The effects of drain clearing on water quality of receiving environments

Water quality effects of drain clearing

Prepared for Andy Hicks, Environment Southland

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Version

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Executive summary

Environment Southland maintains over 1200 kilometres of waterways. This maintenance includes clearing sediment and weeds that accumulate over time in the waterways and decrease outfall and hydrological efficiency. During drain clearing, water quality decreases markedly, with large fluxes of suspended sediment and nutrients. This study was undertaken to help Environment Southland understand the potential water quality impacts of drain clearing, and the effects of the associated release of nutrients and sediments to downstream ecologically sensitive environments. A review of relevant literature and analysis of data from the drain clearing events in Southland was carried out and the findings evaluated.

Analysis of data showed that, through the drain clearing procedure, total suspended solids concentrations and concentrations of some water quality variables increased sharply. Total phosphorus concentrations increased through the drain clearing events. The highest total suspended solids and total phosphorus concentrations since measurements began in Southland (1995) were during the drain clearing period. There was little difference in nitrate and total nitrogen concentrations between the drain clearing period and the long term record. After drain clearing, even small increases in flow gave sharp increases in turbidity and concentrations of water quality variables.

As well as having water quality effects, drain clearing significantly affects the morphology of the drain channel, bank vegetation and structure, in-stream ecology (significant disturbance to fish populations) and in-stream physical conditions (e.g. water temperature).

Where drains have been cleared, turbidity will be elevated in the short term immediately following clearance. The reduced visual clarity may have impacts on any remaining aquatic animals and associated reduction in light penetration may cause light ‘starvation’ of (remaining) aquatic plants. We would expect that elevated flows shortly after the drain clearing events will give rise to higher sediment and sediment-associated loads of pollutants and light attenuation being transported from the drains to downstream environments. Depending on environmental conditions in receiving waters, there may be the potential for phosphorus release from sediments which may trigger ecological changes. Visual clarity and light attenuation will be reduced in the short term, until suspended sediment settles and consolidates, and accumulation of sediment in downstream environments may smother aquatic ecosystems. As channel beds re-stabilise, we would expect that turbidity levels and water quality variable concentrations would ‘relax’ to pre-clearing levels.

In the longer term, we advocate the implementation of beneficial management practices (BMPs) to reduce sediment and nutrient loads from agricultural land, so that clearing of drainage channels is needed less often. In the meantime however, we suggest promoting improved drain clearing procedures so that environmental impacts are minimised.

1 Introduction

Environment Southland helps communities reduce the risk of flooding and erosion to their properties by carrying out river and drainage works within river catchment rating districts. Their land drainage and river catchment programmes focus on providing physical works, services, advice and assistance to landowners with the aim of:

- reducing the risk of flooding and soil erosion, and thereby reducing the amount of sediment entering waterways
- maintaining soil quality, through drainage control and preventing soil saturation
- improving water quality, river stability and river environments, for example creating a better habitat for a wide variety of animals and plants.

Environment Southland maintains over 1200 kilometres of waterways. This maintenance includes the use of diggers to manually excavate the weed and sediment that has accumulated in channels, which decrease outfall and hydrological efficiency. During drain clearing, water quality decreases markedly, with large fluxes of suspended sediment and nutrients. After drain clearing, the disturbed channels may also release more sediment because the binding/trapping ability of weeds is no longer present. From a broader perspective, however, the diggers are removing tonnes of nutrient and sediment from the waterways that might otherwise be mobilised during large magnitude floods.

In the context of improving regional water quality, Environment Southland are attempting to evaluate the advantages and disadvantages of drain clearing to help them better understand the overall effect of this activity on downstream receiving environments, such as Waituna lagoon. They also require information on mitigation measures likely to be effective at reducing the nutrient and sediment flux that is transported downstream during future drain clearing activities.

Environment Southland seeks information on the benefits of clearing sediment and nutrients from drains, and information on how to minimise the immediate negative effects drain clearing has on water quality. If, as a result of this study, drain clearing is identified as an overall negative effect on water quality, the council will continue to look seriously at how it manages waterways for drainage purposes. The mitigation tools advised by this project will be evaluated and, if reasonable, incorporated into drain clearing programmes. It is thought that regional water quality, especially in key aquatic ecosystems like the Waituna Lagoon, should improve as a consequence of more informed drain management practices.

The aim of this report therefore is:

- To undertake a brief review from the available scientific literature of the effects of sediment and nutrients in storage in streams and drains, and of potential measures to mitigate the negative short term effects of drain clearing. If possible, actual data should be provided to demonstrate the effectiveness of alternative mitigation measures.
- To estimate, as far as possible, using data collected from the Waituna Creek by Environment Southland, the short and long term sediment and nutrient load in streams that have been cleared and those that have not been cleared. This

should include, if possible, an assessment of the immediate effects of drain clearing, an estimate of sediment that is likely to settle after clearing, and the likely effects in cleared reaches during floods.

- To compare the likely effects when using weed rakes versus buckets.

The information from this advice grant will be used in the continued refinement of drain management in Southland. At Environment Southland, the environmental information and catchment management teams are both managed by the Environmental Director, and advice received will be used to guide in-house discussions by internal groups to ensure the best and most realistic environmental outcome is achieved. If appropriate, information on drain management will also be incorporated into policy and the advice that the land sustainability team delivers to land owners. The Environment Southland catchment division has on-going funding, and is capable of assimilating any new and reasonable approaches/ideas into the drain management programme. This project will be particularly relevant to discussions around how catchment load targets will be achieved in accordance with the National Policy Statement for Freshwater, which is being addressed via Environment Southland's Water and Land 2020 Project. Environmental problems are faced by other regional councils, as well as private landowners, while they manage waterways on their property.

2 A review - Sediment and nutrient storage in streams and drains and the effects of drain clearance

2.1 Sediment and nutrient dynamics in streams and drains

Runoff and drainage water from pastoral land are known to be significant contributors to declining water quality in many regions, particularly those managed under intensive farming practices where inputs, nutrient recycling rates and stocking densities are high. The transfer of nutrients, sediment and faecal bacteria from soil to water has been documented for a range of pastoral farming systems and intensities (see review by Monaghan et al. 2007 for the NZ perspective). Reviews (Haygarth & Jarvis 1999, Oliver et al. 2005, Watson & Foy 2001) show that soil type, drainage pathways, topography, climate, stock type, stocking rate and grazing management practices are some of the key factors that determine the size of nutrient and faecal bacteria transfers from land to water. Drains and lowland streams flowing through intensive agricultural land can therefore be in receipt of significant amounts of agricultural pollutants (sediment, nutrients and faecal material) which, depending on flow conditions, may accumulate in the channel to be episodically re-mobilised and transported to other receiving waters in high flows. The main pollutants of concern for this study are sediment itself, including its effects on water clarity (both visual range and light penetration), and the associated nutrients phosphorus and nitrogen.

As well as being a vector for pollutants, sediment is a pollutant with significant effects in its own right. Sediment reduces visual water clarity and light penetration (Davies-Colley & Smith 2001, Davies-Colley et al. 2003) and causes downstream sedimentation issues with multiple impacts on the health of aquatic ecosystems, leading to the loss of diversity and dysfunction of community structure (Bilotta & Brazier 2008, Collins et al. 2010, Kemp et al. 2011, Wood & Armitage 1997).

Phosphorus (P) occurs in drains and streams mainly through surface runoff carrying P – rich sediments that are deposited in the drainage ditch. Phosphorus retention can cause large quantities of P to accumulate in stream systems. Several studies have noted that, depending on flow and nutrient input conditions, stream sediments can be a source of phosphorus. The sediment 'equilibrium phosphorus concentration' (EPC) is a sediment chemical parameter that has often been used to evaluate whether sediments are a sink or a source to the flowing water (Froelich 1988). If the sediment EPC is approximately equal to the dissolved P stream water concentration, then sediments and the water column are in apparent equilibrium. Sediments will absorb P (act as a sink) if the stream water concentration is greater than the EPC, and will desorb P (act as a source) if the stream water dissolved P concentration is less than the EPC.

Drainage sediments therefore have the ability to be both sources and sinks of P depending on their P saturation status, soil type and biogeochemical conditions. Their potential to become a major source of P to streams may be a problem, because even low concentrations of soluble P can enhance nuisance growth of algae and aquatic weeds. P transport in drains and streams is partly governed by sediment P status, and P release and retention characteristics within drainage sediments and these processes may be important in drains in Southland.

Less information is available on nitrogen (N) dynamics in sediments as N is less well known for transformations at the sediment-water interface. Agricultural drains and low order streams are important for the uptake, removal and transformation of nutrients.

2.2 Current methods for drain management in Southland

Drain maintenance is practiced because drains become clogged due to sediment inputs, in-channel aquatic plant growth and debris accumulation. Drains can become so grown over that no water is visible. The channels can be completely filled with vegetation. Such clogging leads to associated reductions in hydraulic capacity, and so, in Southland, to maintain flow in waterways, drains are routinely cleared. While these channels are collectively known as drains, many of the larger drains are actually small headwater streams with significant flow, which are fed by a network of smaller surface and sub-surface artificial drains.

Throughout Southland, it is Environment Southland's responsibility to maintain the streams/drains with higher flows, while the smaller drains are generally cleared by private agricultural contractors. Private contractors will also clear tile drains. This involves blasting sediment out of the drains, which causes sediment pulses.

Sediment gradually accumulates in these drains, to the point that flow is impeded, so drain clearance is an on-going process. Drains are cleared on a cycle, which, for most drains, is generally three years, depending on accumulation and condition. For some drains the cycle is longer, e.g. the Waituna Creek at Marshalls Road is cleared every 10 years. Drain clearing is generally done before and after Christmas, with breaks for the trout spawning season. In estuarine catchments clearing stops for the whitebait season.

Drains are generally cleared using a digger with either a bucket or a rake. A digger is used from the bank of the stream, which scoops the sediment and aquatic plants from the channel bed. This sediment is dumped on the bank of the stream or on the fringes of the paddock. This method can significantly change the shape of the drain and how the water flows, thereby altering its long-term effectiveness. Banks are also significantly modified and gravel bars and in-channel gravel will be removed.

The rake causes fewer disturbances to the channel. When the rake is lowered into the channel, it grabs onto the vegetation and pulls it out of the channel bed, along with channel sediment into which it is rooted. With this method, invertebrates and fish should not be physically removed from the channel; fish should be able to escape through the rake. Because of the gaps in the rake however, much of the sediment that is removed can fall back into the drain or the banks, meaning that removal is not so effective. It would seem that this method leaves more loose sediment in the drain channel, ready to be mobilised in elevated flows, meaning that it will possibly take a longer time for the drain to relax back to a steady water quality regime.

