NIWA
Taihoro Nukurangi

Avon River Sediment Survey

Prepared for Christchurch City Council

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Contents

Tables

Figures

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Executive summary

Stormwater discharges transport a range of contaminants into receiving environments and many of these contaminants (particularly metals and persistent organic contaminants) may accumulate over time in stream sediment. Sediment quality surveys can therefore show the effects of stormwater discharges on a time-integrated basis. Contaminants accumulated in stream sediments can also adversely affect stream biota.

Stream sediment quality was examined at 34 sites across the Avon River / Ōtākaro catchment, with 15 sites in the mainstem and 19 sites in tributaries. Multiple samples from each site were collected from the surface of the benthic sediment and combined into a single composite sample for analysis of metals, PAHs, phosphorus, organic carbon and grain size.

The survey found the sediment metal concentrations were within the range previously measured in urban stream sediments from elsewhere in Christchurch and around New Zealand. Within the Avon River / Ōtākaro catchment, higher concentrations of metals were measured in Riccarton Main Drain, Addington Brook, Dudley Creek and its tributaries and the middle reaches of the Avon River / Ōtākaro. Lower concentrations were measured in the Avon River headwaters, tributaries to the north-west (Ilam, Wairarapa, Waimairi, Wai-iti Streams), No.2 Drain and Corsers Stream.

Lead, zinc and PAHs concentrations at 15 out of 35 sites exceeded ANZECC sediment quality trigger values, showing these are the major contaminants of concern. There were also numerous other trigger value exceedances as follows:

- Zinc ISQG-high value of 410 mg/kg exceeded at 5 sites measuring 420 to 770 mg/kg;
- Lead ISQG-high value of 220 mg/kg exceeded at 1 site (site 20, middle reach of Riccarton Main Drain), measuring 780 mg/kg;
- Total PAHs ISQG-high value of 40 mg/kg exceeded at 1 site (site 18, lower Dudley Creek) based on the initial measurement of this sample (693 mg/kg when normalised to 1% TOC), but not for the reanalysed measurement (30 mg/kg when normalised to 1% TOC);
- Arsenic ISQG-high of 70 mg/kg exceeded at 1 site (site 22, Addington Brook), measuring 78 mg/kg and ISQG-low exceeded at 1 other site (site 21, Riccarton Main Drain) and;
- Copper ISQG-low exceeded at 1 site (site 19, upper Riccarton Main Drain).

Cadmium, chromium and nickel concentrations in the sediment did not exceed their respective trigger values at any sites.

A comparison of the present survey results with a prior survey 30 years ago indicated that lead concentrations are now lower, and chromium and nickel concentrations are higher. There was no clear difference in the concentrations of zinc, copper or cadmium between surveys. This contrasts with results for other Christchurch catchments where zinc concentrations appeared to be higher in recent surveys. This may be due to differences in the sediment grain sizes between surveys or due to the input of liquefaction sediments.

This report investigated potential influences on sediment quality including soils, landuse, roading materials and earthquake-related liquefaction, dredging and wastewater discharges. The following findings were made:

- The sources of cadmium, copper, lead, and zinc are likely to be the same, and different from that for organic carbon, phosphorus, arsenic, chromium, nickel and PAHs.
- Arsenic, chromium, lead and nickel in sediment are likely to be sourced primarily from soils. Soils contain elevated concentrations of lead compared to outside urban areas as a result of lead additives in petrol.
- Impervious surfaces appear to result in higher concentrations of copper, lead, zinc and PAHs.
- Rural landuse appears to be associated with (no statistical analysis was undertaken) the lowest concentrations of metals in sediment whereas commercial and industrial landuse was associated with typically higher copper, lead and zinc concentrations.
- Elevated arsenic (higher than all other sites and above trigger values) in Addington Brook is likely due to historical soil and groundwater contamination from a sheep dip site upstream of the sampling site.
- Elevated PAHs (higher than all other sites and above trigger values) in Dudley Creek are likely due to historical use of coal tar used as roading material.
- Post-earthquake dredging of stream sediments appears to have reduced concentrations of metals presumably as stormwater-derived sediments were removed along with liquefaction-derived metals. The influence of liquefaction itself on contaminant concentrations was not clear. The wastewater discharges do not appear to have had any effect on the sediment quality in terms of the contaminants measured in this study.

For stormwater management in the Avon River / Ōtākaro catchment there are several recommendations:

1. Catchment-wide measures to reduce zinc concentrations, such as source control, treatment devices or non-structural best management practices.
2. Control of inputs of roading material into stormwater and stream networks in areas where coal tar was used.
3. Sediment toxicity testing to elucidate whether current concentrations are resulting in adverse effects on biota at sites where sediment concentrations of zinc, lead or arsenic exceeded the ANZECC ISQG-high.
4. Further investigations to identify contaminant sources (current and historic) at locations with much higher contaminant concentrations compared to the rest of the catchment.
5. Where sources can be identified, introduce on-site stormwater management to prevent on-going degradation.
6. Remediation of the sediments through dredging to remove contaminated sediment if toxicity testing shows that sediment is affecting aquatic biota.

1 Introduction

1.1 Introduction

The Christchurch City Council (CCC) is developing a Stormwater Management Plan (SMP) for the Avon River / Ōtākaro catchment. This will contribute to a catchment-wide application to Environment Canterbury for consent to discharge stormwater. There are several background studies that are currently being undertaken to provide information for the SMP and consent application. These cover the:

- Water quality of the catchment waterways;
- Sediment quality of the catchment waterways;
- Ecological status of the catchment waterways; and
- Contaminant load modelling for the catchment.

This report covers the sediment quality of the waterways which was assessed through field collection of samples and laboratory analysis.

1.2 Project Scope

The purpose of this project, as outlined in the Request for Proposals from CCC is to:

"undertake a sediment quality survey of the Avon catchment to establish a current benchmark for the contamination status of sediment in the major waterways within the Avon SMP area. The report should include an analysis of trends over time and identification of areas of the catchment where poor sediment quality is likely to be impacting on ecological values by making comparisons with relevant sediment quality guidelines. The report will contribute to characterising, categorising and prioritising the waterways within the catchment for management. Recommendations should be made as to where stormwater design or catchment management should be used to improve sediment quality as required."

The tasks required included:

- Review of existing sediment quality information in the catchment.
- Sediment quality survey at sites proposed by CCC using the outlined sampling methodology which required sampling of at least five sub-samples at each site to form a composite suitable for analysis of the prescribed list of analytes. Some of the proposed sites were amended where required due to in-stream works.
- Data analysis and reporting, including methodology, presentation of results and comparison with the results of previous surveys and relevant guidelines, and the use of other catchment information, such as the surrounding geology, soil types, stream characteristics, existing water quality monitoring data to assist with interpretation of results.

This report covers all aspects of the scope outlined above.

1.3 This Report

This report is organised in nine sections including this introduction as listed below.

- Section two explains why this study has been undertaken.
- Section three provides background information on issues influencing the sediment quality of the Avon River / Ōtākaro based on previous studies in the catchment and elsewhere in Christchurch.
- Section four describes the methods used in this sediment survey, including field, laboratory and statistical methods used in this report.
- Section five presents the current state of sediment quality in the Avon River / Ōtākaro catchment, including spatial patterns, exceedance of sediment quality guidelines and compares the results to that in other locations.
- Section six compares the current state in the Avon River / Ōtākaro catchment with previously measured data for this catchment to investigate change over time.
- Section seven discusses the main influences on sediment quality in the catchment.
- Section eight summarises the major findings of this sediment survey.
- Section nine suggests recommendations for management of the Avon River / Ōtākaro catchment.

Because this survey used single samples at each site, statistical comparisons between sampling sites could not be undertaken. Differences described in the text (e.g., higher, lower) are relative differences only based on the single results. Additional sampling of the Avon River / Ōtākaro catchment sediments may indicate that differences observed in this study are not statistically significant.

2 Sediment Studies and Stormwater Management Planning

2.1 Why Measure Sediment Quality in the Avon Catchment?

Rain falling on impervious surfaces generates stormwater. When rainwater hits these surfaces, it picks up dust, deposited aerosols and can dissolve surfaces. Consequently urban runoff contains all sorts of metals and other contaminants, reflective of the activities on the land over which it has passed. The runoff then flows into the stormwater system and is discharged into stream receiving environments. A number of physical and chemical processes occur here, which result in many contaminants adsorbing to suspended sediments and then depositing on the stream bed in slow flowing reaches. Thus, stormwater discharges result in accumulation of sediments with above-background concentrations of various metals and persistent organic contaminants.

Because metals do not degrade, and persistent organic contaminants degrade very slowly, sediment quality reflects the effects of stormwater over time. Measurement of the contaminants in stream sediments at multiple locations can therefore provide useful information on catchment activities. This has many benefits over traditional stormwater monitoring which would require a large number of samples to be collected during multiple storm events to provide similar information.

In addition, benthic sediments are the home of many types of stream biota, particularly macroinvertebrates. When contaminants in the sediments accumulate to toxic levels, this affects the abundance and diversity of the biota living in and near the sediments.

2.2 Sources of Contaminants in Stormwater

Of the trace metals typically measured in stormwater, zinc is at the highest concentration and is primarily sourced from tyre wear (rubber tyres are ~1% zinc, Councell et al. 2004) and from galvanised steel roofing and similar products that contain zinc-based anti-corrosion surface treatments (Kennedy & Sutherland 2008). Copper is generally found at lower concentrations and is derived mainly from brake wear as metallic copper is a common ingredient in brake linings (Kennedy & Sutherland 2008). Copper roofing and spouting contribute a high concentration of dissolved copper compared to other roofing types and this source may become more significant with the increasing use of the copper as an architectural material (Pennington & Webster-Brown 2008).

Historically the major source of lead was in petrol as an anti-knocking agent and it was present in stormwater at concentrations at least 10-times higher than today (see Williamson 1993 and Williamson & Mills 2009). This has resulted in its accumulation in roadside soils and in stream sediments (Williamson & Mills 2009). Since its removal from petrol in the 1980s, lead is now found in stormwater at similar concentrations to copper and its actual sources are not as clearly identifiable as previously (Kennedy & Sutherland 2008). There are however some on-going sources of lead, including catchment soils (which may be contaminated with lead due to historical uses of lead in fuel or paints), rainfall and dry deposition (see Kennedy & Sutherland 2008).

Cadmium is found at low concentrations relative to these other metals, but it is also toxic at lower concentrations (see ANZECC 2000). Sources of cadmium are often the same as zinc, as it can be found in zinc products as a minor impurity (Williamson 1993). PAHs can be found in stormwater particulates and are generally thought to be due to exhaust emissions, atmospheric deposition and wear of roading materials (Depree & Ahrens 2007). Other metals and metalloids analysed in this survey, such as arsenic, chromium and nickel, may also be found in stormwater, however they tend to be associated with specific industrial activities, such as timber treatment or metal works, rather than general urban stormwater (Kennedy 2003).

In general, landuse is thought to influence stormwater quality, with contaminant concentrations often considered to decrease from industrial, to commercial, and residential landuses. However, this is not always the case, and is not necessarily the case for all contaminants. For example, in the US, a nationwide survey found no significant differences between landuses (see USEPA 1983). In New Zealand, Timperley et al. (2005) found that zinc concentrations were generally higher in runoff from industrial landuses where a large proportion of the impervious area is comprised of zinc-galvanised steel roofing materials, when compared to commercial or residential landuses. This pattern was not shown for copper (Timperley et al. 2005). As the primary source of copper is brake wear (Kennedy & Sutherland 2008), the concentrations may be related more to the number and activity of vehicles, rather than the landuse per se.

Stormwater is discharged untreated into stream receiving environments in the majority of the Avon River / Ōtākaro catchment, particularly within residential areas. There are a small number of Council-owned stormwater treatment devices in the catchment, including ponds in Riccarton Main Drain and Addington Brook, ponds and wetlands in Snellings Drain and some rain-gardens in the Dudley Creek catchment (pers. comm. K. Couling, B. Norton, CCC). There are many more privately owned treatment devices, particularly in carparks and at industrial sites (pers. comm. K. Couling, B. Norton, CCC). Stormwater treatment devices aim to reduce the loads of stormwater contaminants entering the streams (CCC 2003) and thus reduce their accumulation in the stream sediments.

3 Review of Existing Information

3.1 Overview of the Avon River / Ōtākaro Catchment

The Avon River / Ōtākaro is one of two rivers that drain the majority of Christchurch City, with the Heathcote River / Ōpawaho being the other. The Avon River / Ōtākaro arises in the north-west of the city and meanders its way eastwards across the city, through the CBD and eastern suburbs before discharging into the northern tip of the Avon-Heathcote Estuary / Ihutai (Figure 3-1).

The river is primarily spring-fed with a low and slow flow and is approximately 26 km long (PDP 2007). The flow becomes tidally influenced somewhere around the Avondale Bridge, although the water remains predominantly freshwater, at least at the surface. There are numerous tributaries, most of which are also predominantly spring-fed. Some tributaries, such as the No.2 Drain, are man-made drains which were constructed to lower the groundwater levels in the surrounding rural land (PDP 2007), although some, like Corsers Stream and Papanui Stream, have since been renaturalised.

The river catchment area is approximately of 84 km^2 (PDP 2007) and is very flat, with the maximum height only 30 m above sea level. Landuse in the catchment is almost completely urban apart from some rural land to the north and north-west of the catchment. The majority of the urban land is residential, though there are also large areas of commercial land in the CBD and some industrial land in the Addington Brook catchment.

3.2 Sediment Studies in the Catchment

3.2.1 Metals

A major survey of sediment quality in the Avon River / Ōtākaro catchment was undertaken by the Christchurch Drainage Board in 1981/82 (Robb 1988), with sampling at 89 locations from the Avon River / Ōtākaro headwaters to mouth and at multiple locations within tributaries. Samples were analysed for grain size (silt/clay, sands, gravel); and six metals (cadmium, chromium, copper, lead, nickel and zinc) using methods comparable to those in the current survey (see Table 3-1 for a summary of the results compared to ANZECC guidelines). Samples were also collected in the Heathcote and Styx River catchments, the City Outfall Drain and in the Avon-Heathcote Estuary.

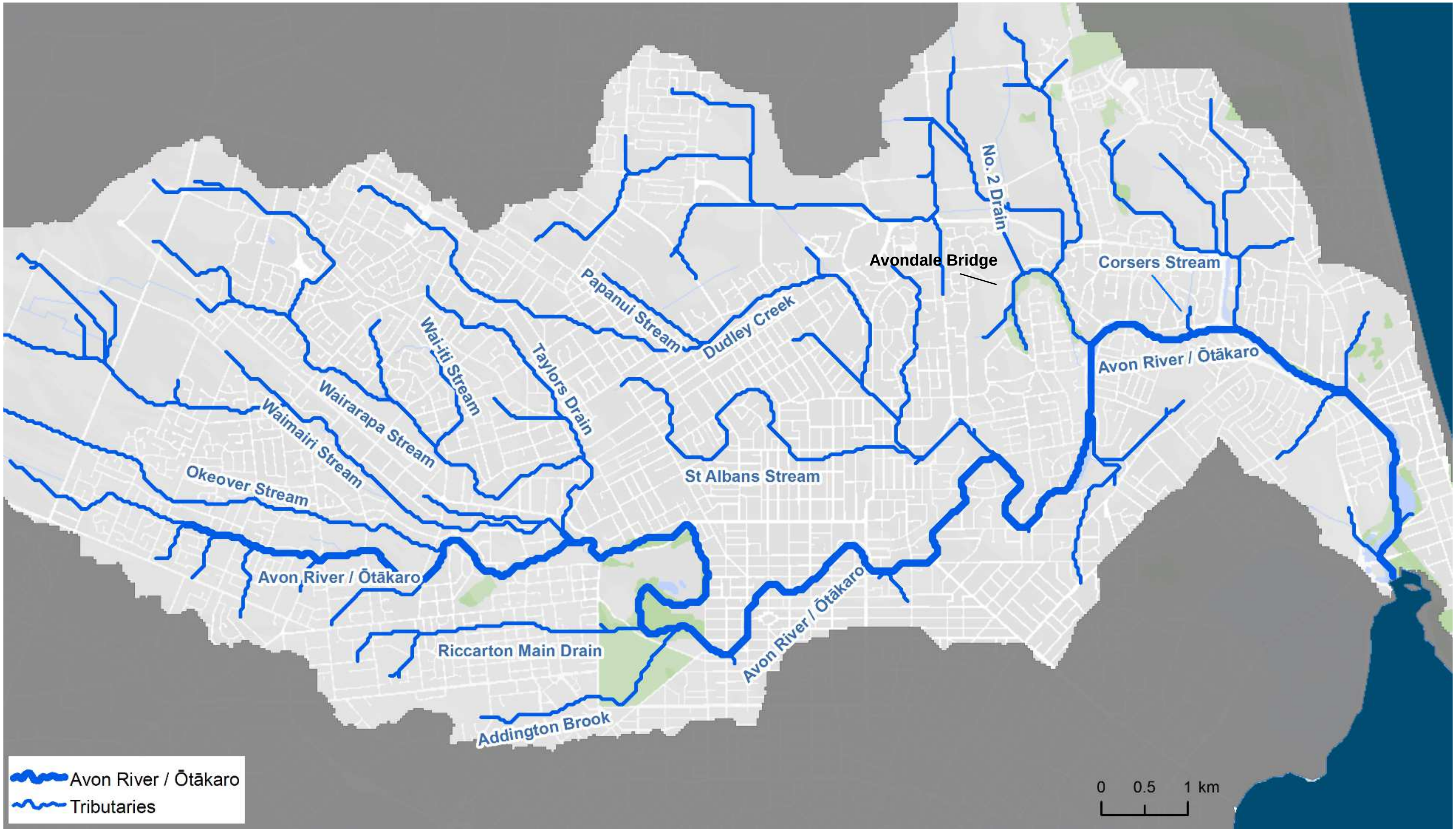

Figure 3-1: The Avon River / Ōtākaro River, indicating major tributaries and approximate catchment boundary.

