biotic score, richness, or abundance. Nor were impact and control sites separated by multivariate analysis. Berry *et al.* (1975) concluded that the use of a diquat and endothall mixture to control Egeria in a reservoir in Virginia USA did not directly harm invertebrate populations. In Irish canals, Monahan & Caffery (1996) found that dichlobenil selectively applied only along the centre of the channel (thus leaving the margins intact) did not significantly alter the normal seasonal trends in macroinvertebrate numbers. In New Zealand, Wells & Clayton (1996) found no evidence to suggest regular diquat use in Lake Rotorua had been detrimental to freshwater mussel abundance. In Christchurch's Avon River Tremblay (2004) assessed the effect of diquat on the physiological responses (biomarkers) of caged shortfin eels. After a three week exposure to diquat eels displayed no observable signs of acute toxicity and biomarker responses were not significantly altered.

Sometimes where effects were seen they are likely a consequence of the study environment (e.g., small versus large water bodies). For example, Yeo (1967) investigated the effects on fish of diquat in reservoirs and in experimental pools. In the reservoirs fish were unharmed and no fish appeared distressed immediately after treatment or by the rapid decomposition of macrophyte material. However, in experimental pools, mosquito fish were killed by the diquat treatment presumably because of a higher relative concentration.

4.2.3 Habitat Alteration

In the days and weeks following chemical application, susceptible macrophytes typically die and collapse, altering the habitat from one of a matrix of plant material to one with open water and a layer of decaying plant material on the streambed. This can drastically alter the habitat conditions for species that are associated with macrophytes and subsequently alter the faunal assemblage. In Marlborough spring-fed drains Young *et al.* (2004) observed no acute toxic effects of diquat application on aquatic invertebrates; however interestingly, survival of invertebrates living among overhanging vegetation was reduced. Aquatic invertebrate taxonomic richness decreased at the sprayed site after diquat application, possibly due to an increase in detritus within the drain, indicating that while the herbicide had no direct effect on invertebrates there was an indirect effect through changes to habitat conditions. Similarly toxicity experiments in a reservoir by Brooker & Edwards (1974) indicated that changes in the fauna following the use of paraquat for weed control were likely to be indirect effects caused by the death and decay of macrophytes. They found that in general invertebrates living amongst the emergent vegetation in the margins of the reservoir and on the sediments were unaffected. Many of the invertebrates intimately associated with the macrophytes (e.g., caterpillers, caddisflies, and snails) were lost completely or colonized the replacement growth of *Chara globularis* at reduced densities, with such effects extending to the year after treatment. Data from fish gut analyses indicated that there was a change in the diet of eels following the death of the macrophytes and that this was largely a reflection of the loss, or reduction in density, of many invertebrates associated with the macrophytes.

These indirect effects are further illustrated by McMurtrie (2001) who assessed the effect of diquat application in Christchurch's Avon River by surveying benthic and aquatic-plant associated invertebrates and performing an instream cage experiment. This study found that invertebrates living on macrophytes were not affected by diquat application, possibly because there was only a 30% reduction in plant cover.

In contrast however, total densities and the density of ostracods and two snail species were significantly lower along the stream margins one month after diquat application, possibly because of the greater die off of plants in those marginal environments. Effects of habitat change rather than direct toxicity was further confirmed by the instream cage experiment which showed that the field concentrations of diquat were not acutely toxic to the caged snail and amphipod species.

The collapse of macrophytes following herbicide treatment can release nutrients (e.g., Nichols & Keeney, 1973; Walker, 1963) and create habitat space in which macrophytes or algae will often rapidly regrow; either the sprayed species will recover or a new species will proliferate. For example, Brooker & Edwards (1973) observed a major shift in the dominant plants of a reservoir treated with paraquat from *Potamogeton pectinatus* and *Myriophyllum spicatum* (before treatment) to the macroalga *Chara globularis* which had not been recorded there previously. Similarly, Engel (1990) observed rapid regrowth of macrophytes in a lake with them reaching pre-harvest biomass within a few weeks and even becoming denser.

In drains the main purpose of chemical treatment is to increase channel capacity to facilitate drainage and in some instances to eradicate or control noxious weeds. Unfortunately, very few studies in flowing channels ever measure the efficacy such treatments at increasing and maintaining channel capacity (or controlling noxious weeds), making it difficult to critically examine if macrophyte chemical treatment regimes used in New Zealand do indeed have the desired outcomes and if the periodic drastic habitat alterations are always necessary.

5 MECHANICAL vs. CHEMICAL

While mechanical and chemical management of macrophytes in artificial drains and drainage-modified waterways has the same general aim of increasing channel flow capacity, there are some distinct differences in their potential physicochemical and ecological effects (Table 2). The main difference is the immediate impact on the physical habitat; with chemical application generally having very little, and mechanical methods by their very nature causing dramatic changes. While chemical methods are generally cheaper and arguably cause less disturbance to instream habitat there are concerns over the effect of herbicides on human health, fauna, and persistence in the environment (Hudson & Harding, 2004). Most studies investigating chemical control find no direct impact of herbicides on aquatic fauna (Table 1) and observed effects (if any) are more related to loss of macrophyte habitat (e.g., death of macrophytes) which equally occurs with mechanical methods. Despite this, the use of submerged plant-specific aquatic herbicides by local and regional councils in New Zealand is rare. Based on a survey presented in Hudson & Harding (2004) only three out of 33 councils surveyed used an herbicide registered for use in water (i.e., diquat). Most did, however, report using glyphosate (mostly Roundup); presumably only on marginal and emergent vegetation and not submerged plants, and most also used mechanical excavators.

