Drainage management in New Zealand

A review of existing activities and alternative management practices

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ABSTRACT

The literature on drainage maintenance activities, both within and outside New Zealand, was reviewed. Current drainage management activities used by regional and district councils were summarised from responses to a mail survey. The environmental and economic costs of the most widely adopted strategies, specifically: channel excavation, weed clearance by hand and cutter boat, chemical spraying, and controlled grazing, were assessed. Nutrients, chemicals, and soil erosion problems associated with maintenance were considered as causal factors in degrading in-stream habitats, and altering aquatic plant, benthic invertebrate, and fish communities. The literature identified at least 20 native and introduced aquatic plant species in New Zealand drains. Benthic invertebrate communities were generally low in diversity and dominated by snails, worms, and midges, whereas approximately 30 freshwater fish species have been recorded in lowland drains. Alternative drain management strategies from within and outside New Zealand were canvassed, particularly: performance-based management (i.e. measuring improvements in flow and water quality), riparian management (e.g. shading and fencing), naturalisation of drains (i.e. meandering and increasing in-stream habitat). Gaps were identified in New Zealand knowledge of how best to manage drains. There was a basic lack of understanding of the effects of current practices on the hydrology and ecology of drains. While much is still to be learned about specific applications, and the cost-effectiveness of best-management practices in New Zealand, several management principles and practices can be tested and implemented immediately.

Keywords: drainage, management, best practice, drain ecology, aquatic weeds, benthic invertebrates, fish, New Zealand

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1. Introduction

Drainage management is an intrinsic component of successful and sustainable agriculture in most regions throughout New Zealand. Historically, extensive construction of drainage networks has been common practice, so that by 1983 the New Zealand Land Drainage and Rivers Association maintained 4100 km of drains nationally (Hughes 1984). The development of new drainage networks continues. In 2000, Environment Southland alone maintained some 90 community drainage systems on behalf of ratepayers, totalling about 1285 km of channels. This probably represents about only 10% of the total drainage network in Southland (Noel Hinton, Environment Southland pers. comm.). Nationally, the costs of maintenance of drainage networks are considerable. Although no estimate of the total expenditure is available, large councils such as Environment Waikato allocate $1.53 million per annum (with additional spending on capital works for drain upgrading and maintenance of culverts, floodgates, pumping stations, etc.), and Environment Southland budgeted $520 000 in 2000 (Table 1). The actual costs of drainage maintenance nationally are far greater when the hidden costs associated with drains maintained by individual farmers are considered.

TABLE 1. REGIONAL AND DISTRICT COUNCIL-MAINTAINED DRAINAGE NETWORKS, FROM RESPONSES TO THE CAWTHRON INSTITUTE SURVEY, OR FROM ANNUAL PLANS.

COUNCILS	MAINTAINED DRAIN		OTHER DRAINS	TOTAL
	LENGTH (km)	COSTS ($)	(km)	(km)
Hawke's Bay	> 465			
Manawatu–Wanganui	700	200 000		
Marlborough	160			
Northland	n.a.			
Southland	1285	520 000	c. 11 000	c. 12 000
Tasman		420 000*		
Waikato	1800	c. 1 530 000		
Wellington	155	70 000		

* Tasman District Council costs from 1996/97 annual plan. Scheduled maintenance has ceased.
n.a. = Not available.

In this review drainage systems are defined as natural, or artificial channels, sub-surface collection systems, and water control structures that are managed for water drainage purposes on farmland. The main functions of these drains are to remove and control excessive surface water, and lower water tables on farmland.

Three main tenets underpin this review:

- Drains have multiple functions: they should act as efficient, cost-effective channels for removing excess water, while still providing sustainable habitats for flora and fauna
- Adopting effective and sustainable drain maintenance practices requires understanding of both the hydraulic and ecological effects of these practices

- Drains are a part of, and intimately linked to, larger freshwater systems

Popular perceptions about what drainage maintenance activities are appropriate are changing as expectations about farming, and how farming relates to the environment, change. For example, the shift to certified organic farming has involved a change in thinking about the acceptability of the use of chemicals around the farm.

There is also increasing recognition that:

- Many farm drains are environmentally and ecologically important in their own right, and that current drainage management activities may have significant adverse effects
- The statutory requirement to avoid, remedy, or mitigate significant adverse environmental effects stated in the Resource Management Act (1991) may also apply to many drains

These views have the potential to cause conflict between drainage engineers, who might focus on the hydraulics of drainage networks, and environmental advocates (e.g. DOC and Fish & Game) who support minimal disturbance to streams and drains. The ultimate objective of sustainable drainage management should be to rationalise these apparently opposing perspectives through the use of best management practices, based on best available science and adaptive management.

This review summarises the literature and state of our knowledge on several key aspects of drainage management. Much of the information presented here has come directly from discussions with regional, and district council and Department of Conservation staff. The impetus for this review came from concerns raised by DOC, MfE, and MAF that some current maintenance methods are costly, inefficient, and may threaten aquatic species of conservation interest. It is not an exhaustive review of all current management techniques, nor has it been possible to adequately assess all alternative practices. The first part of this document summarises our current understanding of the ecology of drains. The commonest drainage management practices used in New Zealand are discussed. The next section addresses alternative management practices from both within New Zealand and overseas, and assesses the advantages and disadvantages of these alternative practices. Finally, to clarify research priorities for the future, gaps in our understanding of drainage systems are identified, and recommendations for improving current management are made.

2. Ecology of drains

2.1 PHYSICAL HABITAT

Councils manage a wide variety of natural and engineered channels as part of their drainage networks. These drains vary in physical form (e.g. width, depth, channel shape and channel pattern, bed and bank substrates, and gradients), as well as bank vegetation. Other factors that influence the ecological integrity of drains, such as runoff regime and water quality, are also highly variable.

Furthermore, the distance inland, presence of physical barriers (e.g. culverts and floodgates), truncation of the drainage system, and cumulative land uses may influence aquatic fauna. Drains are also usually part of a network that eventually feed into larger rivers and streams, therefore inputs into farm drains are usually cumulative and may directly impact larger downstream waterways. Thus the ecological importance of an individual drain may range from negligible to highly valued, however, its role in the functioning of the wider waterway network to which it is linked must also be considered.

To our knowledge, there has been no systematic assessment of agricultural drains, or of their values as habitat in New Zealand, although methods to undertake such surveys are available (e.g. Platts et al. 1983; Plafkin et al. 1989; Newton et al. 1999). However, preliminary assessments of habitat use, or potential use, are used to guide in-stream activities in Southland (e.g. Hudson 1998a).

General water quality conditions have been assessed in several national and regional surveys of lowland streams (Close & Davies-Colley 1990a, 1990b; Environment Waikato 1998; James et al. 1999; Tasman District Council 2000). However, agricultural streams and drains have been the subject of fewer studies (Marshall & Winterbourn 1979; Harding & Winterbourn 1995; Quinn et al. 1997; Wilcock et al. 1998; Young et al. 2000). Point-source and non-point-source inputs into farm waterways and drains are relatively well documented, and are reviewed by Nguyen et al. (1998).

The major water quality conditions of concern are:

- Elevated nitrogen and phosphorus levels
- Increased suspended sediment and turbidity
- Increased agricultural chemicals
- Low dissolved oxygen
- Increased range of water temperatures

2.2 ALGAE AND MACROPHYTES

Algal communities have been widely studied in streams and rivers throughout New Zealand (Biggs & Price 1987; Biggs 2000), however virtually no work has been documented on agricultural drains. Marshall (1978) conducted one of the few studies in which benthic algal biomass, but not species richness was assessed in a small Canterbury drain. He found relatively low algal biomass (10–330 mg per cubic metre) despite relatively high nitrate, and light levels. However, algal biomass in this study may have been reduced by heavy siltation and grazing pressure from benthic invertebrates.

Aquatic weeds are frequently abundant throughout New Zealand drains, and several studies have identified weed species of concern (e.g. the oxygen weed *Egeria* in Marlborough and Christchurch—Young et al. 2000). Marshall & Winterbourn (1979) found different species dominated the communities in different parts of a Canterbury drain, however, the most abundant species were the pondweed *Potamogeton* spp., the starwort *Callitriche* sp., swamp willow weed *Polygonum* sp., *Azolla* sp., the Canadian pondweed *Elodea* sp., the water milfoil *Myriophllum* sp., the duckweed *Lemna* sp., the watercress *Nasturtium* sp., and the water buttercup *Ranunculus* sp. In Toenepi Stream, Waikato, three main aquatic weed species dominated the drain: a native stonewort *Nitellla hookeri*, *Potamogeton* spp. (a native species *P. ochreatus* and the introduced *P. crispus*), and *Polygonum* sp. (Wilcock et al. 1998). Common aquatic weed species found in drains are listed in Table 2.