Table 3-1: Summary of metal concentrations in sediments of the Avon River / Ōtākaro catchment. Mean concentrations (mg/kg) ± standard deviation. Yellow shading indicates mean exceedance of ISQG-low, pink shading indicates exceedance of ISQG-high.

Location	Survey	Cadmium	Chromium	Copper	Lead	Nickel	Zinc
ISQG-Low		1.5	80	65	50	21	200
ISQG-High		10	370	270	220	52	410
Avon upper (u/s CBD)	Robb (1988)	0.18 ± 0.12	11 ± 3	18 ± 13	84 ± 40	7 ± 2	156 ± 71
	Golder (2012)	0.16 ± 0.11	13 ± 2	19 ± 16	39 ± 27	10 ± 1	153 ± 92
Avon mid (CBD to Avondale)	Robb (1988)	0.48 ± 0.41	16 ± 5	30 ± 28	102 ± 70	10 ± 3	256 ± 187
	Golder (2012)[1]	0.32	18	27	68	14	245
Avon lower (d/s Avondale to mouth)	Robb (1988)	0.2 ± 0.13	23 ± 8	16 ± 7	46 ± 27	9 ± 2	156 ± 71
	Golder (2012)[2]	0.15	30	20	32	15	150
North-west tributaries (Okeover to Taylors)	Robb (1988)	0.58 ± 1.49	10 ± 4	16 ± 9	332 ± 1017	6 ± 2	139 ± 98
Dudley Creek tributaries	Robb (1988)	0.71 ± 0.93	12 ± 4	28 ± 25	228 ± 162	8 ± 3	436 ± 304
	Golder (2012)[2]	0.05	10	5	14	8	61
Riccarton & Addington Drains	Robb (1988)	0.44 ± 0.34	21 ± 15	39 ± 33	250 ± 234	9 ± 3	347 ± 216
	Golder (2012)[2]	0.24	16	16	39	14	500
Overall	Robb (1988)	0.48 ± 0.89	14 ± 8	23 ± 21	200 ± 563	8 ± 3	238 ± 207
	Golder (2012)	0.19 ± 0.15	16 ± 6	19 ± 13	42 ± 32	12 ± 3	207 ± 158

Note: 1 Only two samples collected from this area, standard deviation not calculated. 2. Only one sample collected from this area.

Zinc and lead were elevated at many sites when compared to the rural Styx River. Lead was also noted to be higher in the Avon River / Ōtākaro catchment sediments (from non-tidal reaches) than in the Heathcote River sediments (Robb 1988). This was attributed to greater volume of stormwater from roading sources in this catchment compared to the Heathcote catchment (Robb 1988). Zinc and lead concentrations in the tidal reaches were lower in the Avon than in the Heathcote, attributed to the industrial landuse and discharges in the lower Heathcote (Robb 1988).

In particular, there were four waterways in the Avon River / Ōtākaro catchment where zinc and lead were considered to be extensively contaminated (Robb 1988). St Albans and Dudley Creeks had high concentrations of zinc and lead at multiple locations; Riccarton Main Drain also had high lead concentrations throughout its length; and Addington Brook had elevated concentrations of zinc at four of the six sites in the catchment. The elevated zinc and lead concentrations in St Albans and Dudley Creeks and Riccarton Main Drain was considered due to residential stormwater (Robb 1988). Elevated metal concentrations in Addington Brook were attributed to the Addington Railway Workshops which had previously allowed a lot of metal waste to reach drains, including zinc, lead, copper and chromium (Robb 1988). An exceptionally high value for lead was found in Wairarapa Stream, at 5300 mg/kg (site 68). No explanation could be found for this measurement and the biota did not appear to be affected (Robb 1988). Elsewhere there were no distinctive patterns in concentrations (Robb 1988).

In general, cadmium, chromium and nickel were no more elevated in the Avon River / Ōtākaro than in the rural Styx River and showed no distinctive pattern in their concentrations (Robb 1988). The only significant point to note was the high chromium in Addington Brook, which as mentioned was attributed to the Addington Railway Workshops (Robb 1988). The sediment data collected in the Christchurch Drainage Board study (Robb 1988) are presented in more detail in Section 6.1 in comparison to the data collected in this current survey.

In 2011, urban stream sediments throughout the Canterbury Region were surveyed (Golder 2012), including six sites in the Avon River / Ōtākaro and two in tributaries (Dudley Creek and Addington Brook). This data is also presented in Table 3-1. Copper, lead and zinc concentrations were elevated compared to sites outside of the Christchurch urban area, and both lead and zinc exceeded the ANZECC (2000) trigger value (ISQG-low), at four and five sites respectively (Golder 2012). Zinc also exceeded the upper sediment quality guideline (ISQG-high) in Addington Brook, the only site in the region where this occurred, measuring 500 mg/kg. Addington Brook also had elevated arsenic, exceeding the trigger value and all other locations in the region (Golder 2012). One site in the Avon River / Ōtākaro (upstream of Fitzgerald Avenue) also exceeded the trigger value for mercury and was the highest equal concentration measured in the region (Golder 2012). Mercury concentrations had not previously been regularly measured in sediment surveys. Arsenic and chromium concentrations in the Avon River / Ōtākaro appeared to be related to the mud content of the sample, with higher concentrations in muddier samples. Cadmium concentrations showed a weaker relationship with mud and zinc but were related to copper concentrations. This study confirmed that the Avon River / Ōtākaro sediments have elevated concentrations of several metals in comparison to other streams.

3.2.2 PAHs

A PhD thesis in the early 1980s investigated PAHs in the Christchurch urban environment, including sediments from 8 locations in the Avon River / Ōtākaro (Lee 1982). He noted that PAHs were lowest at the river source, increased downstream and then decreased near the river mouth. Atmospheric particulate matter, automobile exhaust particulates and domestic soot particulates were also studied as part of source identification. Lee (1982) found that domestic soot was the primary source of PAHs in stream sediments based on PAH and lead ratios.

In 2005, an investigation showed that PAH concentrations were between ~50 and 100 mg/kg in St Albans Stream, Dudley Creek and the section of the Avon River / Ōtākaro downstream of these tributaries, substantially higher than at sites in the Heathcote River catchment measured at the same time (Depree & Ahrens 2005). A follow-up series of studies of the roading material, footpaths and roadside soils, particularly around the central northern suburbs of St Albans and Richmond, identified PAHs at concentrations of ~1000-7000 mg/kg in roading seal layers and generally 7000-12,000 mg/kg in footpath seals (Depree 2006; Depree & Olsen 2005a, 2005b). Roadside soils also contained high concentrations of PAHs, at 100-400 mg/kg in shoulder soils (area between road seal and channel) and 10-160 mg/kg in berm soils (area between the footpath and property boundary).

These PAH concentrations in the soils and road sealing layers were well above that normally found in runoff particulates (Depree & Olsen 2005a) or roadside gutter debris (Kennedy & Gadd 2003) of < 5 mg/kg. Other sources such as wood/coal soot from domestic combustion also could not readily account for the PAHs found in the stream sediments and soils. For example, soot contains PAH concentrations of around 1000 mg/kg, so for soils to contain up to 400 mg/kg would require soils to contain very high percentages of soot – which is simply not the case. Moreover, diagnostic wood/smoke marker compounds were not detected in soil, runoff particulate or stream sediment samples.

The elevated PAH concentrations were therefore attributed to the use of coal tar, a by-product from gas works, which was used in roading construction up until the 1970s. In locations where coal tar was used in road sealing, the concentrations of PAHs in runoff particulate material ranged from ~20 to 200 mg/kg of PAHs, substantially higher than concentrations in the absence of coal tar.

3.3 Sediment Studies Elsewhere in Christchurch

Sediment quality has also been investigated in other urban streams in Christchurch, with comprehensive studies in the Heathcote, Halswell and Styx River catchments (Kingett Mitchell 2005; Golder 2009); and seven sites included in the regional survey (Golder 2012). The results of these studies are summarised in Table 3-2.

Table 3-2: Summary of metal concentrations in sediments from other Christchurch catchments. Mean concentrations (mg/kg) ± standard deviation. Yellow shading indicates mean exceedance of ISQG-low, pink shading indicates exceedance of ISQG-high.

		Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc
		20	1.5	80	65	50	21	200
		70	10	370	270	220	52	410
Heathcote	Kingett Mitchell 2005	Not measured	Not measured	Not measured	43 ± 44	69 ± 73	Not measured	436 ± 281
Styx	Golder 2009	9.0 ± 5.1	0.27 ± 0.23	20 ± 9	18 ± 11	45 ± 45	11 ± 3	268 ± 239
Halswell	Kingett Mitchell 2005	Not measured	Not measured	Not measured	14 ± 15	25 ± 18	Not measured	168 ± 191
Christchurch other	Golder 2012	3.8 ± 1.8	0.32 ± 0.44	16 ± 6	26 ± 27	24 ± 15	11 ± 2	196 ± 154

The main findings of these studies were that copper, lead and zinc concentrations were lower in the rural streams (e.g., much of the Halswell River and many sites in the Styx River catchment) compared to the urban streams and the Heathcote River. Within the Heathcote River catchment, metal and PAH concentrations tended to differ by land use, increasing from rural to residential, mixed urban, to industrial (Kingett Mitchell 2005). A similar pattern was shown in the Styx catchment, although nickel was at higher concentrations at rural sites than urban (Golder 2009). Curletts Drain, in the Heathcote River catchment, was identified as having exceptionally high copper and lead (Kingett Mitchell 2005).

There were several locations in the Halswell, Heathcote and Styx catchments that exceeded sediment quality guidelines for lead and zinc, including the ISQG-high. No sites in the Styx catchment exceeded the copper guidelines, compared to one in the Halswell catchment and five in the Heathcote catchment. Arsenic, cadmium, chromium and nickel concentrations were also measured in the Styx survey with no exceedances of guidelines (Golder 2009).

In the Heathcote and Halswell, sediment texture was mixed in the upper catchment, but dominated by fines in tidal reaches (Kingett Mitchell 2005). In the Styx catchment, the sediment was dominated by fine sand and mud throughout the catchment with only one exception (Golder 2009).

There were only weak relationships between metal concentration and the particle size of samples collected. Nickel and copper in the Styx catchment showed some evidence of a relationship whilst other metals did not. In the Halswell catchment, there was a relationship between copper and mud only when data for the urban sites were excluded.

When the data from these two studies was compared to the previous studies in the Heathcote and Styx catchments (Robb 1988), there were generally increases in zinc (and cadmium in the Styx catchment); decreases in lead; and copper was variable.

3.4 Stormwater and Water Quality Studies in the Catchment

3.4.1 Stormwater quality

There have been at least four studies of stormwater quality in the catchment:

- Three storm events monitored in Riccarton Main Drain in 1992 (Main 1992) in a study of stormwater from 6 different sites across Christchurch;
- First flush of 38 storm events monitored in a carpark during 1999-2002 (Main 2005);
- Multiple storm events at the University of Canterbury from 2007 to 2009; and
- Four storm events monitored in Addington Brook in 2010-11 (ECan unpublished).

The most relevant findings of these studies in relation to the present study include:

- Stormwater in Addington Brook had higher arsenic than usually found in urban stormwater but copper, lead and zinc were at typical concentrations (based on comparison with data from NIWA's stormwater quality database, urqis.niwa.co.nz).
- Riccarton Main Drain had higher concentrations of zinc than usually found in urban stormwater (based on comparison with data from NIWA's stormwater quality database)
- Copper concentrations in stormwater from the University of Canterbury were higher than usually found in urban stormwater (based on comparison with data from NIWA's stormwater quality database) and were traced to air-conditioning units on site (Wicke et al. 2009).

While these studies do provide stormwater quality data for the catchment, the latter three are isolated investigations which focus on small areas of the catchment. Only one study investigated multiple sites with different landuses (Main 1992), although all the other sites were located outside the Avon River / Ōtākaro catchment. Although these studies do provide some information on stormwater quality at that particular location, which will inevitably influence the sediment quality, because there is no data for other sources or locations in the Avon River / Ōtākaro catchment with which to compare, the studies can only point to potential issues for the present catchment-wide sediment study. There may be other locations in the catchment where stormwater has much higher concentrations of contaminants, but which have not been measured.

3.4.2 Stream water quality

Water quality, including metals and phosphorus, is monitored monthly by Christchurch City Council since 2007 (and was monitored sporadically prior to then) in the Avon River / Ōtākaro and several of its tributaries. Thirteen sites are monitored, 11 of which closely coincide with the sediment sites used in this study. However, for most of the measurements, metals have been below the detection limits used. The most recent monitoring presented by Environment Canterbury (Bartram 2013b) showed that zinc was highest in Addington Brook, Dudley Creek and in the lower Avon River / Ōtākaro at Dallington Bridge (Figure 3-2). The total and dissolved zinc concentrations at these locations frequently exceeded trigger values (Bartram 2013b). Copper concentrations were also highest in Addington Brook and Dudley Creek and at times exceeded trigger values at these sites and others, including Wairarapa and Waimairi Streams and in the lower Avon River / Ōtākaro at Pages Road and Bridge Street (data not shown here). Dissolved copper concentrations were below detection at all sites except Addington Brook.

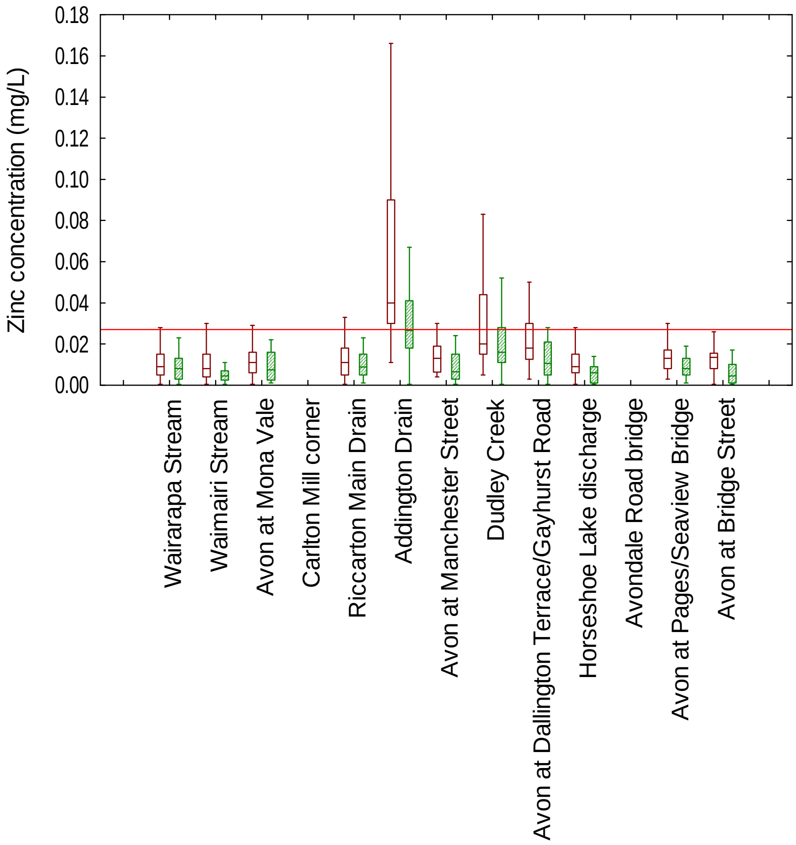

Figure 3-2: Total zinc (maroon) and dissolved zinc (green) concentrations at monitoring sites in the Avon River / Ōtākaro catchment compared to trigger value (red horizontal line). From Bartram (2013b).

Other reports of water quality in the Avon River / Ōtākaro catchment (e.g. PDP 2007) indicate that Addington Brook, Dudley Creek and Horseshoe Lake are sources of contaminants to the Avon River / Ōtākaro, however the contaminants referred to are suspended solids, nutrients and bacteria. Although the nutrients measured include phosphorus, this is as dissolved reactive phosphorus, rather than total phosphorus. Whilst this is more relevant for stream ecology, total phosphorus would be more relevant for assessing potential for impacts on sediment quality.

3.5 Synthesis and Summary of Issues Identified

Previous studies within the Avon River / Ōtākaro catchment and elsewhere in Christchurch indicate that urban stream sediments have elevated concentrations of zinc, lead and copper. Zinc concentrations in the sediments frequently exceed sediment quality guidelines, while copper concentrations do so more rarely. Generally arsenic, cadmium, chromium and nickel are not markedly different in the urban stream sediments compared to rural stream sediments, and in some cases show a relationship with sediment texture. In catchments other than the Avon, where there have been multiple studies, zinc concentrations in the sediments appear to be higher now (2005 onwards) than previously (1980/81), while lead concentrations appear to be lower.

Within the Avon River / Ōtākaro catchment several 'hotspots' have been identified (though the causes remain unknown) and are shown in Figure 3-3. Compared to other sites in the catchment, St Albans and Dudley Creeks have high concentrations lead and zinc in the sediment and Dudley Creek may be a source of other contaminants such as bacteria and nutrients. These tributaries both drain residential land use with no obvious sources of contamination. Very high PAH concentrations have also been identified in these tributaries and are thought to be related to historic use of coal tar in the roading material. Riccarton Main Drain had high lead concentrations in the sediment and appears to have poor stormwater quality (based on a very limited study). Addington Brook has elevated zinc and arsenic concentrations in sediments and the stormwater also contained elevated arsenic in a recent study (Ecan, unpublished data). These issues are discussed further in later sections of the report in relation to the sediment quality measured in this survey.