2.3 Potential impacts from clearing streams and drains

Drain clearing in Southland is practiced to maintain the flow of water and to ensure adequate capacity for drainage. There are however various negative impacts associated with this activity that we will illustrate with references to the relevant scientific literature. Under current agricultural land management practices in Southland (and elsewhere in New Zealand), drain management through clearance is important. It is therefore important that, if it has to be done, it is done in the least environmentally disruptive manner. Ultimately it is more important to implement beneficial management practice (BMPs) on agricultural land to reduce the need for mechanical drain clearance into the future.

To date, there are few actual documented studies of sediment and nutrient dynamics in drains and the impacts of drain clearance in New Zealand and elsewhere. One of few for which detailed information is available is that carried out by Mike Scarsbrook (Wilcock et al. (1998) in the Toenepi Stream in the Waikato to examine the immediate impacts of clearing sediment. An 80 metre reach of the stream was chosen and dredged by an agricultural contractor. Samples were collected for water quality analysis for the 12 hours immediately after dredging, while turbidity probes were deployed for a week after the clearing. Stream surveys were done to record changes in vegetation, invertebrate communities and in-channel morphology. Wilcock et al. (1998) found that the drain clearing was very effective at clearing the weed and willow trees that were choking the channel. A similar study was carried out in streams in Marlborough by Young et al. (2004). We will describe the impacts of sediment and weed clearing making regular reference to these studies and others.

2.3.1 Channel shape

Mechanical drain clearing inevitably alters the channel shape, which will have further impacts on physical and hydraulic characteristics. Gravel bars on the channel margins will be removed, and channel bed gravels will be disturbed. Wilcock et al. (1998) compared channel morphology before and after mechanical clearance of the stream, and observed major changes in channel shape. Increases in water width and channel cross section were observed. In their study, Young et al. (2004) also observed that the cleared channel was deeper after excavation than before. Channel shape had also been modified, and was asymmetrical, with the deepest point and the steepest bank on the side opposite to where the digger had been.

2.3.2 Water quality variables – short term

Drain clearing will have effects on water quality variables and instream conditions. Wilcock et al. (1998) and Young et al. (2004) observed significant but relatively short term changes in water quality variables in their respective studies of the Toenepi and Marlborough streams. Water temperature increased, perhaps due to the removal of shading vegetation from the channel. Young et al. (2004) monitored temperature continuously over 24 hour periods at regular intervals both before and after drain clearance, and noticed larger diurnal ranges in temperature in the post-clearance period. Turbidity increased as a result of the clearing activity, but rapidly returned to background levels and no effects were observed 1500 metres downstream.

In the study by Wilcock et al. (1998), concentrations of nutrients were affected by the clearing activity. Ammoniacal nitrogen (NH_4-N) concentrations increased threefold during the clearance. Young et al. (2004) observed a sharp temporary increase in NH_4-N concentrations in the period immediately after drain clearing, while De Medina et al. (2003) observed a similar increase in NH_4-N from sediment in aerobic conditions, which they attributed to the degradation of organic matter. The sediments, newly exposed after clearance, may have different NH_4-N adsorption abilities. For example, Shigaki at al. (2009)

found that the coarser textured sediments exposed by dredging had a lower capacity to remove NH_4-N from flowing water than the finer sediments that had been removed.

In the Toenepi study, dissolved reactive phosphorus (DRP) concentrations dropped sharply, and these concentration reductions are most likely attributable to adsorption onto mobilised sediment particles. In this situation, the water column concentration will have been higher than that in the sediment, leading to adsorption as mentioned earlier. Had this situation been reversed then DRP would have been released to the water column. Young et al. (2004), for example, observed a sharp temporary increase in DRP concentrations after drain clearance, which may be the reverse of what occurred in the Toenepi Stream, i.e., a lower DRP concentration in stream water relative to the sediment concentration which triggered P release from the sediment to the water column, thereby increasing stream DRP concentrations.

Nitrate-nitrogen (NO_3-N) concentrations dropped sharply through the Toenepi experiment which contrasts with what was observed by Shigaki et al. (2009), who found that NO_3-N transport was relatively unaffected by sediment disturbance. As in other studies (e.g. Smith 2009), water quality variables returned to pre-clearing concentrations soon after the activity and effects were negligible downstream.

Previous studies have not examined optical effects of sediment clearance from drains; however we would expect that optical impacts are likely to be severe on downstream waters including estuaries and lagoons.

2.3.3 Stream ecology

Aquatic plants, stream invertebrates and fish will be disturbed with mechanical drain clearance using a bucket. Wilcock et al. (1998) took samples of invertebrates in the recovery period after mechanical clearing, and observed changes in species present and their abundance. Young et al. (Young et al. 2004) found that invertebrate density one week after clearance was approximately half that recorded before clearance. They also observed that invertebrate densities had recovered to pre-clearance levels within one month. Wilcock et al. (1998) recorded that aquatic plants were largely cleared, and plants recovered slowly. In the post-clearance period, there may be on-going effects on stream ecology attributable to the higher turbidity levels and lower visual clarity.

Removal of sediment and vegetation is likely to affect fish habitats in drains via destruction of refugia. Fish may also be removed if the bucket method is used, but if a weed rake is used, some fish may be able to escape back into the channel. Prior to drain clearance, there was a healthy population of eels in the Marlborough stream monitored by Young et al. (2004). Many of these were removed when the drain was cleared mechanically, however a section of the drain spoil was examined and eels found were returned to the channel. If the eels had not been collected from the digger spoil, their chances of survival might have been reduced (Young et al. 2004).

Vegetation removal from the banks and channels of drains may also lead to increases in water temperature. Water temperature has a direct impact on many aquatic species, as many fish and invertebrate species do not like the high temperatures frequently found in un-shaded channels.

Drain clearing may not always have negative effects. Where drains are very badly clogged, clearing may actually represent a habitat improvement as fish may be able to move more freely. Also, stream water might flow more quickly, leading to cooler, better-oxygenated water.

2.3.4 Bank stability and erosion potential

When channels are cleared and vegetation removed, vegetation also tends to be stripped from the channel banks. Depending on when the clearing is done, banks may remain bare over winter. There are generally more high flow events through winter, which may lead to bank erosion and undercutting. Also, temperatures are lower and there may be frequent frosts. As ice freezes and thaws, bank material may be loosened and more susceptible to erosion and transport downstream. To prevent bank erosion, channel banks could be smoothed and seeded after the channel is cleared. Species planted would have to be compatible with future drain-clearance operations, e.g. densely rooted plants like toi toi might not be suitable. Conversely, riparian shading by (taller) riparian plants might inhibit weed growth sufficiently (by shading) as to prevent drain clogging.

Many native New Zealand plant species can be found growing on banks of drains and waterways. Native plants have a valuable role in providing habitat for birds and insects, and in erosion control. Mechanical drain clearing often destroys these plants, thereby reducing bio-diversity. Furthermore, removal of riparian plant shade releases water weeds from shade control so increasing rate of drain clogging.

2.3.5 Biological potential of removed sediments

The drain clearing activity most likely removes the sediments which contain the most available fractions of P. For example, Nguyen & Sukias (2002) found that the top sediment layers in drains had higher concentrations of bioavailable P than deeper sediment layers. Phosphorus in sediments undergoes multiple reactions at the sediment-water interface based on varying bio-geochemical parameters (Palmer-Felgate et al. 2011), meaning that these top sediments may have a higher potential to impact on the biological productivity of surface waters than the 5-15 cm sediment layers. P release mechanisms will however depend on the P concentrations in overlying water. In addition, dredging exposes sediments that most likely have different nutrient buffering capacities that those that were removed. Removal of organic sediments will also lower stream's capacity to remove N by denitrification.

2.3.6 Nutrient dynamics in recently exposed sediment

There may be longer term effects of mechanical drain clearing of sediment and weeds. In their study, Nguyen & Sukias (2002) found that, 3-6 months after drain dredging, drain sediments had a lower P content and P retention than those in drains which had not been cleared for 5 years, which they attributed to the removal of P accumulated in sediments and the loss of P sorption sites. Shigaki et al. (2008) equally found that after dredging, sediments were less able to remove P from flowing water. Smith & Huang (2010), in their study of the impacts on dredging drainage ditches in Indiana, observed that sediments may not be so absorbent in the period immediately following dredging, perhaps due to altering the physiochemical properties of the sediments exposed to the water column, or removal of vegetation and other biota that removed nutrients. However findings from their study suggested that, in the longer term (i.e., the period up to a year following dredging), changes would have occurred that would allow sediment to be stronger sinks for water column nutrients than in the pre-dredging period. They observed that nutrient loads in stream water (NH_4-N, NO_3-N, TN, total Kjeldahl nitrogen (TKN), DRP and total phosphorus (TP)) were all less in the year following dredging than before. This would occur because newly exposed reduced sediments would become oxidised and fresh sediments would be deposited, which would produce surface sediments with a higher affinity for nutrient removal from the water column.

Nguyen & Sukias (2002) observed lower suspended sediment levels in streams which had been recently cleared, and higher levels in streams that had not been dredged for more than 5 years due to accumulation of fine sediment and its resuspension in elevated flow conditions. In Southland drains and tributaries however, in the period after clearance, loads of sediment are higher than before clearance, even in slightly elevated flows, due to the disturbance of the channel bed (Figure 2-2). Monitoring data shows that it takes some time for bed sediments to be anchored in the channel bed.

Clearance also tends to remove finer textured sediments with higher organic matter content. Phosphorus adsorption tends to correlate strongly with organic matter content, as can be seen from sediment sampling results from Southland streams. P sorption to newly exposed sediments will decrease in the absence of organic matter. This may result in higher DRP concentrations in the water column. On the other hand, sediments in uncleared drains would have been exposed to high nutrient levels in the ditches over the period since the last clearance and so their relative ability to remove nutrients from the water column may have already been limited because of saturation.

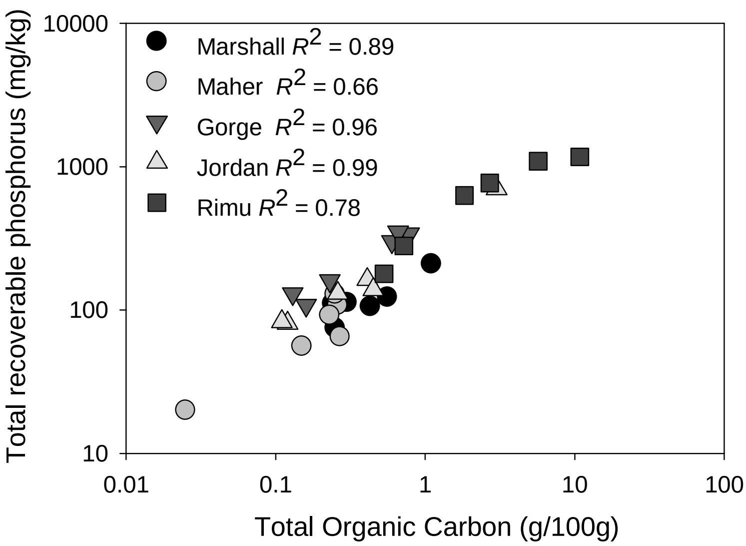

Figure 2-1: Relationship between total recoverable phosphorus and total organic carbon in sediments from 5 Southland drains from data collected between March and May 2012.