TABLE 2. COMMON AQUATIC WEED SPECIES RECORDED IN NEW ZEALAND DRAIN AND FARM WATERWAY STUDIES*.

SCIENTIFIC NAME	COMMON NAME
Alisma spp.	Water plantain
Azolla spp.	Azolla
Bidens frondosa	Beggar's tick
Callitriche spp.	Starwort
Carex secta	Niggerhead
Egeria densa	Oxygen weed
Elodea canadensis	Canadian pond weed
Glyceria fluitans	Floating sweet grass
Lagarosiphon major	Oxygen weed
Lemna minor	Duckweed
Mimulus guttatus	Monkey musk
Myriophyllum spp.	Water milfoil
Nasturtium spp.	Watercress
Nitella hookeri	Nitella (Stonewort)
Phormium tenax	New Zealand flax
Polygonum spp.	Swamp willow weed
Potamogeton spp.	Curly leaved pondweed
Ranunculus spp.	Water buttercup
Riccia fluitans	Liverwort
Typha orientalis	Raupo

* Burnet 1972; Edwards & Moore 1975; Marshall & Winterbourn 1979; Wilcock et al. 1998; Goldsmith 2000; Young et al. 2000.

2.3 BENTHIC INVERTEBRATE COMMUNITIES

Several studies throughout New Zealand have described the benthic invertebrate fauna of drains. Marshall & Winterbourn (1979) recorded 34 taxa at 4 sites where the benthic communities were dominated by 5 species of worms (*Tubifex* sp., *Limnodrilus* sp., *Lumbriculus* sp., *Potamothrix* sp., and *Nais* sp.), the snails *Potamopyrgus antipodarum* and *Sphaerium novaezelandiae* and the common New Zealand amphipod *Paracalliope* sp. High invertebrate densities are not uncommon in drains, particularly where nutrient and light levels and plant biomass are high. Marshall & Winterbourn (1979) recorded densities of 280 000 animals per square metre at their most nutrient-enriched site. In Southland, Ryder (1997) found 30 invertebrate species in drains in the Oteramika catchment with communities dominated by amphipods, particularly *Paracalliope* sp., and *Paraleptamphopus* spp., which reached densities of 129 000 per square metre. The snail *Potamopyrgus antipodarium* and the mayfly *Deleatidium* were also abundant. In a Waikato drain, Scarsbrook et al. (2000) and Wilcock et al. (1998) found 31 species, with communities dominated by snails, particularly *Potamopyrgus* and to a lesser degree *Gyraulus* and *Physa*. Other important invertebrates included sandflies (*Austrosimulium* spp.), worms, the caddisfly *Oxyethira albiceps* and non-biting midges (Chironimids). In agricultural streams and drains associated with Spring Creek, Marlborough, Young et al. (2000) recorded 32 species of aquatic invertebrates. These communities were generally dominated by amphipods, worms, and *Potamopyrgus*, however in tributaries subject to drain maintenance amphipods were greatly reduced in abundance.

2.4 FISH COMMUNITIES

Most migratory freshwater fish species (e.g. whitebait and eels) may migrate through or use agricultural drains for temporary habitat, refuge, or spawning. New Zealand's three eel species, the freshwater crayfish or koura, freshwater shrimp, and most of the whitebait species and salmonids have been frequently observed in lowland farm waterways (Young et al. 2000). Several threatened species (e.g. the Canterbury mudfish *Neochanna burrowsius*, the Brown mudfish *Neochanna apoda*, and the Giant kokopu *Galaxias argenteus*) have been found in drains, particularly where preferred habitat, such as wetlands, no longer exist (Skrzynski 1968; Cadwallader 1975; McDowall 1990; Goldsmith 2000).

Interrogation of New Zealand's freshwater fish database (a national database managed by NIWA) provides an indication of species likely to be found in agricultural lowland regions throughout the country, while Table 3 lists 29 species recorded from drains.

TABLE 3. FISH FOUND IN DRAINS AND DRAINAGE CANALS IN NEW ZEALAND STUDIES*.

SCIENTIFIC NAME	COMMON NAME	SCIENTIFIC NAME	COMMON NAME
Aldrichetta forsteri	Yelloweyed mullet	*Gobiomorphus cotidianus*	Common bully
Ictalurus nebulosus	Catfish	*Gobiomorphus goboides*	Giant bully
Anguilla australis	Shortfinned eel	*Gobiomorphus breviceps*	Upland bully
Anguilla dieffenbachii	Longfinned eel	*Mugil cephalus*	Grey mullet
Arripis trutta	Kahawai	*Neochanna apoda*	Brown mudfish
Carassius auratus	Goldfish	*Neochanna burrowsius*	Canterbury mudfish
Ctenopharyngodon idella	Grass carp	*Neochanna diversus*	Black mudfish
Cyprinus carpio	Koi carp	*Paranephrops*	Koura
Galaxias anomalus	Roundhead galaxias	*Perca fluviatilis*	Perch
Galaxias argenteus	Giant kokopu	*Retropinna retropinna*	Common smelt
Galaxias fasciatus	Banded kokopu	*Rhombosolea leporina*	Yellowbelly flounder
Galaxias maculatus	Inanga	*Rhombosolea retiaria*	Black flounder
Galaxias vulgaris	Common galaxias	*Salmo trutta*	Brown trout
Gambusia affinis	Mosquitofish	*Scardinius erythrophthalmus*	Rudd
		Tinca tinca	Tench

* McDowall & Lambert 1996; Ryder 1997; Goldsmith 2000; Young et al. 2000; and R.R. Strickland pers. comm.

2.5 MANAGEMENT MEASURES

Most of the regional councils recognise the use of coastal drains by fish and wildlife, and usually avoid maintenance during spawning, nesting, and migration periods. Figure 1 indicates the main spawning, nesting, and migratory periods of fish and bird species commonly associated with drains. However, although these species are known to use drains, no literature exists which identifies or has classified environmentally sensitive drain channel habitats, or the actual or potential use of these habitats. Similarly, few attempts have been made to assess the impacts of drain maintenance on aquatic communities. In contrast, monitoring of effects of drainage management are common place overseas (e.g. British Columbia—Lalonde & Hughes-Games 1997).

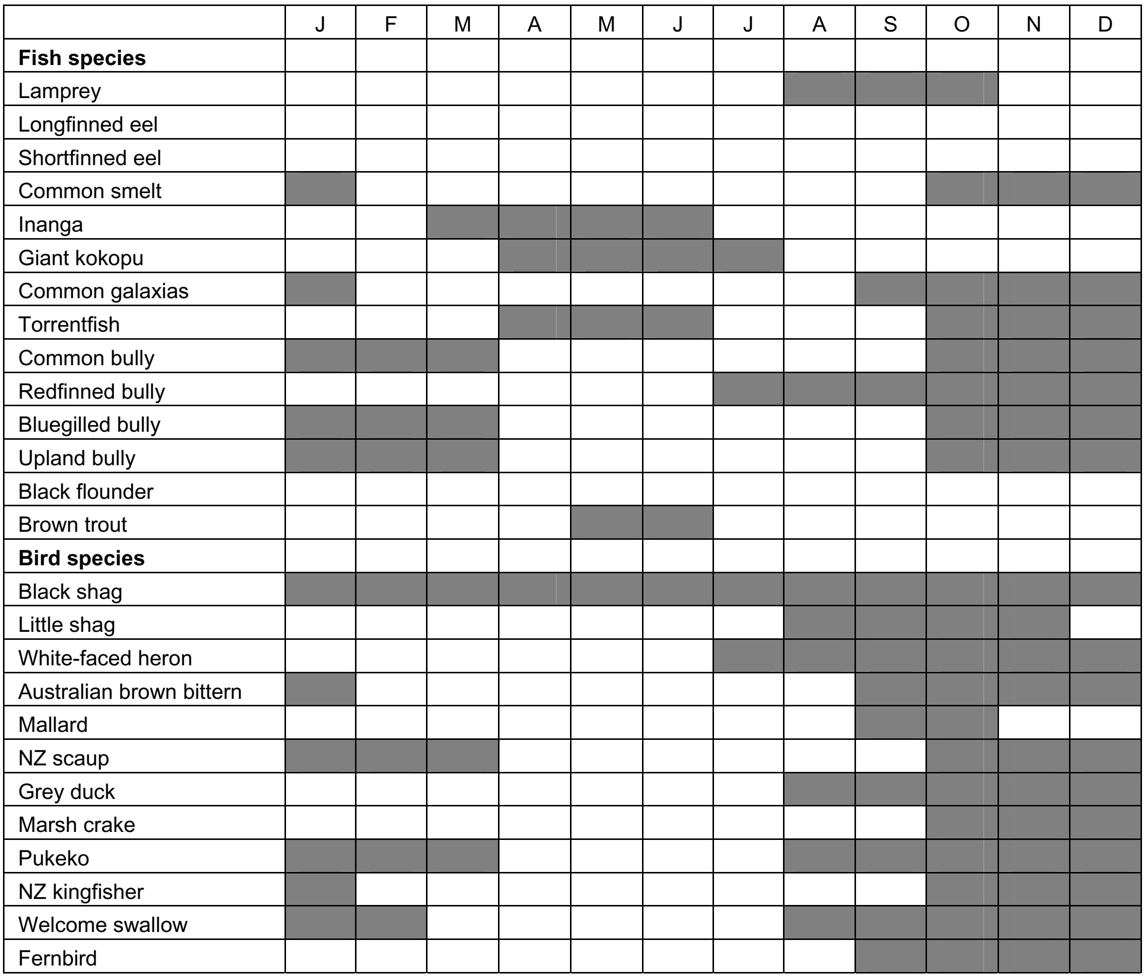


Figure 1. Summary of likely fish spawning and riverine bird nesting periods for species found in farm drains in the Southland region (compiled by Hudson 1998b).