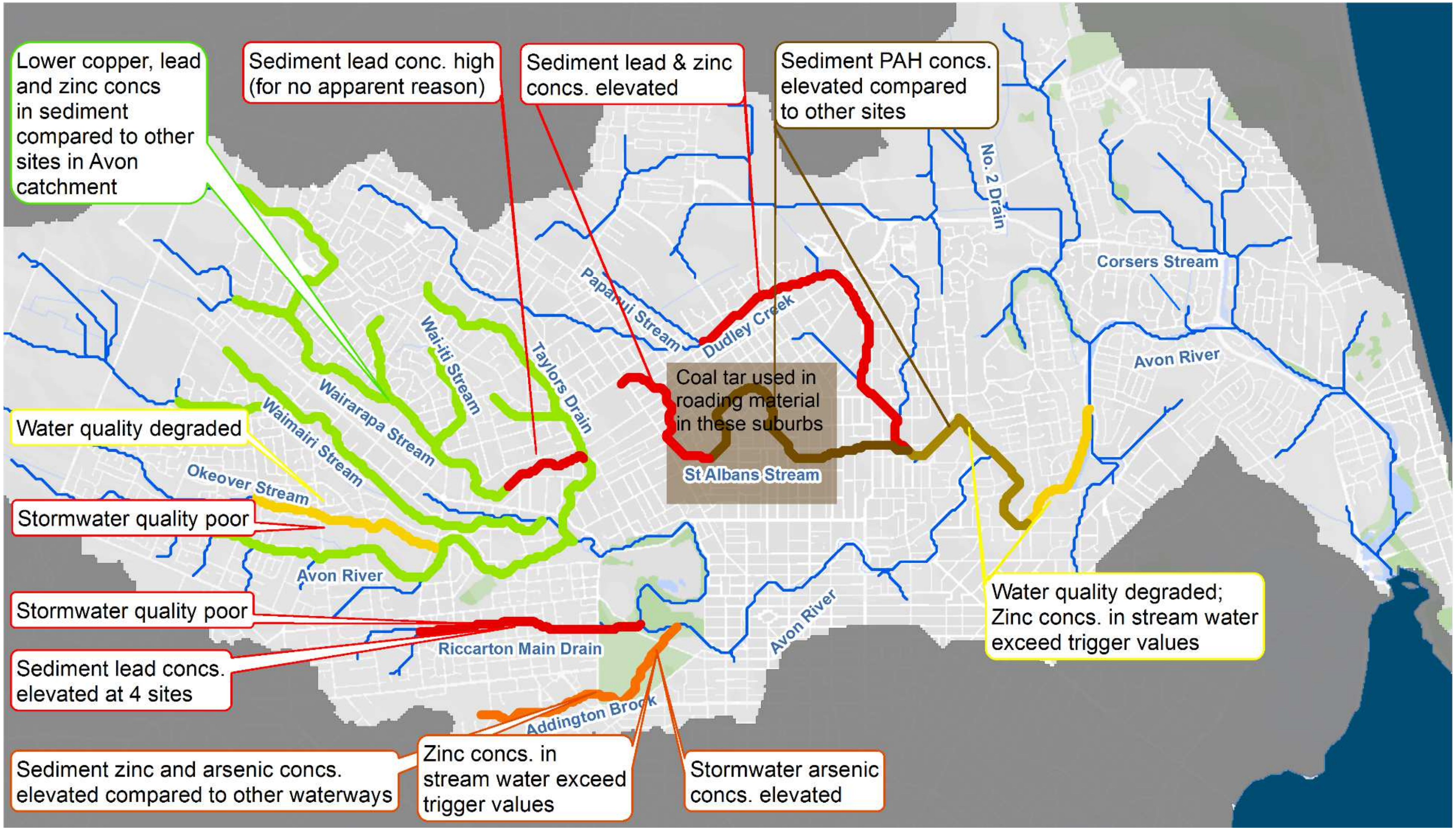

Figure 3-3: Summary of sediment and stormwater related issues in the Avon River / Ōtākaro catchment. Different colouring of the stream and text boxes indicate different issues.

4 Methods Used to Assess Sediment Quality in the Avon

4.1 Sampling Sites

CCC proposed sampling at 35 sites in the Avon River / Ōtākaro catchment (see Appendix A), with sites covering the mainstem of the river from the headwaters to the mouth and major tributaries. Sites were visited and sampled between 5th and 8th August 2013. The sites actually sampled in the catchment differ from these proposed sites at 10 locations. The Land Drainage section of CCC indicated that there were several sites where there had been in-stream dredging, either to remove earthquake-derived liquefaction sediments, or for repair to bridges. In some cases the proposed sites were moved upstream of the dredged area. In some locations the entire stream reach had been dredged and a decision was made whether to sample or not. There were also several changes to the sites during the field work, as original sites had no sediment or had been piped. These changes are all tabulated in Table 4-1 below. The final sampling sites are shown in Figure 4-1 and listed in Table 4-2 along with their map references and cross-reference to previous Christchurch Drainage Board (CDB) sampling site numbers (from Robb 1988).

Table 4-1: Changes to sampling sites proposed by CCC in RFP.

Site No.	Location description	Changes to site
3	Avon River - at Avonhead Road	Moved downstream 80m as no sediment at original site
9	Taylors Drain – Heaton Street	Moved upstream to Jeffreys Rd, as dredged at Heaton St
14	St Albans Creek – Hills Road	Not sampled as whole stream dredged
15	Shirley Stream - Stapletons Road	Not sampled as whole stream dredged
16	Dudley Creek – downstream of Jameson Ave	Moved upstream to Lindgard St, not affected by dredging
17	Dudley Creek – Julius Tce, upstream Shirley Stream	Not sampled, additional site in Avon River added (site 17 in Table 4-2)
19	Riccarton Main Drain – Matipo St (upstream of mall)	Moved upstream to Shand Cres as drain at Matipo site is now piped
27	Avon River – Antigua Boatsheds	Moved u/s to avoid dredging at boatsheds
30	Avon River – upstream Fitzgerald Ave	Moved u/s to avoid dredging at bridge
31	Avon River – Gayhurst Road Bridge	Moved u/s to avoid dredging at bridge

Table 4-2: Final sampling sites.

Site No.	Site Description	Easting (NZTM)	Northing (NZTM)	CDB site no.	Date sampled
1	Waimairi Stream - confluence of two branches	1566275	5181560	7	6/08/2013
2	Waimairi Stream - upstream of railway line	1568123	5181241	13	6/08/2013
3	Avon River - at Avonhead Road	1564593	5181035	14-16	8/08/2013
4	Ilam Stream - Waimairi Road	1565510	5181023	21	6/08/2013
5	Avon River - at Clyde Road	1566658	5180622	24	7/08/2013
6	Clarksons Drain (Okeover Stream) - 30 m downstream of Clyde Road	1566805	5180952	C15	6/08/2013
7	Avon River - confluence with Wairarapa	1568282	5181042	31	6/08/2013
8	Wai-iti Stream - Clyde Road	1566817	5182218	45	7/08/2013
9	Taylors Drain - Railway line	1568158	5182463	51	7/08/2013
10	Wairarapa Stream - Greers Road Bridge	1566187	5182986	54	6/08/2013
11	Wairarapa Stream - Idris Road	1568032	5181953	68	6/08/2013
12	Wairarapa Stream - above confluence of Waimairi & Wairarapa	1568246	5181193	78	6/08/2013
13	St Albans Creek - Abberley Park	1570074	5182069	85	8/08/2013
16	Dudley Creek - Lingard St	1569408	5183256	97	7/08/2013
17	Avon River- opposite Galbraith Ave	1573210	5182024	163	7/08/2013
18	Dudley Creek - North Parade (McKillop College)	1572573	5182149	108	7/08/2013
19	Riccarton Main Drain - Park near Shand Crescent	1566893	5180023	110	8/08/2013
20	Riccarton Main Drain - Clarence St (downstream of mall)	1567879	5180103	113	6/08/2013
21	Riccarton Main Drain - upstream Riccarton Ave	1568997	5180030	118	5/08/2013
22	Addington Brook - Hagley Park	1569291	5179676	129-131	7/08/2013
23	Papanui Stream - Erica Reserve	1569069	5183865	None	6/08/2013
24	No. 2 Drain - Christchurch Golf Club	1573422	5184340	None	5/08/2013
25	Corsers Stream - Brooker Reserve	1575477	5183698	None	5/08/2013
26	Avon River - Carlton Mill Bridge	1569719	5181269	138	6/08/2013
27	Avon River - opposite Curators house	1569811	5179956	U/S 146	7/08/2013
28	Avon River - downstream Armagh Street	1570489	5180411	149	5/08/2013
29	Avon River - opposite Chch Drainage Board	1570809	5180476	151	5/08/2013
30	Avon River - opposite Churchill St	1571615	5181049	153-154	7/08/2013
31.1	Avon River - below Gayhurst Road Bridge	1573578	5181218	168	5/08/2013
31.2	Avon River – just upstream, opposite Morris St	1573450	5181598	166	7/08/2013
32	Avon River – u/s Avondale Bridge	1574541	5183554	181	5/08/2013
33	Avon River - 10 m downstream of Wainoni Rd Bridge	1576372	5183226	187	5/08/2013
34	Avon River - New Brighton Power Boat Club House	1577820	5182363	193	5/08/2013
35	Avon River - 30 m upstream of Bridge Street	1577662	5180861	204	5/08/2013

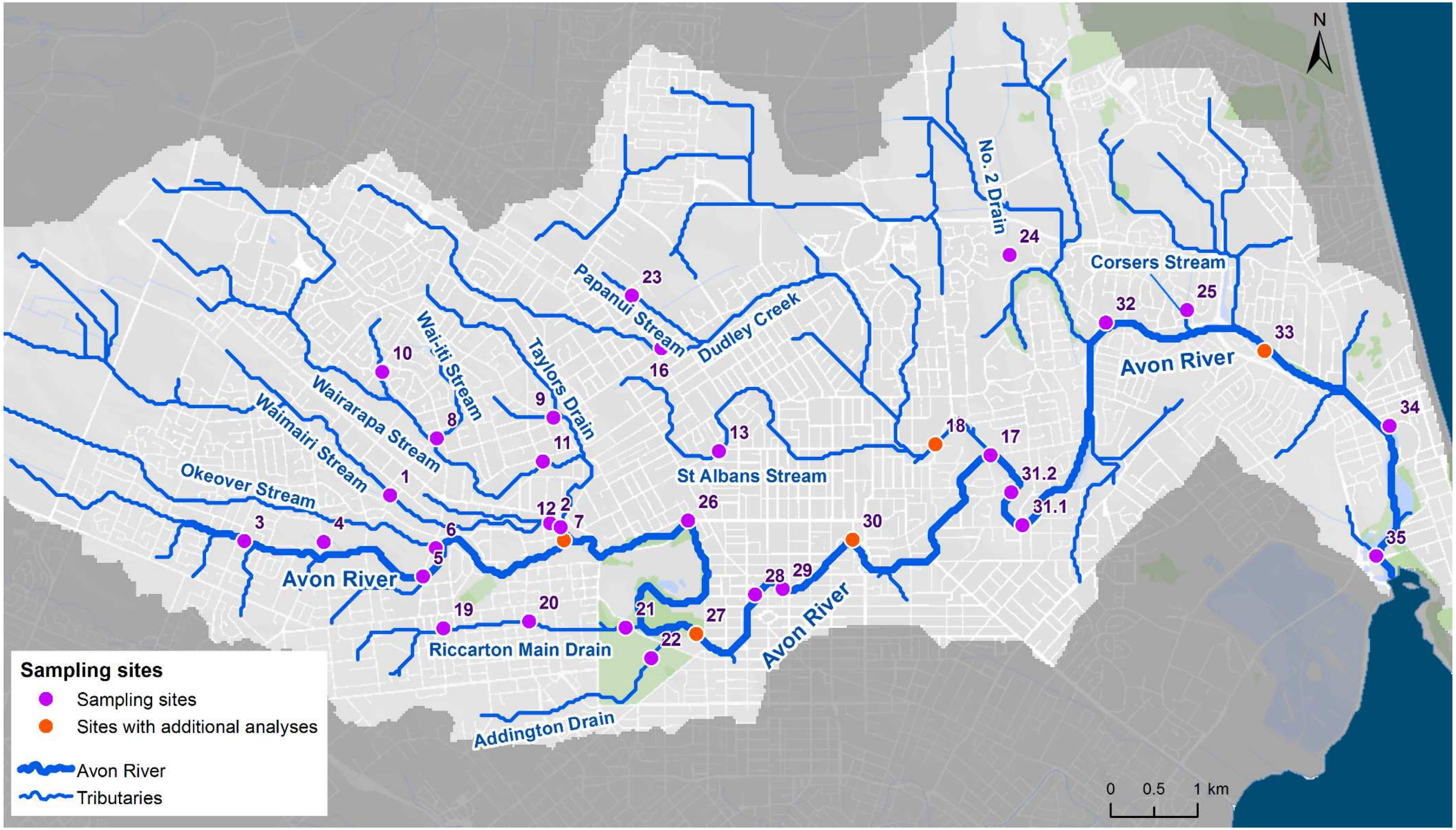

Figure 4-1: Sampling sites in the Avon River / Ōtākaro catchment, indicating five sites (in orange) selected for additional analyses for SVOCs.

4.2 Sampling Methods

Samples were collected following a period of at least three days of dry weather, to ensure that sediments were settled and fine surface sediments had not been removed by high flows. The methods used for sampling were similar to those previously used in sediment surveys around Christchurch (Kingett Mitchell 2005; Golder 2009; 2012). Sediment samples were collected from the surface 2-3 cm of sediment which reflects the most recently accumulated sediment. Sampling methods were employed with the aim of ensuring capture of sufficient fine material (< 2 mm) for laboratory analyses. Samples were collected by making multiple sweeps of an acid-washed plastic container across the stream bed to collect at least 5 sub-samples. While core samplers are the standard method for collection of estuarine and coastal sediments (Burton & Pitt 2002), in our experience these are very difficult to use in streams due to a) the continuous presence of overlying water; b) the heterogeneous substrates encountered; and c) the shallow depth of sediment to be collected. These factors can result in cores not holding together during extraction from the stream bed and loss of the fine sediments being targeted.

Between sampling sites all equipment was washed thoroughly with water to remove all visible sediment, then rinsed with acid (10% HCl) to remove any metals adsorbed to the sampler, then rinsed thoroughly to remove all acid (Burton & Pitt 2002). Sediment samples were composited in labelled plastic bags at every site. Samples were double-bagged with a label between bags to ensure there was no leakage of material and to ensure sample labels were legible to samplers and the analytical laboratory. Samples were stored overnight in a refrigerator and transported to Hill Laboratories in Christchurch in a chilly bin containing pre-chilled ice-bricks. At four locations selected at random prior to sampling, duplicate samples were collected in the field for laboratory analysis.

4.3 Analytical Methods

All analyses were conducted by Hill Laboratories in Hamilton. The analyses undertaken are described below. Hill Laboratories are IANZ accredited for these tests with the exception of TOC and the grain size analysis. The scope of the project required that samples from five sites be analysed for SVOCs. These were sites 7, 18, 27, 30 and 33.

Table 4-3: Analytes and their analytical methods.

Analytes	Analytical method	Reference
Grain size analysis	Wet sieving, gravimetric analysis	
Total recoverable arsenic, cadmium, copper, chromium, nickel, lead, zinc	Air dried at 35°C and sieved, <2mm fraction. Nitric / hydrochloric acid digestion, ICP-MS, trace level.	US EPA 200.2
Total organic carbon (TOC)	Air dried at 35°C and sieved, <2mm fraction. Acid pretreatment to remove carbonates if present, neutralisation, Elementar Combustion Analyser.	
Total phosphorus (TP)	Air dried at 35°C and sieved, <2mm fraction. Nitric / hydrochloric acid digestion, ICP-MS, screen level.	US EPA 200.2
PAHs	Air dried at 35°C and sieved, <2mm fraction. Dried at 103°C for 4-22hr, sonication extraction, SPE cleanup, GC-MS SIM analysis.	US EPA 3540, 3550 & 3630
Semi-volatile organic compounds (SVOCs)	Air dried at 35°C and sieved, <2mm fraction. Sonication extraction, SPE cleanup, GC-MS full scan analysis.	US EPA 3540, 3550, 3640 & 8270

4.4 Statistical Analyses and Plots

Statistical comparisons between sites in this sediment survey were not possible as single samples were analysed at each location. Comparisons between sites are made generally, using tables and with maps produced in ArcMap 10.

Box plots were used to graphically compare differences in contaminant concentrations in the Avon River / Ōtākaro catchment sediments with previous studies in this catchment (Section 6.1) and from other studies in Christchurch and elsewhere (Section 5.5). Box plots were produced in R (Version 2.15.0). A band in the middle of the box indicates the median concentration. Left and right bounds of the box indicate the 25th (lower) and 75th (upper). Whiskers extend to the nearest data points that are within 1.5 times the inter-quartile range (IQR) of the median value. Data points lying outside this range (outliers) are shown as individual points.

Sediment quality in the Avon River / Ōtākaro catchment was investigated in the 1980s (Robb 1988), but there have been no significant studies of sediment quality since that time. The lack of repeated measurements at the same locations precludes the statistical assessment of trends over time, as can be undertaken for water quality attributes that are regularly measured (e.g., at monthly intervals). Furthermore, in both the Robb (1988) survey and the current study, only single samples were analysed at each site and this lack of replication prevents statistical comparisons on a site-by-site basis. Statistical comparisons between the current survey and the previous survey (Robb 1988) are therefore only possible after grouping the data at a 'sub-catchment' level. Sites were pooled into 6 sub-catchments: the north-western tributaries (Okeover Stream to Taylors Drain); Addington Brook & Riccarton Main Drain; Dudley Creek and tributaries; Upper Avon River (headwaters to CBD); Middle Avon River (CBD to u/s Avondale Bridge); and Lower Avon River (Avondale Bridge to mouth). All sites in each sub-catchment that had been measured in each survey were used, even if not sampled in both surveys, which means there is a greater number of samples for the 1980/81 data than the 2013 data. This is not a problem for the statistical analysis as in both surveys sites were designed to represent the entire sub-catchment. A repeated measures analysis of variance (ANOVA) was undertaken in R to assess statistical differences between the years, using years, sub-catchment and mud content of the samples as factors, as well as interaction terms between these factors.