2.3.7 Microbial nutrient removal processes

Mechanical drain clearing removes biomass and a range of sediment dwelling microbes. These microbes are important to P dynamics in fluvial systems. Studies have shown that immobilization of dissolved forms of P by sediment-associated microbes can significantly enhance the ability of a stream to buffer P inputs. For example, Haggard et al. (1999)

observed that sediment P sorption potential was due to both biotic and abiotic factors. Qian et al. (2011) found that biological interactions were the main factor affecting P transformation processes at the sediment-water interface of a lake. McDowell & Sharpley (2003) estimated that 30% of dissolved P uptake by fluvial sediments occurred as a result of microbial immobilization. Newly uncovered sediments typically contain different microbial species composition, abundance and diversity than the removed sediments (Koel & Stevenson 2002). Therefore, changes in organisms may also influence rates of P uptake and release from sediments (Smith et al. 2006).

2.3.8 Water quality variables – longer term impacts

The effects of dredging on nutrient concentrations or turbidity are not thought to be lasting, and, according to some authors, removing sediments may have benefits for water quality. For example, Smith et al. (2006) considered that there would be effects on water quality immediately after dredging, and reported temporary increases in soluble P concentrations (i.e., a short-lived effect but not necessarily beneficial for water quality). Equally, Wilcock et al. (1998), in their study in the Toenepi stream, observed that nutrient concentrations and turbidity returned to pre-clearance levels within a short time (lNO_3-N, NH_4-N and DRP concentrations had returned to pre-clearance levels less than three hours later). Unfortunately samples were not collected from the Toenepi stream in the months after the drain clearing, or after rainfall events (as elevated nutrient and sediment loads might have been expected in elevated flows), so little is known about how long it took for sediments to become consolidated in the channel bed and for the sediment 'regime' of the drain to relax to pre-clearance conditions. Young et al. (2004) observed short lived increases in DRP and NH_4-N in the period immediately following clearance. No similar increases were observed for NO_3-N or TN. TP concentrations however were significantly higher in the drain that had been cleared relative to the control for some time after clearance, which they attributed to reduced uptake by aquatic plants and/or the physical effects of the digger mobilising P-rich sediments. We might expect to have higher DRP concentrations in drain water following sediment clearance due to the removal of organic matter with which phosphorus is positively correlated. However, the freshly exposed sediments may have higher P sorption abilities than the removed sediments, meaning that DRP concentrations may not change significantly. In other countries, sediment dredging/removal has shown to have water quality benefits, e.g. removal of sediments from polluted rivers and lakes in China have resulted in reduced nutrient concentrations after dredging (Wang & Feng 2007, Wu et al. 2012).

Although drain clearance is effective in removing unwanted vegetation, the channel bed and banks are significantly disturbed by this activity and loose sediment remains in the channel bed. While there is little evidence to substantiate this, apart from Environment Southland data, we believe that this loose material will be mobilised in elevated flow events in the months following the drain clearing. Loose soil remaining on the channel banks will be easily mobilised even following relatively small increases in flow, as shown in data from the Waituna Creek collected by Environment Southland (Figure 2-2). After the drain clearing activities on the Waituna Creek, turbidity was significantly elevated even with small increases in flow. That is to say, clearance significantly changed the sediment regime of this stream. Data from Environment Southland also suggests that the extremely high turbidities are accompanied by sharp increases in both total nitrogen and phosphorus, however these are likely to have minimal impact as nuisance plants do not respond to sharp increases. Until the channels and banks stabilise, more pulses of sediment (and nutrients) are expected, with even small increases in flow. Depending on the flow increase, the sediment may only be transported a short distance downstream before being re-deposited in the channel bed.

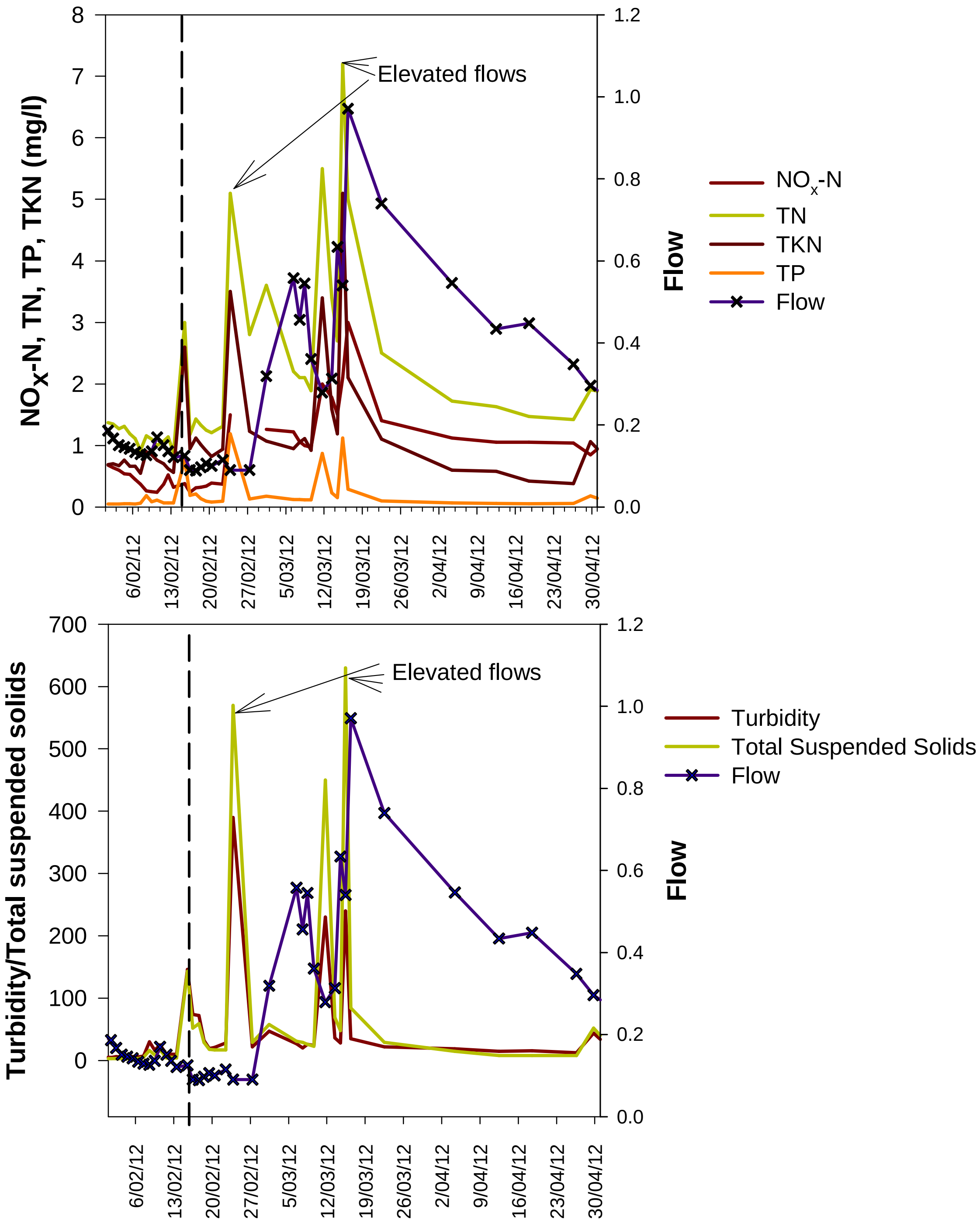

Figure 2-2: Sediment and nutrient dynamics through and after drain clearing in the Waituna Creek.

2.3.9 Sediment disposal

Care should be taken when dealing with extracted materials. Rather than being deposited on ditch banks and in adjacent fields where spoil may be susceptible to erosion and runoff, if at all possible (fine silty sediment, not stony or otherwise unusable material), spoil should be returned to pastures at a distance from the waterway (an excavator turning circle might be sufficient), so that their nutrient and organic content can be used and fine sediment is less likely to re-enter the drain.

2.4 Impacts of drainage management summarised

To summarise, some consistent direct and indirect effects of mechanical drain clearance using a bucket have been identified in this review process, and also by Brookes (1988). Little is known of effects of drain clearing using a weed rake rather than a bucket, as few studies have been documented. From available studies of effects from mechanical bucket clearing, direct effects include:

- Reduced aquatic weed biomass.
- A dramatic increase in turbidity for several hours following clearance as bed sediment is suspended.
- Changes to the physical morphology and flow characteristics of the drain, depending on the extent and method of excavation.
- Loss of in-stream habitat.
- Removal of invertebrates and fish along with weeds and sediment.

Indirect (and longer term) effects include:

- Loss of food for birds and fish species.
- Loss of in-stream habitat for benthic invertebrates and fish.
- Disturbance of channel bed, including removal of cobbles and gravels, which are essential for spawning of some fish species.
- Physical damage to the drain margins, banks and riparian vegetation by the digger, increasing bank instability and erosion, and loss of shade.

Impacts of drain clearance using current practices can therefore be significant.

3 Effects of drain clearing on sediment and nutrient concentrations/loads in Waituna Creek

3.1 Drain clearing in Waituna Creek – February/March 2012

In February and March 2012 a period of drain clearing contracted by Environment Southland occurred in the Waituna catchment. The drain clearing was carried out by two separate digger operators between 8 February and 28 March. The clearing began in the lower reaches of the catchment and the two digger operators systematically worked their way up through the catchment (at different locations) until all major drains were cleared. The sediment removed from the drains was dumped on the land immediately adjacent to the channels (Figure 3-1).

Figure 3-1: Digger clearing sediment from Carrans Creek in the Waituna Lagoon catchment. Photo: Katrina Robertson (Environment Southland).

Over this drain clearing period, Environment Southland staff collected data to enable an assessment of the water quality effects of this activity to be carried out. At the Waituna Creek hydrometric site at Marshall Road, approximately 40 water quality samples were collected between 31 January and 31 May 2012. This sampling period encompasses the entire drain clearing period, including several weeks after the cessation of drain clearing activities. The water quality samples were collected over a good range of flows with samples obtained from flows up to ~5000 l/s (5 m^3/sec, 6^{th} percentile flow). Two Greenspan turbidity probes were also installed at the Waituna Creek site at Marshall Road, logging at 10 minute intervals. One turbidity probe had a nominal turbidity range of 0 – 400 NTU while the other had a range of 0-1500 NTU.

During this same period, Environment Southland staff also collected water quality samples from the lower reaches of two other Waituna Lagoon tributaries (Carran's Creek and Moffat Creek). No Environment Southland contracted drain clearing occurred in these catchments, so the data obtained from these catchments provided a 'control' for assessing the impact of drain clearing in the Waituna catchment.