3. Current drainage management practices

3.1 WHY MAINTAIN DRAINS?

Successful land drainage ultimately depends on the ability of drains to remove excess water and yet maintain soils in a physical, chemical, and biological condition favourable for crop growth and grazing (Lalonde & Hughes-Games 1997). Hence, the primary aim of drain maintenance is the removal of excess water (often surface run-off) quickly and efficiently. Maintenance is required because sediment, nutrients, and farm chemicals associated with this run-off accumulate in the drains. It is the addition of these inputs and the response of aquatic plants to high nutrients, sediment and light that are responsible for the poor hydraulic performance of many drains.

3.2 MAINTENANCE PROBLEMS

As part of this report a survey of current drain maintenance practices used by regional and district councils was conducted by the Cawthron Institute (see Appendix 1). Findings from this survey indicated that council staff view clogging of drains, and associated reductions in their hydraulic capacity to be the major problem in drainage maintenance in New Zealand. Council staff suggested that reduced capacity is usually caused by excessive aquatic and riparian plant ('weed') growth, sediment infilling, and debris accumulation, however, there does not seem to be any New Zealand studies that quantify the loss of hydraulic capacity from weed growth or sediment build up. Hudson (1998b) calculated the effects due to sediment and weed build up, based on empirical relations for hypothetical drains. However, the hydraulic characteristics of aquatic and bank vegetation are poorly documented, and effects appear to be highly variable. For example, aquatic weeds may be hydraulically rough at low flow, thus significantly reduce stream flow, but at high flow the plants bend over and are hydraulically smooth, thus increasing drain capacity.

Plant growth, sediment infilling and debris accumulation can all significantly reduce the hydraulic capacity of waterways by changing the streambed roughness, cross sectional area and/or slope of a watercourse. Another important cause of reduced drain capacity is channel instability that usually results from excessive bank erosion or stock trampling.

Although degraded water quality is not generally considered a drainage management problem, drains collect runoff, sediment, and contaminants (e.g. pesticides and fertilisers) from surrounding land. These contaminants strongly influence the plant and animal life that can exist in the drain, and impact downstream freshwater systems into which drains discharge.

3.3 MANAGEMENT STRATEGIES

Drain maintenance is either corrective (e.g. repair of floodgates) or preventative (e.g. riparian planting). One of the key decisions facing managers is when to undertake preventative maintenance. Currently, each regional council has different criteria about when maintenance is required and how the effectiveness of maintenance will be measured. In North Waikato, drain maintenance is considered effective if 38 mm of runoff is flushed from the catchment within 24 hours (Environment Waikato 2000). Whereas in the Heretaunga Plains, 50 mm/ha/day of runoff is expected from gravity systems, and 32 mm/ha/day for pumped systems. The availability of funds may determine the frequency and type of drain cleaning. Frequently informal 'performance based' methods are used to decide when to carry out cleaning—for example, a decision to clean a drain because 'significant' weed growth is perceived to be a problem, or when a land owner complains about the condition of their drain, or when tile drain outlets are not flowing freely.

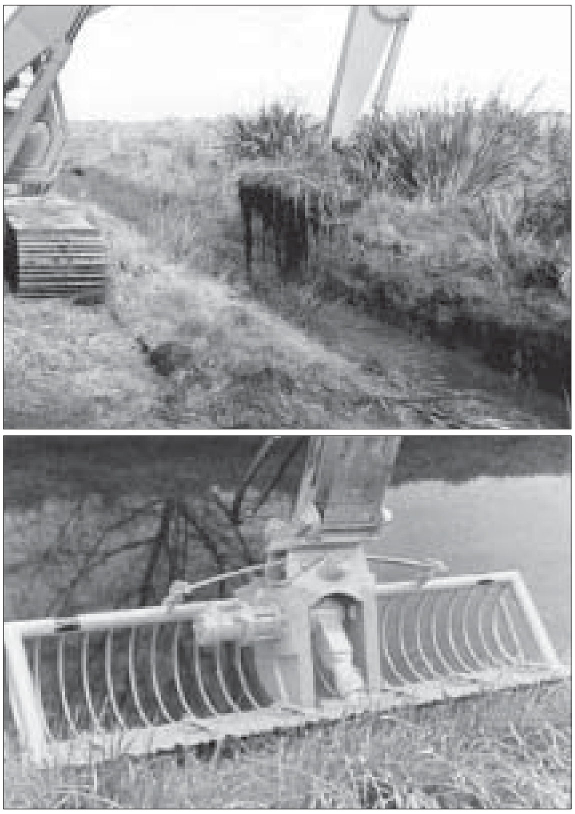


Figure 2. Normal excavator buckets are used to remove weeds and sediment (*top*), but weed buckets are often recommended (*bottom*).

Regional councils, such as Bay of Plenty, Hawke's Bay, and Waikato have instituted in-house codes of practice for drain maintenance. Canterbury and Marlborough have formal environmental guidelines for river management, and several other regions are in the process of developing guidelines (e.g. Manawatu–Wanganui and Southland). For some maintenance activities New Zealand operator guidelines are available (e.g. chemical spraying) and the use of certified applicators is standard practice. In some cases councils state their requirements in the spray or diggers contracts (e.g. contractors are to avoid spraying directly into the water), but these may not include specific environmental practices. Frequently, management practices are based on anecdotal evidence or trial and error, without supporting scientific documentation or references.

The intensity and frequency of cleaning practices vary considerably from region to region. When drains are maintained to increase hydraulic capacity (normally by increasing the width, and depth of the channel), the bed and banks are excavated (Fig. 2). In some cases, the council's maintenance specification simply states: 'The cleared drain shall be free of vegetation and obstructions which will impede the flow of water' (Waitaki DC for road drains). During routine maintenance, it is common practice to only remove sediment and or plants from a portion of the drain (e.g. the bed and one bank), and in some cases, only the bed of the drain is cleared, and disturbance to the banks is avoided as far as practicable (see Fig. 3 next page) (Crabbe & Ngapo 2000). Maintenance may be staggered so that small sections are cleared in successive years. However, in some regions the entire length of drain may be cleared at one time.

Figure 3. Excavated weed and sediment should be placed close to the bank to enable eels and crayfish to return to the drain.

3.4 COMMON PRACTICES

The following section summarises the main practices currently used by regional and district councils. Appendix 1 includes a summary of regional and district council survey responses. These fall into three broad categories: mechanical maintenance, chemical control, and biological control.

Mechanical maintenance includes:
- Channelisation and excavation of weeds and sediment
- Manual removal and cutting of weeds
- Weed cutting by boat
- Mowing riparian margins

Chemical control includes:
- Spraying of aquatic and riparian plants

Biological control includes:
- Stock grazing of riparian areas
- Control of aquatic weeds with Grass carp

New Zealand and overseas experience indicates that no single management practice is consistently better than others, nor will one management practice (e.g. use of herbicides or hydraulic excavators) be appropriate for all situations. Rather, each technique should be considered a tool in the manager's toolbox (Madsen 1997). A suite of best management practices should to be developed to address specific site conditions, economic, environmental, and technical constraints, and priorities and management goals in each drain.

3.5 MECHANICAL CONTROL

3.5.1 Channelisation, and excavation of weeds and sediment

Brookes (1988) reviewed the international literature on the impacts of channelisation, weed growth and sediment of streams and rivers, and the major findings of these effects on habitat and benthic invertebrates are summarised in

Table 4. Brookes (1988) identified a number of consistent direct and indirect effects.