ANOVA was also used to compare between means for the Avon catchment and other locations around Christchurch and elsewhere in New Zealand (undertaken using R). When a significant difference was found ($p < 0.05$), a post-hoc test (Ryan's Q test) was used to examine where these differences were found.

Correlations between individual contaminants and between contaminants and mud content were assessed with Pearson's correlation coefficients, which measure the strength and direction of the relationships between each of the two variables. A correlation coefficient greater than 0.7 is considered strong, whereas as a coefficient less than 0.7 is considered weak.

The total PAHs presented in this report represent the sum of the 16 PAHs analysed, which are the PAHs listed as priority pollutants by the USEPA (1982). Where one or more compounds was below the detection limit, half the detection limit was used in the calculation. This is consistent with the approach used in other Christchurch sediment surveys.

5 What is the Current State of Sediment Quality?

5.1 Sampling Variation and Its Implications

Contaminant concentrations in sediments are naturally variable, particularly stream sediments, due to their heterogeneous nature. Four duplicate samples were collected in the field to assess the variation due to sampling and analysis. As described in Section 4.2, the duplicate consists of two separate samples collected in the same manner at the same site. The duplicates are compared to the ‘primary samples’ in tables and figures in Appendix B.

For the majority of the parameters measured, in most samples, the variation between the primary sample and the duplicate was less than 50%. Total organic carbon (TOC) had relatively high variability in most samples, being over 50% for samples from site 9 and 11. This may be related to the variation in the proportion of mud in these samples which varied by a similar amount and was relatively low at only 3-7% (compared to approximately 50% for site 32).

Overall, the variation was lowest for the metals, being less than 20% for samples 11, 24 and 32 (with the exception of chromium at site 32). There was greater variation in concentration of some metals at site 9, with 30-40% difference between duplicates for cadmium, copper, lead and zinc. This is not due to the difference in texture between the two duplicates (see Section 5.2 for more information on how texture influences metal concentrations), as there was little variation between chromium and nickel concentrations and normalising by the proportion of mud did not reduce the variability.

The contaminant concentrations in three of the samples selected for duplicate analysis were towards the low end of the samples collected from throughout the Avon River / Ōtākaro catchment (see following sections) and one sample was at the middle-to-upper end of the range.

It is likely that the variation seen in the duplicate results is representative of the variation at other sites in the catchment. This means that when interpreting the results in the following sections, a difference of at least 20% for metal and PAH concentrations and 50% for TOC is considered to be a meaningful difference between sites.

5.2 Sediment Texture and Its Implications

Metals and metalloids tend to be preferentially attached to fine particles and are therefore higher in sediments with a greater proportion of these fine particles (silt- and clay-sized). This is clearly seen in samples collected from background locations, such as offshore sediments or estuaries not influenced by urban landuse (see Kingett Mitchell 2003 for a Canterbury example of this). This relationship between contaminants and texture can confound comparisons of sediment quality between sites and between different sampling periods as the samples are also likely to have different proportions of fines.

Figure 5-1 shows the relationship between the percentage of mud and the concentration of phosphorus, arsenic and metals in the sediment samples from the Avon River / Ōtākaro (green points) and the tributaries (purple points). Chromium and nickel show a clear relationship (R >0.7) with the percentage mud in the samples collected (R 0.89 and 0.87

respectively) indicating that any differences observed between sites in the Avon River / Ōtākaro catchment may be purely due to differences in the texture of the samples.

Cadmium, copper, lead and zinc have a weaker relationships (R <0.7) with correlation coefficients between 0.44 and 0.62. Many of the samples with low percent mud appear to have concentrations similar to those with high percent mud, that is, cadmium, copper, lead and zinc concentrations appear to be independent of the amount of mud in the sample. This suggests that differences observed between sites in the Avon River / Ōtākaro catchment are more likely to be due to anthropogenic activities affecting the stream sediments than differences due to texture alone.

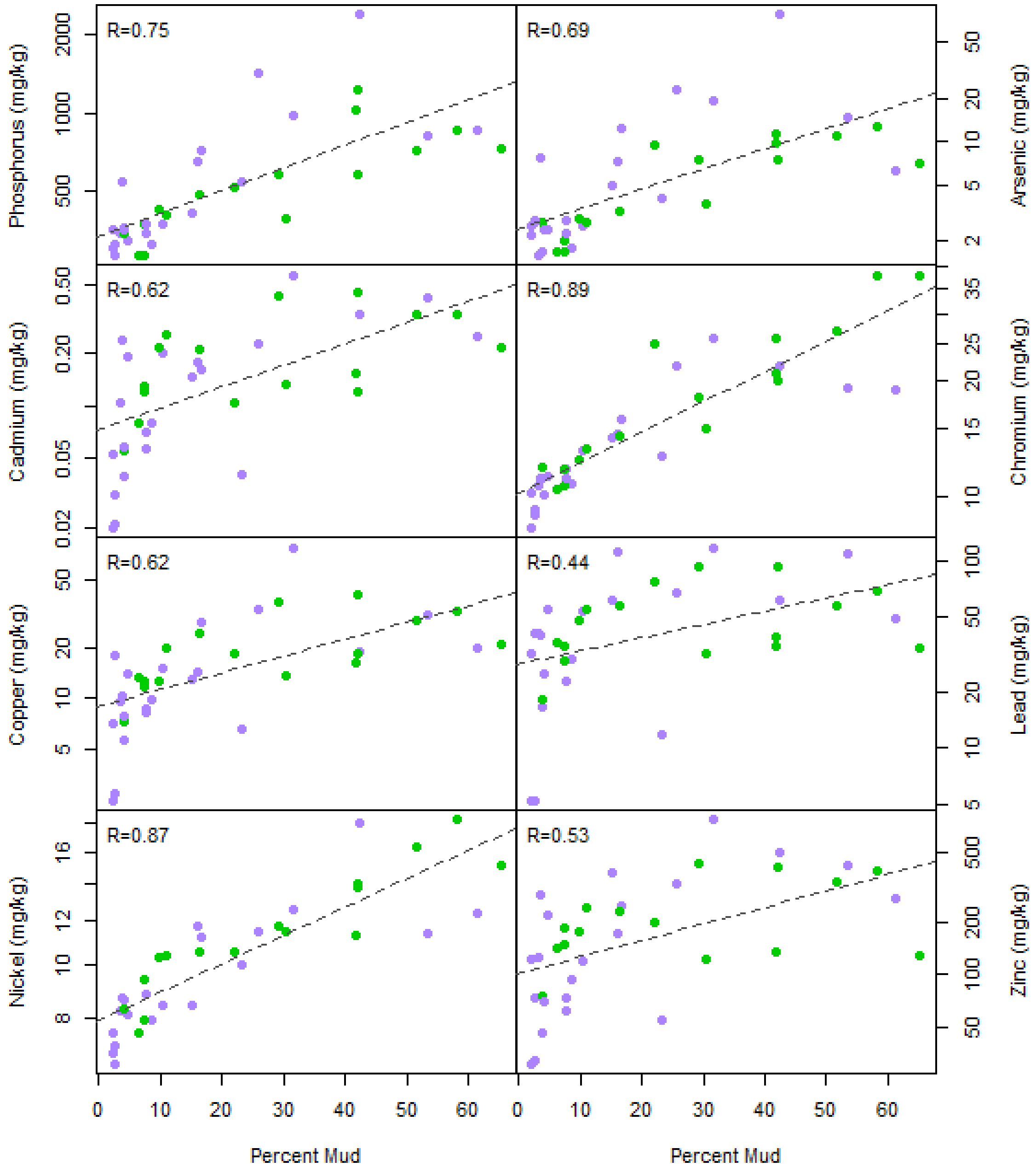

Figure 5-1: Correlations between proportion of mud and metals in sediments. Note: Phosphorus and metals plotted on log scale. Outlier for lead with concentration of 780 mg/kg excluded.

5.3 Sediment Quality in the Catchment

Selected results are presented in Table 5-1 for easy referral for the sections that follow. The full results are presented in Appendix C, including field observations of the stream bed substrate and depth of soft sediments; the texture of sediment samples collected; and the concentrations of individual PAH compounds.

In Table 5-1 coloured data bars are used to signify the relative concentration of each analyte in the samples. The sites are arranged as tributaries from west to east then the Avon River / Ōtākaro mainstem. This table indicates that there are a number of areas with lower concentrations of contaminants and some areas with generally higher concentrations. For example:

- Number Two Drain, in Christchurch Golf Course, has very low concentrations of all contaminants compared to all other sites.
- Addington Brook, Riccarton Main Drain, St Albans Creek, Dudley Creek and at sites in the mid-to-lower Avon River / Ōtākaro have the highest concentrations of metals.

Large variations in the size of the data bars indicate large variation in the concentrations between samples, for example, for mud the percentage ranges from 3 to 65%; and for zinc there is a ~20-fold range from 32 to 770 mg/kg. In contrast chromium and nickel concentrations appear very similar between sites, ranging from 9 to 38 mg/kg and 7 to 18 mg/kg respectively.

High concentrations of arsenic, lead and PAHs are apparent at some sites (relative to the remainder of sites):

- Arsenic measured 78 mg/kg in Addington Brook (site 22 in Hagley Park), and 13-23 mg/kg in Riccarton Main Drain, compared to <10 mg/kg at most other sites.
- Lead measured 780 mg/kg from the Riccarton Main Drain (site 20 at Clarence St, downstream of Riccarton Mall). This was much higher than the next highest measurement of 117 mg/kg, found further upstream in Riccarton Main Drain. Possible causes for the elevated arsenic and lead concentrations at these sites are discussed further in Section 7.
- PAHs measured 506 mg/kg from the downstream Dudley Creek site (site 18 at North Parade). This was much greater than the next highest measurement of 31 mg/kg, in the mid Avon River / Ōtākaro.

As part of quality assurance procedures, the high PAH sample from downstream Dudley Creek was reanalysed by the laboratory to confirm the result (Table 5-2). The sample was also analysed for PAHs as part of the suite of semi-volatile organic compounds (SVOCs). These reanalyses showed that the concentrations were highly variable within the bulk sample collected at the site: the subsamples analysed by the laboratory each returned a substantially different result. The cause of this high result is almost certainly due to coal tar particulate material within the bulk sample, as discussed further in Section 7.5. In subsequent sections and in Figure 5-6, the average of the initial and reanalysed results is used. The SVOC results are not included in the average as this test used slightly different methods and is less robust for PAHs.

Table 5-1: TOC, phosphorus, metals/metalloids, PAHs and mud in the Avon River / Ōtākaro catchment. Note: All data mg/kg except TOC & mud.

Stream	Site No.	Mud (%)	TOC (%)	Phosphorus	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc	Total PAHs
Addington Drain	22	42	1.5	2400	78	0.34	22	19	62	18	500	2.1
Riccarton Main Drain - u/s	19	32	5.3	980	19.5	0.57	26	78	117	13	770	6.4
Riccarton Main Drain - mid	20	17	1.0	720	12.6	0.16	16	28	780	11	250	21.1
Riccarton Main Drain - d/s	21	26	3.3	1420	23.0	0.23	22	34	67	12	330	6.7
Okeover Stream	6	3	0.4	280	2.8	0.03	9	18	41	7	73	2.9
Ilam Stream	4	15	1.9	410	4.9	0.15	14	13	61	8	380	1.1
Waimairi Stream - u/s	1	5	0.9	320	2.4	0.19	11	14	55	8	220	2.3
Waimairi Stream - d/s	2	9	0.7	310	1.8	0.08	11	10	30	8	94	6.2
Wairarapa Stream - u/s	10	2	0.7	350	2.2	0.05	10	7	32	8	122	2.9
Wairarapa Stream - mid	11	7	0.5	345	2.6	0.06	11	8	24	9	72	2.1
Wairarapa Stream - d/s	12	10	1.7	370	2.6	0.20	13	15	54	8	119	14
Wai-iti Stream	8	3	0.6	340	1.6	0.10	11	10	41	8	126	2.5
Taylors Drain	9	5	0.7	365	2.0	0.05	11	7	20	9	54	5.5
St Albans Creek	13	53	5.0	810	14.9	0.42	19	31	108	11	420	31.5
Papanui Stream	23	61	4.8	860	6.3	0.25	19	20	49	12	270	2.7
Dudley Creek - u/s	16	4	0.4	540	7.8	0.24	11	10	40	9	290	8.9
Dudley Creek - d/s	18	16	0.7	650	7.3	0.18	15	14	111	12	172	506
No. 2 Drain	24	2	0.4	305	2.7	0.02	9	3	5	7	32	0.1
Corsers Stream	25	23	1.0	540	4.0	0.04	13	7	12	10	55	0.4
Avon River - headwaters	3	22	2.6	510	9.6	0.10	25	18	77	11	200	1.4
Avon River - upper	5	7	0.7	280	1.7	0.13	11	12	29	8	187	2.1
Avon River - upper	7	6	0.7	280	1.7	0.08	10	13	37	8	143	2.5
Avon River - upper	26	4	0.4	340	2.7	0.06	12	7	18	8	76	10.6
Avon River - upper	27	29	4.7	580	7.4	0.43	18	37	92	12	430	8.7
Avon River - mid	28	8	0.4	370	2.0	0.12	12	13	35	9	149	9.2
Avon River - mid	29	16	1.6	480	3.3	0.21	14	24	57	11	230	15
Avon River - mid	30	11	1.5	400	2.7	0.26	13	20	55	10	240	30.8
Avon River - mid	17	30	1.0	390	3.7	0.13	15	14	32	12	121	3.8
Avon River - mid	31(a)	10	0.8	420	2.9	0.22	12	13	48	10	178	10.2
Avon River - mid	31(b)	53	4.6	580	7.6	0.45	20	41	93	14	410	8.6
Avon River - lower	32	42	4.4	785	11.9	0.34	33	31	64	17	365	7.2
Avon River - lower	33	42	2.5	1020	9.9	0.15	21	16	39	11	136	7.4
Avon River - lower	34	42	2.5	1240	11.5	0.12	26	19	35	14	134	1.7
Avon River - lower	35	65	1.4	730	7.1	0.22	38	21	34	15	128	1.7

Table 5-2: PAHs in sediment from lower Dudley Creek. All data mg/kg.

Compound	Initial result	Reanalysed result	SVOC suite result
Acenaphthene	0.88	0.041	0.28
Acenaphthylene	5.8	0.096	1.26
Anthracene	14	0.26	2.3
Benzo[a]anthracene	28	1.47	10.2
Benzo[a]pyrene (BAP)	27	1.62	9.4
Benzo[b]fluoranthene + Benzo[j]fluoranthene	53	1.93	9.4
Benzo[k]fluoranthene	21	0.83	4.2
Benzo[g,h,i]perylene	27	1.23	5.7
Chrysene	49	1.43	8.2
Dibenzo[a,h]anthracene	3.5	0.32	1.8
Fluoranthene	90	5.3	21
Fluorene	3.4	0.086	1.18
Indeno(1,2,3-c,d)pyrene	20	1.04	4.9
Naphthalene	2.2	0.065	< 0.14
Phenanthrene	73	1.55	14.7
Pyrene	88	4.5	17.4
Sum of PAHs	505.8	21.77	111.9

SVOCs were analysed in five of the 34 samples collected, comprising sites in the Avon River / Ōtākaro from the headwaters to the mouth, and in lower Dudley Creek (Table 5-3). Of the 75 SVOCs included in the suite, only four were detected in addition to PAHs (which were already analysed via a separate method). These four SVOCs were 2-methylnaphthalene, a PAH metabolite that was not included in the previous PAH analysis; bis(2-ethylhexyl)-phthalate, a ubiquitous plasticiser; carbazole and dibenzofuran, both of which are released from combustion of coal, petroleum and wood. All of these compounds are commonly found in environmental sediment samples, though there is little comparative data for New Zealand. In a study in the Netherlands, bis(2-ethylhexyl)phthalate was measured in freshwater sediments at concentrations from <0.015 to 1 mg/kg (Peijnenburg & Struijs 2006); whilst in China concentrations up to 30 mg/kg have been reported (see Chen et al. 2012).

Table 5-3: Semi-volatiles detected in five samples selected for additional analysis . All data mg/kg.

Compound	Avon River headwaters (Site 7)	Avon River u/s CBD (Site 27)	Avon River d/s CBD (Site 30)	Avon River mouth (Site 33)	Lower Dudley Creek (Site 18)
2-methylnaphthalene	< 0.10	< 0.11	0.13	< 0.11	< 0.14
Bis(2-ethylhexyl)phthalate	0.7	3.6	4.5	< 0.9	1.2
Carbazole	< 0.16	< 0.3	0.24	< 0.3	0.9
Dibenzofuran	< 0.16	< 0.3	0.24	< 0.3	0.5

The results are also shown in relation to their location within the catchment in Figures 5-2 to 5-6. The particle size distribution of the samples collected is shown in pie charts indicating the amount of gravel, sand, and mud in the samples (Figure 5-2). This shows a predominance of fine and medium sand in the upper catchment, particularly Waimairi and Wairarapa Streams and their tributaries. Riccarton Main Drain and Addington Brook have greater proportions of both gravel and mud than those tributaries. Papanui and St Albans Streams have a large proportion (50% or more) of mud and fine sand (~30%). The No.2 Drain at Christchurch Golf Course was 95% fine sand, much higher than all other sites in the catchment.

The Avon River / Ōtākaro headwaters had a large proportion of gravel in the sample, which is reflective of the substrate at this site with little fine sediment for collection. Other sites upstream of the CBD are dominated by fine and medium sand whereas downstream of the CBD the proportion of medium sand appears much lower. The lower reaches of the Avon River / Ōtākaro have a greater amount of mud than other sites, reaching a maximum of 65% mud at the stream mouth.