3.2 Water quality data

To assess the impact of the drain clearing activities on contaminant (i.e., sediment and associated light attenuation, nitrogen and phosphorus) concentrations and loads, the water quality data collected during and after the drain clearing was compared to that from the long-term record for the Waituna Creek site at Marshall Road. With this previous data record and the control monitoring this provides a robust BACI (Before-After-Control-Impact) design. The long-term water quality data for this site was collected from July 1995 and consists of monthly samples prior to April 2011 and bimonthly after that date. TN and TP have been measured since 1998, and total suspended solids (TSS) since 2008. In an attempt to capture information on water quality over a greater range of flows, Environment Southland has also recently carried out some flood-event sampling. A more detailed description of the water quality and flow record is presented in a recent joint Diffuse Sources Ltd/NIWA report to Environment Southland (Williamson et al. 2012). For this current analysis we removed first 6 months of data for 2000, 2003, 2006 and 2009 (where it existed) from the long-term record. Environment Southland contracted drain clearing also occurred during these years and its exclusion was considered appropriate so that any difference in datasets resulting from drain clearing could be detected.

The flow-contaminant concentration relationships for TSS, TP, NO_3-N and TN (for both the long-term record and drain clearing period) are illustrated in Figure 3-2, Figure 3-3, Figure 3-4, and Figure 3-5. It is clear from these relationships that the concentrations of TSS (Figure 3-2) and TP (Figure 3-3), for a given flow, were higher during the drain clearing period than for the long-term record. Furthermore, the highest TSS and TP concentrations ever measured at the Waituna Creek Marshall Road site occurred during the drain clearing period. The highest TSS (from 85 samples collected from 2008 - 2011) and TP (from 225 samples collected between 1998 - 2011) concentrations in the long-term record were 96 mg/l and 0.53 mg/l, respectively. Both of these maximum concentrations were obtained during flood events when the flows exceeded 9500 l/s. During the drain clearing period the TSS and TP concentrations of four samples exceeded these long-term record maximum concentrations (Table 3-1).

Table 3-1: TSS and TP concentrations of the four samples that exceeded the maximum concentrations from the long-term water quality record.

Date/Time	Flow (l/s)	TSS (mg/l)	TP (mg/l)
15/02/2012 11:31	77	143	0.76
23/02/2012 20:26	776	570	1.19
11/03/2012 16:40	2154	450	0.87
15/03/2012 9:46	4963	630	1.12

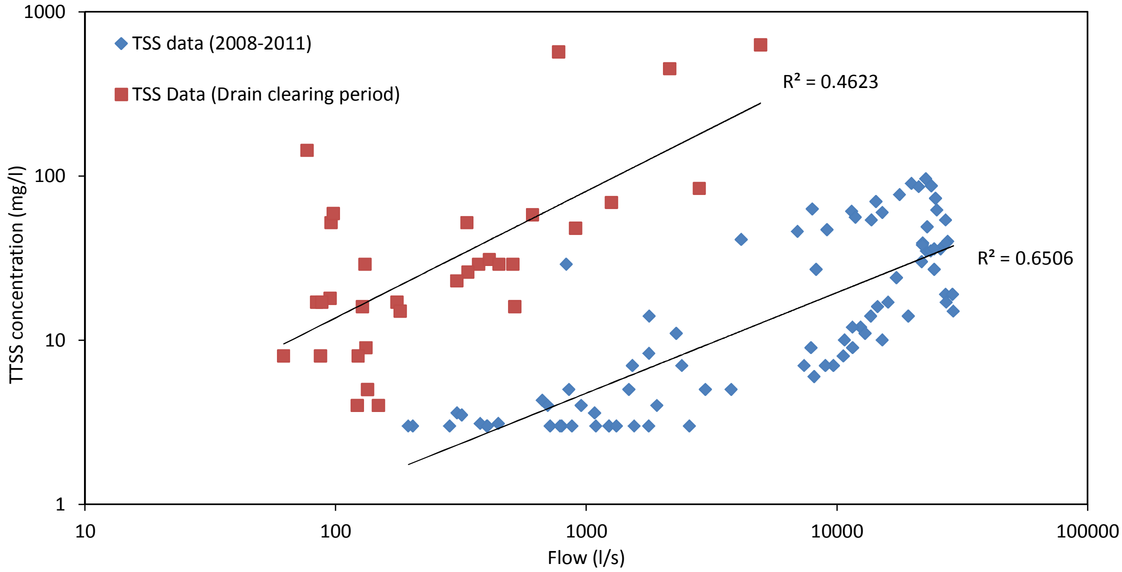

Figure 3-2: TSS concentration-flow relationship (Waituna Creek at Marshall Road) for the 2012 drain clearing period and for the long-term record.

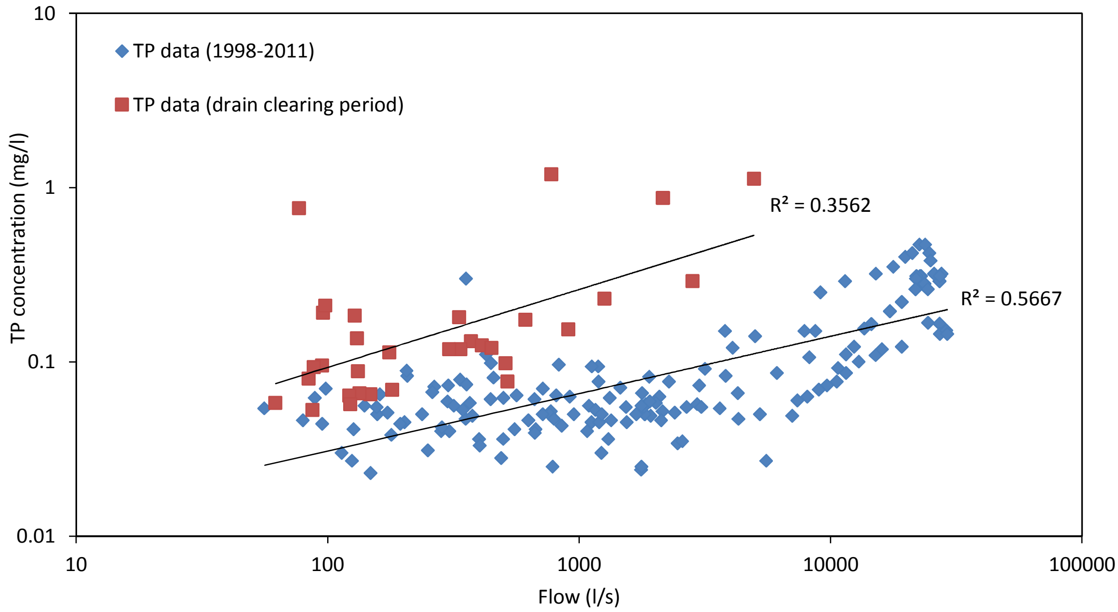

Figure 3-3: TP-flow relationship (Waituna Creek at Marshall Road) for the 2012 drain clearing period and for the long-term record.

The increase in TP concentrations during the drain clearing period is likely to be directly related to the increase in TSS concentrations. As discussed earlier, phosphorus is readily adsorbed onto sediment particles. The TSS/TP relationship for the drain clearing period data suggests that a high proportion of the TP load is transported in association with the sediment. TP did not increase so markedly as TSS, which suggests that the cleared sediment is actually lower in PP content than the material travelling in the undisturbed drain.

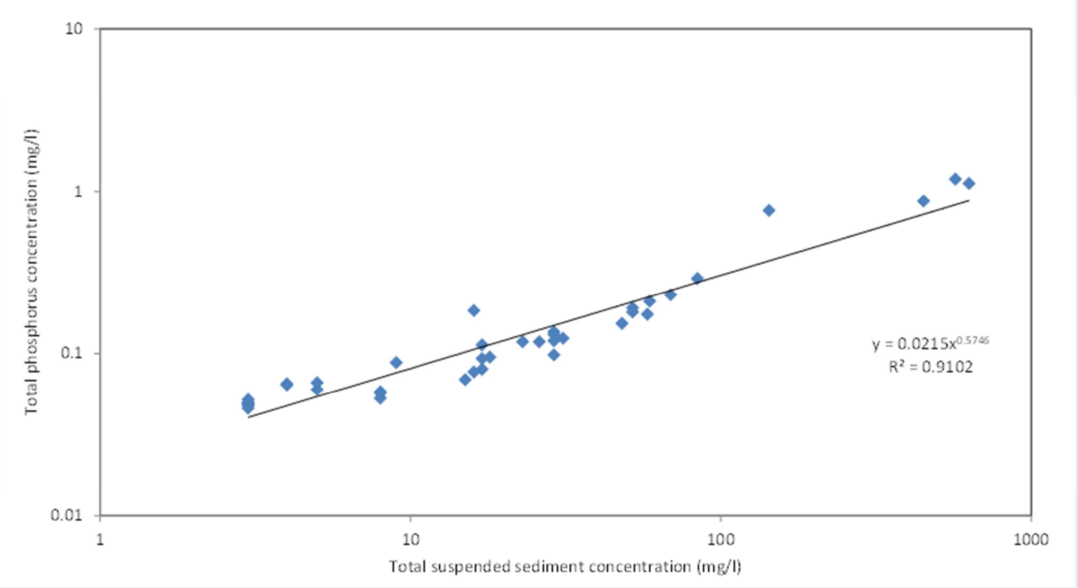

Figure 3-4: TSS-TP relationship for the water quality samples collected during the drain clearing period.