Direct effects include:

- Sediment levels and aquatic weed biomass were reduced
- Turbidity in the drain increases dramatically for several hours as bed sediment becomes suspended
- The physical morphology and flow characteristics of the drain are changed depending on the extent and method of excavation
- Loss of in-stream habitat (e.g. substrate is removed)
- Invertebrates, fish, eels, and crayfish are physically removed with the sediment and weeds

TABLE 4. REVIEW OF STUDIES ON THE EFFECTS OF CHANNELISATION, EXCAVATION AND WEED CUTTING ON IN-STREAM HABITAT AND BENTHIC INVERTEBRATE COMMUNITIES (after Brookes 1988).

ACTIVITY	EFFECT
Excavation	Physical removal of benthic invertebrates
	Changed substrate effects invertebrate recovery
	No effect on invertebrates, where habitat in not changed
Channelisation	Siltation smothering invertebrates or changing communities
	Degraded substrate resulting in habitat loss and reduced benthic invertebrates
	Degraded habitat (loss of pools and riffles) and reduced benthic invertebrates
	Altered invertebrate drift due to poor substrate
Weed cutting	Increased drift (170 fold)
	Increased abundance of some species decreased others

Indirect effects include:

- Disturbance of sediment re-suspends agricultural chemicals and sprays that have accumulated in the sediment
- Loss of food for bird and fish species
- The removal of all weeds results in loss of overhead cover essential for regulating water temperature
- Loss of in-stream cover and habitat for benthic invertebrates and fish (e.g. giant kokopu, shrimp)
- Disturbance of drain bed, including removal of cobbles and gravels, which are essential for spawning sites of some fish species (e.g. trout)
- Physical damage to the drain margins and banks by the digger, increasing bank instability and erosion
- Spread of some aquatic plant species that grow from fragments disturbed by the excavator

Sediment accumulation and re-suspension can result in significant problems. The impacts of sediment and turbidity on freshwater communities and habitats have been reviewed by several researchers (e.g. Cordone & Kelly 1961; Ryan 1991; Waters 1995; Wood & Armitage 1997).

Major impacts include:

- Reduced primary productivity as turbid waters reduce light penetration, suspended sediment can also damage aquatic plant leaves and stems, and moss due to physical abrasion
- Smothering of algae, and aquatic plants, with fine material and reducing their quality as a food resource for benthic invertebrates
- Reducing feeding of fish and benthic invertebrates
- Altering the magnitude of invertebrate drift
- Infilling pools and riffles with sediment that reduces habitat for drain biota
- Clogging of interstitial bed material further reducing habitat quality

While the impacts of sediment on stream systems have been the subject of a number of studies, the effects of bed disturbance during excavation are not known. Brookes (1988) reported significant deposition following channel clearing in Wallop Brook in England, while in the River Wylye sediment deposition was negligible when cleaning operations coincided with a period of high flow. Attempts to quantify the effects of sediments in drains have been rare in New Zealand, and the few available studies are not definitive. Wilcock et al. (1998) assessed the effect of mechanical excavation of an 80 m reach in a Waikato drain. The excavator widened the channel, lowered the water level, and removed approximately 56 m^3 of sediment. This caused short-term increases in turbidity and ammonia (3–4 hours) while dissolved reactive phosphate and nitrate levels were reduced. After excavation, willow weed (*Polygonum* sp.) was still absent after six months, whereas densities of the Curly leaved pondweed *Potamogeton* sp. recovered. Benthic invertebrates were affected by macrophyte and sediment removal, in particular, densities of the snail *Gyraulus* sp. were reduced by 90%.

Goldsmith (2000) sampled three mechanically cleaned, two chemically sprayed (glyphosate and diquat), and four control sites before and six weeks after treatment. Mechanical cleaning significantly reduced plant coverage (mainly Sweetgrass *Glyceria*, *Potamogeton* and watercress *Nasturtium*), but did not cause significant changes in individual species or in water depth, velocity, or median substrate size. No difference was found in fish species richness or density six weeks after treatment. Five fish species were commonly found including long finned eel (*Anguilla dieffenbachia*), upland bully (*Gobiomorphus breviceps*), common galaxias (*Galaxias vulgaris*), common bully (*G. cotidianus*) and brown trout (*Salmo trutta*), while inanga (*Galaxias maculatus*), giant bully (*G. goboides*), giant kokopu (*Galaxias argenteus*) and short finned eel (*A. australis*) were also present at some sites.

Although hydraulic excavators were commonly used to remove sediment from drains, some councils viewed them as the 'last resort' for weed control. Where weeds trap sediment, and the ability of the drain to flush water is reduced, an excavator bucket may be used to remove both plants and sediment (Fig. 2). Excavators can usually extend across drains that are several metres wide, enabling operations to be carried out from one bank only and thus minimising impacts along the drain banks. In wide drains draglines were frequently used (i.e. wire rope which is dragged along the bed to remove weeds). McDowall & Lambert (1996) concluded that annual 'drag-lining' in the Oteramika Stream destroyed virtually all fish habitat and caused direct fish mortality, resulting in significant reductions in fish stocks.

Weeds and sediment were sometimes deposited close to the riverbank to enable eels and crayfish to escape back to the drain (Fig. 3). The spoil was later removed or spread across farm fields. In some cases, spoil was left alongside the drain. These practices vary depending on council guidelines or the contractor's attitude.

The timing of operations were highly variable (Appendix 1). In some regions, spawning and fish migration periods were avoided (e.g. Bay of Plenty and Southland), however, in many areas, work was reactive and undertaken following complaints by landowners.

In Southland, weed and sediment excavation typical costs averaged $0.55 per metre (Hudson 1998a), $0.82 per metre in the Waikato (Environment Waikato 2000), and $0.80–$1.20 per metre in Hawkes Bay (Norm Olsen pers. comm.). However, drain clearing costs were as high as $2.80–$8.37 per metre in Marlborough (Williman & Bezar 1999). These costs varied with access, size of the drain, and details of work required. Additional costs may be associated with disposal of spoil, if it is not left along the drain margin or incorporated into adjacent paddocks. In Hawke's Bay, disposal costs (cart and dump) range from $1.30 to $2.10 per metre (Norm Olsen pers. comm.).

3.5.2 Manual removal and cutting

Manual methods of weed removal are used worldwide for small drains and canals (Cooke et al. 1993; Madsen 1995). Hand removal usually involves pulling of weeds, and is frequently limited to sensitive areas with poor access (Cooke et al. 1993). It generally causes significantly less disturbance to banks and the drain bed, and is frequently used in sites sensitive to public use (Cooke et al. 1993). In New Zealand most councils manually clear some drains or drain reaches.

Two main methods are employed:

- Pulling of individual plants by hand
- Using hand-operated machines to cut vegetation (e.g. hand scythes, brush cutters, and chainsaws for brush and trees)

Hand pulling of plants physically removes the roots, which reduces the chance of regrowth. Although in theory it is possible, in reality, manual removal rarely results in eradication of the plants from a reach, because complete root removal is unlikely. In riparian zones, trees and scrub are cut, so that the root structure remains intact to hold the soil in place. Trees are burnt or removed off site and regrowth may be prevented by applying a chemical to the stump.

The annual cutting of aquatic weeds has been shown to significantly effect benthic invertebrate communities (Kern-Hansen 1978; Pearson & Jones 1978; Wilcock et al. 1998). Weed cutting on the Hull River in England resulted in the direct removal of large numbers of individuals with the weed and increased drift rates of species associated with weeds (Pearson & Jones 1978), while weed cutting in a Danish stream resulted a 1700% increase in invertebrate drift rates with 24 700 animals per cubic metre (Kern-Hansen 1978). This increase in numbers in the drift was attributed primarily to species associated with weeds (e.g. caddis, beetle, and dance flies), and continued for several days after cutting. Where bed disturbance occurred, invertebrate recovery may be slow (e.g. Kern-Hansen 1978), however, if there is little or no bed disturbance, then rapid recovery has been recorded (Pearson & Jones 1978). Large-scale removal of weeds changes the habitat, and has been shown to remove semi-aquatic vertebrates, and possibly fish eggs (e.g. inanga eggs) on riparian plants (Mitchell 1990). However, the impacts of selective harvesting in New Zealand drains have not been documented.

Few councils provided information on timing of operations in their responses to the Cawthron survey. Costs were similar to hydraulic excavators (e.g. an average cost of $0.67 per metre—Environment Waikato 2000), but actual costs are dependent on the degree of invasion by weed, access, and size of the drain. Marlborough District Council reported costs ranging from $4.49 to $7.74 per metre (Williman & Bezar 1999).