Sediment TOC and phosphorus concentrations are presented in Figure 5-3 and appear to show lower concentrations of TOC in the north-western tributaries (Okeover Stream, Waimairi Stream, Wairarapa Stream and its tributaries), Dudley Creek, the No.2 Drain and Corsers Stream. There are several sites where TOC is much higher than others: Papanui Stream, St Albans Stream, Riccarton Main Drain, Avon River / Ōtākaro near Curators House; Avon River / Ōtākaro at Morris Street and Avon River / Ōtākaro at Avondale Bridge. There is no clear pattern in the concentrations in the Avon River / Ōtākaro mainstem.

Compared to other sites sediment concentrations of phosphorus were also lower in the north-western tributaries, Dudley Creek, the No.2 Drain and Corsers Stream and in the Avon River / Ōtākaro headwaters. The highest concentration was at Addington Brook and concentrations were also higher than average throughout Riccarton Main Drain, and highest at the most downstream site in Hagley Park. Phosphorus concentrations in the lower and tidal reaches of the Avon River / Ōtākaro were approximately double those measured in the middle and upper reaches.

For lead, copper, cadmium and zinc (Figure 5-4), highest concentrations were measured in Riccarton Main Drain and Addington Brook. Lead was very high in the middle site of Riccarton Main Drain, measuring 780 mg/kg. The concentrations upstream and downstream in this waterway were much lower, at 117 and 67 mg/kg respectively suggesting there may be a localised source at this site. Dudley Creek, and its tributaries Papanui and St Albans Streams, also appeared to have higher concentrations of lead, copper, cadmium and zinc compared to many other sites in the Avon River / Ōtākaro catchment (Figure 5-4). Lowest concentrations of these four metals were measured in the tributaries to the north-west, i.e., Wai-iti, Wairarapa, Waimairi Streams and Taylors Drain. For the Avon River / Ōtākaro mainstem, lead, cadmium and zinc concentrations appear generally highest in the middle reach, from near the Curators House to Avondale Bridge. In the lower, tidal reach, these metal concentrations appear lower than further upstream.

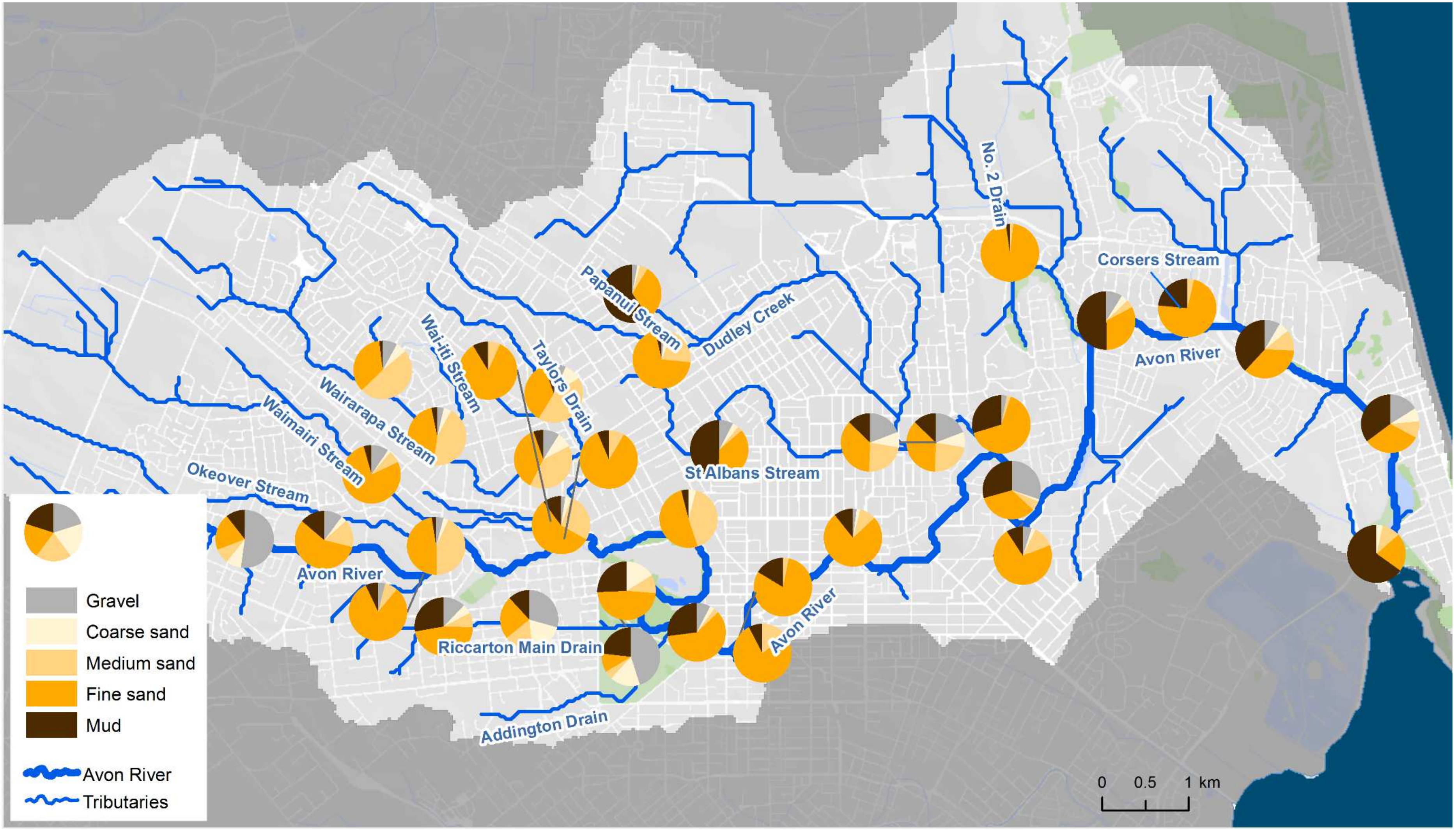

Figure 5-2: Distribution of particle sizes in samples collected from each site in the Avon River / Ōtākaro Catchment.

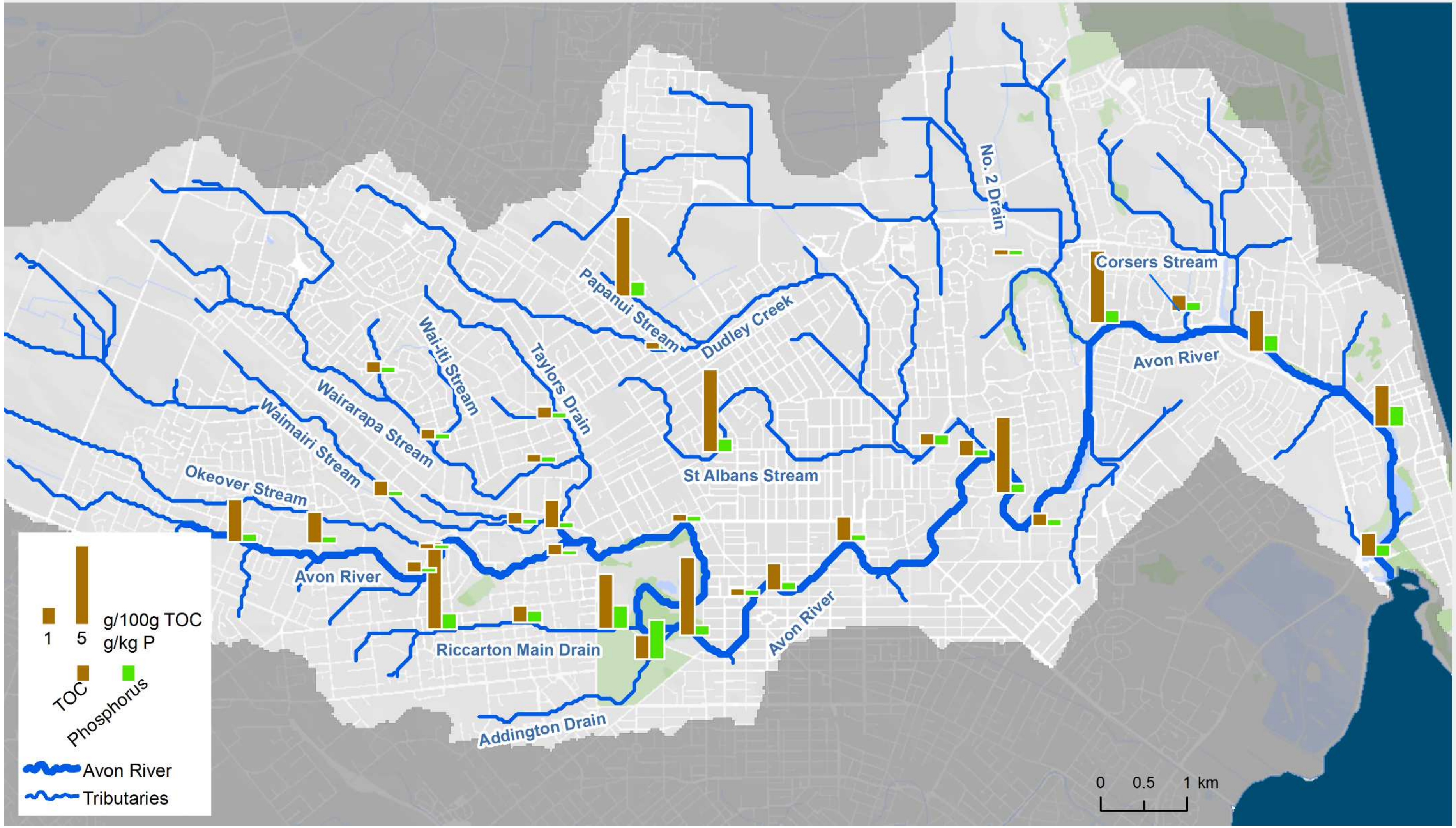

Figure 5-3: TOC and phosphorus at each site in the Avon River / Ōtākaro Catchment. Note: Units for TOC and phosphorus differ to ensure both are visible on this map.

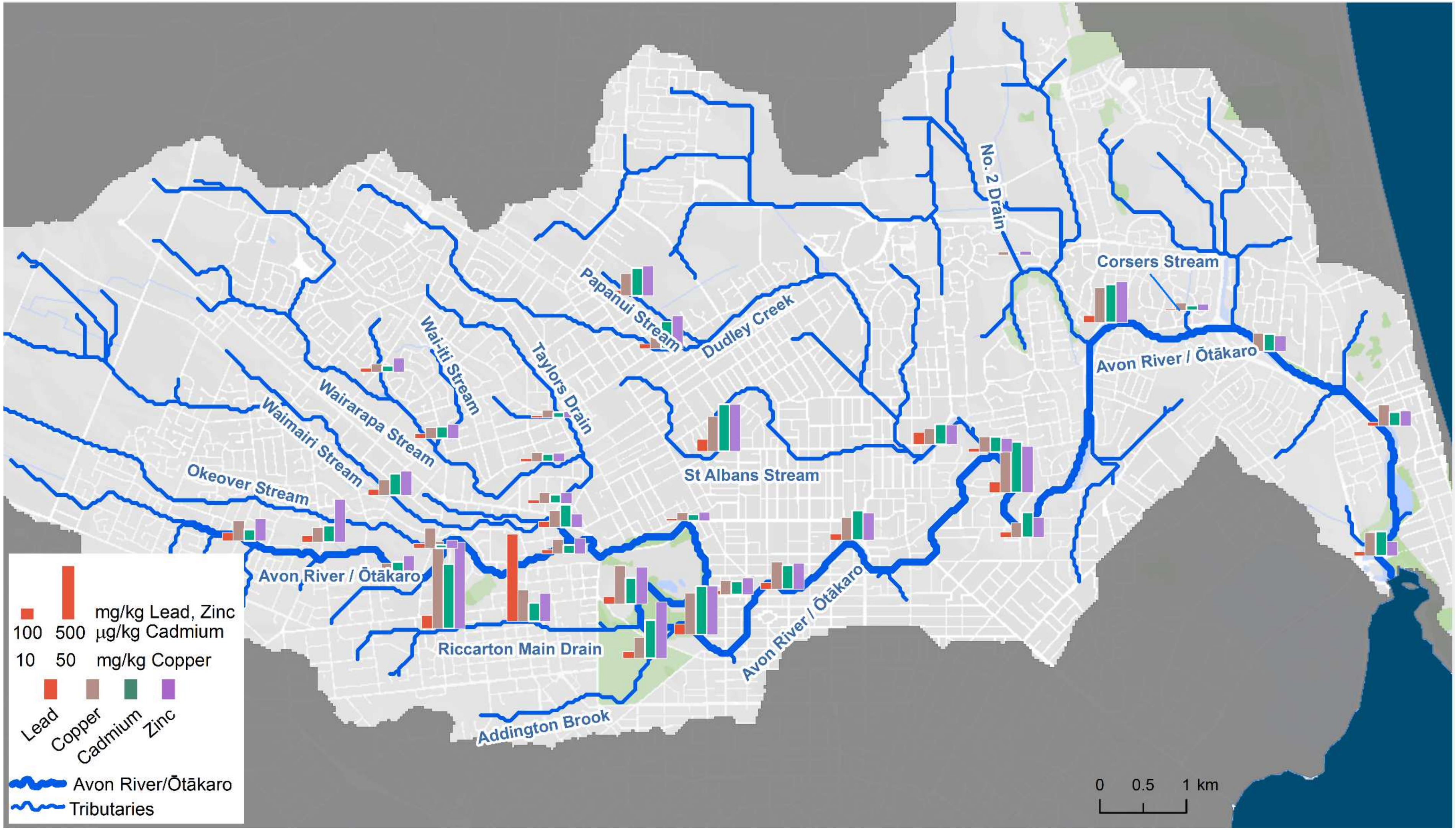

Figure 5-4: Lead, copper, cadmium and zinc at each site in the Avon River / Ōtākaro Catchment. Note different scales and units for copper and cadmium, scaled to allow visibility on map.

Arsenic, nickel and chromium concentrations at each site are all shown in Figure 5-5. Similar to the other metals measured, the concentrations of arsenic, nickel and chromium were highest in Riccarton Main Drain, Addington Brook, Papanui Stream and St Albans Stream; and at sites in the middle and lower reaches of the Avon River / Ōtākaro, though there were some exceptions to this in the mainstem. For the Avon River / Ōtākaro, higher values in the lower reaches may be partly due to the texture of these samples, which had a much greater proportion of mud compared to upstream sites. The relationship between metals and texture is described in Section 5.2. As with TOC and phosphorus, concentrations of these elements were much lower in the north-western tributaries, Dudley Creek, the No.2 Drain and Corsers Stream compared to most other tributaries. As with phosphorus and the other metals, the upper reaches of the Avon River / Ōtākaro (excluding the headwaters site), north-western tributaries, the No.2 Drain and Corsers Stream also had relatively low concentrations compared to most other sites.

Sediment concentrations of metals/metalloids were generally in the order cadmium < arsenic < nickel < copper < chromium < lead < zinc. However there were a few sites where this differed, for example in the upper Riccarton Main Drain site, copper concentrations were elevated compared to the other metals, measuring 78 mg/kg.

Total PAHs at each site are presented in Figure 5-6 and indicate a wide variation in concentrations across the catchment. The highest concentration was measured in lower Dudley Creek: an average of 264 mg/kg from measurements of 506 and 22 mg/kg. This average is substantially higher than further upstream in Dudley Creek (9 mg/kg) or in the tributaries of Papanui Stream (2.7 mg/kg) or St Albans Stream (32 mg/kg). Probable sources of elevated PAHs in stream sediments are discussed in Section 7.5.

The spatial distribution of the PAHs has some similarities with the trace elements and other parameters previously discussed. Like the other parameters, total PAH concentrations were low in the No.2 Drain and Corsers Stream, in some of the north east tributaries and Avon River / Ōtākaro headwaters. However, unlike the pattern for other parameters, there were some relatively high concentrations of PAHs in the lower reaches of Wairarapa and Waimairi Streams, near the confluence with the Avon River / Ōtākaro. Total PAHs were low in Addington Brook, whereas other parameters were at moderate to high concentrations here. Similar to lead, cadmium and zinc, PAHs in the Avon River / Ōtākaro mainstem were highest in the middle reaches and generally a bit lower in the lower, tidal reaches, particularly near the mouth.