Conversely, there is little difference between the drain clearing period and long-term record relationships for NO_3-N (Figure 3-5) and TN (Figure 3-6). Although a number of samples (including the highest TN concentration (7.2 mg/l on 15/3/2012) measured at the Marshall Road site) were measured during the drain clearing period. Given that nitrogen is less readily adsorbed to sediment than phosphorus, it is not surprising that the nitrogen concentrations for the two sampling periods are similar. This is particularly the case for NO_3-N which is transported mainly in dissolved form. The limited observed increases in TN concentrations may be attributable to particulate nitrogen being mobilised during the drain clearing. This also reflects the dominance of TN by nitrate in dairy catchments

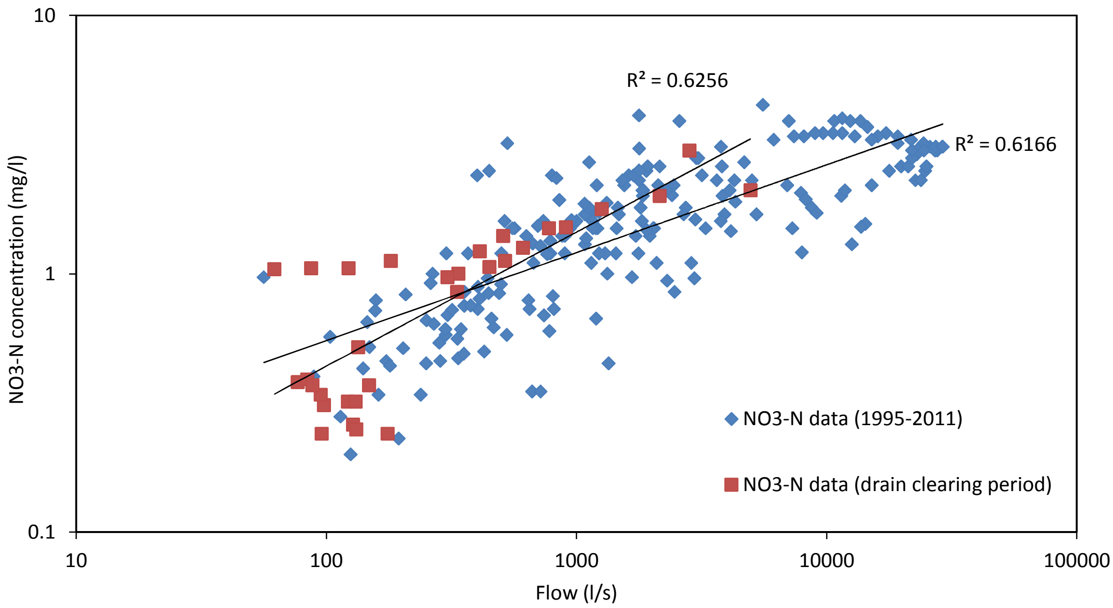

Figure 3-5: NO_3-N-flow relationship (Waituna Creek at Marshall Road) for the 2012 drain clearing period and for the long-term record.

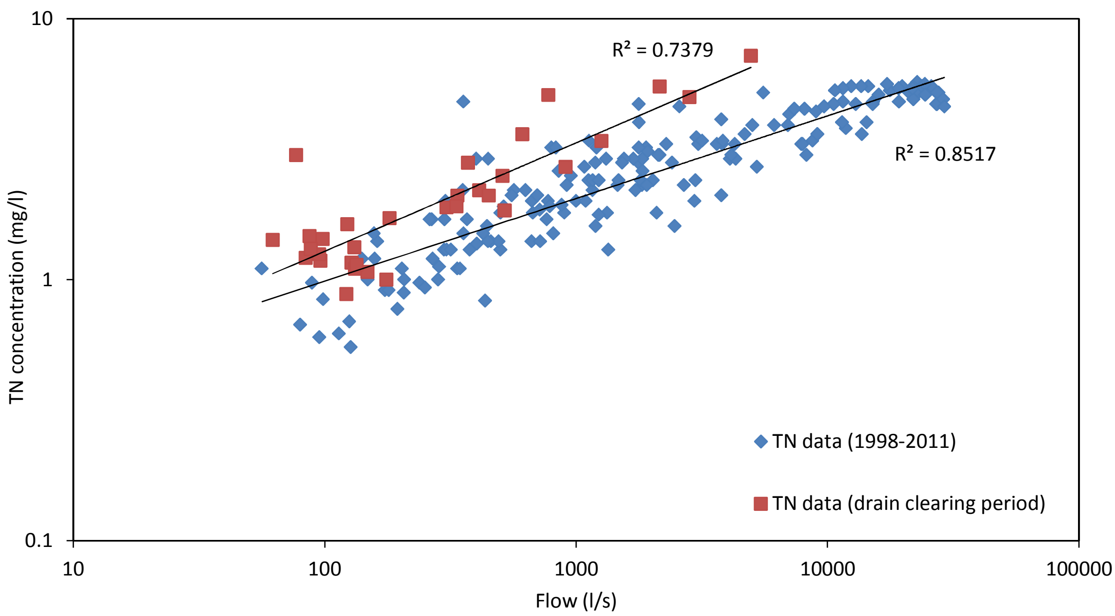

Figure 3-6: TN-flow relationship (Waituna Creek at Marshall Road) for the 2012 drain clearing period and for the long-term record.

The availability of flow-contaminant relationships for both the long-term record and the drain clearing period enables us to calculate contaminant loads under two scenarios. The first uses the drain clearing period relationships to estimate actual loads for the drain clearing period. The second uses the long-term data relationship and applies it to the same period of flow. This allows us to test what the loads may have been if there was no drain clearing activity. This approach assumes that the difference in the two sets of flow-contaminant relationships is solely due to the drain clearing activity and therefore any difference in loads is also a result of the drain disturbance. It is possible that some of the difference in relationships is due to other environmental factors but the disturbance caused by the diggers was high, and the robust BACI design allows confident attribution of the change in the flow-contaminant relationships to the drain clearing activity.

Water quality data collected from Carran's and Moffat Creeks over the same period show that there was little change in the flow-TSS (Figure 3-7 and Figure 3-8) and flow-TP (Figure 3-9 and Figure 3-10) relationships for these catchments. This provides strong support for attributing changed flow-contaminant relationships to drain clearing activity.

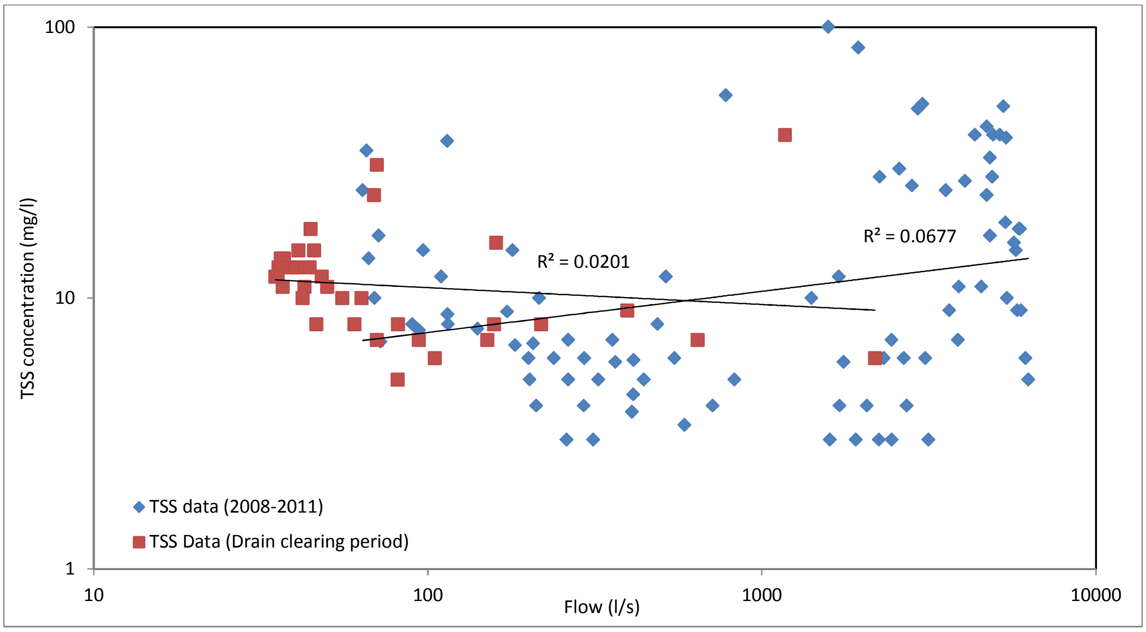

Figure 3-7: Total suspended sediment-flow relationship (Carran's Creek) for the 2012 drain clearing period and for the long-term record.

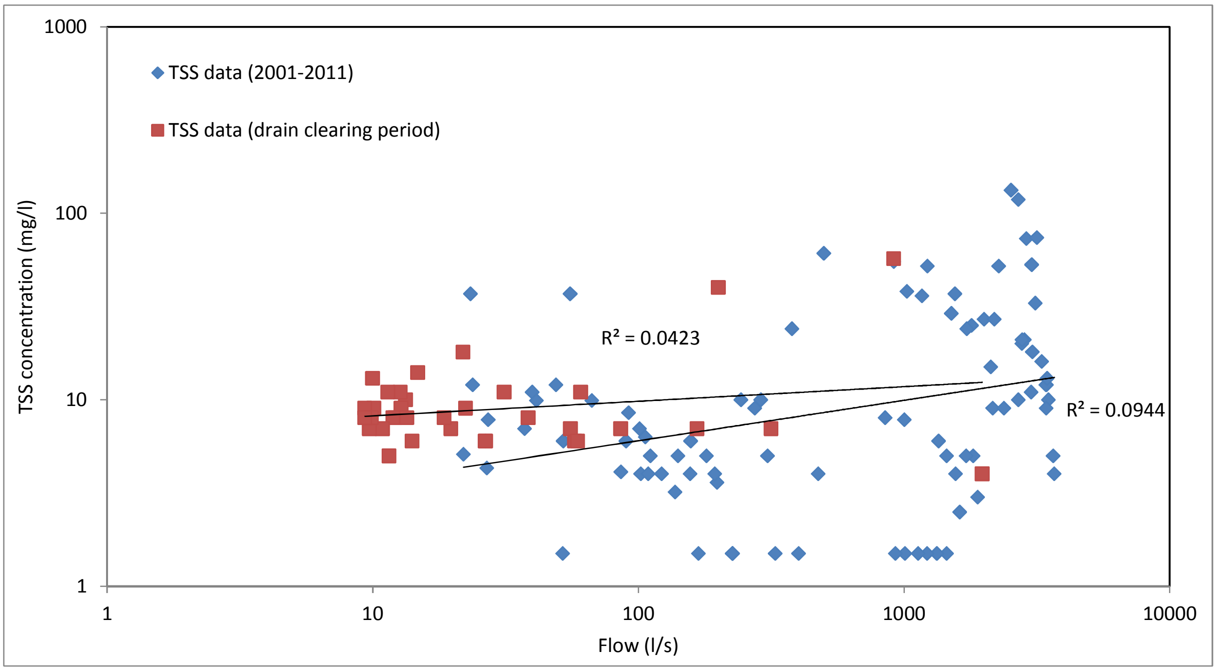

Figure 3-8: Total suspended sediment-flow relationship (Moffatt Creek) for the 2012 drain clearing period and for the long-term record.

