Farming, Food and Health. First™
Te Ahuwhenua, Te Kai me te Whai Ora. Tuatahi

Waituna Sediment Fingerprinting Study

October 2013

RE500/2013/136

New Zealand's science. New Zealand's future.

Waituna Sediment Fingerprinting Study

Environment Southland

R.W. McDowell

M. Norris

N. Cox

RE500/2013/136

October 2013

Table of Contents

Executive Summary

Sediment influx has been highlighted as a source of concern within the Waituna Lagoon. Efforts to decrease the load of sediment entering the lagoon require that the source be targeted for mitigation. Sediment fingerprinting was conducted to better define the source of sediment loss at four sites within the lagoon's catchment, two in the Waituna Creek catchment (upstream and downstream), and one each on Carran Creek and Moffat Creek. Multiple time-integrated samplers were installed at each site to capture sediment in flow for periods usually of 2 weeks, but up to 6 weeks when samplers could not be collected due to flooding. Trapped sediments were then tested for a range of analytes (e.g. rare earth and heavy metals) along with multiple samples of topsoil, subsoil, stream bank and stream bed sediment at locations up to 1.5 km upstream of each site. A two stage statistical model was used to determine if sources contributed towards a signature that enabled it to be distinguished from another source. These signatures were then compared to trapped sediments in a mixing model on the assumption that each source had an equal chance of contributing to trapped sediment. Confidence intervals (95%) were generated either side of the optimal solution using a bootstrap method. Trapped sediments over the period April 2012 to May 2013 indicated a wide range of concentrations (0.1 to 15.2 g L^{-1}) that, in general, paralleled flow regimes, but also landuse and soil and climate factors at each site. Sources could not be distinguished beyond bed sediments and all other sources for Carran Creek and Moffat Creek, whereas good resolution between sources was achieved for the two sites in the Waituna Creek catchment. The majority of sediment was sourced from stream banks in the Waituna Creek catchment (64 and 94% at the upstream and downstream sites, respectively), with the remainder attributed to topsoil. This was attributed to a combination of bank collapse and drain clearing. Evidence for the latter was found as the loads of trapped sediment were greater at the start of the monitoring period despite latter samples being collected after greater storm flows, possibly due to Environment Southland's three yearly drain clearing cycle of a stretch of the main Waituna Creek and some of its tributaries being carried out earlier in 2012, and then subsequent landowner open/tile drain clearing. It is recommended that strategies to mitigate sediment delivery in the Waituna Creek catchment focus on minimising the contribution of sediment from stream banks, for example, through process such as bank collapse or modification of current drain clearing methods, in addition to minimising topsoil erosion from landuses such as winter forage cropping in the wider Waituna Lagoon catchment.

1. Introduction

The erosion and transport of particulate matter *in situ* from land based sources to downstream sinks (Torri and Borselli, 2012), is a natural process; however, losses are accelerated in areas where human activities result in land disturbance. In agricultural systems, soil erosion has been attributed to a range of factors including cultivation (Yang *et al.*, 2003), straightening of stream channels (Kronvang *et al.*, 1997a; Kronvang *et al.*, 1997b) and soil treading damage from stock (McDowell *et al.*, 2003). Due to the application of fertilisers and dung, eroded material may also be enriched in nutrients (Withers *et al.*, 2001), in particular phosphorus (P). Much of this P is transported as P bound to particulate material (PP) in suspended solids (thereafter termed suspended sediment; SS) (Brunet and Astin, 1998). As the mobilisation and bioavailability of P in fluvial systems is central to eutrophication (Edwards and Withers, 2007), increased inputs of P-enriched SS may lead to a number of environmental problems including decreased water quality, reduced ecological diversity and a decrease in the aesthetic properties of rivers and streams (Johnson and Dawson, 2005). It is, therefore, important that erosion losses from agricultural ecosystems are minimised to preserve surface water quality and the soil resource which farmers rely on for their livelihoods.

A prerequisite to mitigating the transport of particulate bound contaminants is an understanding of the nature and location of potential source material (Stutter *et al.*, 2009). This information has traditionally been captured using direct measurement techniques such as visual assessment or the use of erosion plots (Collins *et al.*, 2001). However, the use of these techniques is often hampered by operational difficulties, spatial sampling constraints and the costs involved (Peart and Walling, 1986; Loughran, 1989; Walling *et al.*, 1993). As an indirect approach to determine sources of eroded material, sediment fingerprinting avoids many of these problems. The technique is based on the premise that each source has a unique composite signature based on its physical, geochemical and biogenic properties. By collecting samples of SS, it is possible to compare their properties with the fingerprints of potential sources and thereby establish the dominant source or sources (Russell *et al.*, 2001). This is achieved through the use of multivariate statistical methods (*viz.* mixing models) which, when applied to these properties, may be used to discriminate different source materials and their proportional contributions to stream sediment loads (Walling *et al.*, 1999; Stutter *et al.*, 2009).

Sediment fingerprinting is a well-established method and has been widely used to address catchment sediment transport issues (e.g. Klages and Hsieh, 1975; Collins *et al.*, 1998; Walling *et al.*, 2008). It has proved to be a useful tool in the context of implementing best management practice (BMP) for P loss. For example, McDowell and Wilcock (2007) used ^{137}Cs, total P (TP) and organic carbon (OC) data to determine sediment sources in an intensively farmed dairy catchment. In this case, stream banks were found to be a major source of sediment and associated P in winter and spring while topsoil sources dominated summer and autumn inputs. Riparian protection measures and decreasing Olsen P (OP) to nearer optimum agronomic levels were suggested as BMP recommendations. In an earlier study, McDowell and Wilcock (2004) were able to isolate the source of SS in an agricultural catchment to topsoil derived from either overland flow or tile drainage. The BMP was to decrease P loss by decreasing Olsen P concentrations, which were already in excess of optimum concentrations for plant production. However, if SS had been found to originate from subsoil, the stream bank or the stream bed then focussing on decreasing topsoil Olsen P concentrations back to the plant optimum would have little effect on PP concentration and load in the stream (McDowell and Wilcock, 2007).

The Waituna Lagoon is a large, brackish coastal lagoon on the southern coast of New Zealand’s South Island and is part of the internationally recognised Awarua Wetland. Land development of the surrounding catchment over the past century (e.g. clearance of wetlands, drainage enhancement and fertiliser inputs) has resulted in increased inputs of suspended solids and nutrients into the lagoon. Consequently, the water quality of the lagoon has declined in recent years to the extent that the lagoon is at risk of having a regime shift from an oligotrophic to an eutrophic state (Robertson *et al.*, 2011). The identification of contaminant sources (e.g. suspended solids) within the catchment has been viewed as one key strategy likely to improve the state of the lagoon. Therefore, the aim of this study was to test whether the sediment fingerprinting technique may be a useful tool in determining likely sources of sediment within an intensively farmed lowland catchment. More specifically, the study aimed to derive the probability of a match between suspended solids samples taken at four stream sites in the Waituna catchment and potentially contributing sources.

2. Methods and Materials

2.1 Study Area

The Waituna Lagoon catchment, located 40 km south east of Invercargill, is an intensively farmed area of approximately 20,000 ha on the southern coast of Southland, New Zealand. It drains to Waituna Lagoon, which is part of the internationally recognised 20,000ha Awarua Wetland. The lagoon and immediately surrounding wetland (an area of 3,500ha) now known as the Waituna Wetland Scientific Reserve, was designated a Ramsar Wetland of International Importance in 1976, with the wider wetland complex being included in 2008. It is one of the largest remaining wetland complexes in New Zealand and is made up of a number of nationally significant ecosystems. The cultural significance to the local Ngāi Tahu people was recognised by a Statutory Acknowledgement under the Ngāi Tahu Claims Settlement Act 1998.

Land use within the catchment includes arable, forestry, sheep, beef and dairy. The numbers of dairy cows have more than doubled since 2000 with an estimated 20,000 to 30,000 cows now present within the catchment. Small pockets of native vegetation remain, predominantly in wetland areas in the southeast of the catchment and bordering the lagoon. The three main streams which drain the catchment include Moffat Creek, Carran Creek and Waituna Creek, all of which flow into the lagoon. Relief throughout the catchment is gently undulating to flat with elevation ranging from about 65 metres above sea level in the upper catchment to sea level at the lagoon. Mean annual rainfall and temperature is 1050 mm and 9.5^{o}C, respectively. The main soil orders present within the catchment are the more freely drained Brown soils of the upper catchment and the poorly drained Organic, Podzol and Gley soils of the lower catchment (Figure 1). The use of artificial drainage is widespread, particularly in the lower half of the catchment.

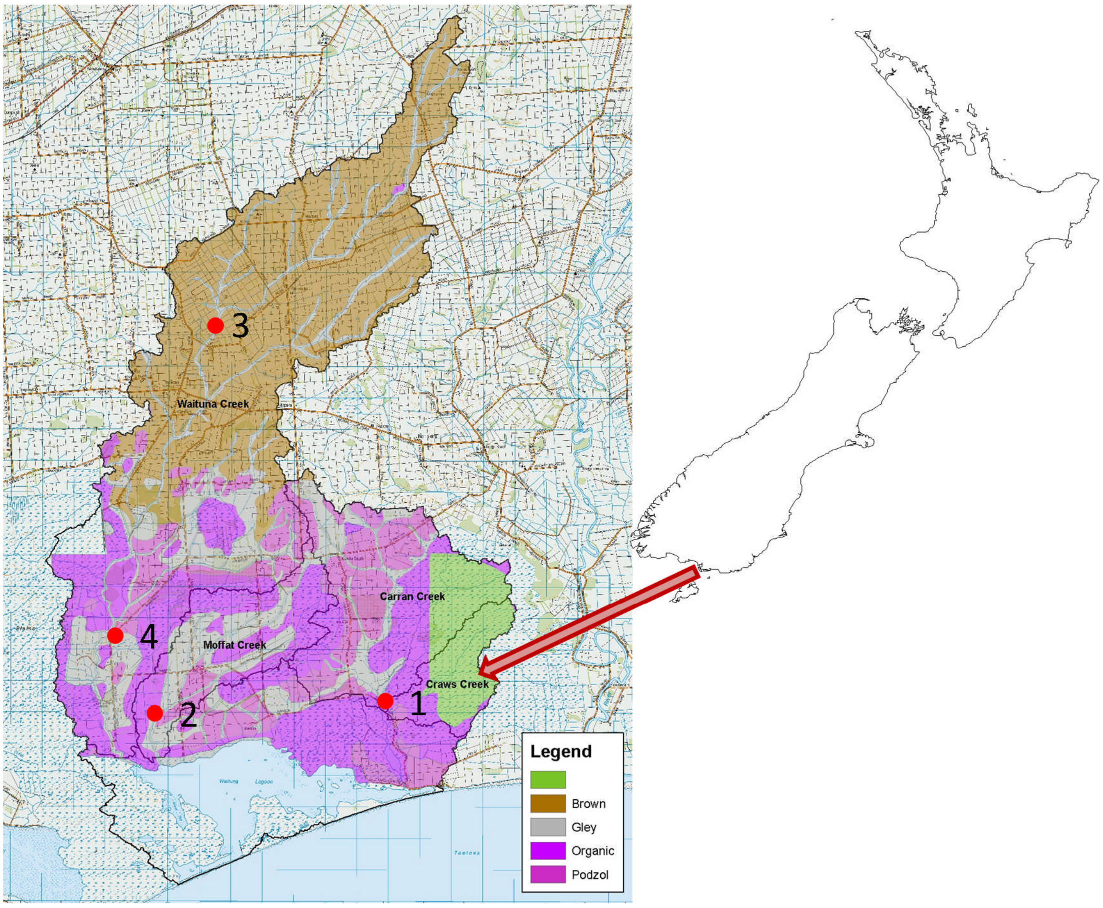


Figure 1. Location of the (1) Carran Creek, (2) Moffat Creek, (3) Waituna Creek upper and (4) Waituna Creek lower sampling sites and soil types within the Waituna Lagoon catchment, Southland, New Zealand.