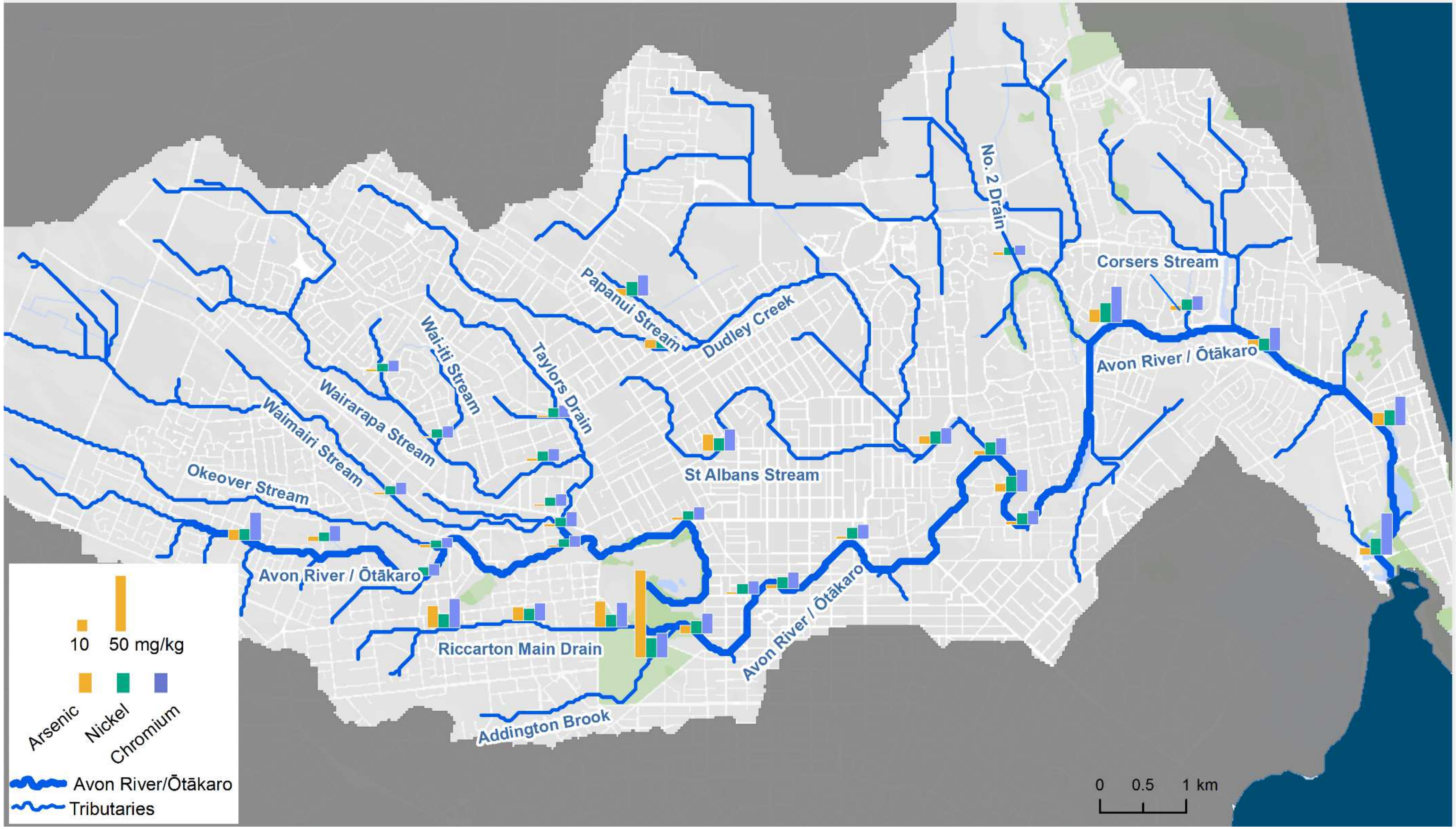

Figure 5-5: Arsenic, nickel and chromium at each site in the Avon River / Ōtākaro Catchment.

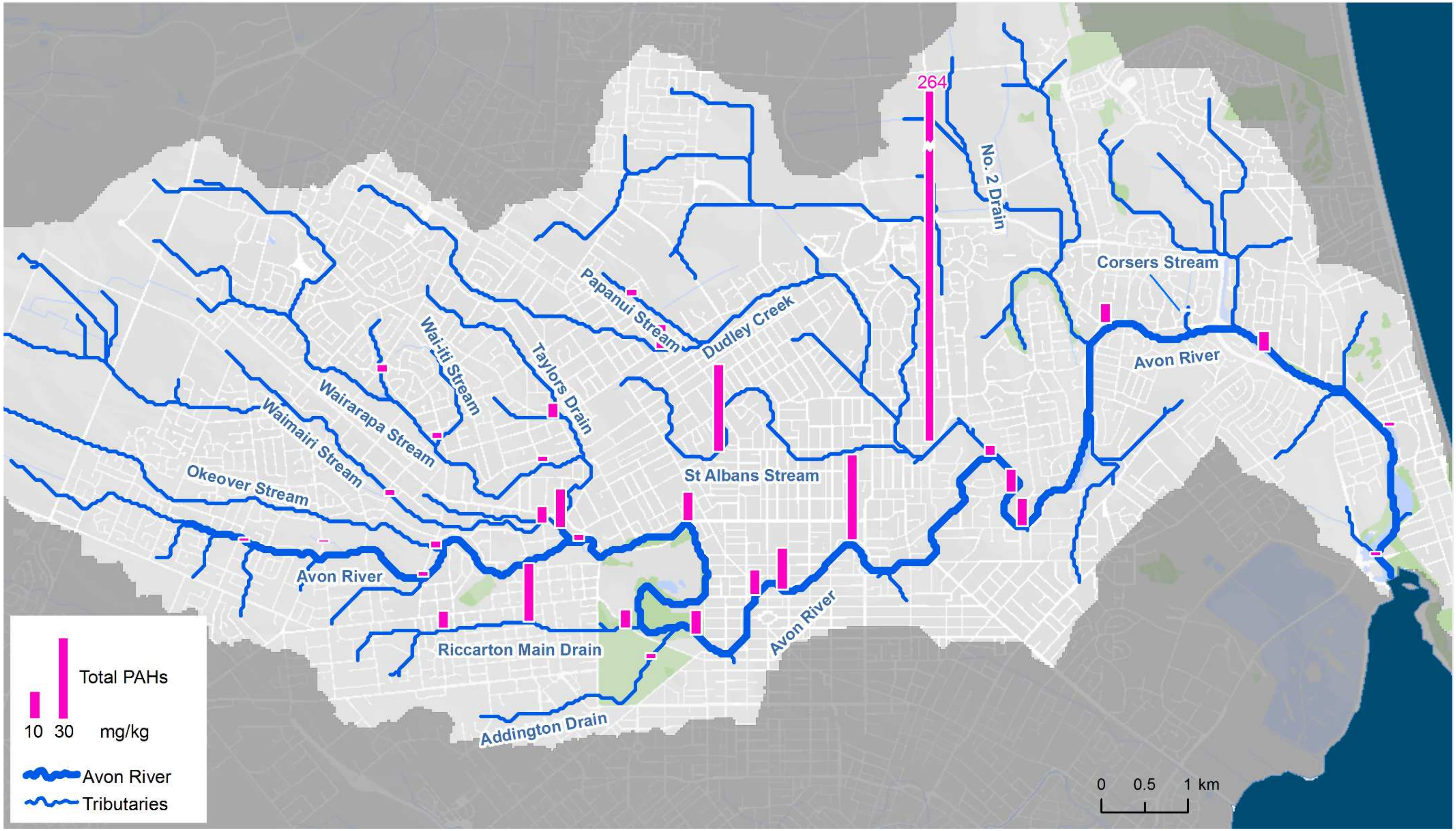

Figure 5-6: Total PAHs in the Avon River / Ōtākaro Catchment sediments. Note break in bar for Dudley Creek sample which measured average of 264 mg/kg. Concentrations at No.2 drain and Corsers Stream are too low to be visible on the map.

5.4 Current State Compared to Guidelines

The ANZECC (2000) guidelines are the most commonly used in New Zealand for evaluating sediment quality. Trigger values are provided for metals, metalloids, and PAHs for comparison to measured concentrations in sediments. If the sediment concentration is below the trigger value (Interim sediment quality guideline – low) it is unlikely that there will be any effect on biota in the sediment. If the trigger value, or the ISQG-high is exceeded, then further studies should be carried out, including checking background concentrations and toxicity studies, to examine whether effects are likely.

The trigger values are compared to the results for the Avon River / Ōtākaro catchment in Table 5-4. This shows that the main contaminants of concern are zinc, lead and PAHs. Zinc and lead exceeded the ISQG-low at 15 of 35 sites (11 sites where lead and zinc both exceeded the ISQG-low). Of these 15 sites, 1 site (20, in middle reach of Riccarton Main Drain) exceeded the ISQG-high value of 220 mg/kg, measuring 780 mg/kg. Five sites exceeded the zinc ISQG-high value of 410 mg/kg, indicating that zinc is potentially the highest priority ‘’contaminant of concern’ with respect to sediment quality in the Avon River / Ōtākaro catchment.

PAHs also exceeded the current ISQG-low value of 4 mg/kg at 15 sites (many of which were different sites to those that exceeded lead and zinc trigger values), and at site 18 in the lower Dudley Creek, the PAHs exceeded the high value of 40 mg/kg (based on the average concentration measured). However, the reanalysis of this sample (22 mg/kg cf 563 mg/kg) showed that the contaminated particulates were distributed heterogeneously throughout this sediment.

Despite often being an issue in other catchments, copper concentrations were below the ISQG-low value of 65 mg/kg at 34 of the 35 sites. There were two sites (21 in Riccarton Main Drain and 22 in Addington Brook) where arsenic concentrations in the sediments exceeded the ISQG-low. Arsenic concentrations in Addington Brook sediments also exceeded the ISQG-high value of 70 mg/kg, measuring 78 mg/kg. There were no sites where cadmium, chromium or nickel concentrations in the sediment exceeded the respective trigger values.

The ANZECC guidelines are currently being reviewed and updated. Simpson et al. (2010) have proposed a number of changes to the sediment quality guidelines, including a new emphasis on considering a greater number of lines of evidence (LOE) such as toxicity testing and ecological assessments, in addition to comparisons to chemistry trigger values. These changes are not relevant to this report, as it covers sediment chemistry only. However, there are a number of proposed changes to the trigger values which are of relevance to this report. No changes are proposed for the metals / metalloids measured in the sediments in this study but there is a proposed change to PAHs. The proposed guideline revisions suggest removing trigger values for individual PAHs and comparing total PAHs only; or using the equilibrium sediment benchmark (ESB) approach when substituted PAHs have also been measured (not relevant for this study). The proposed trigger value for total PAHs has been revised from 4 mg/kg (normalised to 1% organic carbon) to 10 mg/kg; and the ISQG-high from 45 mg/kg to 50 mg/kg, based on modelling of the toxicity of PAHs (Di Toro & McGrath 2000).

Table 5-4: Comparison of metals and metalloids in sediment (mg/kg) to sediment quality guidelines. Yellow shading indicates ISQG-low exceedance, pink indicates ISQG-high exceedance.

Site No.	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc	Total PAHs *	Total PAHs *
ISQG-Low	20	1.5	80	65	50	21	200	4	10
ISQG-High	70	10	370	270	220	52	410	45	50
1	2.4	0.193	11.3	13.9	55	8.1	220	2.4	2.4
2	1.8	0.079	10.8	9.8	30	7.9	94	8.6	8.6
3	9.6	0.104	25.0	18.3	77	10.5	200	0.5	0.5
4	4.9	0.147	14.2	13.1	61	8.4	380	0.6	0.6
5	1.7	0.130	10.7	11.8	29	7.9	187	3.1	3.1
6	2.8	0.031	9.2	17.8	41	6.6	73	8.1	8.1
7	1.7	0.080	10.4	13.2	37	7.5	143	3.7	3.7
8	1.6	0.104	10.7	9.6	41	8.2	126	4	4
9	2.0	0.048	11.2	7.0	20	8.6	54	7.7	7.7
10	2.2	0.053	10.2	7.1	32	7.5	122	4.1	4.1
11	2.6	0.064	11.0	8.2	24	8.7	72	4.3	4.3
12	2.6	0.200	13.2	14.9	54	8.4	119	8.1	8.1
13	14.9	0.420	19.3	31.0	108	11.4	420	6.3	6.3
16	7.8	0.240	11.2	10.4	40	8.7	290	21.7	21.7
17	3.7	0.134	15.0	13.6	32	11.5	121	3.8	3.8
18	7.3	0.181	14.5	14.2	111	11.7	172	693	693
19	19.5	0.570	26.0	78.0	117	12.6	770	1.2	1.2
20	12.6	0.163	15.9	28.0	780	11.2	250	20.9	20.9
21	23.0	0.230	22.0	34.0	67	11.5	330	2	2
22	78.0	0.340	22.0	18.9	62	18.1	500	1.4	1.4
23	6.3	0.250	19.0	20.0	49	12.4	270	0.6	0.6
24	2.7	0.021	8.6	2.6	5	7.0	32	0.3	0.3
25	4.0	0.040	12.7	6.6	12	10.0	55	0.4	0.4
26	2.7	0.055	11.9	7.3	18	8.3	76	24.1	24.1
27	7.4	0.430	18.1	37.0	92	11.7	430	1.9	1.9
28	2.0	0.120	11.8	12.7	35	9.4	149	20.9	20.9
29	3.3	0.210	14.4	24.0	57	10.5	230	9.4	9.4
30	2.7	0.260	13.3	19.9	55	10.4	240	21.1	21.1
31.1	2.9	0.220	12.4	12.8	48	10.3	178	13.2	13.2
31.2	7.6	0.450	20.0	41.0	93	13.8	410	1.9	1.9
32	11.9	0.340	32.5	31.0	64	17.4	365	1.6	1.6
33	9.9	0.153	21.0	16.1	39	11.3	136	3	3
34	11.5	0.122	26.0	18.6	35	14.0	134	0.7	0.7
35	7.1	0.220	38.0	21.0	34	15.1	128	1.2	1.2

Note: Total PAHs have been normalised to 1% TOC as recommended in the ANZECC guidelines.

When the proposed revised ANZECC trigger value for total PAHs of 10 mg/kg is used, there were only 7 sites (compared to 15) where the sediment concentrations were in excess. Sites in the Wairarapa Stream and its tributaries would not exceed the proposed trigger value. The site in Dudley Creek would also exceed the proposed ISQG-high of 50 mg/kg.

The major stormwater metals copper, lead and zinc and PAHs at each site are compared to the ISQG-low trigger values in Figure 5-7. This geographically shows that many of the exceedances are in the following tributaries:

- Riccarton Main Drain
- Addington Brook
- Dudley Creek and its tributaries
- St Albans Stream
- Papanui Stream.

For the Avon River / Ōtākaro mainstem, the majority of exceedances were located in the middle section of the Avon River / Ōtākaro, downstream of the CBD but upstream of Avondale Bridge. At the very top of the catchment, there were exceedances of trigger values in Okeover Stream, Ilam Stream and the headwaters of the Avon River / Ōtākaro. The ISQG-high for metals was exceeded in the Riccarton Main Drain, Addington Brook, St Albans Stream and in the Avon River / Ōtākaro at the site just downstream of Addington Brook.

Copper, lead and zinc are below the ISQG-low in the Wairarapa Stream and its tributaries Waimairi and Wai-iti Streams; in the Avon River / Ōtākaro headwaters to CBD (with one exception); and in the lower reaches of the Avon River / Ōtākaro, from Avondale Bridge to the mouth. There were however some exceedances of the current PAH trigger value in the Wairarapa Stream and its tributaries. Consistent with the metals, for PAHs there were no sites in the lower Avon River / Ōtākaro that exceeded the ISQG-low trigger value.

The comparison of sediment quality to trigger values is summarised in Table 5-5 and shows that at over two-thirds of the sites in the catchment, at least one of the trigger values was exceeded. The implications of this are that elevated concentrations of multiple contaminants are widely distributed throughout the Avon River / Ōtākaro catchment. This does not necessarily imply that there will be adverse effects on biota, but should trigger further monitoring and investigations.

Table 5-5: Summary of the exceedance of trigger values in the Avon River / Ōtākaro catchment.

	Total number of sites (%)	Individual site numbers
No exceedance of any trigger value	9 (26%)	5, 7, 8, 17,24, 25, 33, 34, 35
Exceeds 1 trigger value	6 (18%)	2, 6, 9, 10, 11, 23
Exceeds 2 trigger values	10 (29%)	1, 3, 4,12, 26, 27, 28, 31.1, 31.2, 32
Exceeds 3 trigger values	7 (21%)	13, 16, 18, 19, 21, 22, 29
Exceeds 4 trigger values	2 (6%)	20, 30

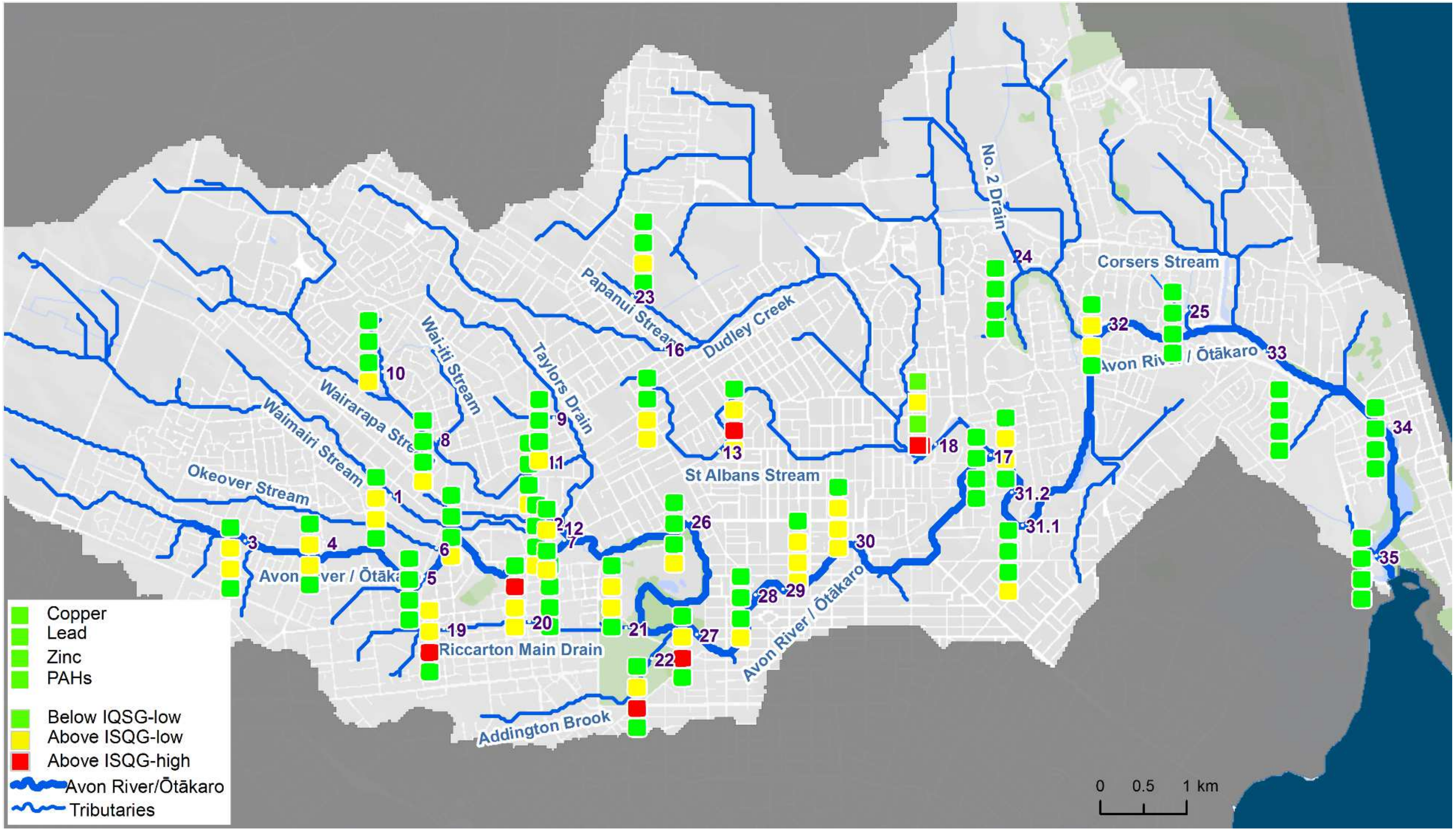

Figure 5-7: Exceedance of revised sediment quality guidelines by metals and total PAHs. Sites numbered (see Table 4-2 for key). Boxes at each site from top to the bottom represent copper, lead, zinc and PAHs. Traffic lights are green when below ISQG-low, yellow if above ISQG-low and red if above ISQG-high.