TABLE 2 A comparison of the potential impacts and effects of mechanical and chemical control of macrophytes. Note that many of these impacts and effects are theoretical and most have scarcely been quantitatively investigated in practice.

Potential Impact and Effects	Macrophyte Control Method	
	Mechanical	Chemical
Resuspension of sediment - Smothering of downstream bed and associated fauna/flora. - Increased turbidity and suspended solids. - Mobilisation of any contaminants in sediment.	Yes (if excavator used, especially if silt removal is done at same time) No (if weed harvester boat used)	No
Removal of fauna from channel - Reduced fish and invertebrate densities. - Loss of biodiversity. - Loss of food for birds.	Yes (unless weeds are cut and left to decay in situ)	No
Removal/death of desirable macrophytes (e.g., native species). - Loss of biodiversity. - Loss of habitat.	Yes	Yes
Herbicide inputs - Lethal and sub-lethal toxicity effects.	No	Yes
Bank damage/disturbance - Expose bare earth. - Cause bank instability. - Crush riparian vegetation. - Prevent planting of riparian zone.	Yes (if excavator used)	Yes (but less so than mec-hanical as only light vehicles required)
Spread of invasive species - Increase range of invasive species via introduction to new areas.	No (if weed harvester boat used)	No
Loss of habitat - Reduced fish and invertebrate densities. - Loss of biodiversity.	Yes (if excavator or weed harvester is not properly cleaned or plant material floats downstream)	Yes
Release of nutrients - Facilitate rapid regrowth of macrophytes and/or nuisance algae.	Yes	Yes
Loss of shade (by emergent macrophytes) - Increased temperature fluctuation. - Increased light facilitating growth of phytoplankton or nuisance algae.	No (unless weeds are cut and left to decay in situ)	Yes
Altered gross primary productivity and ecosystem respiration - Reduced diel dissolved oxygen variation. - Reduced dissolved oxygen production because of reduced photosynthesis.	Yes	Yes
Sudden increase in dissolved oxygen demand - Low dissolved oxygen levels that may harm/kill some fauna.	No (unless cut weed is left in situ to decay)	Yes
Loss of food sources for birds and fish - Loss of biodiversity.	Yes	Yes

Because of the vast variation among studies of the types of aquatic environments investigated, the chemicals used, the mechanical methods used, the species of macrophytes controlled, and the size of the areas treated, it is difficult to make a definitive statement recommending any particular method. Additionally very few studies have directly compared the impacts of mechanical and chemical control methods on aquatic fauna and/or water quality (Table 3). Of the three such studies that did this, chemical treatment of macrophytes was found to have no impact on aquatic invertebrates while mechanical methods either had no effect (one study) or some effect (decreased invertebrate numbers; two studies). Only Young *et al.* (2004) investigated the impact on fish finding that numerous eels were removed by mechanical clearance, but they did not make any direct chemical-mechanical comparison. There are thus vast knowledge gaps in our understanding of the ecological effects of drain clearance activities. Furthermore, despite the management of macrophytes being common throughout New Zealand, our understanding of drain hydrology and if macrophyte control by any method has the desired effect of improving drainage is extremely limited, making the development of policy and improved practices difficult (Hudson & Harding, 2004).

There is probably no one 'perfect' method that could ever be recommended as every drain or drainage system has its own characteristics (e.g., macrophyte species present, channel width and depth) and values (e.g., fauna present, aesthetics, riparian condition) that need to be taken into account, along with cost, landowner preferences, and public health concerns.

6 BEST PRACTICES AND GUIDELINES

6.1 International

With the general global increase in environmental awareness in recent decades, several organisations have produced guideline or best practice documents relating to the control of macrophytes (Table 4). It is likely that many other similar documents have been produced around the world but are not readily accessible. International documents fall into two basic categories; those that list the advantages/disadvantages of various methods of macrophyte control techniques (e.g., Madsen, 2000) and those that provide actions that can be taken to theoretically limit the negative ecological effects of macrophyte control (e.g., Barrett *et al.*, 1999). Many are written for a non-technical audience so the information is understandable by managers, drainage authority staff, and the workers actually undertaking macrophyte control activities.

Of the international guidelines, "The Drainage Channel Biodiversity Manual – Integrating wildlife and flood risk management" by the Association of Drainage Authorities and Natural England (Buisson *et al.*, 2008) is perhaps the most comprehensive and the most relevant to the management of drainage waterways in New Zealand. While it is obviously biased towards UK fauna, which includes several mammalian species

TABLE 3 Studies that have compared mechanical and chemical macrophyte control methods.