3.5.3 Weed cutter boat

Weed cutter boats were used for aquatic plant removal by Bay of Plenty and Hawke's Bay Regional Councils, and Christchurch City Council. Crabbe & Ngapo (2000) describe a purpose-built boat used to trim aquatic weeds to just above the bed level, across a channel. Weed cutter boats typically use a sickle-bar cutting blade. Cutting is quick, but may leave large mats of plants which can result in re-establishment or spread of the plant. It also creates a floating obstacle which may wash up on shorelines, and/or cause water-quality problems through decomposition (Madsen 2000). Because of these problems, cut plants are frequently removed. Cut weed is disposed of on land where practicable, or the material is allowed to wash downstream. Methods for harvesting (removing) cut weeds from the drain were not addressed in the survey, and no timings were specified, but cutting usually occurred twice per year. Costs varied with drain width and amount of weeds, but clearing which regularly maintained channels up to 3 m wide in Hawke's Bay typically cost $0.10–$0.20 per metre. For channels more than 7 m wide the costs were $0.40–$0.60 per metre. Collection, carting and disposal of cut weed typically cost $0.10–$0.50 per metre (Norm Olsen pers. comm.).

3.5.4 Mowing riparian margins

Mowing riparian margins was common practice. Long-reach mulching mowers were frequently used on steeper-sided drains and embankments. Hastings District Council undertook mowing 3 times per year (September, December, and April), while Hawke's Bay Regional Council mowed 2–4 times per year (or more frequently for aesthetic reasons). Generally, a council aimed to maintain grass in any dry drain beds and along drain margins (Olsen et al. 2000). Tractor-mounted long-reach mowing costs vary with drain depth and range from $0.05–$0.20 per metre. For sites with poor access, portable scrub-bar cutters were used at least once annually. Costs were typically $0.50–$0.60 per metre (Norm Olsen pers. comm.).

3.6 CHEMICAL CONTROL

Chemical spraying was the commonest and cheapest vegetation control method used by councils. Environment Waikato (2000) reported chemical costs averaging $0.03 per metre, with application costs varying, depending on access (total costs averaging $0.08–$0.11 per metre). In Hawke's Bay, spraying drains up to 3 m wide from a tractor-mounted hydraulic boom cost $0.10–$0.20 per metre (Norm Olsen pers. comm.), whereas Marlborough District Council reported costs of $0.28 per metre (Williman & Bezar 1999).

Cooke et al. (1993) noted that historically there have been widespread concerns over the use of chemicals for aquatic plant control. However, the review process for pesticides used in water has received considerable attention in recent years (Madsen 2000). The major concerns about the use of chemicals are associated with human health, potential biomagnification in wildlife, and persistence in the environment. Wade (1994, 1995) reviewed the potential impacts of herbicides on the stream system, which include death or damage to non-target plants, and possible cumulative downstream effects.

The main chemicals used by councils were Glyphosate (e.g. Roundup) and Diquat dibromide (e.g. Diquat, Reglone, Reward, and Torpedo), while Gallant may be used for roadside ditches.

Glyphosate is a systemic herbicide for use on emergent macrophytes and bank-side vegetation. The herbicide is translocated throughout the plant, which often has the effect of killing the entire plant. It is not effective on submersed plants. Environment Waikato used Glyphosate 360 with the addition of an organosilicone penetrating agent because of the silt on the vegetation (Guy Russell pers. comm.). Glyphosate is readily adsorbed by soil, but it is supposedly not persistent (average half life of 47 days) (Wauchope et al. 1992; WSSA 1994). However, the herbicide could be transported with soil particles in runoff, but Malik et al. (1989) estimated that less than 2% of the applied chemical was lost to runoff. In a North American study its half-life in pond water ranged from 12 days to 10 weeks (EPA 1992). Glyphosate was slightly toxic to aquatic invertebrates (WSSA 1994), and wild birds (Kidd & James 1991; WSSA 1994), but non-toxic to fish and mammals (Monsanto 1985, EPA 1987; Malik et al. 1989). A variation (Rodeo) was frequently used in aquatic situations.

Diquat dibromide was a quick-acting contact herbicide and plant growth regulator that caused injury only to the parts of the plant to which it was applied. It is reportedly non-selective, and will affect 'non-target' plants (Howard 1991), however, there was some indication that it may be selective to some New Zealand species. It is rapidly absorbed from the surrounding water and concentrated in the plant tissue so that aquatic weeds are affected even at low concentrations (NLM 1995). Peirce (1998) noted that submerged plants were perhaps the hardest aquatic weeds to kill because chemicals used need to be maintained at a sufficiently high concentration in the water for them to become effective. Diquat is rapidly absorbed by submergent plants, but without sodium alginate in the formulation it is less effective in water velocities > 0.03 m s^{-1}. However, anecdotal observations of applications in faster waters (without and without alginate) indicate that it may be equally effective. It is strongly, and rapidly, adsorbed and inactivated by clays and other organic particles (Wade 1994), hence the performance of Diquat is greatly reduced in turbid waters or waters where plants are covered by silt. High water hardness also reduces the uptake of Diquat. Diquat dibromide's half-life is less than 48 hours in the water column, but it may persist for 160 days in sediments (Gillett 1970; Tucker 1980).

Diquat dibromide ranged from slightly to moderately toxic to birds (EPA 1986) and has shown conflicting results in some studies on fish and benthic invertebrates. Pimentel (1971), Simonin & Skea (1977), and Johnson & Finley (1980) suggested little effect, however, in at least one New Zealand study, toxic effects on benthic invertebrates were indicated (Young et al. 2000). NLM (1995) stated there was little or no bioaccumulation of diquat dibromide in fish.

As Paraquat (another spray historically used in drain maintenance) is no longer approved for use in New Zealand waters we have not covered its effects here.

3.7 BIOLOGICAL CONTROL

3.7.1 Controlled grazing

Controlled grazing practices along waterways in New Zealand have been reviewed by Hicks (1995). Although controlled grazing by livestock such as sheep, cattle, and geese, can be very effective in controlling bank vegetation (ASCE 1991), there are some significant disadvantages:

- Livestock usually preferentially graze on the most palatable species, which favours survival of less palatable, and often nuisance weeds
- Livestock can be significant seed dispersers, and may spread weeds to drains from adjacent fields
- Livestock defecate, urinate, and trample in and near drains, which can impact on water quality
- High stocking rates, concentrated activity (e.g. stock crossings), and wet conditions can cause substantial bank and bed damage, which result in increased erosion and sedimentation

The impacts of stock grazing can be highly variable and dependent on the livestock type—for example, deer wallow in shallow pools (Fig. 4), while sheep generally avoid water—and on site conditions (Williamson et al. 1990). The overall benefit of excluding livestock from streams and drains is usually high. Environment Waikato (2000) found that drains with stock excluded needed clearing less frequently. They attributed this to reduced inputs of effluent and sediment. Drain cleaning has shifted from a 2–3 year cycle to a 10–15 year cycle (Guy Russell pers. comm.).

3.7.2 Control of aquatic weeds with grass carp

Chinese grass carp (*Ctenopharyngodon idella*) were introduced into the Waikato in the early 1980s. Environment Waikato have attempted controlled releases at 6 sites over the last 10 years and 4 sites in 2000 (Guy Russell pers. comm.). Grass carp were suggested as a possible biocontrol in New Zealand by Rowe & Schipper (1985) and MfE (1992). They reported that grass carp have been

Figure 4. The view upstream (*top*) of a paddock where grazing of the stream area has been controlled, and the view downstream (*bottom*) of a deer paddock where grazing of the stream area has been uncontrolled.

shown to be capable of eradicating nuisance plant growths in standing waters, and suggested they might effectively control weeds in small water bodies.

The effectiveness and survival of grass carp is strongly influenced by water temperature, dissolved oxygen levels, and water quality (Rowe & Schipper 1985). Carp mortality was high in an agriculturally polluted stream in New Zealand (Rowe & Schipper 1985). The majority of carp died in a trial in Churchill East drain in the Waikato, presumably as a result of low dissolved oxygen levels (Hicks pers comm.). Alberta Agriculture (1998) reported that the amount of food consumed by grass carp is directly related to temperature. At 13°C, grass carp consumed 5% of their body weight per day while at temperatures of 18–25°C, they consumed 24% of their body weight. Feeding ceased at lower temperatures, indicating that carp may be ineffective as a biocontrol agent in South Island waterways. Edwards & Moore (1975) examined effects of stocking two-year-old grass carp (*Ctenopharyngodon idella*) in a farm drain over summer. Water temperature ranged from 13°C to 20°C with a mean temperature of 16.5°C. Initially, 25 carp were introduced for 3 months and a further 20 carp were added for the final 2 months, giving rates of 350–650 kg per hectare. The carp reduced standing crops and percentage cover of *Callitriche* sp. and *Nasturtium* sp., but had no effect on *Polygonum* sp.. It seemed the fish preferentially ate *Callitriche*, then *Nasturtium* and finally *Polygonum* only when the other two species had been reduced. The release of 250 carp into the Churchill East drain resulted in major reductions in submerged macrophytes such as *Certophyllum*, and *Potamogeton* while emergent species, such as *Glyceria* increased (Wells et al. 2000). Similarly, Clayton et al. (1995) found that sterile triploid grass carp removed > 99% of the *Hydrilla verticillata* biomass from a small lake in Hawke's Bay over 17 months. Maintenance of fish browsing pressure for a further 5 years was recommended to minimise risk of tuber regrowth. When the *Hydrilla verticillata* was effectively removed, the carp began to feed on marginal emergent plants such as *Typha orientalis*.