5.5 Current State of Avon Catchment Compared to Elsewhere in Christchurch or NZ

Metal concentrations in the sediments from the Avon River / Ōtākaro catchment are generally within the range previously measured in urban stream sediments from elsewhere in Christchurch (i.e., Heathcote, Halswell, Haytons and Styx River catchments), around Canterbury and around New Zealand. This is shown in Figures 5-8 to 5-11, along with a comparison to the ANZECC (2000) sediment quality guidelines (background colour) to provide context to the measured concentrations. An ANOVA was used to compare between the means of these groups. When a significant difference was found ($p < 0.05$), a post-hoc test (Ryan's Q test) was used to examine where these differences were.

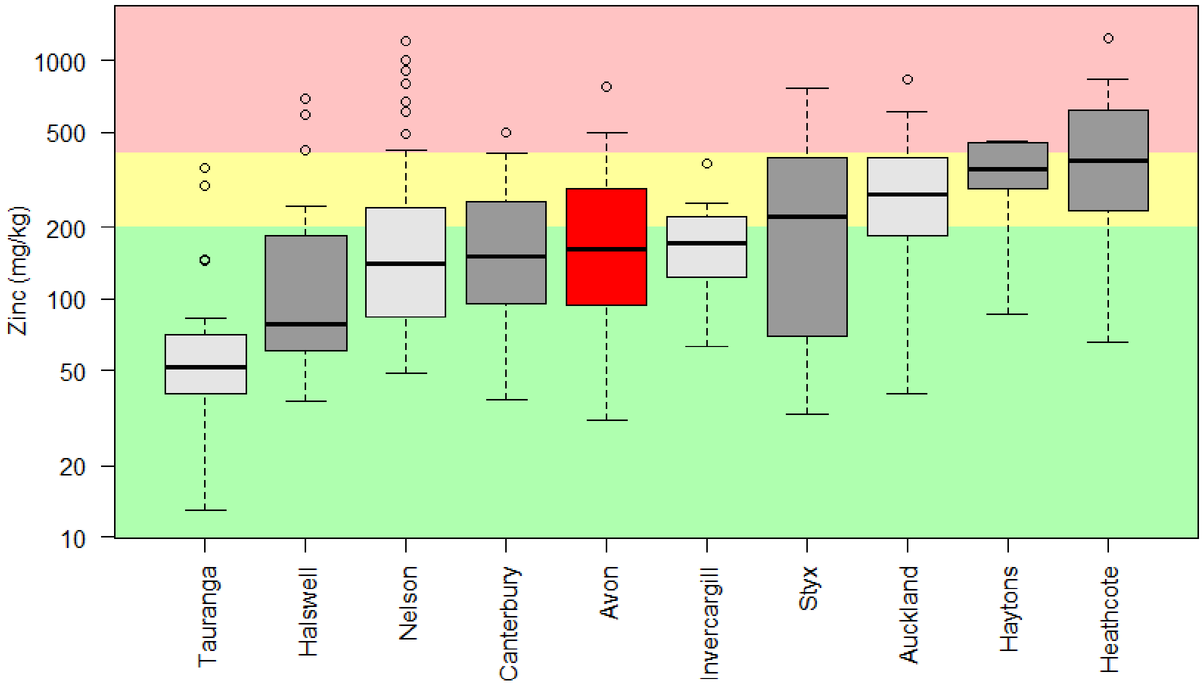

Figure 5-8: Zinc in the Avon catchment sediments compared to other locations around Canterbury (darker grey) and New Zealand (light grey). Note: Plotted on log10 scale on y-axis. Colours in background represent the sediment quality guidelines (green is below ISQG-low; yellow is above ISQG-low; pink is above ISQG-high).

Zinc, copper and lead concentrations in the Avon River / Ōtākaro catchment appear lower than those measured in Heathcote River, but this difference was significant only for zinc (p-value ≤0.05 using Ryan's Q test). Zinc, copper and lead concentrations in the Avon River / Ōtākaro catchment appear higher than those from Halswell River catchments but these differences were not statistically significant. Zinc concentrations in the Avon River / Ōtākaro catchment were similar to those for the regional survey and the Styx River and appear somewhat lower than those in the Haytons Stream survey, but were not statistically significantly different. Copper concentrations in the Avon River / Ōtākaro catchment were similar to those for the regional survey, Styx River and the Haytons Stream survey (no significant differences). Lead concentrations in the Avon River / Ōtākaro catchment appear slightly higher than (but were not statistically different to) those for the regional survey, the Styx River and the Haytons Stream survey, all three of which showed very similar median concentrations.

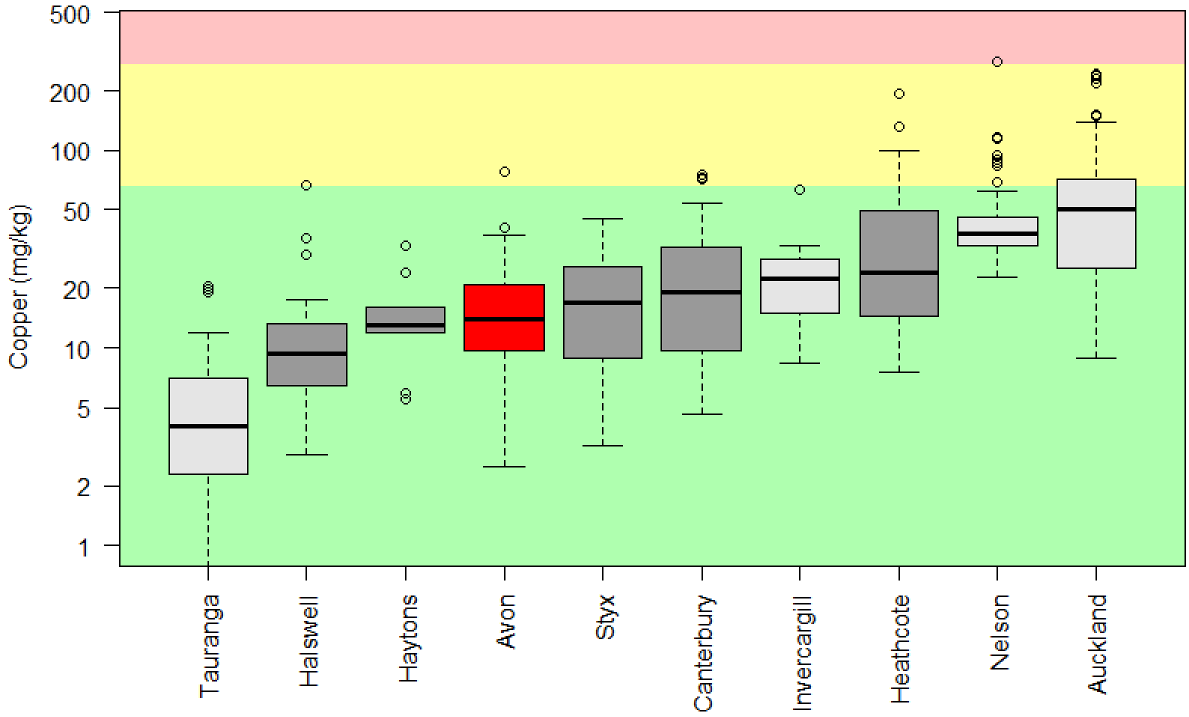

Figure 5-9: Copper in the Avon catchment sediments compared to other locations around Canterbury (darker grey) and New Zealand (light grey). Note: Plotted on log10 scale on y-axis. Colours in background represent the sediment quality guidelines (green is below ISQG-low; yellow is above ISQG-low; pink is above ISQG-high).

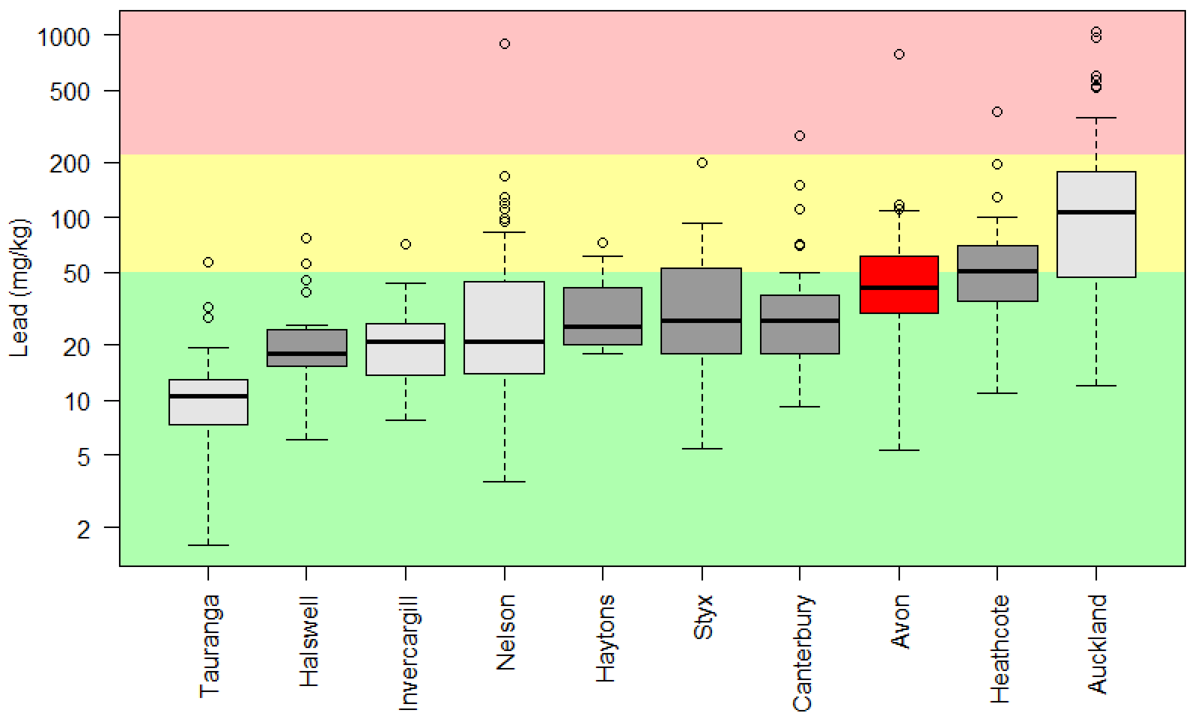

Figure 5-10:Lead in the Avon catchment sediments compared to other locations around Canterbury (darker grey) and New Zealand (light grey). Note: Plotted on log10 scale on y-axis. Colours in background represent the sediment quality guidelines (green is below ISQG-low; yellow is above ISQG-low; pink is above ISQG-high).

Zinc, copper and lead concentrations in the Avon River / Ōtākaro catchment appear lower than those measured in Auckland urban streams, and this was a significant difference for copper and lead (p-value ≤0.05 using Ryan's Q test). The Auckland urban streams contained the highest copper and lead concentrations of all locations for which data was available. Copper concentrations in the Avon River / Ōtākaro catchment sediments were also significantly lower than those in stream sediments from Nelson.

Arsenic, cadmium, chromium and nickel have been measured at fewer locations (Figure 5-11) than the main metals copper, lead and zinc. Although the median concentrations in the Avon River / Ōtākaro catchment sediments are lower than most other locations, the spread of data for all locations is such that there are no significant differences between the metal concentrations here and at other locations, with the exception of chromium and nickel concentrations in Invercargill, which were significantly higher.

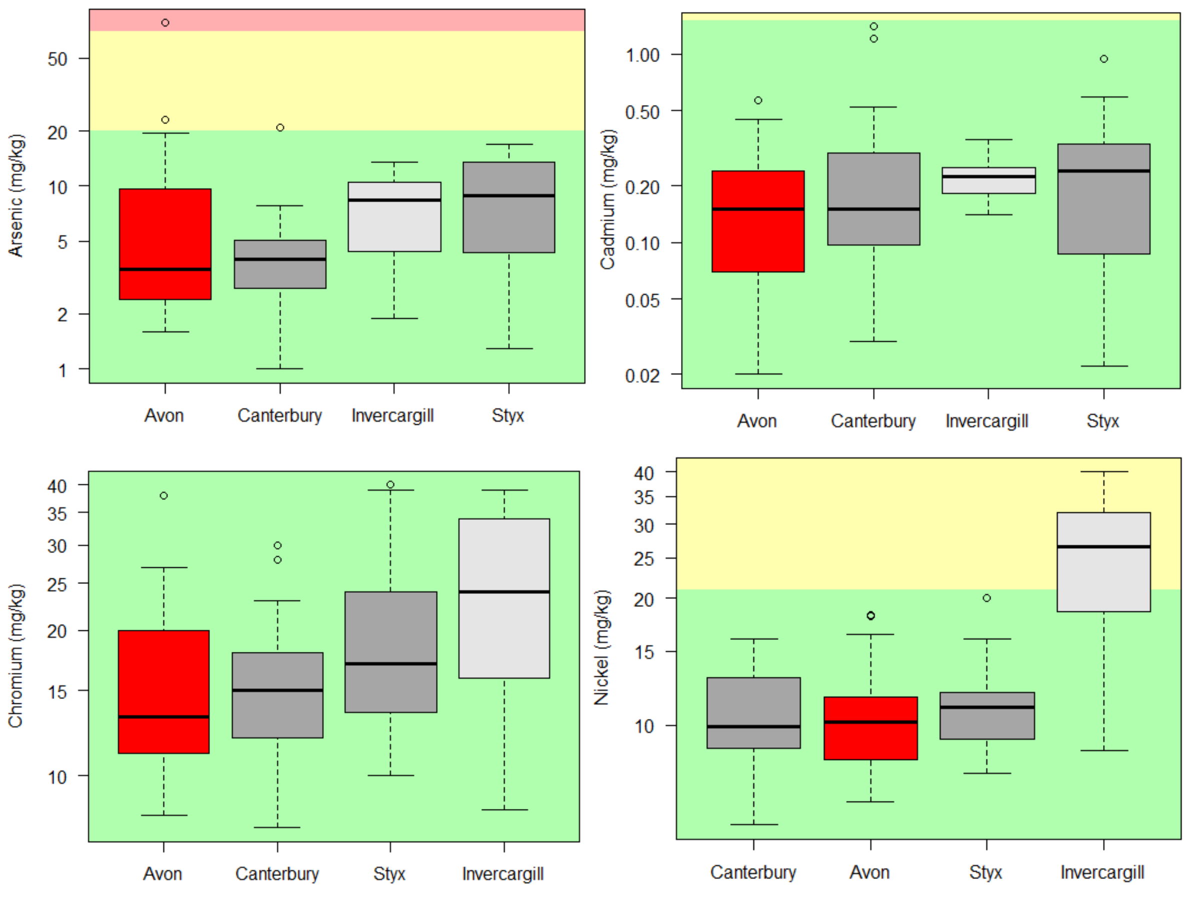

Figure 5-11:Arsenic, cadmium, chromium and nickel in the Avon catchment sediments compared to other locations around Canterbury (darker grey) and New Zealand (light grey). Note: Plotted on log10 scale on y-axis. Colours in background represent the sediment quality guidelines (green is below ISQG-low; yellow is above ISQG-low; pink is above ISQG-high).

PAHs have been measured in all the recent studies of Christchurch and Canterbury urban streams, but have been measured at fewer other locations in New Zealand (Figure 5-12). The concentrations in the Avon River / Ōtākaro catchment sediments are higher than all other locations around Christchurch and about the same as those in Auckland, where coal tar has also been used in roading material.

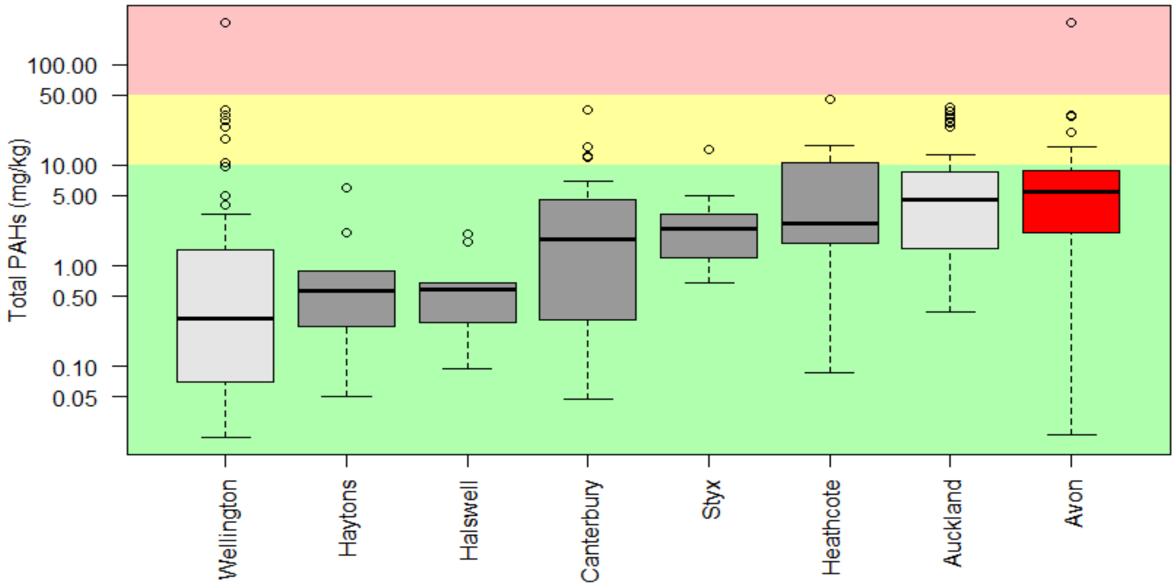

Figure 5-12:PAHs in the Avon catchment sediments compared to other locations around Canterbury (darker grey) and New Zealand (light grey). Note: Plotted on log10 scale on y-axis.