2.2 Sites and Suspended Solids Sampling

Sampling sites were located on each of the three main streams within the catchment (Figure 1). The Carran Creek and Moffat Creek sites were located approximately 1 and 2.5 km from their respective entry points into the lagoon. On the Waituna Creek, two sampling sites were chosen, one in the upper catchment and one in the lower catchment, approximately 18 and 6 km respectively from its entry point into the lagoon. To collect suspended sediments, six time-integrated sediment samplers were installed at the Carran Creek and Waituna Creek sites and due to the smaller stream width only four were installed at the Moffat Creek site. Samplers, based on the design of Phillips *et al.* (2000) were installed at 0.6 times median water depth to avoid regularly sampling bed load and attached to steel uprights by rubber ties. Samplers, which operated in situ, consisted of a narrow (2-mm diam.) inlet and outlet tube with a larger cavity (48 mm diam.) in between. This cavity (2.5 L) has a cross sectional area approximately 600 times greater than the inlet and outlet tubes and reduces water flow velocity relative to ambient flow, thereby enhancing sedimentation. Such samplers have successfully been used previously for sampling SS and associated P in similar sized streams dominated by pastoral agriculture (McDowell and Wilcock, 2004, 2007). However, there is concern that deposition within the samplers is not complete and will result in samples that contain a disproportionately larger grain size than present in streamflow. For instance, sediment from samplers located on an Arctic stream in Canada captured larger sediment compared to water samples (McDonald *et al.*, 2010). However, the Arctic stream had a highly variabe flow regime influenced by snowmelt. This would result in a wide range of sediment particle sizes. The streams of the Waituna catchment have a more consistent flow regime than the Canadian example cited above. Furthermore, a plot of the relationship between time integrated sediment concentration and cumulative flow for each site with a continuous flow record exhibited a linear trend (Figure 2). If samplers were preferentially collecting larger particle sizes then it is likely that there would have been curvature in the trend between these two variables.

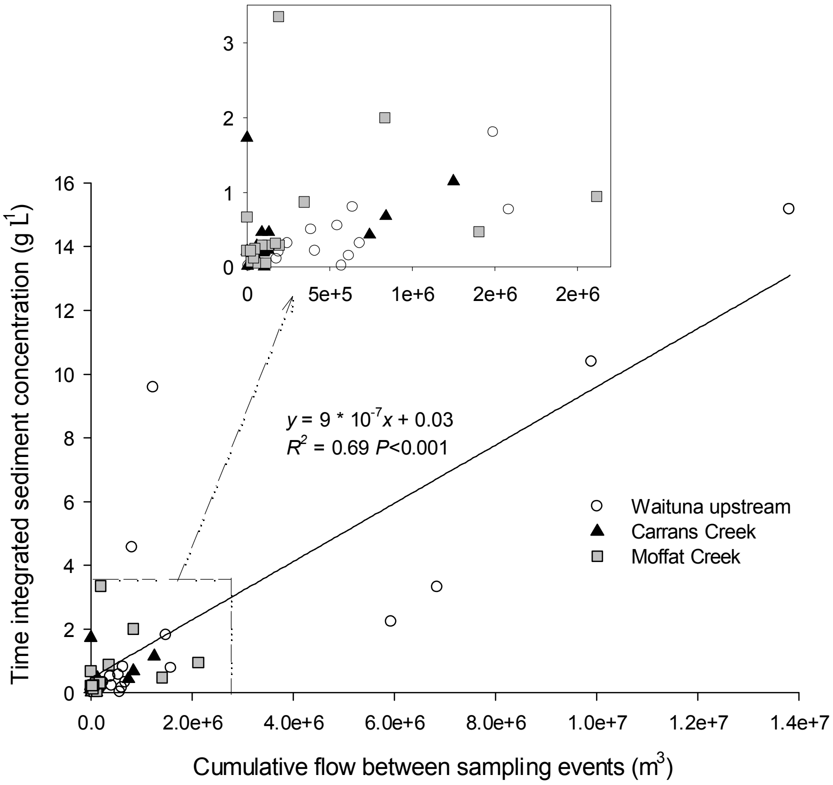


Figure 2. Relationship between time integrated sediment concentration and cumulative flow for each site with continuous flow records.

2.3 Suspended Solids, Soil Sampling and Analysis

Samples of time-integrated SS using the *in situ* samplers were taken fortnightly beginning on the 26th of April 2012, for the sites at Carran and Moffat Creek and the downstream Waituna Creek site: collection at the upstream Waituna Creek site commenced on the 25th of July. Samples were not obtained for two sampling periods in

June and for the month of October due to high stream levels and hence data may potentially under-represent these periods. Suspended solids retained within the samplers were collected by flushing the contents of the cavities into 2 L plastic sampling bottles. At the Carran and both Waituna Creek sites, samples from samplers 1 and 3, 2 and 5 and 4 and 6 were bulked (Figure 3a) while at Moffat Creek, bulking occurred for shuttles 1 and 3 and 2 and 4 (Figure 3b).

Suspended solids were determined by weighing a foil dish before and after the drying of a 20 ml sample at 40°C for 6 hrs. Sediment samples for chemical analyses were obtained by freezing and then thawing subsamples, which flocculated SS. Excess water was decanted from the storage vessel following thawing and the remaining SS placed in a beaker in an oven at 40°C until dry. The dried sediment samples from each sampling sequence (April to November 2012) were analysed for a suite of trace and rare earth elements (Ca, K, Mg, Na, P, S, Al, Fe, Mn, As, Cd, Cr, Cu, Li, Mo, Ni, Pb, Sr, Zn, Ce, Dy, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Th, Tm, U and Yb) via ICP-OES following nitric acid - hydrogen peroxide digestion (U.S. Environmental Protection Agency, 1997).

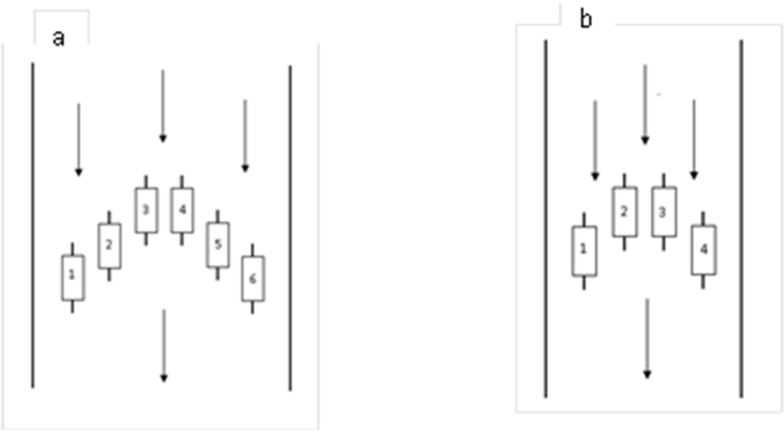


Figure 3: Sediment shuttle layout at (a) Carran Creek and Waituna Creek upstream and downstream catchment sites and (b) Moffat Creek. Arrows indicate the direction of flow.

Collection of sediment source materials upstream from the sediment shuttles took place on the 1st and 4th of October and the 23rd of November 2012. Likely sources within 1.5 km of the sediment shuttles included bank slips, drain cleanings, bare soil surfaces and any visible areas of disturbance (e.g. lane ways and bridges) within 15 m of the edge of the stream (Appendix 1 - 4). At each site, roughly spaced 100 m apart, four replicates were taken of the sources: top soil to 7.5cm depth, subsoil from 50-57.5 cm deep, a stream bank sample at a height equating to 1.5 times median flow, and the top 2 cm of bed sediment. Samples were dried at 40°C, ground and sieved (< 2mm) before analyses of total elements as above.

The sorption of many of the analytes tends to increase with decreasing particle size (Queralt *et al*., 1999). Particle size sorting of transported sediment occurs in-stream, while sediments will also be influenced by different soil types (e.g. sediment from Organic soils will likely be larger than from mineral soils; Stone and Murdoch, 1989). Therefore, it was necessary to adjust source materials if their particle size differed significantly from sediment captured in the shuttles. This was achieved by comparing the particle size distribution (PSD) of the sink material (shuttle sediment) with that of the source material (top soil, subsoil, bank and bed). Particle size analyses were carried out on each sample via laser ablation using a Malvern Laser particle sizer after samples had been disaggregated by sonication and shaking in sodium hexametaphosphate overnight. For the source material, a bulked sample from each of the four sampling depths was analysed. Results from a one way ANOVA on log-mean particle sizes (volume weighted) from the four sites indicated a significant difference ($P<0.05$) between the PSD of sampled bed sediments compared to other sources and shuttle sediment. Bed sediment samples from each site were subsequently fractionated to a mean particle size equivalent to that of the captured sediment (*c*. 75 µm). This was achieved by rapidly mixing (Kensington blender) 30 to 50 g air dry sediment with 250 ml reverse osmosis water for 1 minute. The dispersed sample was then transferred to a 500 cm^3 cylinder and thoroughly mixed before being sampled with a 10 ml pipette after the required settling time as determined by Stoke's Law (Rowell, 1994). Samples were dried at 100^oC to isolate the sediment before undergoing total elemental analysis as previously described. The fractionation process was also carried out on the topsoil samples (0 – 7.5 cm) from the upstream Waituna Creeksite.

2.4 Data Analysis

Data were analysed via a two stage selection process based on that proposed by Collins *et al.* (2010). The first stage used an analysis of variance on ranks to examine the potential for analytes to distinguish between topsoil, subsoil, bank sediment and bed sediment. This analysis provides justification for the removal of analytes that will be unlikely to contribute to a unique source sediment fingerprint.