Study	Environment	Fauna	Mechanical Effects	Chemical Effects
Armitage *et al.* (1994)	Stream	Aquatic invertebrates	None	None
Monahan & Caffery (1996)	Canal	Aquatic invertebrates	Decrease in numbers	None
Young *et al.* (2004)	Spring-fed drain	Water quality, eels, & aquatic invertebrates	50% reduction in invertebrate densities. Removal of many eels.	No acute toxic effect observed on invertebrates. No decrease in dissolved oxygen observed.

TABLE 4 **Summary of overseas best practice or guideline documents that include content related to limiting the ecological effects of macrophyte management activities. All are freely available online and their URL's are provided in the references (Section 9).**

Document/Country	Summary	Main Points Related to Limiting Ecological Harm
Barrett *et al.* (1999); England	Aims to supply the water manager with a set of guidelines which allows them to select the most cost effective and environmentally acceptable form of weed control.	- Where valuable biota present, maintain the same management regime that has been used in past. - Avoid weed control operations during times when majority of biota are reproducing. - Preserve as wide a range of habitats as possible. - Where possible retain non-target, untroublesome plants. - Consult conservation officers about the particular biological value of a watercourse before carrying out weed control operations. - Do not carry out weed control or dredging operations unless strictly necessary.
Buisson *et al.* (2008);	Aims to provide assistance for operating authorities engaged in the complex management of lowland drainage systems to balance the benefits for flood risk, agricultural drainage, and biodiversity.	- Provides detailed information on protecting particular aquatic and riparian fauna and flora. - Numerous channel, margin, and bank management techniques are detailed (including diagrams) which are all rated for biodiversity and flood management effectiveness.
Madsen (1995); Denmark	Written for people who are responsible for the physical maintenance of Danish watercourses – the "riverkeepers". Good water flow is no longer the sole objective of their work – environmental conditions in general have assumed equal importance.	- Advocates macrophyte control only when necessary. - Advocates maintenance of habitat variability. - Advocates retention of riparian vegetation and beneficial macrophytes. - Cut plant material should be removed from the channel. - Free fish passage must be maintained.
Gibbons *et al.* (1999); USA	Detailed guide for developing integrated aquatic vegetation management plans in Oregon.	- Sets out a process to determine the most efficient management regime for any particular aquatic weed problem. - Provides table of advantages and disadvantages of various mechanical methods and herbicide types.
Madsen (2000); USA	Summary of the advantages and disadvantages of various macrophyte control methods including mechanical and chemical. Biased towards lakes.	- Provides table of advantages and disadvantages of various mechanical methods and herbicide types.
Scottish Environment Protection Agency (2009); Scotland	Provides guidance on the establishment and sustainable management of vegetation in the riparian zone of rivers, lochs and wetlands for the benefit of the environment and people.	- Selective control of macrophytes should be practiced to maintain zones from which fauna can recolonise. - Care should be taken not to spread invasive species. - Cut macrophyte material should be removed from the channel. - Prior to control works the area should be checked to identify and preserve important and protected fauna and flora. - Only herbicides cleared for aquatic use may be used in or beside water.
Durocher & Chilton (2004); USA	Describes the best available strategies and alternative treatment methods for preventing and controlling nuisance aquatic vegetation problems, consistent with the principles of Integrated Pest Management (IPM).	- Provides advantages and disadvantages of various macrophyte control methodologies including mechanical and chemical. - Recommends species-specific control methods.
WWF Scotland (2000); Scotland	A handbook targeted principally at those advising farmers and others responsible for management of waterways. It aims to increase awareness of how farming affects watercourses and to identify simple practical ways in which management could be improved for multiple benefits.	- Advocates maintaining drainage ditches on a rotational basis leaving 30–50% of vegetation undisturbed, working short sections on alternate banks to leave undisturbed areas as a source for recolonisation. - Lists disadvantages of herbicide use. - Advocates use of selective herbicides rather than broad-spectrum. - Limit potential deoxygenation effects by only treating one-quarter to one-third of area at a time. - Use only herbicides cleared for aquatic use and follow manufacturer's instructions precisely.

(i.e., otters, water voles, badgers), it contains numerous techniques that may be beneficial in the New Zealand context. Additionally, this document could serve as a template for the development of a similar guide specific to New Zealand flora, fauna, and waterways.

While a number of these international documents provide some apparently good techniques to minimise the ecological impacts of macrophyte control, none of these techniques are supported by quantitative assessment of their efficacy. However, some techniques have solid theoretical grounding. For example, ecological theory indicates that an environment with greater habitat variability will support a more diverse range of species than one with lower habitat variability. Thus it is highly likely that in many instances where patches of macrophytes and marginal vegetation are retained, rather than the complete removal or 'scorched earth' approach, then biodiversity is also maintained. But research is certainly required to determine the proportion of vegetation that needs to be retained to achieve such an outcome while still maintaining the required drainage function that necessitated macrophyte removal.

6.2 New Zealand

Best practice documents or guidelines that relate to mechanical and chemical macrophyte management can be found in a number of New Zealand documents that usually cover land and water management practices in general (Table 5). Common themes include cleaning machinery between sites to prevent the spread of unwanted plants/organisms, minimising bed disturbance, and not spraying entire water bodies (i.e., leaving some areas undisturbed). While these documents are well intended, perhaps the most important place for best practices to be stated is in the rules of regional planning documents, which have legal standing and thus must be followed to avoid penalty (Table 6). Indeed, some regional council's have environmental codes of practice that are an auxiliary document to the regional plan and are referred to in the planning rules (e.g., Horizon Regional Council and Hawke's Bay Regional Council).