In a 2 km reach of the Mangawhero Stream (Aka Aka–Otaua Plains), Rowe & Schipper (1985) demonstrated that 100% weed control could be achieved with cost savings of 20% over herbicides. Current costs were not reported by the councils. Trials in the Waikato indicate that grass carp may be cost-effective and provide benefits by reducing the frequency of machine and hand clearing (Russell pers. comm.). In addition, some weeds are particularly difficult to control with chemicals or mechanically (e.g. *Hydrilla verticillata*—Clayton et al. 1995). *Hydrilla verticillata* spreads readily through fragmentation; therefore, using mechanical controls while the plant is still invading tends to increase its rate of spread (WSDE 2000).

The value of grass carp as biocontrols has still not been fully determined, nor has the effect of this species on wider freshwater communities. When introduced into new environments, exotic species, such as grass carp, have the potential to introduce diseases into existing fish population, and displace existing species by removing aquatic plants which act as food and breeding habitats (Alberta Agriculture 1998). This risk to existing fish populations has been recognised in current trials (Bay of Plenty 2000).

4. Impacts of other drainage management practices

In this section the impacts of other management practices (including 'no maintenance') are reviewed, based on the New Zealand experience and the international literature.

4.1 BARRIERS

Many drainage networks have physical barriers, including:

- Culverts
- Weirs
- Current operated flapgates (floodgates)
- Pump stations

Many New Zealand freshwater fish species are migratory and require unimpeded access to the sea. Some are relatively poor climbers so overhanging culverts and weirs can act as significant barriers to migration. Furthermore, Roper-Lindsay (1991) noted that flood-gates were disruptive to fish that rely on the saltwater–freshwater gradient for navigation and habitat selection. Some whitebait species lay their eggs at the point where high tides meet freshwater, and floodgates present an abrupt transition from salt to fresh water. She suggests that in the Styx River, near Christchurch, the lack of an extended saltwater–freshwater transition may limit whitebait spawning, despite the presence of large adult galaxiid populations.

4.2 NO MANAGEMENT

When evaluating management techniques there is a danger that doing nothing may seem to be a safer option, with fewer consequences (Madsen 2000). However, when controlling introduced pest species, the environmental consequences of doing nothing may be high, possibly even higher than the effects of active management techniques. Unmanaged, these species can have significant negative effects on water quality, native plant distribution, abundance and diversity, and the abundance and diversity of benthic invertebrates and fish (Madsen 1997). By comparison, indigenous aquatic plant species rarely become pests.

5. Alternative management concepts and practices

In this section alternative management concepts and practices which have been instituted or trialled overseas are reviewed. 'Alternative' in this regard refers to concepts or practices that are not widely used or well publicised in New Zealand, and have not been discussed in previous sections.

5.1 PERFORMANCE-BASED MANAGEMENT

In New Zealand drainage maintenance has traditionally focused on maximising hydraulic efficiency (i.e. draining floodwaters quickly—Fig. 5). However, the effectiveness of drain maintenance in terms of determining the level of maintenance required to achieve acceptable flow control have rarely been assessed (Dunderdale & Morris 1996; Thoreson et al. 1997). As a result, the effectiveness of drainage maintenance is frequently reported as a 'process' measure (e.g. how much drain is cleaned) rather than a 'performance measure' (e.g. how has drainage efficiency increased), and what gain in agricultural productivity resulted from the maintenance. Currently, no studies are generally available which have documented the economic costs of process-based management compared to farm productivity benefits.

Figure 5. A roadside drain from which all in-stream and riparian vegetation has been removed, leaving no habitat for aquatic wildlife and biota.

The disadvantage of not linking drainage maintenance to hydraulic efficiency, and to agricultural productivity, is that drains are cleaned too frequently, or not frequently enough, and that the value and effectiveness of drain maintenance is not actually known (Dunderdale & Morris 1996; Lalonde & Hughes-Games 1997; Thoreson et al. 1997).

5.2 INTEGRATED MANAGEMENT

Drainage management strategies often focus on problems rather than solutions. For example, excessive sediment deposition in a drain is addressed by excavating the sediment. While this may be one way of dealing with the immediate problem, it does nothing to address the cause, which may be bank erosion and soil loss from farmland runoff.

Cost-effective and environmentally friendly drainage management requires a combination of best farming practices on the land as well as in the waterways. Ministry for the Environment (MfE 1997, 2000) and Ministry of Agriculture (Haynes 1995; Hicks 1995), and the EPA (2000) promote integrated land, channel margin, and in-stream management using a broad range of management measures that address both the problem and its causes.

Management measures in an integrated drainage programme include:

- Controlling soil loss and contaminants through stock, crop and effluent management
- Controlling farm soil erosion and contaminants with buffer strips along drain margins
- Reducing nutrients and sediments in streams with nutrient stripping and sediment control measures
- Controlling bed and bank erosion by improved channel design and erosion control measures e.g. with the construction of sediment traps
- Using a combination of practices (e.g. chemicals, grazing and mechanical harvesting) for the control of weeds in an integrated pest management programme

5.3 CONTROLLED DRAINAGE

'Controlled' drainage involves managing drains across a range of water levels (i.e. not just managing flood flows). This method has been adopted overseas where the aim is to manage water levels over a prescribed range, rather than trying to maximising outflow (NRCS 1990; ASAE 1994; Lalonde & Hughes-Games 1997). Controlled drainage, which might be achieved with adjustable weirs or variable weed clearance protocols, enables drain managers and farmers to:

- Store and manage infiltrated rainfall for more efficient crop production
- Improve surface water quality by increasing infiltration and reducing the intensity of runoff
- Reduce nitrates in the drainage water by enhancing conditions for de-nitrification
- Reduce subsidence and erosion of organic soils
- Control water levels for sub-irrigation (where water is transmitted from the controlled water table through the subsurface drains to the plant roots)
- Maintains in-stream habitat for aquatic life
- Maintain water levels in adjacent wetlands and lakes (e.g. in Manawatu–Wanganui and Waikato)

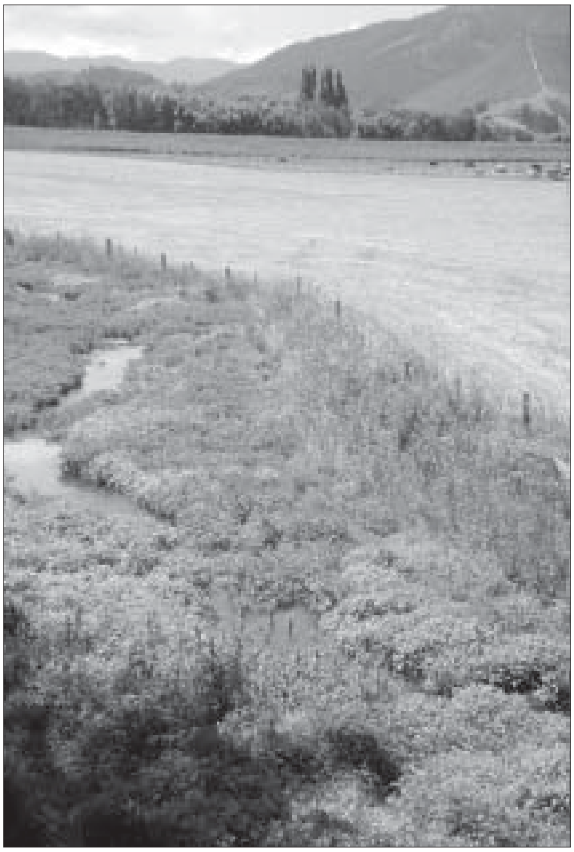
Manipulation of water levels, to flood or dry out the drain, has been used as a method of weed control for *Hydrilla* (Ludlow 1995), Eurasian water milfoil (Siver et al. 1986), and other milfoils or submersed evergreen perennials (Tarver 1980).