The output for the analysis of variance on ranks for each analyte across each of the potential sources is given in Tables 1 and 2 for each site. Out of the 34 analytes tested significant differences were found for all analytes except four (Gd, Ho, S and Th) for the upstream Waituna Creek site, none for the downstream Waituna Creek site, one (S) for the Carran Creek site and five (As, Cd, S, Sr and U) in the Moffat Creek site. However, an important point to mention is that differences detected were generally driven by the disparity of bed sediments to other source samples. Further investigation of the LSD_{05}

(back-transformed with bias correction) for each analyte shows that while bed sediment was different to other sources, only in the two Waituna sites were there a large number of analytes that exhibited differences between topsoil, subsoil or bank sediment. We therefore conclude that there is good evidence for separating bed sediments from all other sources across all four sites, but only in the two Waituna Creek sites is there sufficient evidence to use analytes to separate sources further. In addition, very few of the analytes were excluded where sources could be distinguished from one another. Hence, it was decided to use all of the analytes in the second stage of analysis, except for Na which was often an order of magnitude greater in bed sediment than in other sources perhaps due to infrequent intrusion of brackish water (Tables 1 and 2).

Table 1. Mean concentrations (mg kg^{-1}) in source samples from selected sites within the upstream and downstream Waituna Creek sites. Source means were compared within an analyte via an analysis of variance using ranks; however, the least significant difference at the P<0.05 level is given for comparison between sources within an analyte.

Analyte	-------------------------------- Upstream --------------------------------						-------------------------------- Downstream --------------------------------					
	Topsoil	Subsoil	Bank	Bed	Significance	LSD$_{05}$	Topsoil	Subsoil	Bank	Bed	Significance	LSD$_{05}$
Al	22415	30979	20928	30924	<.001	4968	50338	29268	22698	41037	<.001	4248
As	3.1	2.5	3.1	4.1	<.001	1.4	4.0	2.0	3.1	7.3	<.001	1.8
Ca	6057	6116	4068	7016	<.001	1377	10899	8179	7686	8881	<.001	1016
Cd	0.2	0.2	0.1	0.2	0.011	0.1	0.3	0.2	0.2	0.2	<.001	0.06
Ce	27.4	33.4	28.6	37.6	<.001	4.4	49.4	33.9	29.9	50.9	<.001	3.9
Cr	18.9	25.3	16.8	171.7	<.001	23.8	51.6	24.7	21.0	179.2	<.001	37.9
Cu	125.6	4.3	5.7	34.9	<.001	170	15.4	4.8	5.1	40.7	<.001	6.7
Dy	1.5	1.8	1.6	2.5	<.001	0.3	2.7	1.9	1.8	3.5	<.001	0.3
Er	0.7	0.8	0.8	1.1	<.001	0.2	1.5	0.9	0.9	1.6	<.001	0.2
Eu	0.5	0.7	0.6	0.8	<.001	0.1	1.1	0.7	0.6	1.1	<.001	0.1
Fe	17729	21632	15654	25433	<.001	3293	26898	17301	18426	33444	<.001	3573
Gd	1.8	2.2	2.0	2.0	0.077	0.4	2.8	2.4	2.2	2.9	<.001	0.2
Ho	0.2	0.2	0.2	0.2	0.899	0.1	0.3	0.2	0.2	0.3	0.039	0.1
K	1414	1404	1622	3254	<.001	517	4436	1353	1731	4414	<.001	519
La	11.3	13.1	11.7	16.0	<.001	1.9	21.1	14.0	12.6	22.0	<.001	1.8
Li	15.8	21.3	14.9	15.5	0.003	3.7	32.3	26.6	20.4	26.1	<.001	3.5
Mg	2503	2230	2767	195	<.001	567	323	2381	2671	219	<.001	405
Mn	263	235	217	280	0.001	67	346	282	278	361	0.011	74
Na	162	195	168	1731	<.001	135	251	269	161	2296	<.001	245
Ni	7.7	9.8	7.9	42.9	<.001	6.9	16.8	9.2	9.1	46.8	<.001	8.6
P	566	353	211	378	<.001	126	1093	354	386	701	<.001	146
Pb	9.1	11.1	7.6	10.0	0.006	1.8	13.7	9.2	8.8	13.9	<.001	1.6
Pr	5.9	6.9	6.2	8.1	<.001	0.9	10.4	7.3	6.5	10.9	<.001	0.8
S	567	470	1199	713	0.36	804	619	452	753	843	0.002	487
Sm	3.6	4.7	3.6	5.2	<.001	0.7	7.3	4.4	4.1	7.4	<.001	0.6
Sr	70.3	92.9	53.4	84.7	<.001	18.7	141.8	128.6	110.1	117.3	0.002	16.3
Tb	0.6	0.8	0.6	0.7	<.001	0.1	1.0	0.7	0.8	1.1	<.001	0.1
Th	1.8	2.6	1.8	2.1	0.056	0.6	3.1	2.2	1.8	3.0	<.001	0.3
U	2.2	3.2	2.1	1.1	<.001	0.6	1.4	2.2	2.6	1.4	<.001	0.6
Yb	0.9	1.0	1.0	1.3	<.001	0.2	1.6	1.0	1.0	1.7	<.001	0.1
Zn	37.2	31.8	39.6	107.8	<.001	26.5	86.0	33.4	42.8	96.4	<.001	13.6

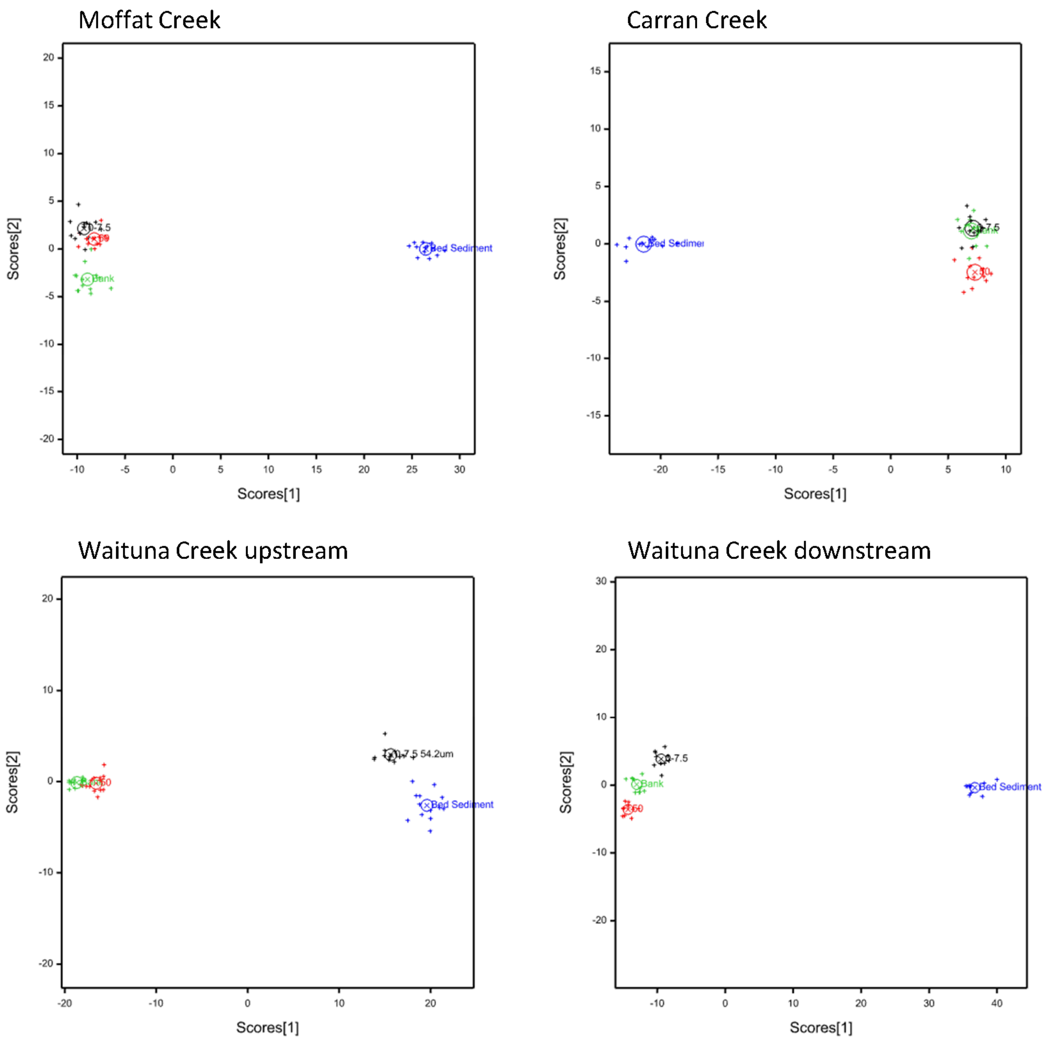
Table 2. Mean concentrations (mg kg^{-1}) in source samples from selected sites within the Carran Creek and Moffat Creek sites. Source means were compared within an analyte via an analysis of variance using ranks; however, the least significant difference at the $P<0.05$ level is given for comparison between sources within an analyte.

Analyte	Carran						Moffat					
	Topsoil	Subsoil	Bank	Bed	Significance	LSD_{05}	Topsoil	Subsoil	Bank	Bed	Significance	LSD_{05}
Al	21871	24175	26835	32843	<.001	4776	22924	23572	21809	47497	<.001	6300
As	4.5	4.2	6.4	7.4	<.001	2.4	2.5	2.3	2.3	2.5	0.547	1.1
Ca	6608	5477	7076	7685	<.001	944	5916	6512	6818	8858	0.008	1887
Cd	0.3	0.2	0.6	0.5	<.001	0.2	0.1	0.1	0.1	0.2	0.517	0.1
Ce	24.6	28.1	32.1	43.8	<.001	5.5	23.1	28.3	30.5	46.3	<.001	5.9
Cr	18.5	19.2	21.1	130.4	<.001	35.1	20.1	21.8	23.1	127.6	<.001	21.1
Cu	8.6	6.2	10.2	43.2	<.001	7.7	5.7	7.2	7.6	42.5	<.001	6.3
Dy	1.3	1.3	1.9	2.8	<.001	0.4	1.2	1.4	1.6	2.6	<.001	0.3
Er	0.6	0.6	1.0	1.5	<.001	0.2	0.6	0.7	0.8	1.2	<.001	0.2
Eu	0.5	0.5	0.7	1.0	<.001	0.1	0.4	0.5	0.6	1.0	<.001	0.1
Fe	22476	17129	35653	41579	<.001	8456	14011	13476	13981	23935	<.001	3586
Gd	1.5	1.7	2.1	2.4	<.001	0.3	1.5	1.8	2.0	2.4	<.001	0.3
Ho	0.1	0.1	0.1	0.2	<.001	0.1	0.1	0.2	0.2	0.2	0.002	0.1
K	1156	901	1202	3388	<.001	397	1361	1328	1265	3857	<.001	662
La	9.2	10.4	11.8	17.1	<.001	1.9	8.9	11.3	12.5	20.3	<.001	3.9
Li	13.1	14.7	15.1	16.9	0.009	3.6	15.3	16.3	15.3	20.7	0.014	3.9
Mg	1991	1890	2295	308	<.001	423	1771	2100	2132	253	<.001	498
Mn	246	149	417	388	<.001	137	150	160	167	241	<.001	39
Na	362	201	318	1485	<.001	164	230	223	235	2619	<.001	272
Ni	8.4	7.2	10.7	35.1	<.001	7.8	7.6	8.2	9.4	34.4	<.001	5.5
P	1562	650	2407	2494	<.001	723	421	199	355	286	0.007	148
Pb	12.7	9.3	17.9	18.2	<.001	3.8	7.7	7.3	7.4	11.9	<.001	1.9
Pr	4.9	5.6	6.4	8.9	<.001	0.9	4.8	5.9	6.5	9.8	<.001	1.2
S	1135	857	1186	1328	0.081	556	542	387	393	244	0.101	263
Sm	3.7	3.8	5.5	8.2	<.001	1.2	3.1	3.5	3.7	6.1	<.001	0.7
Sr	82.1	76.4	85.8	97.2	0.002	12.0	69.2	74.5	74.1	87.5	0.313	20.6
Tb	0.7	0.7	1.2	1.4	<.001	0.3	0.5	0.6	0.6	0.8	<.001	0.1
Th	1.2	2.0	1.0	1.7	0.013	0.6	2.0	2.6	2.3	4.0	0.001	1.0
U	3.9	2.7	6.1	0.6	<.001	1.4	2.3	2.0	1.9	1.6	0.5	0.9
Yb	0.8	0.8	1.2	1.7	<.001	0.2	0.7	0.9	1.0	1.4	<.001	0.2
Zn	34.5	22.5	41.5	127.5	<.001	13.5	36.1	27.7	30.6	110.6	<.001	18.4