As with the international best practices/guidelines none of the New Zealand documents provide any quantitative study data to support any of the advocated management techniques. The lack of studies into the effectiveness and impacts of macrophyte management techniques was recognised by Hudson (2005), who considered there is still much to be learned before comprehensive best management practices for the control of problem macrophytes can be promoted.

A review of the regional plans from throughout New Zealand indicated the mechanical clearance of macrophytes is a permitted activity (subject to conditions) for 15 out of 16 regional councils/unitary authorities, and while not clear in their plan, I can only assume is also permitted by the other council (West Coast Regional Council; Table 6). The conditions vary among the regions, with some appearing to have very few conditions relating to minimising the ecological impacts of mechanical macrophyte clearance. Common themes include not impeding fish passage, not leaving any material on the streambed, and meeting sediment discharge rules. A few of the regions place restrictions on disturbance of certain reaches at certain times of year to protect inanga and trout spawning activity and/or on the area or length of a water body that can undergo mechanical clearance at one time (Table 6). Some also restrict or prohibit mechanical macrophyte clearance in certain water bodies of high natural value.

The chemical control of macrophytes is a permitted activity (subject to conditions) in 12 out of 16 regional councils/unitary authorities, although the rule of one council (Bay of Plenty Regional Council) seems to only refer to the spraying of emergent plants (Table 6). Of the other bodies, it was a discretionary activity for two (Marlborough District Council and Greater Wellington Regional Council), a controlled activity for one (Nelson City Council), while its consent status could not be determined for the Tasman District Council. The most common condition applied was that the herbicide used needed to be approved for aquatic use in New Zealand and had to be applied according to the manufacturer's instructions. Of the 12 regions where it is a permitted activity, only four had conditions that specifically mentioned avoiding negative ecological impacts (e.g., fish kills, low DO levels). As with mechanical clearance, some regions restricted/prohibited macrophyte control with chemicals in certain designated water bodies of high natural value. It must be noted that the structure of some regional plans made them confusing and hard to follow, making the finding of the appropriate rules difficult. Some were too verbose while others were too brief, which I assume is a direct result of the particular interests or concerns of the personnel involved in drafting the rules related to mechanical and chemical control of macrophytes.

It is apparent that in many regions the ecological impacts of mechanical clearance and chemical control of macrophytes for drainage purposes have not been a priority. This may be because many of the waterways that are subject to such activities are often considered as 'drains' with little ecological value. However, in many instances such waterways contain a significant number of endemic invertebrate and fish (and sometimes plant) species often in a landscape dominated by exotic biota. Often they may be the last remnants of large wetlands (as in parts of the Waikato). As such some rules to protect these taxa are warranted.

Best practices/guidelines for macrophyte management may also be found in the contracts between local and regional government bodies and the contractors who actually undertake the work. As these contract documents may be the only document the operators on the ground actually read in relation to macrophyte management, it is important that any best practices/guidelines are integrated into them. Time restraints prevented an attempt to obtain and review such documents.

TABLE 5 Summary of New Zealand guidelines or best practice documents that include content related to limiting the ecological effects of macrophyte management activities. URL's where available are provided in the references (Section 9).