5.4 CHANNELISATION

The adverse effects of channel engineering, particularly channelisation, have been well documented and have lead to an evolution in river management practices (see review in Brookes 1988). As a result, successful attempts have been made to reduce the negative impacts of channelisation (Brookes 1988, 1989, 1992; Newbold et al. 1989; DEPA 1995; Madsen 1995; Benstead et al. 1997; Lalonde & Hughes-Games 1997; Purseglove 1998). These practices include:

- Limiting cleaning of channels to occasions when drainage efficiency is significantly reduced
- Leaving an undisturbed continuous strip of emergent plants and macrophytes along one bank of the drain
- Excavating one bank and retain vegetation on the other bank
- Avoid excessive drain widening
- Retain/create channel sinuosity and pools and riffles (Fig. 6)
- Selectively cutting macrophytes to create a meander pattern in a straight channel
- Creating by-pass channels, which will take excess flows during floods
- Installing temporary silt barriers (such as straw bales or silt dams) to control sediment movement downstream during excavations
- Constructing sediment traps in the bed to limit the area requiring routine sediment removal
- Manipulating channel shape (e.g. sinuous V-shaped thalweg) to concentrate flow and maintain a weed and sediment free path,
- Creating two-stage floodways in which the existing low flow channel is retained and the floodplain is excavated to provide floodway capacity
- Reducing bank slopes to increase flood capacity and provide water quality and habitat benefits

Figure 6. An ideal sinuous channel and riparian fencing on a dairy farm in Marlborough.



DEPA (1995) reported that selective clearing of weeds, and creation of meandering channels resulted in less disturbance to the stream biota (see Fig. 7, next page) and a significant increase in trout numbers in Idom Å Stream, Denmark. Generally, however, the evidence of successful flow management by selective weed control is anecdotal. For example, Madsen (1995) reported selective weed removal produces a channel that can be self-cleaning of weeds and sediment, have unimpeded water flow, and greater diversity in habitat for aquatic biota.

Manipulating channel shape (King 1996) and vegetation (Pitlo & Dawson 1990) have been shown to improve the hydraulic efficiency of waterways, while Petersen et al. (1992) have tested the benefits of side slope reductions for water quality and reduced frequency of bank failures and channel maintenance. However, the ecological benefits of these channel enhancements have not been rigorously quantified, and it is difficult to generalise the effectiveness of the vegetation and channel shape changes.

5.5 RIPARIAN MANAGEMENT

Several reviews and guidelines now exist on the role of riparian vegetation in New Zealand (Collier et al. 1995; ORC 1996; Heatley 1998; MfE 2000). Benefits of riparian planting include:

- Provision of habitat and food for terrestrial and aquatic species
- Improved light, temperature, nutrient and sediment regimes
- Channel and bank stability
- Shading for aquatic plant control

Riparian fencing and planting are probably the most effective activities that can be undertaken to reduce sediment and contaminate runoff into farm drains. Riparian planting has been shown to reduce bank erosion by up to 50% compared to unplanted banks (Heatley 1998). However, riparian fencing and planting is not a panacea—these practices may reduce contamination, but they do not address or mitigate land management problems. For example, the effectiveness of buffer strips and other control measures are highly dependent on the source, volume, and type of contaminant, as well as the specific local conditions (e.g. EPA 1993; NCSU 1995; EPA 2000). If used incorrectly, riparian planting can cause further problems (e.g. planting willows can increase bank instability because of wind throw—Thorne 1990; Crabbe, eastern Bay of Plenty, pers. comm.). Furthermore, the type and height of vegetation required for shade is dependent on the width and the cross-section of the drain (Dawson 1978; Williamson et al. 1990). Crabbe (1994) and Christchurch City Council (1996) recommend tree species that might be appropriate for riparian planting (Table 5).

Figure 7. Aquatic macrophytes have been selectively removed to create a meandering low-flow channel, with retention of some in-stream habitat.

Riparian planting frequently provides natural shading which can limit the growth of aquatic weeds (Dawson & Kern-Hansen 1978; Crabbe 1994; Young et al. 2000), however, it may be difficult to reduce light to a level which will limit the growth of pest weeds (Rutherford et al. 1997). In an 8-month trial in a small drain in the Waikato, Scarsbrook et al. (2000) reduced light levels by 90% with artificial shading. In this study there was no effect on the overall amount of plant cover that occurred across the stream, however, there was a significant change in both the type and density of plants growing under the shade. During the summer months shading dramatically

TABLE 5. SPECIES THAT MAY BE APPROPRIATE AS DRAIN SHADE TRESS (Crabbe 1994).

SCIENTIFIC NAME	COMMON NAME
Pittosporum eugenioides	Lemonwood
P. crasssifolium	Karo
P. tenuifolium	Kohuhu
Coprosma repens	Taupata
C. robusta	Karamu
Griselinia littoralis	Broadleaf
Leptospermum ericoides	Kanuka
L. scoparium	Manuka
Sophora tetraptera	Kowhai
Dodonaea viscosa	Green akeake
D. purpurea	Purple akeake
Metrosideros excelsa	Pohutukawa
Corynocarpus laevigatus	Karaka
Dacrycarpus dacrydioides	Kahikatea
Podocarpus totara	Totara
Agathis australis	Kauri
Vitex lucens	Puriri
Alnus glutinosa	Alder

reduced the growth of the dominant aquatic plant *Polygonum*, and plant biomass was only 20% of that in an unshaded 'control' reach. The shaded reach also supported a more diverse plant community with several native species being co-dominant (particularly *Potamogeton* and *Nitella*), in contrast the unshaded control was almost entirely dominated by *Polygonum*. Surveys of natural shading by riparian trees have shown significant effects on aquatic plants. Young et al. (2000) found that riparian shading reduced light levels to < 200 mmol/m^2/s. *Lagarosiphon*, willow weed and watercress were significantly reduced, while the native *Nitella* was unaffected by low light levels. Crabbe (1994) surveyed drains throughout the Bay of Plenty and concluded that natural shading could be used to control aquatic weeds in many small drains (1–2 m wide).

5.6 TILE DRAINS

The role of sub-surface drains (e.g. tile drains) as sources of sediments and nutrients has been documented in Europe (Petersen et al. 1992), the United States (EPA 1993), and New Zealand (Nguyen et al. 1998). The construction of mini-wetlands at the exit of tile drains and within waterways has been advocated for control of sub-surface contaminants by Petersen et al. (1992), however, no research has been undertaken in New Zealand to assess either the effectiveness or longevity of wetlands in stripping sub-surface contaminants entering drains (Nguyen et al. 1998).

5.7 DRAIN NATURALISATION

Artificial drains are frequently engineered as straight, narrow and deep channels, but the natural tendency of a lowland stream is to meander, widen and shallow. Consequently, in engineered channels, bank erosion occurs unless there is heavy riparian vegetation, the drain is formed of erosion resistant material (e.g. cohesive soils), or the channel banks are protected (e.g. grade control structures and rip rap). Several overseas reviews have indicated that more cost-effective and sustainable management can be achieved by naturalising the waterway (e.g. Brookes & Shields 1996; Andersen & Svendsen 1997; FISRWG 1999). If left alone, channelised reaches will frequently return to their natural shape (Brookes 1992). A more interventionist and costly approach is to restore natural features in rivers and streams. The Wandse Stream in Germany is one of the first well-documented examples of a stream that was deliberately re-established in a meandering pattern in 1982 (Purseglove 1988). While in Denmark, three years following re-meandering of 580 m of the Idom Å Stream significant increases in the trout population were observed (DEPA 1995). In the re-meandered reach, trout populations had recovered to the levels observed in a natural reach downstream. Stream restoration is still very much in its infancy with much to be learned from basic research and monitoring of the success or failure of projects (Brookes 1996).

The creation of a natural stream shape has rarely been attempted in New Zealand. Environment Southland have trialled a constructed sinuous pattern following natural depressions in Pourahiri Stream, and it is hoped a more natural cross section will develop if the reach is not over maintained. A two-stage channel based on a meandering reference stream has been adopted in the 3 km diversion of the channelised Waikaka River, Southland, however, no data is available on its effectiveness (Hudson 1999).

5.8 VEGETATION CONTROL

Aquatic and riparian vegetation management is a major component of drainage maintenance. Although the focus of maintenance activities is initially the control of weeds, in reality vegetation control becomes a much broader activity. From a drain-efficiency perspective in-stream vegetation often plays an important role in limiting erosion. In addition, in-stream and riparian vegetation provide several environmental benefits (e.g. increased habitat and nutrient filtration). Therefore, effective vegetation management should include careful planning, preparation, and practices to maximise beneficial vegetation growth (e.g. erosion control and habitat), and at the same time minimise potential adverse effects of vegetation in drains (i.e. flow impedance) (ASCE 1991). Successful control of macrophytes is largely dependent on incorporating three key components into a management programme (De Waal et al. 1995):

- Using the knowledge of the auto ecology of the particular species (i.e. understanding the whole life cycle, and requirements of the species) to determine control measures
- Developing a coordinated management programme
- Stopping further spread

Successful vegetation management requires correct taxonomic identification of the problem plants. This enables the selection of appropriate management measures, which vary widely between plants. For example, to control *Fallopia japonica* (Japanese knotweed) it is important to contain and eliminate the large underground rhizome system (De Waal et al. 1995). While the giant hogweed *Heracleum mantegazzianum* has two regeneration strategies; the formation of an over-wintering tap root and the production of a large amount of seeds developing into a persistent seed bank. For lasting control it is necessary to prevent seed dispersal by controlling plants before flowering (De Waal et al. 1995).