The second stage of analysis involved a stepwise discriminant analysis on source data (log transformed) to determine the optimum (by minimising Wilks' lambda) set of elements that separate the four source types (surface, subsoil, bank, bed sediment) best. The results of the discriminant analysis are shown in Table 3 and in Figure 4. As many as 19 analytes were required to generate the optimum composite fingerprint for the Moffat Creek site, whereas 10 were required for the Waituna upstream and Carran Creek sites. Each of the composite fingerprints contains a variety of trace metals, rare earth elements and nutrients consistent with fingerprints that exhibit good discrimination (Collins and Walling, 2002).

Table 3. Rank and range of analytes comprising the optimal composite fingerprints for discriminating between individual sediment sources at each site.

Rank	Waituna Upstream	Waituna Downstream	Carran	Moffat
1	Mg	Mg	Mg	Mg
2	P	K	P	Eu
3	K	Ni	K	Ca
4	Al	Zn	Al	P
5	Li	Al	Li	Li
6	Cr	Pb	Cr	U
7	Sr	Li	Sr	Tb
8	Ca	Gd	Ca	Cu
9	S	Eu	S	Al
10	Tb	P	Tb	Sr
11		Dy		Cr
12		As		Gd
13		Ho		S
14		Ca		Yb
15		Sr		K
16		Ce		Pb
17		Pr		
18		Sm		
19		U		


Moffat Creek

Carran Creek

Waituna Creek upstream

Waituna Creek downstream

Figure 4. Output from the step-wise discriminant analysis showing the ability of the optimal set of elements to distinguish between sources at each site. In all graphs, topsoil, subsoil, bank and bed sediment are in black, red, green and blue, respectively.

Once selected, analytes were used in a mixing model to apportion sediment sources to the sink within a site’s catchment. Each model is based on the assumption that the concentration of analytes comprising the sediment fingerprint and measured in the sink samples is the result of the relative concentrations and amounts of analytes in the source samples. The model for predicted sink concentration for each selected element is a linear combination of the 4 source concentration means where the coefficients for source types are the same across all elements and are constrained to be non-negative, but sum to unity. The model was optimised to minimise the residual (lack of fit) for each element as the difference between the log-transformed sink concentration and the log-transformed modelled concentration. The optimum coefficients are those that minimise the sum of squares of the residuals, subject to the constraints. As sediment size sorting had already been taken account of, it was not necessary to include a term for this in the model (*viz*. Collins et al., 2010).

Confidence intervals for the optimum coefficients were determined using a non-parametric bootstrap method. The log transformed fitted values and residuals from the optimum model were saved. New bootstrap sink values were obtained by sampling (with replacement) the set of residuals, adding the sampled residuals to the log-fitted values, then back-transforming to get a new bootstrap sample of pseudo-observed values. The model was then optimised for each of the 1000 bootstrap samples generated. The confidence limits for the percentage coming from each source type are obtained from percentiles of the 1000 sets of coefficients obtained from the bootstrap samples. Example outputs showing a tight and wide range of confidence intervals for two sampling intervals are given in Figures 5 and 6, respectively.

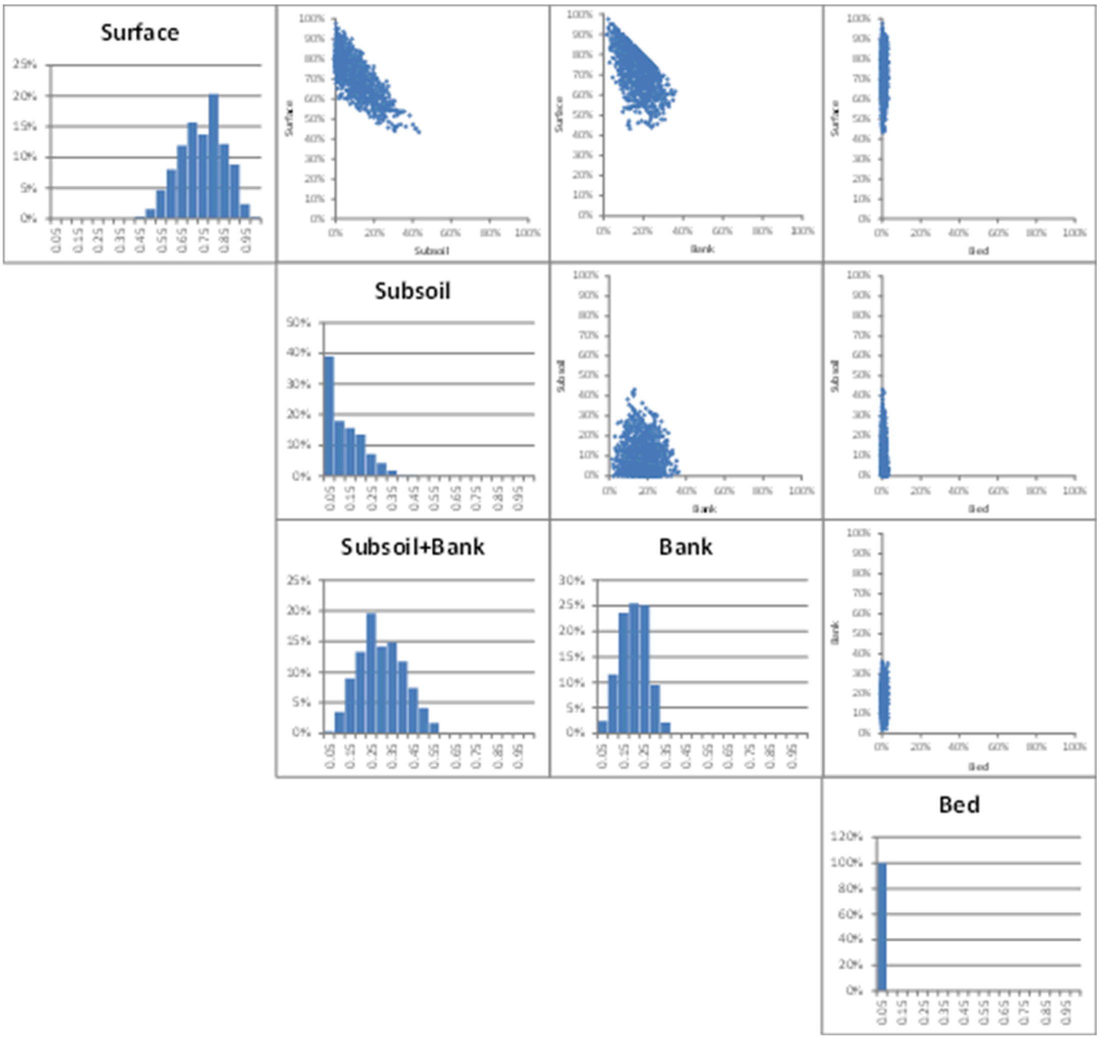


Figure 5. Histograms showing the frequency of confidence intervals for each source (including if subsoil and bank material are considered the same source) and scatter plots showing the distribution of the relative confidence intervals compared between each source to a sample taken from the Waituna Creek upstream site on the 24th of August, 2012.