Document	Summary	Main Points Related to Limiting Ecological Harm of Macrophyte Management
Environment Waikato (2006); Best practice environmental guidelines - land drainage	Prepared to assist regional and local authorities, landowners, consultants, and contractors with the creation of new drains and maintenance of existing land drainage. Focuses on environmental outcomes but recognises operational need for maintaining drainage outfall and minimising long term costs.	- Advocates prevention of macrophyte growth (e.g., shading where appropriate and reducing nutrient inputs) - Limit spread by ensuring machinery used is cleaned between waterways. - Minimise disturbance, avoid sensitive areas, and rehabilitate disturbed land. - Consult with council staff and landowners about habitat value and requirements for avoiding sensitive times and places. - Where excavators are used, use a weed-rake or stream-cleaning bucket to allow water and some stream fauna to escape back into drain. - Avoid spraying native bank vegetation. - Only spray down centre of drain, not along banks. - Spray weeds when they are small.
Hawke's Bay Regional Council (2007); Environmental code of practice for river control and drainage works	Originally written in 1999 (and revised since), this environmental code of practice for river control and drainage works aim to provide clear standards of practice for such works, document the environmental enhancement and preservation practices to be followed to protect conservation interests, clarify public vehicular access locations, and clearly identify those works that are permitted activities in the Regional Plan.	- Where weeds are cut (including by boat) wherever practical cut weeds shall be removed from the river or drain and disposed of on dry land. - Weed cutting shall not be undertaken at specified locations during the whitebaiting season. - Wherever possible a dense sward of grass cover shall be retained on the sides of all channels to provide a filtering effect from overland flow.
Hudson (2005); H20-DSS hillslopes to oceans: decision support system for sustainable drainage management	A decision support system developed to assist waterway management decisions by providing a series of critical Best Management Practices (BMPs), specifically focused on practical drainage management. These BMPs are supported by an analysis of environmental issues within a decision-making framework that encourages that both effects and causes be considered. It has been written to assist landowners, contractors and drain managers. While focusing on environmental benefits it recognises the operational need for maintaining drainage outfall and minimising long term costs.	- Advocates use of a decision framework starting with 'problem framing' and then the development of an appropriate management plan to avoid exacerbating the problem or have major unintended effects. - Considers much is still to be learned before comprehensive BMPs can be drafted and promoted for the control of problem macrophytes, and notes that some treatments are ineffective or even counterproductive. - Treatments should be considered as experiments with monitoring, assessment, and reporting of successes and failures to aid in refinement methodology. - Provides 11 BMP summary sheets two of which have direct relevance to macrophyte control (No. 3: channel excavation and No. 6: *Glyceria maxima* (reed sweet grass))
Ministry for the Environment (2001); Managing waterways on farms - guide to sustainable water and riparian management in rural New Zealand	Aimed at those who provide advice to farmers about how they manage their land, and to those farmers who wish to enhance their properties and reduce the impacts of their farming operations. For use by field officers, consultants, farmers, landcare group members, and hapu and whanau who have practical involvement "on the ground". Seeks to provide some background information about the sources, causes and processes involved with the deterioration of streams in farmed catchments and the consequences of that deterioration. Readers can thus better understand the problems and, as a consequence, be better equipped to manage the problems.	- Has section on maintenance of farm drains that describes the direct and indirect impacts of mechanical clearing and chemical spraying on biota. - Avoid spraying/excavating entire length of drain (leave undisturbed sections) or excavate only one side of drain/spray only the centre. - Avoid spraying/excavation during peak fish spawning and migration and bird nesting periods. - Practice spot spraying to avoid damaging riparian vegetation. - Leave spoil close to drain bank so fish in spoil have a change to re-enter water via the shortest routes. - Ensure machinery is thoroughly cleaned to reduce risk of spreading nuisance plants. - Ensure any exposed banks are seeded/re-planted soon after clearing.

Horizons Regional Council (2010a); Environmental code of practice for river works	An environmental code of practice for river works designed to accompany the One Plan (regional plan). It sets out standards for good practice for a range of river works activities. Detailed standards of good practice are given for mechanical cleaning and weed control by herbicide application in drainage channels/ modified streams. Additionally, a list of significant sites/reaches is provided (as defined in the One Plan) where all activities are strictly controlled, often being prohibited (including macrophyte control).	- All machinery used shall be thoroughly cleaned of weed and silt to minimise the risk of spreading nuisance macrophytes. - Care will be taken to minimise bed disturbance and the design profile of the channel shall be maintained. - Special care will be taken at potential inanga spawning sites. - Shade shall be retained over the channel to help reduced weed growth where practicable. - Frequency of mechanical clearing of drain shall be no more than is needed to maintain design flows and water levels as determined by the scheme's management plan. - Cleaned drains shall retain small imperfections on bed to provide some habitat diversity. - Macrophyte control activities must comply with the special standards that have been set at certain sites of high value (as defined in the One Plan). - Upper bank vegetation shall be maintained and a vegetation buffer strip shall be retained immediately adjacent to the water body where practicable.

TABLE 6 **Summary of mechanical and chemical macrophyte control rules from New Zealand regional plans. Only the rule conditions directly relevant to ecological impacts of mechanical and chemical macrophyte control are summarised. Rules are not given in their entirety due to space restrictions but all plans are freely available online and URL's are given in the references (Section 9).**

Regional Authority	Mechanical Clearance	Chemical Control
Environment Southland (2010); Regional Water Plan Section B (Discharge Rules (to water)) & Section E (Bed disturbance rules)	**Section E, Rule 46 (pg. 7)** Permitted activity provided the following conditions are met. - Bed disturbance shall be minimised. - Fish passage shall not be impeded. - All reasonable steps shall be taken to return captured or stranded fish to the water. - No disturbance to trout or inanga spawning habitats at prescribed time of year. - Machinery must be cleaned between sites to prevent spread of problem plants. - If watercourse is spring-fed, then removal of macrophytes shall be kept to the absolute minimum.	**Section B, Rule 4 (pg. 7)** Permitted activity provided the following conditions are met. Consent required in Natural State Waters. - Approved for aquatic use in NZ and used according to manufacturer's instructions. - Does not result in any significant adverse effects on aquatic life, other than the target species.
Otago Regional Council (2011); Regional Water Plan	**Rule 13.7.1.1 (pg. 224)** Permitted activity for a list of prescribed invasive exotic species. No conditions relating to ecological impacts.	**Rule 12.7.1.1 (pg. 195)** Permitted activity provided the chemical is approved for aquatic use in NZ and used according to manufacturer's instructions.
Environment Canterbury (2011); Natural Resources Regional Plan Chapter 4 (Water quality) & Chapter 6 (Beds of lakes and river)	**Chapter 6, Rule BLR6 (pg. 40)** Permitted activity provided the following conditions are met. - Any discharge of sediment shall not exceed specified levels. - Fish passage is not obstructed and activity can't take place in significant salmon spawning sites. - No vegetation shall be in disposed of in bed of watercourse/lake. Different rule (BLR7) applies in water bodies designated as having "high naturalness", but has same general conditions as above.	**Chapter 4, Rule WQL17 (pg. 153)** Permitted activity provided the following conditions are met. - Approved for aquatic use in NZ and used according to manufacturer's instructions. - Set time-area restrictions (e.g., not exceeding 5000 m^2 in river or artificial watercourse in 24 hour period). - Specific water body restrictions.