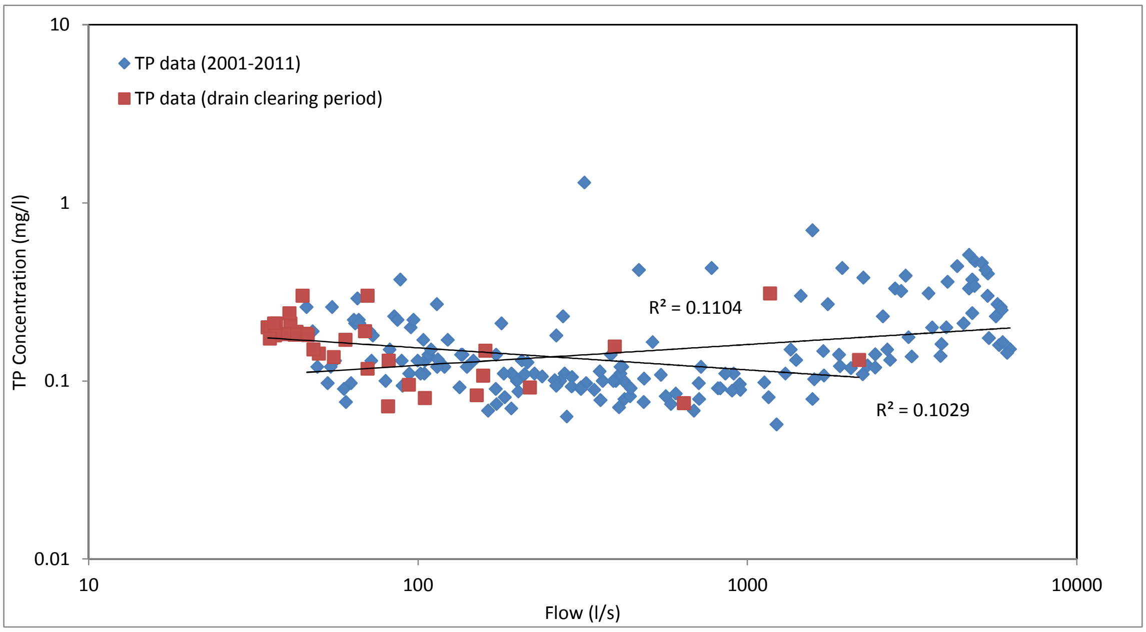

Figure 3-9: Total phosphorus-flow relationship (Carran's Creek) for the 2012 drain clearing period and for the long-term record.

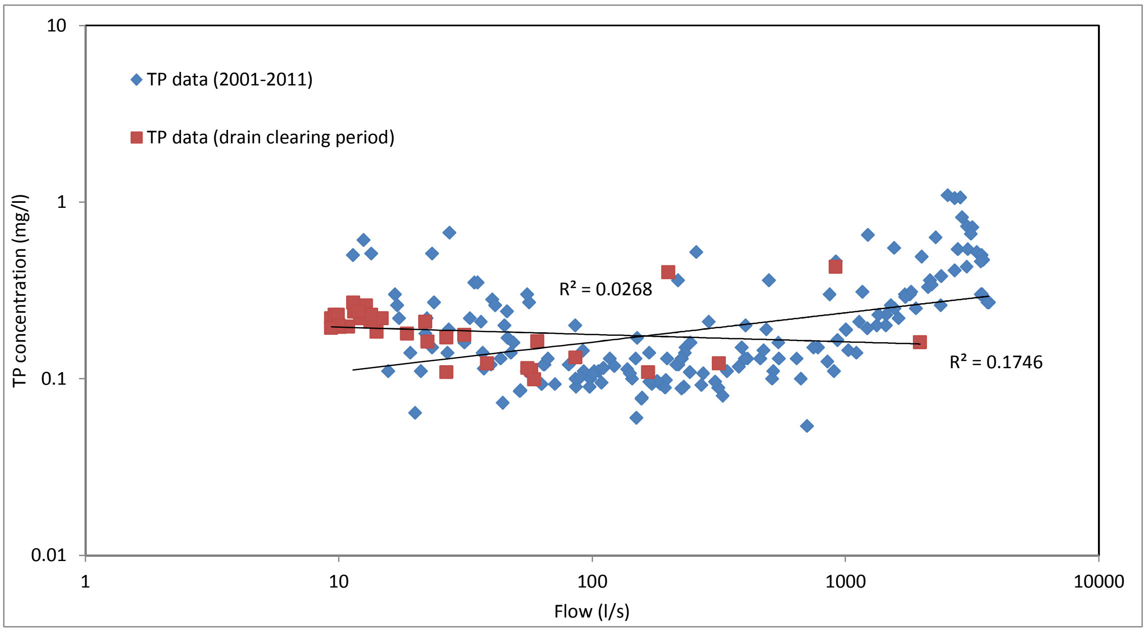

Figure 3-10:Total phosphorus-flow relationship (Moffatt Creek) for the 2012 drain clearing period and for the long-term record.

The coefficient of efficiency, *E*, was used as a measure of the performance of the flow-contaminant relationships. The coefficient of efficiency represents a form of noise to signal ratio, comparing the average variability of model residuals to the variability of the target output (Schaefli & Gupta 2007). Coefficient of efficiency values of between 0 and 1 are considered acceptable with higher positive values indicating superior model performance (Chiew & McMahon 1993, Schaefli & Gupta 2007). A negative *E* value indicates a poorly performing model (Schaefli & Gupta 2007).

Table 3-2 indicates the regression outputs (including *E* values) for each of the flow-contaminant relationships for the two datasets. All the regression models have satisfactory *E* values; accordingly we can have confidence that the rating curves are reasonable representations of the data.

Table 3-2: Regression outputs (Waituna Creek at Marshall Road) for the 2012 drain clearing period and the long-term record.

	TSS	NO_3-N	TN	TP
Long-term record (1995-2011)				
y intercept	-1.1611	-0.93826	-0.63809	-2.23019
Slope	0.6128	0.3400	0.3167	0.3454
E	0.41	0.35	0.82	0.55
R^2	0.65	0.62	0.85	0.56
Number of samples	85	217	225	225
Drain clearing period data (Feb-May 2012)				

	TSS	NO_3-N	TN	TP
y intercept	-0.4054	-1.3949	-0.7221	-1.9255
Slope	0.7710	0.5187	0.4155	0.4468
E	0.52	0.64	0.83	0.36
R^2	0.46	0.63	0.74	0.36
Number of samples	36	34	35	35

Table 3-3 shows the contaminant loads calculated using the two datasets. The loads were calculated for a 98 day period from commencement of drain clearing (8 February 2012) to approximately 6 weeks after the cessation of drain clearing (15 May 2012). The results show that all the contaminant loads are higher when the drain clearing period flow-contaminant relationships are used. Significantly, both TSS and TP loads were predicted to be an order of magnitude higher. Although NO_3-N and TN loads are also higher for the drain clearing period dataset, the magnitude of difference together with the uncertainty of this approach, means that these estimated differences are less likely to be significant.

Table 3-3: Total suspended sediment, NO_3-N, TN and TP loads for the period between 8 February and 15 May 2012. The Long-term data loads are based on the relationships developed from the water quality data collected by ES between 1995 and 2011. The drain clearing period data loads are based on the relationships developed from the water quality data collected by ES between February and May 2012.

	TSS Load (t)	TP Load (t)	NO_3-N Load (t)	TN Load (t)
Long-term data loads	22.2	0.2	4.5	7.3
Drain clearing period data loads	550.4	1.2	5.7	12.0

3.3 Turbidity data

The collection of continuous turbidity data (calibrated to suspended sediment concentration), in conjunction with the measurement of stream flow, is becoming a common approach for assessing suspended sediment yields from catchments (e.g. Tena et al. 2011, Wass & Leeks 1999). Furthermore, turbidity is a valuable continuous surrogate for visual clarity (and light attenuation) – to which it is strongly inversely related (Davies-Colley & Smith 2001). Obtaining a high quality continuous turbidity record can sometimes be problematic because of probe fouling and electronic noise (e.g. Oeurng et al. 2010, Tena et al. 2011) but such an approach has the added advantage of providing near-continuous information on dynamics of suspended sediment and associated light attenuation (Davies-Colley & Smith 2001).

As is often the case with continuously recorded turbidity data in natural waterways, the turbidity records for both Marshall Road probes are reasonably noisy and have a number of gaps. The noise and gaps in the data can be attributed to various sources, such as the probes being covered with sediment or debris, electronic noise and periods of low flow when the probe is exposed. Both probes (especially the low range probe) also over-ranged for periods of time, especially during elevated flows. Accordingly, only the period of data between 8 February and 4 April can be considered reliable (albeit with some noise, gaps and over-ranging). The low and high range records for this period are illustrated in Figure 3-11 and Figure 3-12, respectively. Although the data from both probes is noisy, having dual records allows us make a robust assessment of the data.

As mentioned above, turbidity data (calibrated to suspended sediment concentration), in conjunction with the measurement of stream flow, can be used to calculate suspended sediment loads. The low range turbidity data for the Marshall Road site over-ranges at a number of points (including during elevated flows), therefore we considered it inappropriate to attempt to calculate loads with this record. The high range record has better potential for load determination due to its more reliable record during periods of high flow. There is also a reasonable relationship between measured field turbidity and TSS concentration for the high range data (Figure 3-13). Despite this sound relationship, it should be noted that it only encompasses turbidity values up to ~600 NTU and there are a number of times when field turbidity exceeds 600 NTU. Therefore all TSS concentration predictions based on turbidity values > 600 NTU are extrapolations. Nevertheless, a load of 225 t is calculated when we apply this relationship to the sound section of turbidity record between 8 February and 4 April. This compares to 476 t calculated by applying the drain clearing period rating curve (Figure 3-2) to the same time period. Given the uncertainty of sediment load calculations (commonly ±50%), this a reasonable agreement.

Perhaps more usefully, the turbidity record for Marshall Road also allows us to assess the effects of the drain clearing through time as it progresses upstream through the catchment. Drain clearing began in the catchment on 8 February at two downstream sites. One drain clearing site was downstream of the sampling site, while the other was approximately one kilometre upstream of the sampling site in Maher’s tributary. The turbidity record of both probes show a limited turbidity response in the period from 8 to 14 February. On 15 February the drain clearing began immediately upstream of the Marshall Road sampling site and continued for several days in close proximity to the sampling site. Both turbidity probes recorded an extended period of fluctuating high turbidity over these few days. Beyond about 20 February, as the drain clearing progressed up the catchment, the occurrence of non-flow related turbidity fluctuations were difficult to detect. Therefore, while the drain clearing had an obvious effect on turbidity (and therefore water clarity) in close proximity to the clearing activity, it is likely that this increased turbidity was relatively short-lived as much of the disturbed sediment was re-deposited a short distance downstream. However, this recently deposited (unconsolidated) sediment would be easily entrained by flow events for some considerable time after the clearance, so exposing aquatic life to extended higher turbidity and low clarity.