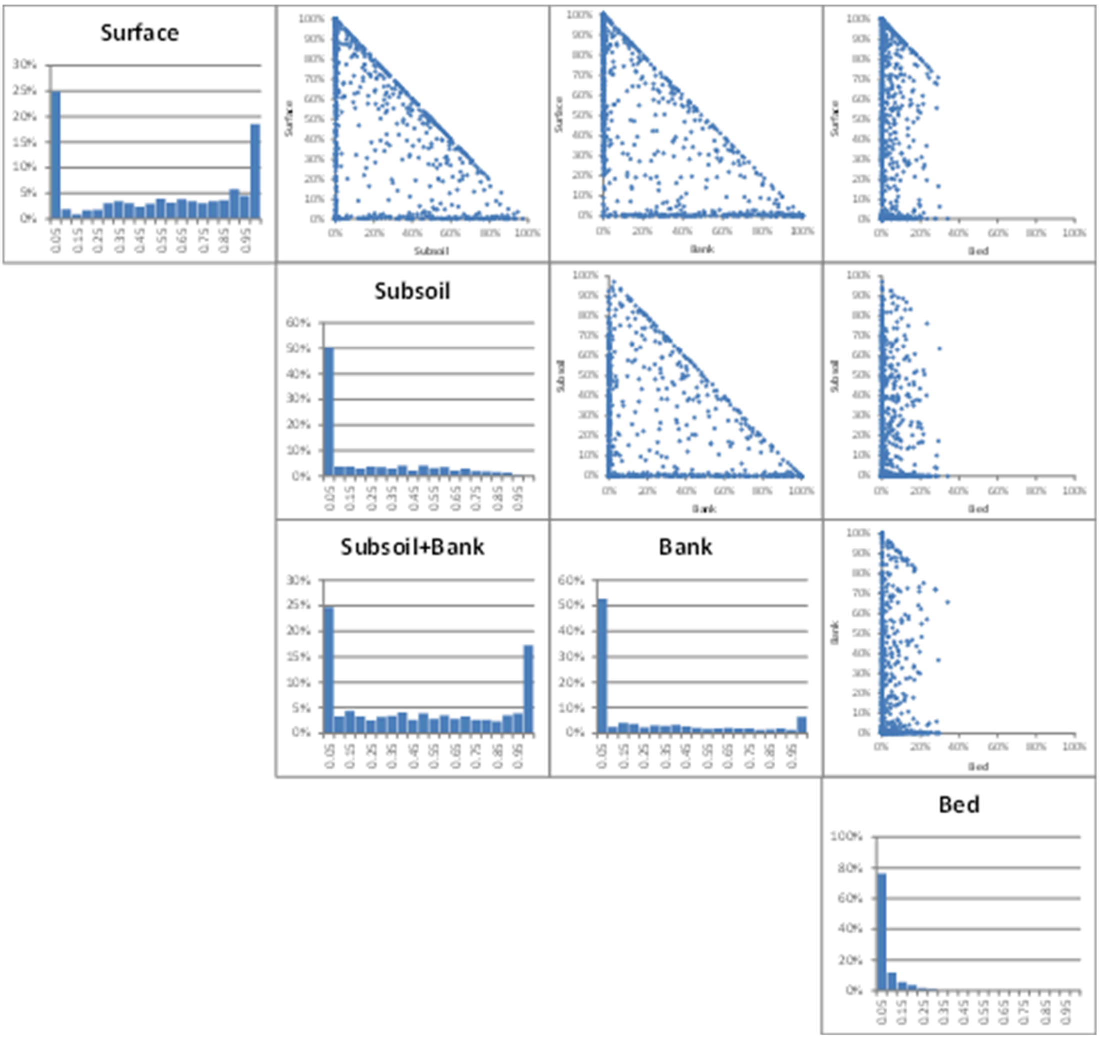


Figure 6. Histograms showing the frequency of confidence intervals for each source (including if subsoil and bank material are considered the same source) and scatter plots showing the distribution of the relative confidence intervals compared between each source to a sample taken from Carran Creek site on the 29th of September, 2012.

3. Results and Discussion

Mean optimal contributions from topsoil, subsoil, stream bank and stream bed sediment for the two Waituna Creek sites are shown in Figure 7. For Carran Creek and Moffat Creek sites, models were only generated for stream bed sediment and for all other sources (topsoil, subsoil and stream bank sediment; Figures 8 and 9). The ability to distinguish and model more sources in the two Waituna Creek sites is most likely due to different soil types. The Waituna Creek catchment is dominated by Brown soils and Podzols while Organic soils predominate in the Carran Creek and Moffat Creek catchments (as per Figure 1). Organic, and some Podzol, soils have a much lower anion storage capacity (ASC; Hewitt, 1998) than Brown soils, while there is also little differentiation into soil horizons for the Organic soils. Soils with a low ASC poorly sorb many of the analytes tested (e.g. P and S), which leads to the possibility of leaching through, and enriching, the entire soil profile rendering sources such as topsoils indistinguishable from subsoils. However, while soils high in organic matter (e.g. Organic and Podzol soils in the Carran Creek and Moffat Creek catchments) may sorb some analytes like Cd better than soils with less organic matter, differentiation between sources relies on these analytes being added in sufficient quantity to be detected. Data in Tables 1 and 2 suggest this was not the case causing sediment from topsoils, subsoils and most likely stream banks to have very similar (and statistically indistinguishable) analyte signatures. Due to the settling and deposition of heavy coarse particles and their sorption of analytes compared to fine particles, bed sediments were easily differentiated from fine particles eroded from other sources.

Data for the Waituna Creek sites show that in general the dominant source of trapped sediment was bank sediment, but that the relative contribution from bank sediment was much greater for the downstream site than the upstream site (Figure 7). Sediment was not collected at the downstream site until August, while flow was only collected at the upstream site. In general, the quantity of sediment trapped at each site generally paralleled the frequency and volume of flow generated in preceding storm events.

The presence of topsoil in the upstream site, but not in the downstream site could reflect a number of factors. One factor is likely to be flashier hydrology with more surface runoff contributing streamflow in headwaters compared to a greater contribution from groundwater at the downstream site – although there are only spot gaugings to confirm this (Holden et al., 2004). Coupled to hydrology, factors likely to contribute to the erosion of topsoil by surface runoff include: greater slope, the widespread use of winter- or spring-grazed forage crops, and excessive animal treading leading to soil disturbance and decreased soil infiltration (McDowell *et al*., 2011).

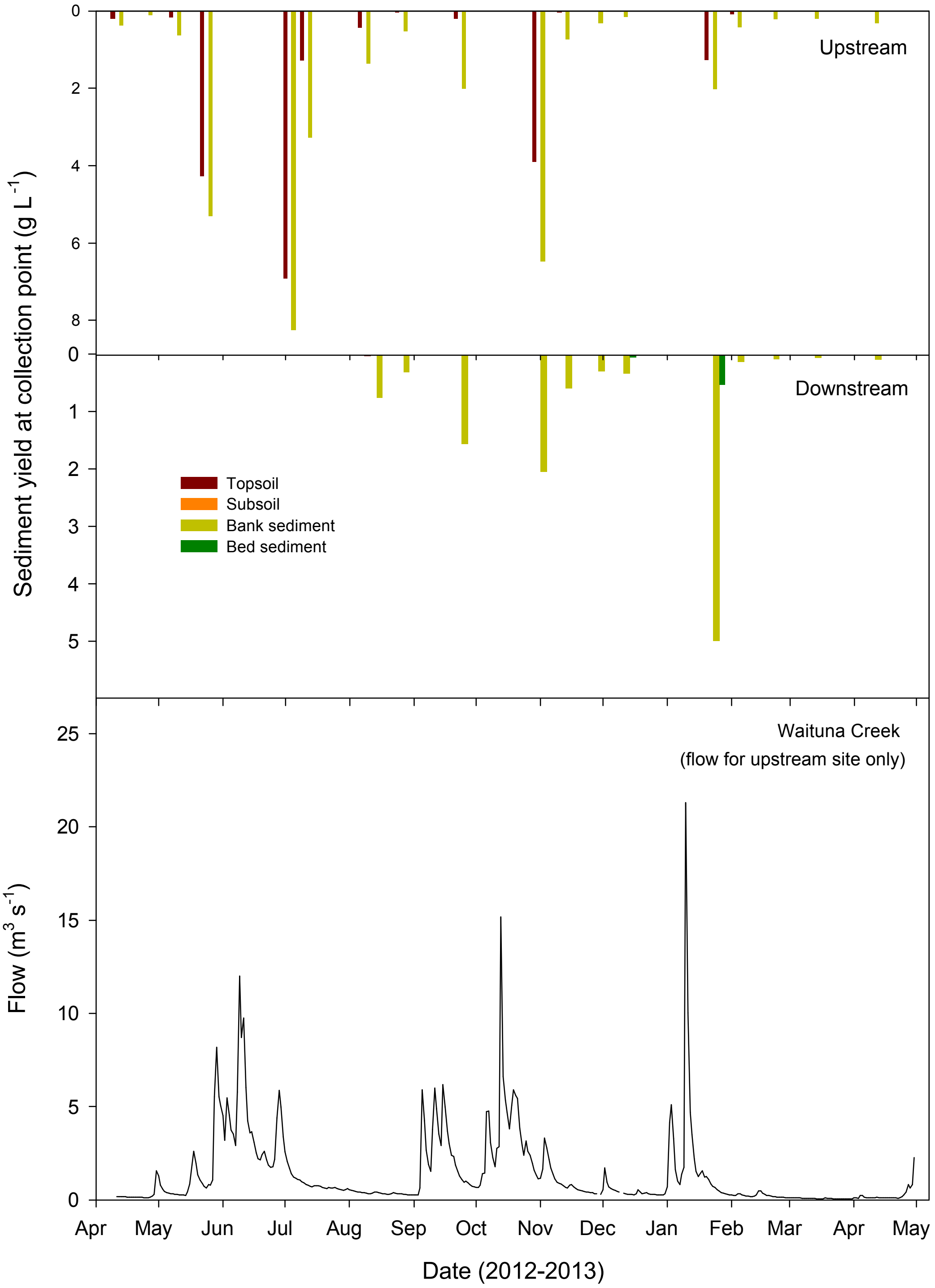


Figure 7. Mean daily flow and the estimated optimal mean sediment yield from topsoil, subsoil, bank sediment and bed sediment captured at the Waituna Creek upstream and downstream sites.

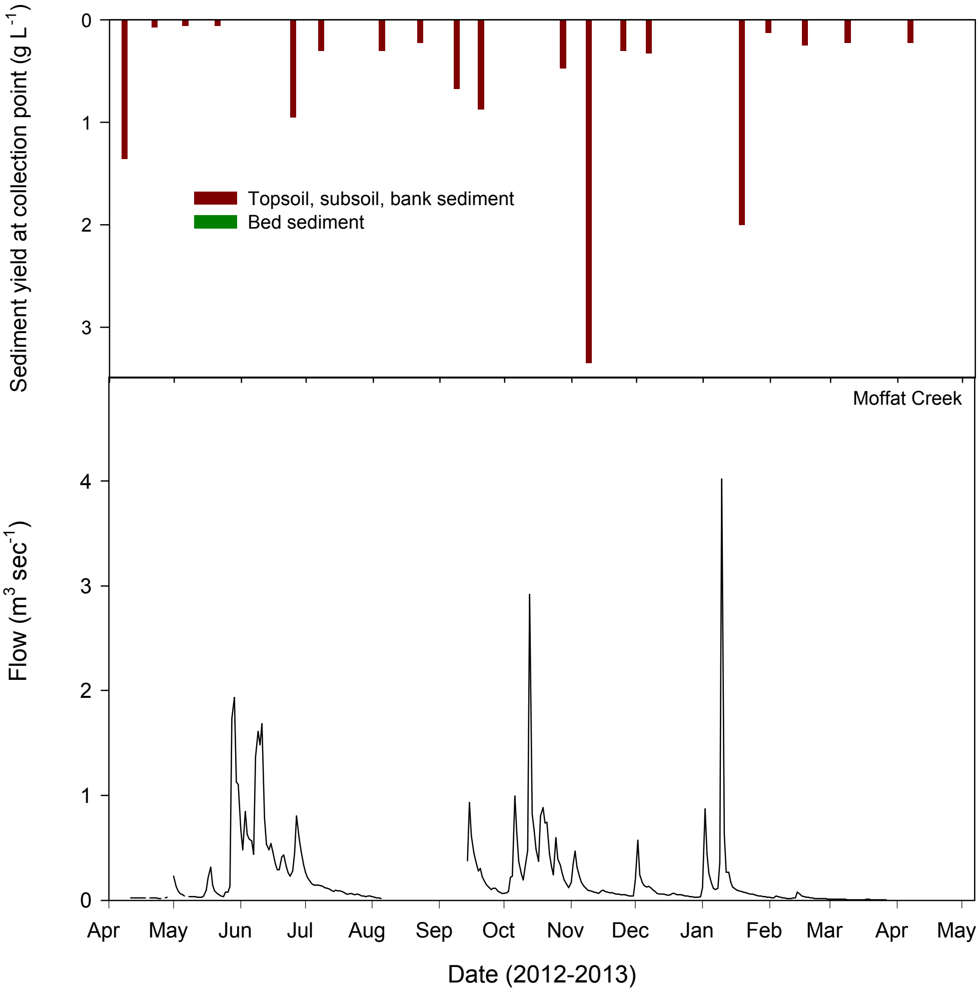


Figure 8. Mean daily flow and the estimated optimal mean sediment yield from topsoil + subsoil + bank sediment, and bed sediment (on average ≤ 1% of total) captured at Moffat Creek.