TABLE 6 Continued

Regional Authority	Mechanical Clearance	Chemical Control
West Coast Regional Council (2011); Proposed Regional Land and Water Plan	No particular rule appears to relate to this activity (assumed to be permitted activity).	**Rule 65 & 66 (pg. 81)** Permitted activity provided the chemical is approved for aquatic use in NZ and used according to manufacturer's instructions.
Marlborough District Council (2011); Marlborough Sounds Resource Management Plan Chapter 26 (General rules having application in all zones, rivers, riverbeds, and lakes).	**Chapter 26, Rule 26.1.6.1.9 (pg. 26-10)** Permitted activity provided the following conditions are met. - Mechanical cutting shall not occur more than once in any 12 month period on any river reach. - Mechanical cutting shall not be carried out over more than 90% of the channel width with an uncut strip left on each side.	Discretionary activity
Tasman District Council (2011); Resource Management Plan Chapter 28 (Rules of activities in the beds and on the surface of rivers and lakes).	**Chapter 28, Rule 28.1.6.1 (pg. 28/8)** Permitted activity provided the following conditions are met. - Not undertaken in certain designated water bodies. - Sediment discharge rules are adhered to.	Unknown as no direct reference to this activity was found.
Nelson City Council (2011); Nelson Resource Management Plan Chapter 12 (rules rural zone).	**Chapter 12, Rule FWr.1 (pg. 12-74)** Permitted activity provided the following conditions are met. - Location and timing conditions relating to spawning of inanga, koaro, kokopu species, and trout. - Does not result in any significant adverse effects on aquatic life. - Fish passage shall be maintained. - Any disturbed riparian areas are rehabilitated to the same or better state than existed prior to disturbance.	**Chapter 12, Rule FWr.23 (pg. 12-114)** Controlled activity if the the chemical is approved for aquatic use in NZ and used according to manufacturer's instructions. Control is reserved over location, area, and timing of discharge and adverse effects on non-pest or non-target freshwater organisms.
Greater Wellington Regional Council (1999); Regional Freshwater Plan for the Wellington Region.	**Rule 39 (specific to farm drainage channels) (pg. 129)** Permitted activity provided all reasonable steps shall be taken to minimise the release of sediment to water during the activity.	Discretionary activity or non-complying if into water bodies designated to be managed in their natural state.

Horizons Regional Council (2010b); Proposed One Plan Chapter 14 (Discharges to air) & Chapter 16 (Activities in artificial watercourses, beds of rivers and lakes, and damming).	**Chapter 16, Rule 16-13 (pg. 16-20)** Permitted activity provided the activity is undertaken in accordance with the appropriate sections of the Environmental Code of Practice for River Works (Horizons Regional Council, 2010a).	**Chapter 14, Rule 14-2 (pg. 14-5)** Permitted activity provided the followiing conditions are met. - Approved for aquatic use in NZ and used according to manufacturer's instructions. - No discharge within any designated rare, threatened or at-risk habitats except for control of pest plants. There is also a section in the Environmental Code of Practice for River Works (Horizons Regional Council, June 2010a) regarding weed control in drainage channels/modified stream with herbicide.
Hawke's Bay Regional Council (2006); Regional Resource Management Plan.	**Rule 70 (pg. 182)** Permitted activity provided the following conditions are met. - Fish passage is not impeded. - Activity undertaken in accordance with the Hawke's Bay Regional Council Environmental Code of Practice for River Control and Drainage Works (2007).	**Rule 10 (pg. 131)** Permitted activity provided the chemical is approved for aquatic use in NZ and used according to manufacturer's instructions.
Taranaki Regional Council (2001); Regional Fresh Water Plan.	**Rule 65 (Use of river and lake beds) (pg. 138)** Permitted activity provided the following conditions are met. - No removed vegetation to remain in bed of river/lake. - Bed disturbance is minimised. - Vegetation removal does not have significant adverse effects on aquatic life and instream habitat. - Sediment disturbance shall not conspicuously change visual clarity of water beyond reasonable zone of mixing. Pg. 145, Rule 78 (Land drainage). Permitted activity provided the following conditions are met. - Bed disturbance is minimised. - Activity does not have significant adverse effects on aquatic life or stream habitat	**Rule 32 (pg. 116)** Permitted activity provided the following conditions are met. - Approved for aquatic use in NZ and used according to manufacturer's instructions. - Discharge shall not cause after reasonable mixing, any conspicuous change in visual clarity or any significant adverse effects on aquatic life. Appendix VI of plan (Good agrichemical spray management practices) includes a range of best practices, some of which are aimed at minimising negative ecological effects. - Should spray when water temperatures are low, the weed is growing and plant biomass is not high. - Should spray parts of water body at intervals of at least 10 days (i.e. not spraying whole area at once).
Gisborne District Council (a,b); Combined Regional Land & District Plan Chapter 7 (Beds of lakes and rivers) & Discharges Plan Chapter 4 (Hazardous substances)	**Chapter 7, Rule 7.7.4 (pg. 9)** Permitted activity provided the following condition is met. - No vegetation debris is to be left in the river/lake bed. Chapter 7, pg. 12, Rule 7.7.13 refers to clearance and maintenance of drains. - Permitted activity with no conditions relating to minimising ecological impacts.	**Chapter 4, Rule 4.5.1 (pg. 10)** Permitted activity provided the chemical is approved for aquatic use in NZ and used according to manufacturer's instructions.