Management measures to prevent weed problems include:

- Controlling upstream sources of weeds (i.e. even if there is no persistent local seed bank, re-invasion may occur with seeds from upstream)
- Limiting the spread of weeds (e.g. cleaning excavators to stop transfer of weeds between drains; control disposal of spoil)
- Maintaining desirable plant species which can compete with the weeds
- Enhancing channels to indirectly control weeds by modifying the light, hydraulic and in-stream sediment-nutrient regimes

6. Knowledge gaps

Our review of existing literature indicates that there are a number gaps in our understanding of the effects of current drain management activities in New Zealand. We have identified some of the key ones here. Specifically, these fall into two broad categories.

6.1 UNDERSTANDING DRAIN HYDROLOGY

There is little or no documented evidence of the effects of either mechanical digging, or weed clearing on the hydraulics of drains (i.e. of their capacity and efficiency at different flow levels) or of the effects on the water table of the surrounding land. The lack of data on these topics is surprising, considering the effort put into these activities. Without understanding how efficient these practices actually are, it is very difficult to develop and promote improved practices.

6.2 MANAGEMENT OF SEDIMENT, NUTRIENTS, AND MACROPHYTES

Some overseas studies indicate that physical removal of macrophytes affect fish communities, however, there has not been any rigorous testing of this in New Zealand. Studies by McDowall & Lambert (1996), Ryder (1997), and Goldsmith (2000) indicate that there may be significant impacts, but their results were confounded by problems with the study design.

Limited overseas research suggests 'selective' weed cutting may be an effective management tool, but there is little quantitative evidence. Anecdotal evidence indicates that aquatic plants significantly increase sediment retention, and promote deposition in drains, it is likely that selective weed-cutting patterns can maintain a weed free and silt free channel. Trials in Okeover Stream (University of Canterbury) indicate this is possible.

Little work has been done on promising alternative strategies to reduce sediment and nutrient transport in drains (e.g. creating sediment 'traps', or sediment-contaminant retention 'wetlands'). The literature suggests there is great potential for using flushing flows to remove sediment in some drains.

Chemical sprays, and low dissolved oxygen (DO) associated with weed decomposition, probably affect drain communities in New Zealand, but this has not been studied. McDowall & Lambert (1996) suggest that as a possibility, while unpublished laboratory experiments at the University of Canterbury indicate that macrophytes can reduce DO to critical levels for native fish. However, there does not seem to be any study that has adequately addressed this issue.

7. Recommendations

While there is much still to learn about drain management in New Zealand, there are several actions that can be taken to improve our understanding and management of these systems.

- As a result of this review and from responses to the council survey we conclude that no one form of drainage management will apply to all situations. Different drain management practices should be used for different locations (e.g. coastal drains v. inland drains), and different types of drain (e.g. ephemeral v. permanent flow, drains with different substrate type, riparian vegetation, and land management). We recommend that a classification system for drains needs to be developed. By being able to classify a drain councils will be able to adopt specific management practices for different values and conditions specific to particular types of drains.
- This review has identified several alternative drain maintenance practices, which have been reported overseas. Trials of the efficiency and applicability of these practices need to be conducted in New Zealand. We recommend that comparative trials of partial drain clearing (e.g. clearing only one bank of weeds or creating meandering channels), drain naturalisation, and use of sediment traps and wetlands be conducted, and these trials be compared to current management practices in order to determine their relative efficiencies.
- The efficiency of performance based approaches to drain management need to be compared to process based approaches. A comparison of these approaches will improve our understanding of these systems and enable councils to manage flood waters and aquatic weed levels.

- All councils should have in place recommended practices for sediment and contaminant control. These should include control of livestock access to watercourses, use of vegetated riparian zones, use of riparian plantings for shade control of weeds and bank stabilisation, and the use of sediment traps to reduce sedimentation within the waterway. Practice guidelines should be developed and rigorously evaluated for New Zealand conditions.

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Appendix 1

SUMMARY OF COUNCIL RESPONSES TO THE CAWTHRON INSTITUTE SURVEY

(On following pages)

SUMMARY OF COUNCIL RESPONSES TO THE CAWTHRON INSTITUTE SURVEY

DISTRICT OR REGION	CoP*	EXCAV-ATOR	HAND	SPRAYING	CHEMICAL	OTHER	AVERAGE FREQUENCY	PERIOD	AVERAGE BUDGET
Banks Peninsula DC	No	Mostly	Rarely	Sometimes	Roundup		1 × /year		$8 500
Bay of Plenty	Yes	Sometimes	Rarely	Mostly (2nd choice)	Roundup, rare use of diquat	Weed cutter boat 1st choice	>2 × /year	As required	$500 000
Buller DC	No	Mostly	Rarely	Sometimes	Roundup		1 × /year	As required	$15 000
Environment Southland	In prep.	Mostly		Sometimes	Roundup, Diquat		1–3–5 year cycle	Pred. Mar & Oct	$520 000
Grey DC		Rarely	Mostly	Rarely	Roundup		2 × /year	Spring, Autumn	$42 000
Hastings DC	Spec.	Rarely	Rarely	Sometimes	Roundup	Mowing	3 × /year	Sep, Dec, Apr	$95 000
Horizons.mw Manawatu–Wanganui	In prep.	Sometimes	Sometimes	Mostly	Roundup		2 × /year	Continuous	$200 000
Horowhenua DC	No	Sometimes	Rarely	Mostly	Roundup, Escort		2 × /year	Spring, Autumn	
Hurunui DC	No	Mostly		Rarely	Roundup		Some 2 –3 year cycle		$15 000
Kaipara DC	No	Sometimes	Rarely	Mostly	Roundup. Gallant		1 × / year	Autumn	$400 000
Kawerau DC	No	Mostly	Sometimes		Roundup		1 × /year	Mar	$5000
Marlborough DC	Yes	Sometimes	Sometimes	Mostly	Roundup, occasion-ally Torpedo	Weed cutting	2 × year spray,	Excavator on demand	$120 000
Nelson City Council	No	Sometimes	Sometimes	Sometimes	Roundup		1 × /year	Mar, Apr	$150 000
Northland RC		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Opotiki DC	Spec.	Mostly	Rarely	Sometimes	Roundup		1 × /year	Summer	$30 000
Otago RC	No	Sometimes	Sometimes	Mostly	Roundup	Mowing	Spray 1 × /year Excav. c.5 year cycle	Nov, Apr	$350 000
Otorohanga DC	No	Sometimes		Mostly	Roundup, Torpedo		As required	As required	$50 000

(Continued next page)

DISTRICT OR REGION	CoP*	EXCAVATOR	HAND	SPRAYING	CHEMICAL	OTHER	AVERAGE FREQUENCY	PERIOD	AVERAGE BUDGET
Queenstown Lakes DC	No	Sometimes	Rarely	Sometimes	Roundup		As required	As required	
Rodney DC	No	Sometimes	Rarely	Sometimes	Roundup, Escort		1 × /year	Apr–Jun	$200 000
South Wairarapa DC	No				Roundup + Escort, simazine		1 × /year		$190 000
Southland DC	No	Sometimes	Sometimes	Sometimes	Roundup		As required	As required	
Stratford DC		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tararua DC	No	Sometimes	Sometimes	Mostly	Roundup G2		2 × /year	Nov–Dec, Apr–May	
Tasman DC	No			Mostly			As required		
Tauranga DC	No	Sometimes	Rarely	Mostly	Roundup		Spray 2 × /year Excav. 3 year cycle	Oct, Feb	$88 000
Timaru DC	No	Sometimes	Sometimes	Rarely			As required	As required	$7500
Waimakariri DC	No	Mostly	Mostly	Mostly	Roundup, Diquat, Triclopyr all with Pulse or Boost		As required	Pred. Jan, Feb, Mar	$263 000
Waimate DC	No	Mostly		Sometimes	Roundup		As required	As required	$100 00
Waitaki DC	Spec.	Mostly	Rarely	Sometimes	Roundup		3 or 5 year cycle	Winter, spring	$90 000
Waipa DC	Yes	Mostly		Mostly	Roundup		2 × /year	Autumn, spring	$80 000
Waitomo DC	No	Rarely					On demand	On demand	$7000
Wellington RC	No	Sometimes	At pump stations	Mostly	Roundup		As required, 1 × to 2 × /year	Dec, Apr, May	$70 000
West Coast RC	No	Mostly		Sometimes	Roundup		As required	As required	$10 000

* CoP = Code of Practice. Refers to an environmental code. 'Spec.' refers to use of a contract or maintenance specification.
n.a. = not available.