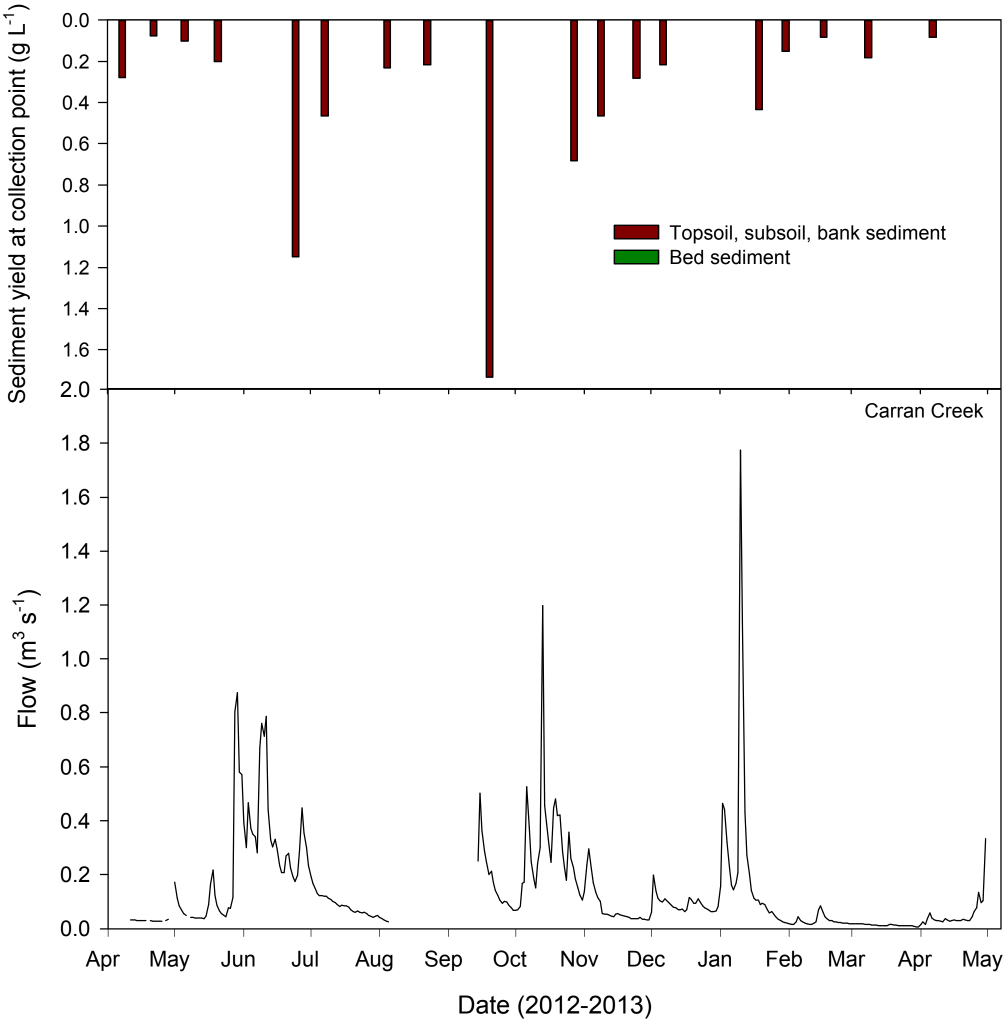


Figure 9. Mean daily flow and the estimated optimal mean sediment yield from topsoil + subsoil + bank sediment, and bed sediment (on average ≤ 1% of total) captured at Carran Creek.

Subsoil was expected to be present in trapped sediment. Many studies have hypothesized, but seldom confirmed, that subsoil contributes substantial quantities of sediment and nutrients to streamflow in catchments that are artificially drained (e.g. Holden, 2006), or where soils have a thin layer of erosion-resistant undeveloped peat on top of finer textured and more easily eroded, subsoil (Marttila and Kløve, 2010a). Tile lines are extensively used within the Waituna Creek catchment and regularly renovated (i.e. cleaned or re-laid) every 10-20 years. However, data would suggest that their contribution compared to other sources is small. Similarly, while there are many instances of thin peat-like topsoils on top of fine-textured subsoil (e.g. Titipua silt loams and silty clays), erosion of subsoil does not appear to be widespread.

At the Waituna Creek downstream site, modelling of one sampling taken in January suggested that bed sediment was a contributing source (Figure 7). Bed sediments contain heavier and coarser particles than present in suspended sediment (Stone *et al.*, 2008). Sediment traps were placed at 0.6 of median water depth to avoid continually sampling bedload (Phillips *et al.*, 2000). Consequently, it took the largest storm event sampled (Figure 7) to provide enough energy to remobilise bed sediments into the water column and be trapped in collectors at the downstream site. Despite some contribution from bed sediments, bank sediment was still estimated to be the dominant source of trapped sediment.

Bank sediments can contribute to SS and is trapped in collectors via bank collapse. Major factors that influence bank stability and collapse include: bank gradient (Budhu and Gobin, 1996); frequent wetting and drying or freeze-thaw cycles (Lawler, 1986; McDowell, 2009); groundwater seepage (Chu-Agor *et al.*, 2009); and changes in bank material erosion or deposition of sediments during streamflow (Fox *et al.*, 2007). However, many of these processes also enable us to distinguish bank sediments from other sources such as subsoil. For instance, in a catchment without Organic soils, McDowell *et al*. (2002) showed that frequent wetting and drying cycles significantly altered bank sediment chemistry from sediments found on the stream bed or from subsoil.

The dominance of bank erosion as a source of trapped sediment may have been exacerbated by the fact that the Waituna catchment contains an extensive network of open drains. In addition to increasing the frequency of possible bank collapse, sediment from drainage networks may also arise from drain cleaning which disturbs stream channels and exposes new surfaces to erosion, and destabilisation due to stock disturbance. However, while the relative importance of each of these processes is seldom fully understood, Ballantine and Hughes (2012) noted that total SS loads during Waituna Creek drain clearing in 2012 of most of the main channel and some tributaries were estimated to be 25 times greater than for the same time periods without clearing (550 vs. 22 Mg). Work began in the lower Waituna Creek catchment in February 2012 and moved upstream finishing in the upper Waituna Creek catchment by May that year. Furthermore following this work some landowners will have cleared out open/tile drains feeding to the creek. Unfortunately, sediment was not collected at the downstream site until August, 2012, but drain clearing may partly explain the high yields of sediment trapped in the upstream site despite storm flow volumes that were much less than subsequent events (Figure 7).

Compared to the Waituna Creek catchment sites, yields of trapped sediment in the Moffat Creek and Carran Creek sites were less (Figures 5-7). This is most likely due to the much smaller contributing catchments, but may also be due to other factors such as land use, lower gradients, and differing steam water chemistry and soil types. Whereas, rainfall onto the stream channel and surface runoff would typically dilute conductivity in streamflow, no change was noted as flow increased in either Carran Creek or Moffat Creek catchments (Anonymous, 2012). This could be due to the rapid supply of analytes due to high surface area and low ASC and high hydraulic conductivity (aided by the drainage network) and rapid subsurface flow through the peat soils (Evans and Warburton, 2007; Holden and Burt, 2003). Whatever the cause, high conductivity will cause suspended sediments to settle, especially if influenced by cations such as Na (Sharpley *et al*., 1998).

Undeveloped peat is relatively resistant to erosion, but becomes susceptible under development as factors such as frost and oxidation occur. The loss of organic matter is exacerbated by cultivation and liming (Grønlund *et al*., 2008; Basi *et al*., 2008) and through drainage (Holden *et al*., 2006). The weathered material is then quickly transported due to the relatively low bulk density of peat material. Although both the Moffat Creek and Carran Creek catchments contain peat-like topsoils, development near the Moffat Creek site began much longer ago (Simmonds *et al*., 2012). This may partly explain why the yield of trapped sediment from Moffat Creek was greater than from Carran Creek despite being a smaller catchment (1733 vs. 2871 ha).

3.1 Management

There are a wide range of strategies available to minimise the erosion and loss of topsoil into streamflow. These include, but are not limited to: fencing off streams from stock and installing a buffer strip or riparian planting; not over-grazing or grazing when soil is susceptible to pugging and treading damage; placing forage crops far from streams or drainage channels and on flat land; ploughing across and not with land contours; using a back-fence in forage cropped paddocks to prevent animals from repeatedly trampling over bare ground; and restricting the grazing of forage crops in winter or spring to 3 or 4 hours to get maintenance feed, but housing them on a feedpad thereafter. These strategies have a range of cost (including labour requirements) and effectiveness, and it is recommended that to avoid impairing farm profitability strategies are implemented in the order of most cost-effective first. However, if greater or quicker decreases are required then strategies may be implemented in a different order. For a fuller discussion of cost-effectiveness for a range of different strategies available to mitigate sediment loss from topsoil see the review by McDowell *et al*. (2013).

Targeting strategies to the correct source of sediment loss will increase their cost-effectiveness. In the Waituna Creek sites, bank sediment was the largest source (Table 4). However, it is possible that bank samples represents silt that has eroded from topsoil and settled on stream banks rather than “true” bank material. Furthermore, bank material could not be distinguished from topsoil or subsoil in the Moffat and Carran Creek sites. Hence, in addition to those strategies that promote bank stabilisation (e.g. fencing and riparian planting), strategies should also be used to prevent topsoil erosion (e.g. not pugging soil by over-grazing wet pastures and minimising the use of winter forage crops).

Studies suggest that when drain cleaning is conducted, losses of sediment and sediment-bound water quality contaminants (e.g. nitrogen, phosphorus and metals) are increased (e.g. Åström *et al*., 2001a,b; Ballantine and Hughes, 2012). Strategies to minimise the impact of drain clearing would include: decreasing the angle of stream banks and vegetating exposed banks (Holden *et al*., 2007); removing only bed material; and clearing sediment from upstream in stages therefore allowing released sediment to be trapped by downstream vegetation before it too is cleared.