TABLE 6 **Continued**

Regional Authority	Mechanical Clearance	Chemical Control
Bay of Plenty Regional Council (2008); Regional Water & Land Plan Chapter 9 (Regional rules)	**Chapter 9, Rule 69 (pg. 296)** Permitted activity provided the following conditions are met. - Where weeds are cut, the all cut material shall be removed from the stream. - Certain listed water bodies and all tidal reaches have timing restrictions, presumably to protect fish migration and spawning. - Where weed-cutter boats are used marginal vegetation shall only be trimmed, not removed. - Fish passage is not impeded. - Bed disturbance is minimised.	**Chapter 9, Rule 16 (pg. 220)** Appears to be for spraying of emergent vegetation only and no rule referring to chemical control of submerged vegetation was found. Permitted activity provided the following conditions are met. - Approved for use over water in NZ and used according to manufacturer's instructions. - Shall not result in any fish kills. - Timing restriction for use in all tidal reaches. Also an advisory note stating users should manage extent of dead and rotting vegetation in a water body as to not decrease water oxygen levels to a level that kills fish.
Waikato Regional Council (2007); Waikato Regional Plan Chapter 4 (River & lake bed module) & Chapter 6 (Air module)	**Chapter 4, Rule 4.3.9.2 (pg. 4-77)** Permitted activity provided the following conditions are met. - Certain listed water bodies have timing restrictions to protect trout and native fish. - All material from vegetation clearance must be removed from the channel. - Must comply with suspended solids discharge standards. Discretionary activity for water bodies designated "Natural State".	**Chapter 6, Rule 6.2.4.9 (pg. 6-56)** Permitted activity provided the following conditions are met. - Used according to manufacturer's instructions. - Application and consequent breakdown of vegetation shall not result in the death of fauna (and/or residues being detected in fish).
Auckland Regional Council (2010); Auckland Regional Plan: Air, Land, & Water Chapter 4A (Agrichemicals – applications & use) & Chapter 7 (Beds of lakes and river and diversion of surface water)	**Chapter 7, Rule 7.5.15 (pg. 304)** Permitted activity provided the following conditions are met. - Continuous length of bed disturbance shall not exceed 100 m and period of two months shall elapse before an area is disturbed within 100 m of a previously disturbed are in the same water body. - Any materials used shall not be toxic to aquatic organisms. - All reasonable steps shall be taken to minimise the release of sediment during activity. - All cleared material shall be removed from the channel. - Bed shall be restored to a profile that does not impede fish passage.	**Chapter 4A, Rules 4A.5 (pg. 133)** Permitted activity provided the chemical is used according to manufacturer's instructions.
Northland Regional Council (2004); Regional Water & Soil Plan Part V (Rules)	**Part V, Rule 27.1.3 (pg. 220)** Permitted activity provided the following conditions are met. - Not to be carried out in water body designated as having outstanding values. - Any vegetation clearance shall be limited to that required to maintain free flow of water or to remove exotic weed species. - All material must be removed from the bed of the water body. - Sediment discharge shall not cause certain changes within prescribed time and distance.	**Part V, Rule 18.1.3 (pg. 170)** Permitted activity provided the chemical is approved for use over water in NZ and used according to manufacturer's instructions.

7 RECOMMENDATIONS

7.1 Best Practices

There is a lack of quantitative data on the relative efficacy of the various best practice techniques to minimise the negative ecological impacts of mechanical and chemical macrophyte control. Despite this there are certainly a few techniques that are worth adopting as their benefits are either intuitive and relatively assured, or the potential effects of not adopting them are sufficiently negative that a conservative approach is warranted.

7.1.1 Leave a Portion of Macrophyte Habitat Undisturbed (Mechanical and Chemical)

It is a fairly safe assumption that in most situations the total physical removal or death of macrophytes would have negative impacts on the fauna that use these macrophytes as food and/or habitat. It follows that selective retention of patches of macrophytes would provide a refuge for many species that make use of such habitat. Numerous studies have recommendations related to leaving some of the macrophyte growth undisturbed for this reason (e.g., Kern-Hansen, 1978; Swales, 1982; Armitage *et al.*, 1994; Garner *et al.*, 1996; Monahan & Caffery, 1996; McMurtrie, 2001). Such a practice is also mentioned in a number of the best practice/guideline documents that were found (e.g., WWF Scotland, 2000; Ministry for the Environment, 2001; Buisson *et al.*, 2008; Scottish Environmental Protection Agency, 2009). Another benefit is that if desirable native macrophytes are present, then the selective removal of only problem plant species may allow native species to expand their coverage at the expense of the less desirable exotic species.