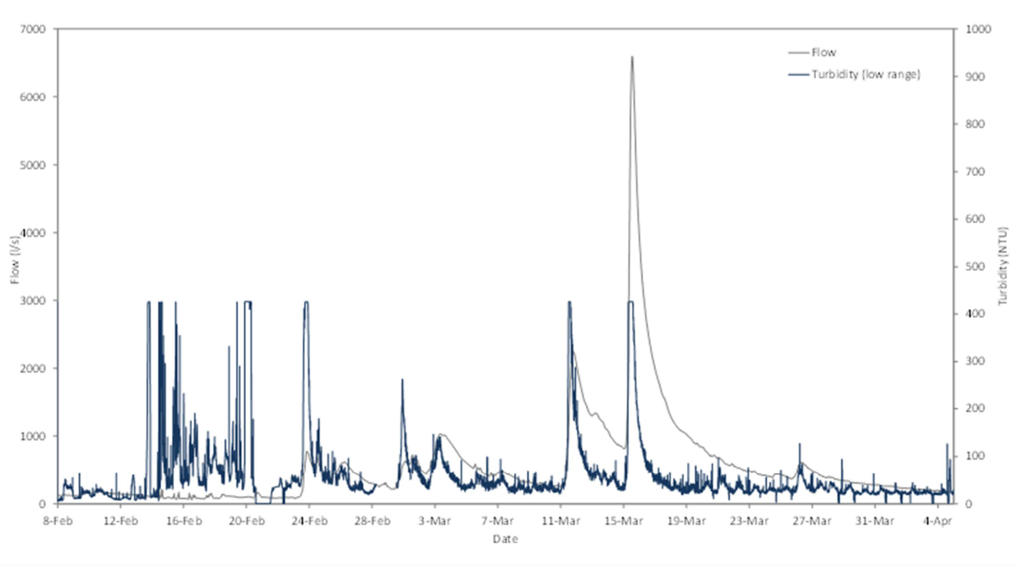

Figure 3-11:Low range (0-400 NTU) turbidity record for Waituna Creek at Marshall Road (8 February 2012 and 4 April 2012).

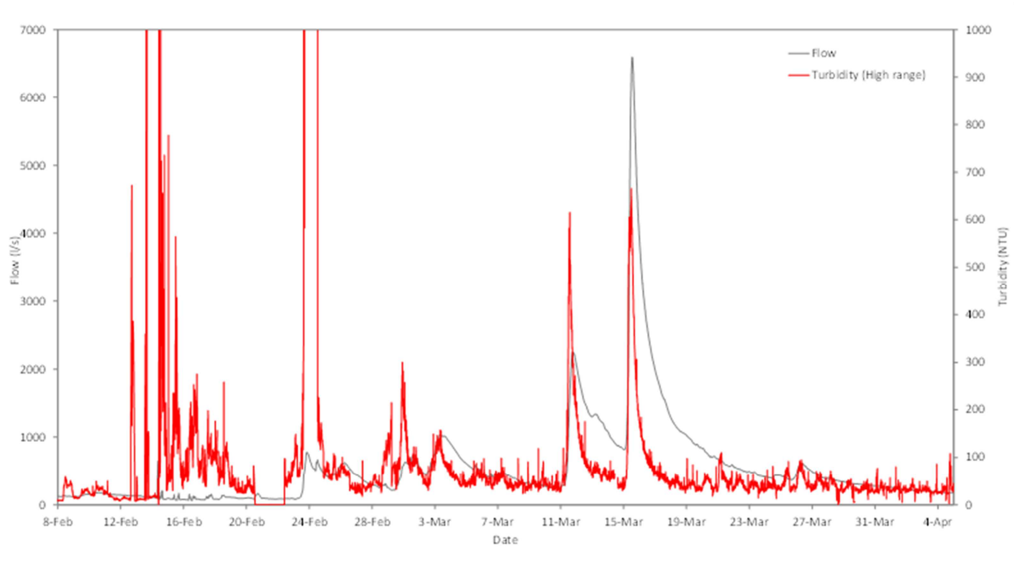

Figure 3-12:High range (0-1500 NTU) turbidity record for Waituna Creek at Marshall Road (8 February 2012 and 4 April 2012).

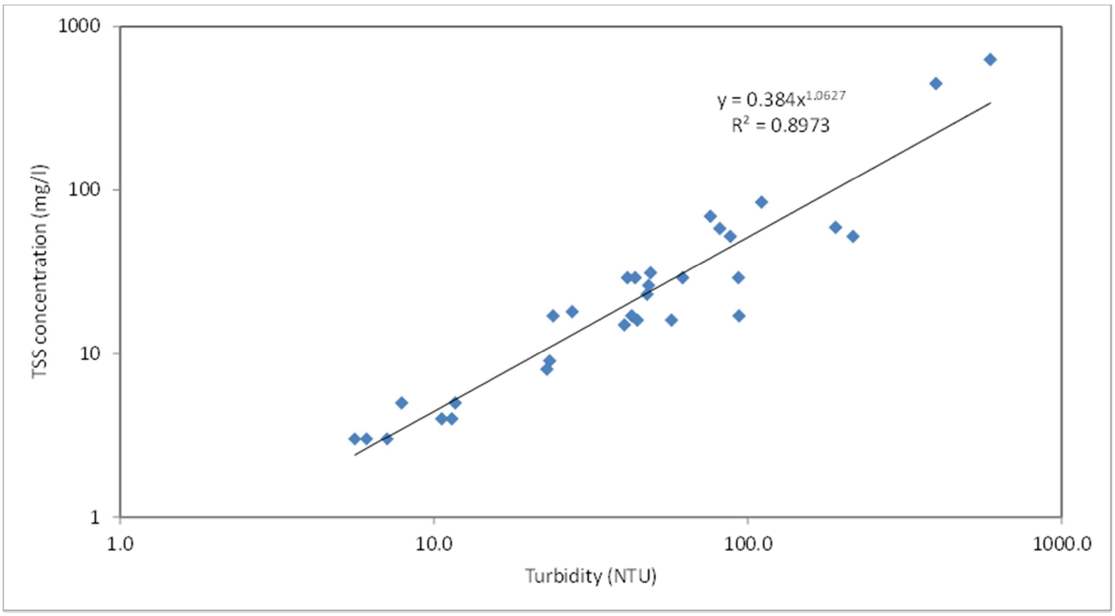

Figure 3-13:TSS-turbidity relationship for the high range turbidity probe at the Waituna Creek at Marshall Road site.

Another observation from both turbidity records is that base level turbidity appeared to be higher (~30 NTU) at the end of the record than it was at the beginning (~7 NTU). Assuming that this was not due to a drift in the turbidity sensor output, it may be that the drain clearing had an on-going detrimental effect on water clarity for some period of time after the clearing has ceased – as we might expect with on-going 'bleeding' of fine sediment into the water column from raw exposed areas in the channel. Presumably, once the drains have recovered (e.g. regrowth of grass on banks; flushing of disturbed in-channel sediment; regrowth of aquatic weeds) the turbidity levels will decline. This supports what has been reported in other studies.

It would therefore appear that the clearing of drains has two principal effects with regards to suspended sediment (and clarity) dynamics. The first is the immediate increase in turbidity that results from the drain clearing activity. This, in itself, is unlikely to have a significant impact on the amount of sediment being exported from Waituna Creek, because drain clearing primarily takes place during low flow conditions and the turbidity record suggests that the downstream effect of drain clearing decreases with distance from the drain disturbance. However, increased turbidity (or decreased water clarity) may have an effect on instream and/or receiving environment (i.e., Waituna Lagoon) biota.

The second major, and perhaps more significant effect, is when flow events occur during, or in the weeks and months after, drain clearing. During these events, sediment concentrations (and therefore loads) are considerably higher than during non-drain clearing periods because of the major shift in the sediment 'regime' illustrated in Figure 3.2 above. It is likely that sediment concentrations would remain elevated for a period of months after the drain clearing, while channel bed and banks recover from the disturbance.

4 Drain management – the future

Drain clearing is not unique to Southland, but rather is done to maintain free flowing drains across New Zealand. Drain clearing is common in the Waikato, and Waikato Regional Council have produced Best Environmental Practice Guidelines for drain maintenance (Gibbs 2007) and we would advise that these guidelines are followed as far as possible.

The main reason for clearing drains is to remove sediment and/or weed growth to allow drainage water to flow and prevent flooding of farm land. Ideally, the ultimate sources of sediment and nutrients on catchment farmland should be controlled so that inputs to drainage channels are reduced. Unless these sources of sediment and nutrients are controlled, rapid drainage channel clogging will continue.

On land measures (beneficial management practices, BMPs) should be implemented to reduce soil erosion. Controlling soil erosion will help maintain productivity and will also reduce sediment inputs to drains and the associated deterioration in water quality.

Erosion control might include:

- Leaving a buffer zone between the cropped area and the waterway.
- Retaining existing riparian shrubs, and planting where absent, to provide channel shading which will reduce water weed growth and slow drain infilling. (Once shading reaches about 50% water weed growth will be eliminated and drain clogging may be greatly inhibited).
- Creating a grassed/vegetated filter strip alongside the waterway to filter sediment.
- Fencing streams to exclude livestock.
- Bridging stream crossings.
- Managing stock (type, numbers, and timing) to reduce damage to soil.
- Tree planting in erosion susceptible areas to hold soil in place.
- Cultivation across the general slope of the land (rather than up and down).

4.1 Low impact drain management

Shading stream channels and drains provide a range of benefits, not least that shading by more than about 50% eliminates aquatic macrophyte growth. Therefore planting of streams and drains together with protection of existing shading riparian shrubs, may greatly reduce or even eliminate the need for mechanical clearance. We recommend that Environment Southland investigate this possibility, together with the wider benefits of drain and stream shading (such as on water temperatures and indigeneous biodiversity).

If drains have to be cleared using mechanical methods, it is preferable that the disturbance is minimal. Good drain management should retain vegetation where possible, carry out drain clearing only where necessary, avoid straightening natural drainage channels as a meandering drain creates better habitat and enhances nutrient retention.

To minimise the impacts of drain clearance:

- Use shading (tall) vegetation to limit the amount of available light to plants and thereby reduce plant biomass. Retain existing shrubs and plant riparian zones to provide shading (Research has shown that approximately 50% shading will eliminate common aquatic plants (Collier et al. 1995, Dawson & Haslam 1983)).
- Drains should be inspected beforehand and riffles, pools and sensitive areas that shouldn't be disturbed marked with pegs or paint.
- One section of the drain should be cleared at a time, so that vegetated parts remain as filters. It is a good idea to leave a buffer of weed at the lower end of the drain to trap silt and then clean this area last. Only clear the sections that need maintenance. If the downstream area is ecologically sensitive, a filter (e.g. a straw bale) could be put into the stream to control the flow of dirty water downstream.
- If possible, material should only be taken from the channel bed and not the channel banks.
- Clear the drain using a weed rake so that fish and other aquatic life can escape back into the drain, or have someone walk alongside the drain to return them.
- Exposed soils on channel/drain banks should be seeded or planted.
- Drain clearings should be spread on paddocks, away from waterways and wetlands, so that the nutrients are returned to farmland rather than the waterways.

5 Conclusion

Drains are frequently cleared in Southland to maintain flow. Drain clearing is mostly done mechanically, using a digger and bucket. This clearing, while effective in removing accumulated sediment and vegetation, other studies suggest that it may cause significant ecological disruption. Concentrations of suspended sediment and some water quality variables also increase through clearing events.