Additional in-stream strategies may help to prevent sediment from entering the lagoon. Sediment traps will be effective for coarse (but not fine) sediment. Another is the use of controlled drainage structures where the water table is raised to enhance denitrification and sedimentation of particles and particulate bound P (Tan and Zhang, 2011). These may prove valuable in parts of New Zealand with a soil moisture deficit during the growing season (e.g. Waikato; Barkle, 2006), but are unsuitable for the Waituna Lagoon catchment. Peak runoff control (PRC) structures are a subset of controlled drainage that contain one or more culverts at a specific depth that attenuate runoff, but allow for some sediment (and phosphorus) to settle-out and denitrification to occur (Marttila and Kløve, 2010b). Such structures are more suitable for use in the Waituna Lagoon catchment and may be easily implemented within the existing network, but would still require drain clearing to maximise sediment removal.

Table 4. Mean optimal solution for the percentage and, in parentheses, the upper and lower 95% confidence intervals of sediment contributed from each source to suspended sediment captured at each site.

Source	Waituna Upstream	Waituna Downstream	Moffat Creek	Carran Creek
Topsoil	36 (0 – 82)[1]	1 (0 – 88)	-[2]	-
Subsoil	0 (0 – 56)	0 (0 – 50)	-	-
Bank sediment	64 (14 – 94)	94 (20 – 100)	-	-
Bed sediment	0 (0 – 11)	5 (0 – 78)	1 (0 – 35)	1 (0 – 46)
Topsoil + subsoil + bank sediment			99 (24 – 100)	99 (4 – 100)

[1] Solutions represent the mean optimal estimate with 95% confidence intervals, determined via bootstrap interrogation of possible solutions. The confidence intervals yield an indication of the fit of the model and the potential range of solutions. An estimate with a narrow range in confidence intervals is more likely, but not exclusively, to be a better fit than an estimate with a wide range of confidence intervals.

[2] Sites could not be distinguished from one another.

4. Conclusions

Trapped sediments for four sites within the Waituna Lagoon catchment indicated a wide range of concentrations that in general paralleled flow regimes, but also landuse and edaphic factors (e.g. soil and climate) at each site. Sources of sediment could not be distinguished beyond bed sediments and all other sources (topsoil, subsoil, bank sediment) for Carran Creek and Moffat Creek sites, whereas good resolution between sources was achieved for the two sites in the Waituna Creek catchment. The majority of trapped sediment was sourced from stream banks in the Waituna Creek catchment (64 and 94% at the upstream and downstream sites, respectively), with the remainder attributed to topsoil. Bank erosion was attributed to a combination of bank collapse and drain clearing. Evidence for the latter was found as the loads of trapped sediment were greater at the start of the monitoring period despite latter samples being collected after greater storm flows. It is recommended that strategies to mitigate sediment delivery in the Waituna Creek catchment focus on minimising the contribution of sediment from stream banks, for example, through processes such as reconstructing collapsed banks or modification of current drain clearing methods, in addition to those minimising topsoil erosion from landuses such as winter forage cropping.

5. References

Anonymous. 2012. Waituna Catchment Loads, Report for Environment Southland, Diffuse Sources and NIWA. Available at: http://www.es.govt.nz/media/19244/waituna_final_13_april.pdf (accessed October, 2013).

Åström M, Aaltonen E-V, Koivusaari J. 2001a. Impact of ditching on a small forested catchment on concetrations of suspended material, organic carbon, hydrogen ions and metals in stream water. Aquatic Geochemistry 57:57-73.

Åström M, Aaltonen E-V, Koivusaari J. 2001b. Effect of ditching operations on steam-water chemistry in a boreal forested catchment. The Science of the Total Environment 279:117-129.

Ballantine D, Hughes A. 2012. The effects of drain clearing on water quality of receiving environments. Report prepared for Environment Southland, NIWA Hamilton. Available at: http://www.es.govt.nz/media/26848/the_effects_of_drain_clearing_on_water_quality_of_receiving_environments.pdf (Accessed October, 2013).

Barkle G. 2006. Evaluating strategic retention of artificial drainage flows for nitrate-N reduction under Waikato conditions. Report for Environment Waikato, Aqualinc Research. pp. 23 Available at: http://www.waikatoregion.govt.nz/PageFiles/5490/tr0645.pdf (accessed October, 2013).

Basi C, Lind SE, Pekkarinen NM, Huttunen JT, Shupali NJ, Hyvönen NP, Repo ME, Martikainen PJ. 2008. Direct experimental evidence for the contribution of lime to CO_2 release from managed peat soil. Soil Biology and Biochemistry 40:2660-2669.

Brunet RC, Astin KB. 1998. Variation in phosphorus flux during a hydrological season: the River Adour. Water Research 32:547-558.

Budhu M, Gobin R. 1996. Slope instability from groundwater seepage. Journal of Hydraulic Engineering 122:415-417.

Chu-Agor ML, Fox GA, Wilson GV. 2009. Empirical sediment transport function predicting seepage erosion undercutting for cohesive bank failure prediction. Journal of Hydrology 377:155-164.

Collins AL, Walling DE. 2002. Selecting fingerprint properties for discrimininating potential potential suspended sediment sources in river basins. Journal of Hydrology 261:218-244.

Collins AL, Walling DE, Leeks GJL. 1998. Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. Earth Surface Processes and Landforms 23:31-52.

Collins AL, Walling DE, Sichingabula HM, Leeks GJL. 2001. Suspended sediment source fingerprinting in a small tropical catchment and some management implications. Applied Geography 21:387-412.

Collins AL, Walling DE, Webb L, King P. 2010. Apportioning catchment scale sediment sources using a modified composite fingerprinting technique incorporating property weightings and prior information. Geoderma 155:249-261.

Genstat Commitee. 2010. Genstat for Windows: 13th ed. Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden, U.K.

Edwards AC, Withers PJA. 2007. Linking phosphorus sources to impacts in different types of water body. Soil Use and Management 23:133-143.

Evans M, Warburton J. 2007. Geomorphology of upland peat: Erosion, form and landscape change. RGS-IBG Book Series, Blackwell Publishing, Malden, MA.

Fox G, Chu-Agor M, Wilson G. 2007. Seepage erosion: A significant mechanism of stream bank failure. Proceedings of the America Society of Civil Engineers (ASCE) World Environmental and Water Resources Congress. May 15-19, Tampa FL. pp.. 1-14.

Grønland A, Hauge A, Hovde A, Rasse DP. 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. Nutrient Cycling in Agroecosystems 81:157-167.

Hewitt AE, 1998 New Zealand Soil Classification. 2nd Edition, Manaaki Whenua Press, Lincoln, New Zealand.

Holden J, Chapman PJ, Labadz JC. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Progress in Physical Geography 28:95-123.2004

Holden J. 2006. Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. Journal of Geophysical Research 111:F02010.

Holden J, Burt TP. 2003. Runoff production in blanket peat covered catchments. Water Resources Research 39:1191-1200.

Holden J, Chapman PJ, Lane SN, Brookes CJ. 2006. Impacts of artificial drainage of peatlands on runoff production and water quality. In: Peatlands: Evolution and Records of Environmental and Climate Change, Martini, I. P., Cortizas, A. M. and Chesworth, W. (Eds.). Elsevier: Amsterdam, pp. 501-528.

Holden J, Gascoign M, Bosanko NR. 2007. Erosion and natural revegetation assocaited with surface land drains in upland peatlands. Earth Surface Processes and Landforms 32:1547-1557.

Johnson AE, Dawson CJ. 2005. Phosphorus in agriculture and in relation to water quality. Agricultural Industries Confederation Report. p. 16-17.

Klages MG, Hsieh YP. 1975. Suspended Solids Carried by the Gallatin River of Southwestern Montana: II. Using Mineralogy for Inferring Sources. Journal of Environmental Quality 4:68-73.

Kronvang B, Grant R, Laubel AL. 1997a. Sediment and phosphorus export from a lowland catchment: Quantification of sources. Water, Air and Soil Pollution 99:465-476.

Kronvang B, Laubel A, Grant R. 1997b. Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment, Gelbaek Stream, Denmark. Hydrological Processes 11:627-642.

Lawler D. 1986. River bank erosion and the influence of frost: a statistical examination. Transactions, Institute of British Geographers, New Series 11:227-242.

Loughran RJ. 1989. The measurement of soil erosion. Progress in Physical Geography 13:216-233.

Martilla H, Kløve B. 2010a. Dynamics of erosion and suspended sediment transport from drainaed peatland forestry. Journal of Hydrology 388:414-425.

Martilla H, Kløve B. 2010b. Managing runoff, water quality and erosion in peatland forestry by peak runoff control. Ecological Engineering 36:900-911.

McDonald DA, Lamoureaux SF, Warburton J. 2010. Assessment of a time-integrated fluvial suspended sediment sampler in a high Artic setting. Geografiska Annaler Series A. Physical Geography 92:225-235.

McDowell RW. 2009. Effect of wetting and drying on phosphorus forms in upland streams sediments: South Otago, New Zealand. Marine and Freshwater Research 60:619-625.

McDowell RW, Sharpley AN, Chalmers AT. 2002. Chemical characterization of fluvial sediment: The Winooski River, Vermont. Ecological Engineering 18:477-487.

McDowell RW, Drewry JJ, Muirhead RW, Paton RJ. 2003. Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland. Soil Research 41:1521-1532.

McDowell RW, Smith C, Stevens DR. 2011. Quantifying the loss of nutrients and sediment in surface runoff from a spring-grazed forage crop and pasture in the upper Waituna Lagoon catchment. Report for DairyNZ, AgResearch, Invermay Agricultural Centre, Mosgiel. pp. 26.

McDowell RW, Wilcock RJ. 2004. Particulate Phosphorus Transport within Stream Flow of an Agricultural Catchment. Journal of Environmental Quality 33:2111-2121.

McDowell RW, Wilcock RJ. 2007. Sources of Sediment and Phosphorus in Stream Flow of a Highly Productive Dairy Farmed Catchment. Journal of Environmental Quality 36:540-548.

McDowell RW, Wilcock R, Hamilton DP. 2013. Assessment of strategies to mitigate the impact or loss of contaminants from agricultural land to fresh waters. Report for the Ministry for the Envrironment. pp. 46.

Peart MR, Walling DE. 1986. Fingerprinting sediment source: the example of a drainage basin in Devon, UK. Drainage basin sediment delivery. Proceedings of Symposium, Albuquerque, NM. pp. 41-55.

Phillips JM, Russell MA, Walling DE. 2000. Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. Hydrological Processes 14: 2589-2602.

Queralt I, Barreiros MA, Carvalho ML, Costa MM. 1999. Application of different techniques to assess sediment quality and point source pollution in low-level contaminated estuarine recent sediments (Lisboa coast, Portugal). Science of the Total Environment 241:39-51.

Robertson B, Stevens L, Schallenberg M, Robertson H, Hamill K, Hicks A, Hayward S, Kitson J, Larkin G, Meijer K, Jenkins C, Whaanga D. 2011. Interim recommendations to reduce the risk of the Waituna Lagoon flipping to an algal-dominated state. Report prepared for Environment Southland by the Lagoon Technical Group (LTG).