It is difficult to ascribe a set proportion of macrophyte cover that should remain undisturbed, and this may indeed vary depending on factors such the fauna present, the macrophyte species present, and the size of the waterway. However, Buisson *et al.* (2008) provides a series of techniques complete with diagrams showing various patterns on how macrophyte cover can be retained with minimal impact on flood or drainage management.

7.1.2 Only Spray a Set Area of Macrophytes at Any One Time (Chemical)

In some situations the rapid death and decay of macrophytes following treatment with herbicide will cause a spike in oxygen demand that may reduce DO to levels that stress or even kill some fish and invertebrate species. From the literature it would seem such an occurrence is hard to predict but as the consequences can be dire it would be pragmatic to take a conservative approach. Thus only spraying a set area of drain at any one time to limit the volume of decaying plant material is a sensible practice. Additionally, this approach will also contribute to maintaining undisturbed areas of macrophyte cover with associated benefits as described in Section 7.1.1 above.

The exact ratios of sprayed versus unsprayed macrophyte cover to avoid potential detrimental decreases in DO levels are unknown and likely vary from location to location.

7.1.3 Recovery and Return of Fauna from Removed Material (Mechanical)

A number of studies have recorded the removal of fauna from waterways in association with the mechanical removal of macrophytes (e.g., Engel, 1990; Serafy *et al.*, 1994; Ryder, 1997; Booms, 1999; Young *et al.*, 2004). The recovery of larger species such as fish (especially eels), freshwater crayfish, and freshwater mussels from the removed plant material and their return to the waterway could save numerous individuals from certain death. To minimise the number of animals removed from waterways, the use of weed buckets (which have gaps through which some animals will fall back into the waterway) rather than standard closed-bottom excavator buckets should also be encouraged (Young *et al.*, 2004; Environment Waikato, 2006).

7.1.4 Avoid/Limit Macrophyte Control Activities at Certain Locations and/or Times (Mechanical and Chemical)

Certain locations may have high ecological values in that they provide habitat for rare or uncommon species (e.g., mudfish) or are known sites of fish spawning (e.g., inanga). It is thus sensible to avoid significant instream disturbances such as macrophyte control either permanently or at certain times of year. Some regional councils already do this (e.g., Environment Southland, Environment Canterbury, Horizons Regional Council, and Waikato Regional Council). Timing restrictions typically relate to fish spawning (mostly inanga spawning in coastal drainage schemes) while permanent location restrictions would usually occur at relatively pristine sites (i.e., not usually drainage water bodies) although some sites of lower habitat quality may have such restrictions if they have certain rare or uncommon taxa present (e.g., mudfish species, freshwater crayfish, and freshwater mussels).

Given it is relatively easy to predict potential inanga spawning sites there is no reason why macrophyte control activities can't be avoided in such reaches during the spawning season and there should be a rule relating to this in all regional plans in New Zealand. I suspect the more general ecological values of waterways managed for land drainage in New Zealand are unknown in many regions as such waterways are assumed to be degraded and rarely have their fauna surveyed. Thus it is quite likely that sites with high ecological values are subject to regular disturbance from macrophyte (and other) management activities nationwide.

7.2 Knowledge Gaps

Hudson (2005) stated, "While considerable research has been undertaken overseas and in New Zealand, much is still to be learned before comprehensive BMPs (best management practices) can be promoted for a range of aquatic vegetation control. Some treatments are ineffective or even counterproductive." This is certainly still the case and quality empirical studies are required to test and refine best practices for the management of macrophytes in New Zealand water bodies.

7.2.1 How Much Macrophyte Cover Should Be Left Undisturbed?

It is highly likely that leaving a proportion of the macrophyte cover undisturbed to provide a refuge for stream biota and/or to minimise the likelihood of hazardously low DO levels would be effective. However, the exact area that should be undisturbed to achieve these goals is unknown. There is a desperate need for studies to investigate this issue so best practice guidelines can be produced that actually provide some guidance as to the area of macrophytes that should be retained.

7.2.2 How Effective is Macrophyte Control at Improving Land Drainage?

Given the aim of clearing macrophytes in waterways is usually to maintain drainage function, there is minimal information on the effectiveness of such activities. Hudson & Harding (2004) indicated that there was little or no documented evidence on the effects of weed clearing on drain hydraulics or on the effects on the surrounding land's water table. They further stated that if we do not understand how efficient these activities are, then it is difficult to develop and promote improved practices.

7.2.3 Identifying the Ecological Value of Drainage Waterways

It is likely that many lowland waterways that are managed for land drainage purposes have never had their ecological values recognised or assessed. If best practices are to be developed specifically to protect New Zealand's unique aquatic biota, then understanding what fauna and flora are present and which require protecting, is imperative to developing appropriate best practice guidelines. Thus surveys with the aim of formally documenting the ecological value of drainage waterways are required.

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