In Southland, suspended solids and TP concentrations increased sharply through drain clearing events, while concentrations of NO_3-N and TN differed minimally from long term concentrations. Small increases in flow after the drain clearing gave rise to sharp increases in turbidity (implying a decrease in clarity), suggesting a shift in the turbidity regime.

We would expect that drains would settle back to pre-clearing concentrations for both turbidity and other water quality variables over a period of months. The relaxation time will depend on the rate of stabilization of the drain bed and banks. With drain clearance mainly in late summer, and because of high flows and rainfall through winter, we would expect the recovery of the normal drain sediment and water quality regime could take six months or more. Low flows are expected be needed to allow sediment to stabilise and settle in the stream channel. We would also expect that ecology would recover in the months following clearance, commensurate with the recovery of the sediment and water quality regime (and assuming no major lags in 'recruitment). We would not expect to see much vegetation growth through the winter immediately following drain clearance, but six months following clearance, in springtime, we would expect to see vegetation growth and regeneration, depending on environmental conditions.

There may be downstream effects of drain clearing. Higher than usual loads of sediment and associated nutrients will be transported downstream in high flows, which will lead to elevated turbidity (and reduced clarity) and higher than normal rates of sedimentation, which may have negative impacts on ecological structure and function. Depending on the environmental conditions in the receiving waters, there may be the potential for the release of phosphorus from sediments.

We strongly recommend that agricultural BMPs are put into place so that land management is improved, and sediment and nutrient loss significantly decreased. Drain management could usefully include protection of existing shrubby riparian vegetation and planting of indigeneous shrubs to shade the channel and eliminate water weed growth – potentially reducing or even eliminating the need for mechanical clearance. It might be a good incentive for farmers to implement erosion control if drains were not cleared regularly by Environment Southland.

It will take some time for BMPs on land and along drains to show positive results, and in the meantime, drains may still need to be cleared. We recommend that drain clearing is done in as environmentally sensitive manner as possible, so that disturbance and impacts are minimised.

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7 References

Bilotta, G.S.; Brazier, R.E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research 42(12)*: 2849–2861. <http://dx.doi.org/10.1016/j.watres.2008.03.018>

Brookes, A. (1988). Channelized rivers: perspectives for environmental management. John Wiley & Sons, Chichester.

Chiew, F.H.S.; McMahon, T.A. (1993). Assessing the adequacy of catchment streamflow yield estimates. *Australian Journal of Soil Research 31*: 665–680.

Collier, K.J.; Davies-Colley, R.J.; Cooper, A.B.; Rutherford, J.C.; Smith, C.M.; Williamson, R.B. (1995). Managing riparian zones along watercourses in modified catchments. 2 volumes. NIWA, Hamilton and Department of Conservation, Wellington. December 1994. 31 p in part I, and 8 major sections in part II. *NIWA Consultancy Report DOC022*.

Collins, A.L.; Walling, D.E.; Stroud, R.W.; Robson, M.; Peet, L.M. (2010). Assessing damaged road verges as a suspended sediment source in the Hampshire Avon catchment, southern United Kingdom. *Hydrological Processes 24(9)*: 1106–1122. <http://dx.doi.org/10.1002/hyp.7573>

Davies-Colley, R.J.; Smith, D.G. (2001). Turbidity, suspended sediment, and water clarity: A review. *Journal of the American Water Resources Association 37(5):* 1085–1101. <http://dx.doi.org/10.1111/j.1752-1688.2001.tb03624.x>

Davies-Colley, R.J.; Vant, W.N.; Smith, D.G. (2003). Colour and Clarity of Natural Waters. Science and Management of Optical Water Quality. Blackburn Press, Caldwell, New Jersey.

Dawson, F.H.; Haslam, S.M. (1983). The management of river vegetation with particular reference ot shading effects of marginal vegetation. . *Landscape Planning 10*: 147–169.

De Medina, H.L.; Marin, J.C.; Gutierrez, E.; Morales, J. (2003). Nitrogenmobility at the sediment-water interface of Lake Maracaibo, Venezuela. *Water Air and Soil Pollution 145(1)*: 341–357. <http://dx.doi.org/10.1023/a:1023632702886>

Gibbs, M. (2007). Best Practice Environmental Guidelines - Land Drainage. *Environment Waikato Technical Report 2006/06R*. Waikato Regional Council Hamilton. http://www.waikatoregion.govt.nz/Services/Publications/Technical-Reports/TR200606R/.

Haggard, B.E.; Stanley, E.H.; Hyler, R. (1999). Sediment-phosphorus relationships in three northcentral Oklahoma streams. *Transactions of the Asae 42(6)*: 1709–1714.

Haygarth, P.M.; Jarvis, S.C. (1999). Transfer of Phosphorus from Agricultural Soil. *In*: Donald, L.S. (ed.). Advances in Agronomy, pp. 195–249. Academic Press, Kemp, P.; Sear, D.; Collins, A.; Naden, P.; Jones, I. (2011). The impacts of fine sediment on riverine fish. *Hydrological Processes 25(11)*: 1800–1821. <http://dx.doi.org/10.1002/hyp.7940>

Koel, T.M.; Stevenson, K.E. (2002). Effects of dredge material placement on benthic macroinvertebrates of the Illinois River. *Hydrobiologia 474(1-3)*: 229–238. <http://dx.doi.org/10.1023/a:1016500324467>

McDowell, R.W.; Sharpley, A.N. (2003). Uptake and Release of Phosphorus from Overland Flow in a Stream Environment. *J. Environ. Qual. 32(3)*: 937–948. <http://dx.doi.org/10.2134/jeq2003.9370>

Monaghan, R.M.; Hedley, M.J.; Di, H.J.; McDowelli, R.W.; Cameron, K.C.; Ledgard, S.F. (2007). Nutrient management in New Zealand pasturesrecent developments and future issues. *New Zealand Journal of Agricultural Research 50(2)*: 181–201.

Nguyen, L.; Sukias, J. (2002). Phosphorus fractions and retention in drainage ditch sediments receiving surface runoff and subsurface drainage from agricultural catchments in the North Island, New Zealand. *Agriculture, Ecosystems & Environment 92(1)*: 49–69. <http://dx.doi.org/10.1016/s0167-8809(01)00284-5>

Oeurng, C.; Sauvage, S.; Sánchez-Pérez, J.-M. (2010). Dynamics of suspended sediment transport and yield in a large agricultural catchment, southwest France. *Earth Surface Processes and Landforms 35(11)*: 1289–1301. <http://dx.doi.org/10.1002/esp.1971>

Oliver, D.M.; Clegg, C.D.; Haygarth, P.M.; Heathwaite, A.L. (2005). Assessing the Potential for Pathogen Transfer from Grassland Soils to Surface Waters. *In*: Advances in Agronomy, pp. 125–180. Academic Press.

Qian, Y.; Liang, X.; Chen, Y.; Lou, L.; Cui, X.; Tang, J.; Li, P.; Cao, R. (2011). Significance of biological effects on phosphorus transformation processes at the water–sediment interface under different environmental conditions. *Ecological Engineering 37(6)*: 816–825. <http://dx.doi.org/10.1016/j.ecoleng.2010.12.005>

Schaefli, B.; Gupta, H.V. (2007). Do Nash values have value? *Hydrological Processes 21*: 2075–2080.

Shigaki, F.; Kleinman, P.J.A.; Schmidt, J.P.; Sharpley, A.N.; Allen, A.L. (2008). Impact of Dredging on Phosphorus Transport in Agricultural Drainage Ditches of the Atlantic Coastal Plain1. *JAWRA Journal of the American Water Resources Association 44(6)*: 1500–1511. <http://dx.doi.org/10.1111/j.1752-1688.2008.00254.x>

Shigaki, F.; Schmidt, J.P.; Kleinman, P.J.A.; Sharpley, A.N.; Allen, A.L. (2009). Nitrogen Fate in Drainage Ditches of the Coastal Plain after Dredging. *J. Environ. Qual. 38(6)*: 2449–2457. <http://dx.doi.org/10.2134/jeq2008.0268>

Smith, D.R. (2009). Assessment of in-stream phosphorus dynamics in agricultural drainage ditches. *Science of the Total Environment 407(12)*: 3883–3889. <http://dx.doi.org/10.1016/j.scitotenv.2009.02.038>

Smith, D.R.; Huang, C. (2010). Assessing nutrient transport following dredging of agricultural drainage ditches. *Transactions of the Asabe 53(2)*: 429-436.

Smith, D.R.; Warnemuende, E.A.; Haggard, B.E.; Huang, C. (2006). Changes in sediment-water column phosphorus interactions following sediment disturbance. *Ecological Engineering 27(1)*: 71–78. <http://dx.doi.org/10.1016/j.ecoleng.2005.10.013>

Tena, A.; Batalla, R.J.; Vericat, D.; López-Tarazón, J.A. (2011). Suspended sediment dynamics in a large regulated river over a 10-year period (the lower Ebro, NE Iberian Peninsula). *Geomorphology 125(1)*: 73–84. <http://dx.doi.org/10.1016/j.geomorph.2010.07.029>

Wang, X.Y.; Feng, J. (2007). Assessment of the effectiveness of environmental dredging in South Lake, China. *Environmental Management 40(2)*: 314–322. <http://dx.doi.org/10.1007/s00267-006-0132-y>

Wass, P.D.; Leeks, G.J.L. (1999). Suspended sediment fluxes in the Humber catchment, UK. *Hydrological Processes 13*: 935–953.

Watson, C.J.; Foy, R.H. (2001). Environmental impacts of nitrogen and phosphorus cycling in grassland systems. *Outlook on Agriculture 30(2)*: 117–127. <http://dx.doi.org/10.5367/000000001101293562>

Wilcock, R.J.; Rodda, H.J.E.; Scarsbrook, M.R.; Cooper, A.B.; Stroud, M.J.; Nagels, J.W.; Thorrold, B.S.; O'Connor, M.B.; Singleton, P.L. (1998). The influence of dairying on the freshwater environment (the Toenepi study). *NIWA client report DRI60202* to the New Zealand Dairy Research Institute. NIWA Hamilton.

Williamson, B.; Hughes, A.O.; Elliott, S. (2012). Waituna Catchment Loads *Joint Diffuse Sources/NIWA Client Report for Environment Southland No.*

Wood, P.J.; Armitage, P.D. (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management 21(2)*: 203–217. <http://dx.doi.org/10.1007/s002679900019>

Wu, M.; Sun, X.-m.; Huang, S.-l.; Tang, X.-q.; Scholz, M. (2012). Laboratory analyses of nutrient release processes from Haihe River sediment. *International Journal of Sediment Research 27(1)*: 61–72. <http://dx.doi.org/10.1016/s1001-6279(12)60016-x>

Young, R.G.; Keeley, N.B.; Shearer, K.A.; Crowe, A.L.M. (2004). Impacts of diquat herbicide and mechanical excavation on spring-fed drains in Marlborough, New Zealand. *Department of Conservation Science for Conservation 240,* Wellington. 35 p.