Rowell DL. 1994. Soil Science: Methods and Applications. 2nd Edition. Longman Scientific and Technical. pp. 29 - 30.

Russell MA, Walling DE, Hodgkinson RA. 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. Journal of Hydrology 252: 1-24.

Sharpley AN, Curtin D, Syers JK. 1998. Changes in water-extractability of soil imorganic phosphate. Soil Science Society of America Journa. 52: 637-640.

Simmonds B, McDowell R, Condron L 2013. Preliminary study of the potential for phosphorus loss with the development of organic soils. In: Currie LD, Christensen CL (Eds.), Accurate and Efficient Use of Nutrients on Farms. Occaiotnal Report No 26, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Available at: http://www.massey.ac.nz/~flrc/workshops/13/Manuscripts/Paper_Simmonds_2013.pdf (accessed October, 2013).

Stone M, Murdoch A. 1989. Effect of particle size, chemistry and mineralogy of river sediments on phosphate adsorption. Environmental Technology Letters 10:501-510.

Stone M, Krishnappan BG, Emelko MB. 2008. The effect of bed age and shear stress on the particle morphology of eroded cohesive sediment in an annualar flume. Water Research 42:4179-4187.

Stutter MI, Langan SJ, Lumsdon DG, Clark LM. 2009. Multi-element signatures of stream sediments and sources under moderate to low flow conditions. Applied Geochemistry 24:800-809.

Tan CS, Zhang TQ. 2011. Surface runof fand sub-surface drainage phosphorus losses under regular free drainage and controlled drainage with sub-irrigation systems in southern Ontario. Canadian Journal of Soil Science 91:349-359.

Torri D, Borselli L. 2012. Water Erosion. Handbook of soil sciences: resource management and environmental impacts 2nd Edition, pp. 22-1.

United Stated Environmental Protection Agency. 1997. Acid digestion of sediments, sludges and soils. Method 3050B.

Walling DE, Collins AL, Stroud RW. 2008. Tracing suspended sediment and particulate phosphorus sources in catchments. Journal of Hydrology 350:274-289.

Walling DE, Owens PN, Leeks GJL. 1999. Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. Hydrological Processes 13:955-975.

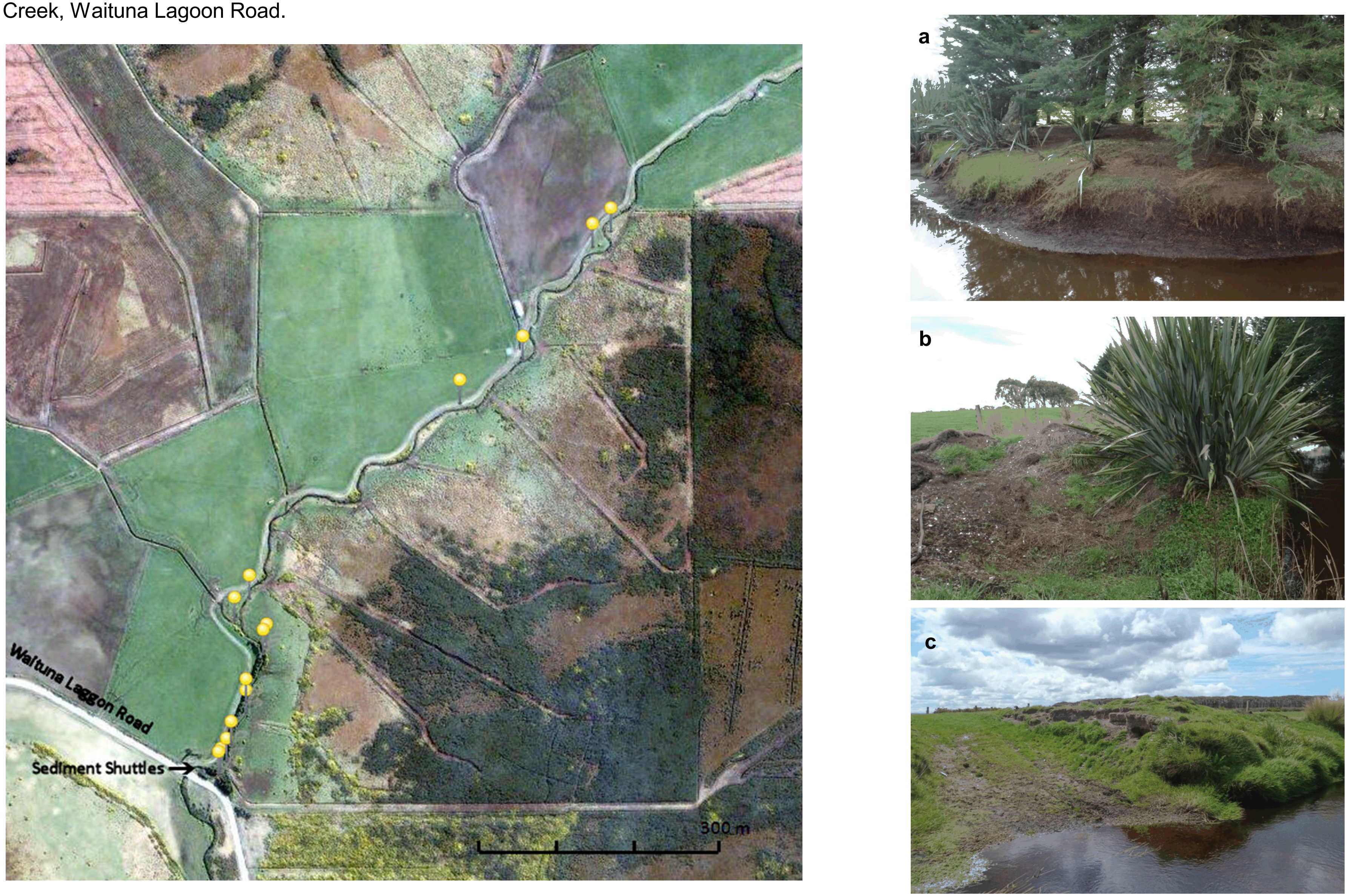
Walling DW, Woodward JC, Nicholas AP. 1993. A multi-parameter approach to fingerprinting suspended-sediment sources. Tracers in hydrology. Proceedings of an International Symposium, Yokohama, Japan. pp. 329-338.

Withers PJA, Edwards AC, Foy RH. 2001. Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil. Soil Use and Management 17:139-149.

Yang D, Kanae S, Oki T, Koike T, Musiake K. 2003. Global potential soil erosion with reference to land use and climate changes. Hydrological Processes 17:2913-2928.

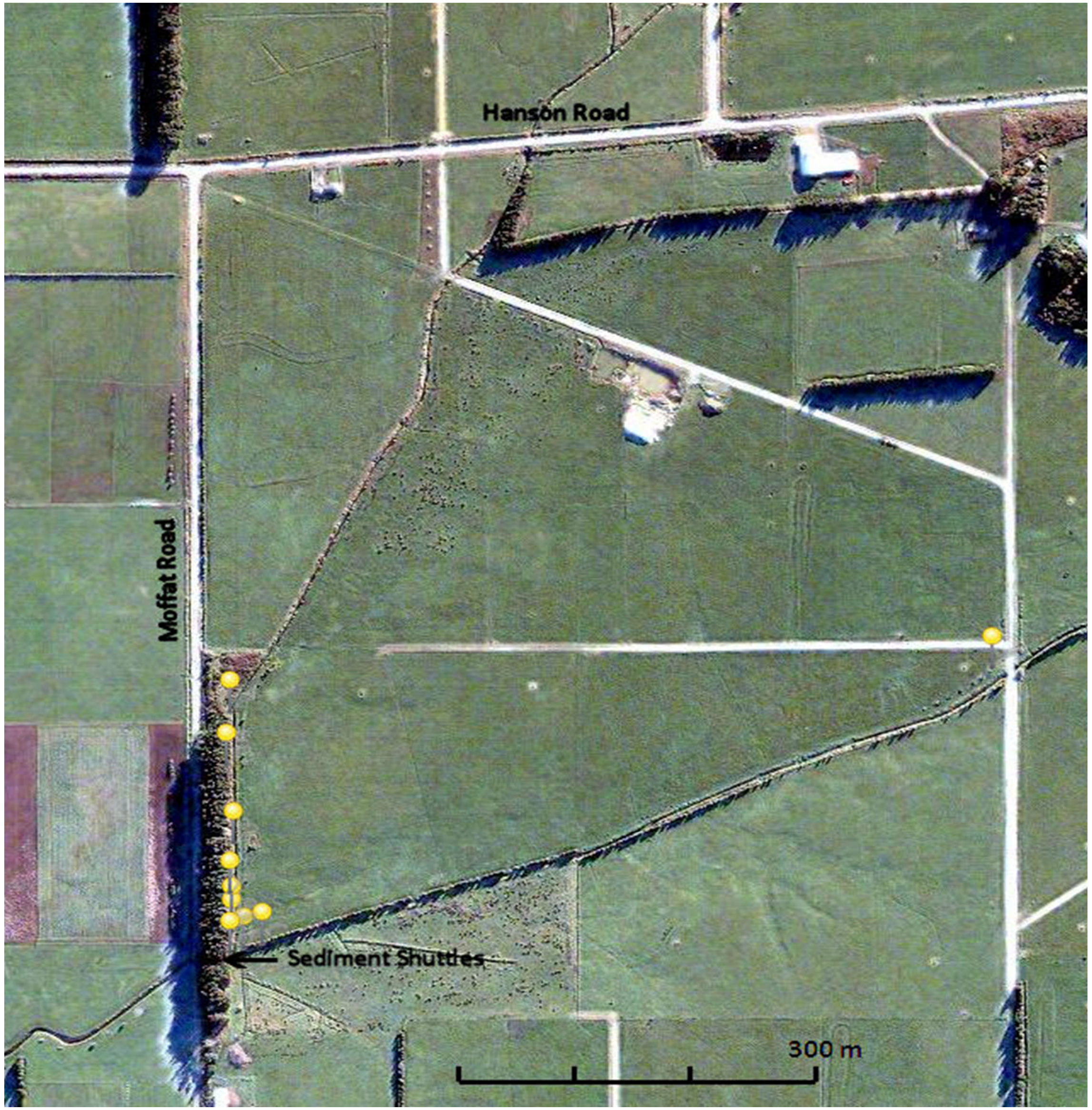
Appendix I

Sampling points and examples of sediment sources from (a) an exposed bank side, (b) drain cleanings and (c) a vehicle track at Carran Creek, Waituna Lagoon Road.



Appendix II.

Sampling points and examples of sediment sources from (a, b) drain cleanings and (c) bank erosion at Moffat Creek, Moffat Road.



Appendix III.

Sampling points and examples of sediment sources from (a) top soil erosion, (b) bank erosion and (c) a bank slip at Waituna Creek, upstream site.

Appendix IV.

Sampling points and examples of sediment sources from (a) a vehicle track, (b) bank erosion and (c) a bank slip at Waituna Creek, downstream site.