6 Has the Sediment Quality Changed Over Time?

6.1 Metals

Possible changes in the concentrations of metals within the stream sediments are of importance to stormwater managers, as increasing concentrations over time would result in a greater number of sites where metals exceed guidelines in the future. On that basis, stormwater management should be considered to reduce inputs and steady any increase. Conversely, decreasing concentrations over time indicate less requirement for management intervention. As described in Section 4.4, trend analysis is not possible for the stream sediment quality due to a lack of repeated measurements (e.g., at monthly intervals) at the same locations.

Sediment quality in the Avon River / Ōtākaro catchment was comprehensively investigated by the Christchurch Drainage Board in the 1980s (Robb 1988), with sampling at 89 sites from the headwaters to the mouth and numerous tributaries. That study measured similar contaminants as this present study excluding arsenic and PAHs, and used similar methods for sample pretreatment and digestion for the metals (i.e., sieving to < 2 mm and strong acid digestion). Of the 34 sites measured in this current study, all but three were located at or near to sites previously measured by Christchurch Drainage Board (Robb 1988). However, in both the Robb (1988) survey and the current study, only single samples were analysed at each site. This lack of replication prevents any statistical comparisons on a site-by-site basis.

To enable a statistical comparison of the two rounds of sampling, the sites have been pooled into 6 sub-catchments as used in Table 3-1: the north-western tributaries (Okeover Stream to Taylors Drain); Addington Brook & Riccarton Main Drain; Dudley Creek and tributaries; Upper Avon River (headwaters to CBD); Middle Avon River (CBD to u/s Avondale Bridge); and Lower Avon River (Avondale Bridge to mouth). A repeated measures ANOVA was undertaken in R to assess statistical differences between the years, using years, sub-catchment, the mud content and the interaction between these as factors (described in more detail in Section 4.4).

Figure 6-1 and Figure 6-2 compare the metal concentrations in each sub-catchment from the 1980/81 survey and 2013. Because differences in the grain size of the samples collected can result in differences in metal concentrations between samples (as explained in Section 5.2) the difference in the mud content between the collected samples for each survey is also compared (Figure 6-3). This figure shows that samples collected in the north-western tributaries, the Upper Avon River and the middle Avon River generally had less mud in 2013 than in 1980/81; whereas samples collected in the other sub-catchments had much more mud. These differences in mud content could mask differences in the metal concentrations between sampling periods.

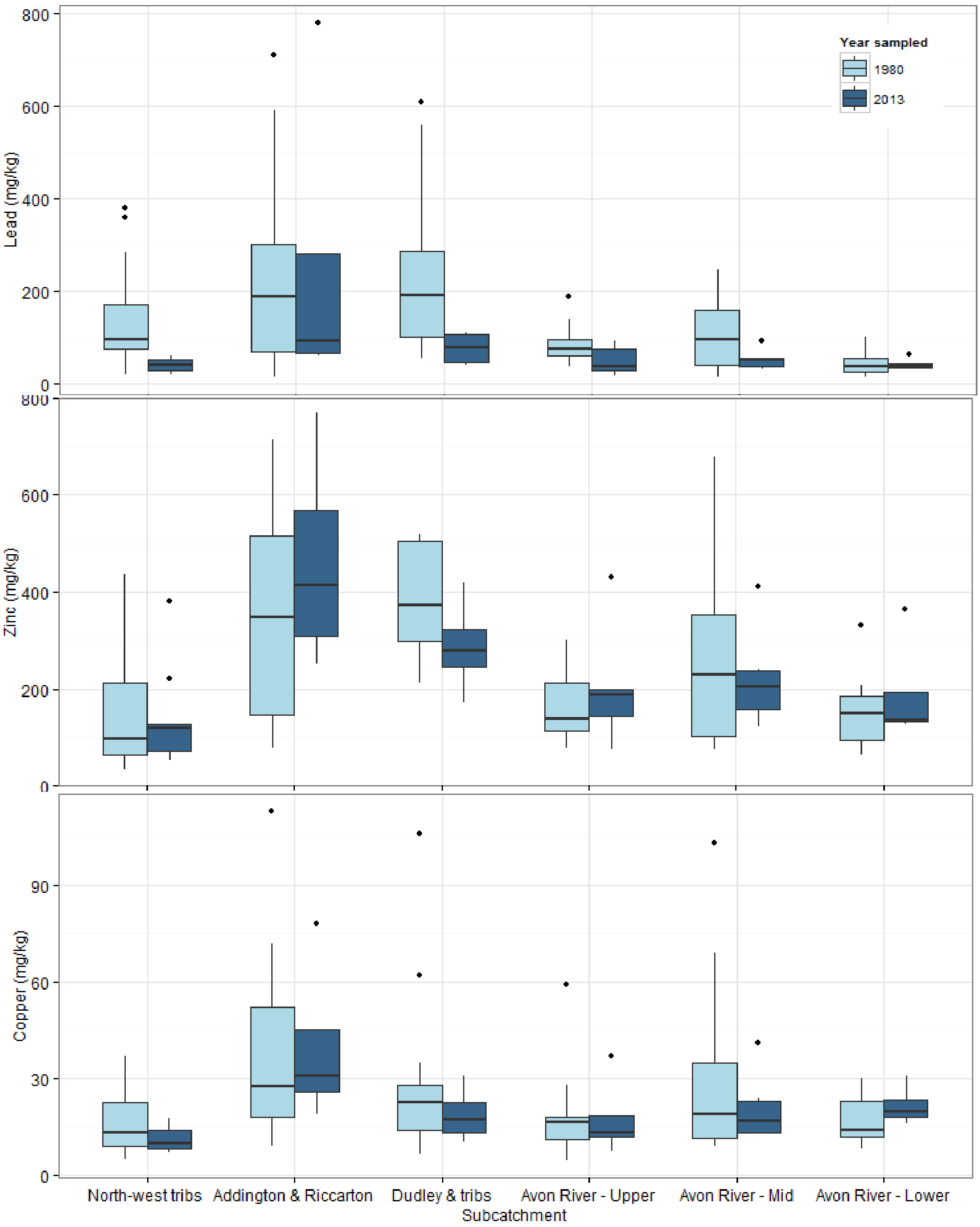

Figure 6-1: Comparison of lead, zinc and copper concentrations in each subcatchment in 1981 and 2013. Excludes outlier for zinc of 1500 mg/kg in Dudley subcatchment in 1980/81.

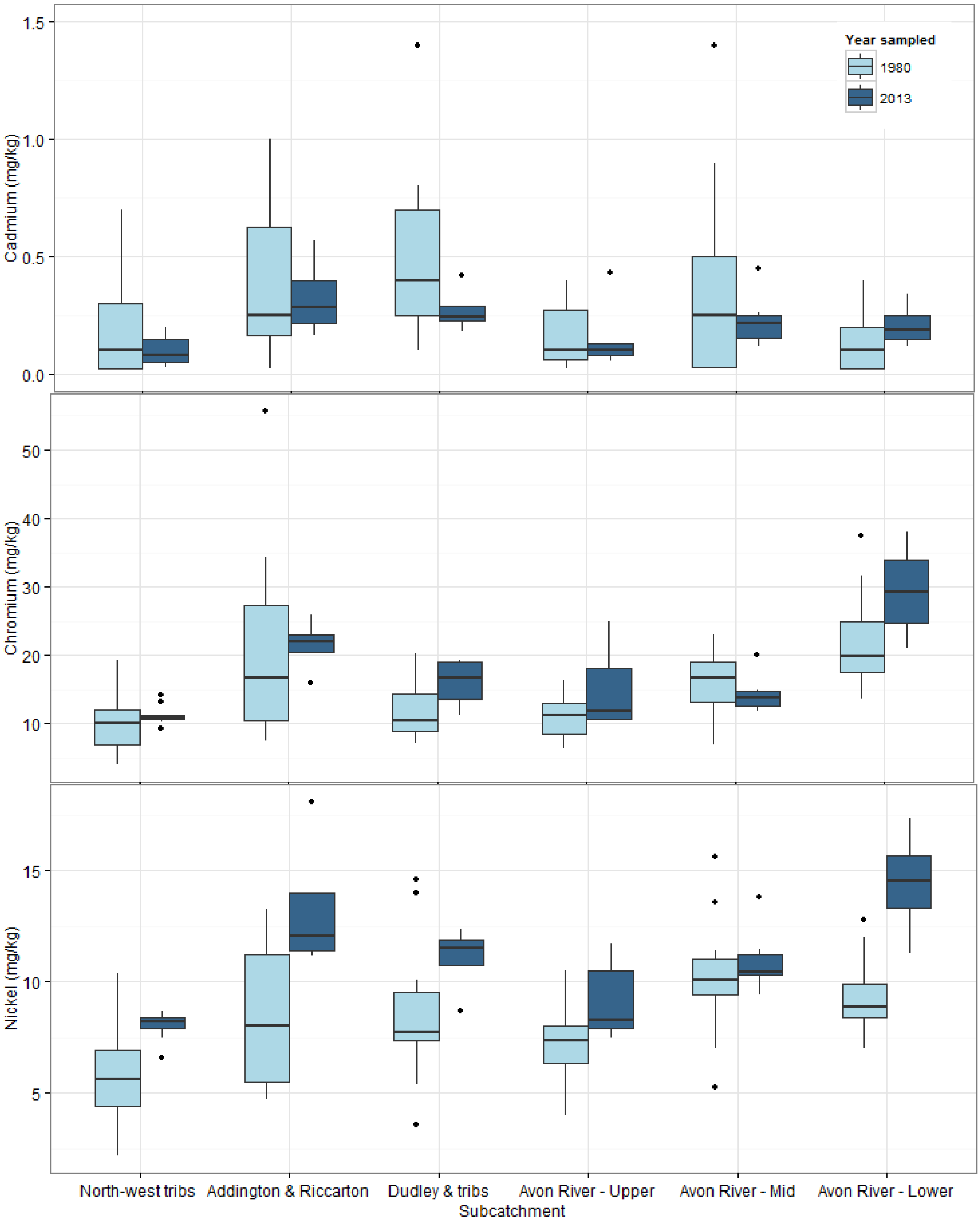

Figure 6-2: Comparison of cadmium, chromium and nickel concentrations in each subcatchment in 1981 and 2013. Excludes outliers in 1980/81 for cadmium of 4 mg/kg in Dudley subcatchment and 6.5 mg/kg in north-west tributaries.

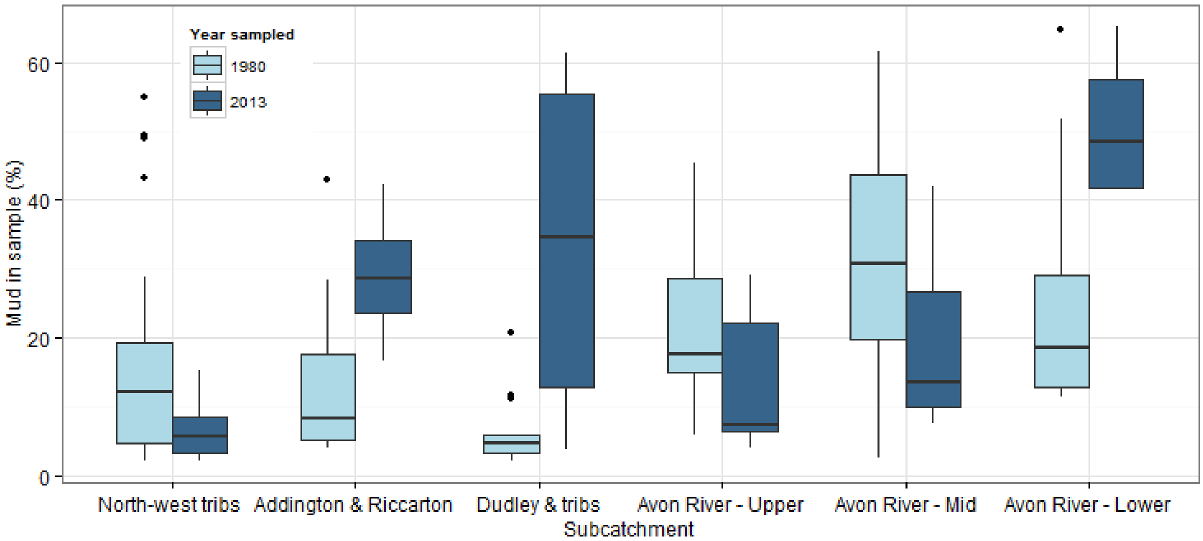

Figure 6-3: Comparison of mud content of samples from each subcatchment in 1981 and 2013.

For lead, the concentrations are lower in 2013 in all sub-catchments, though there is considerable variation in the lead concentrations in the Addington & Riccarton sub-catchment in 2013 compared to other sub-catchments. The ANOVA indicated that there was a significant difference in the lead concentrations between sub-catchments (p-value < 0.001) and importantly, between the two surveys (p-value < 0.05). This is expected, as the major source of lead to urban stream sediments (lead additives in petrol) was removed in the period between these two surveys.

For zinc (Figure 6-1) the median concentrations are higher in 2013 in three sub-catchments, but lower in 2013 for the other three sub-catchments. There was a statistically significant difference in the zinc concentrations between sub-catchments (p-value < 0.001) but not between years (p-value > 0.05). There was also a statistically significant difference in the zinc concentrations due to the mud content of samples (p-value < 0.05) indicating that mud content does influence the zinc concentrations.

For copper (Figure 6-1) the median concentrations appear slightly lower in 2013 in four sub-catchments, and slightly higher in the remaining two. As for zinc, there was a statistically significant difference in the copper concentrations between sub-catchments (p-value < 0.005) but not between years (p-value > 0.05). There was also a statistically significant difference in the copper concentrations due to the mud content of samples (p-value < 0.05).

Cadmium concentrations (Figure 6-2) showed a similar pattern to copper concentrations with the median concentrations slightly lower or similar in 2013 in four sub-catchments, and slightly higher in the remaining two. There were no statistically significant differences in the cadmium concentrations between sub-catchments or years or the mud content of samples (p-value > 0.05).

For both chromium and nickel (Figure 6-2), the median concentrations were higher in all sub-catchments in 2013 compared to 1980/81, with the exception of chromium in the middle Avon River. There was a statistically significant difference between years for the nickel concentrations (p-value < 0.001) and a weaker, but still significant difference, for the chromium concentrations (p-value < 0.05). For both metals, there were statistically significant differences in the concentrations between sub-catchments (p-value < 0.001) and due to the mud content of samples (p-value < 0.001). For chromium concentrations, there was also a significant difference in the interaction term for sub-catchment and mud content of samples (p-value < 0.001).

To summarise the differences between the two surveys: lead concentrations were significantly lower in 2013 compared to 1980/81; whilst chromium and nickel concentrations were significantly higher; and copper and zinc concentrations were not significantly different, but were influenced by differences in the mud content of the samples, which also changed between surveys and catchments. Previously zinc concentrations have been noted as higher in recent surveys compared to the 1980/81 survey, at least within the Heathcote and Styx catchments (Kingett Mitchell 2003; Golder 2009). Elsewhere in New Zealand, increases in zinc concentrations in sediments due to stormwater have been identified as a significant issue (Williamson & Mills 2009). The discrepancy between these studies and the current Avon River / Ōtākaro catchment survey, and the importance of identifying any changes over time, warranted further investigation of the data, as described below.

To counteract grain size differences and make samples directly comparable, the metal concentrations in each sample can be divided by the proportion of mud for that sample (Birch 2003). Figure 6-4 compares the 1980/81 and 2013 sediment zinc and copper concentrations, normalised by proportion of mud. For a standard proportion of mud, both metals were higher in 2013 than in 1980/81 in the north-west of the catchment and in the upper and mid Avon River / Ōtākaro. In the other tributaries and in the lower Avon River / Ōtākaro mud-normalised copper and zinc were lower in 2013 than in 1980/81. This shows that fine sediments in the upper catchment have a greater amount of metal for a given amount of mud; i.e., these sediments are becoming enriched with metals. Over time this may result in increases in the overall metal concentrations in the sediments as a whole. Whilst overall metals concentrations do not currently exceed sediment quality guidelines at these sites, this may be due more to the hydraulics and geomorphology of these tributaries rather than a lack of metal sources. The north-west tributaries and Avon River headwaters are generally steeper with more riffle/run sections than the other tributaries, and therefore may have greater capacity to flush sediments downstream and into the lower Avon River.

The lower concentrations of mud-normalised metals in Addington Brook, Riccarton Main Drain and Dudley Creek (and its tributaries) suggest there may have been a reduction in the sources of metals in these catchments or alternatively an increase in ‘clean’ fine particulates entering the stream. However, the overall metal concentrations are of most importance and given that there are many sites in these waterways where metals still exceed sediment quality guidelines, there is much room for improvement in the quality of the sediment here.

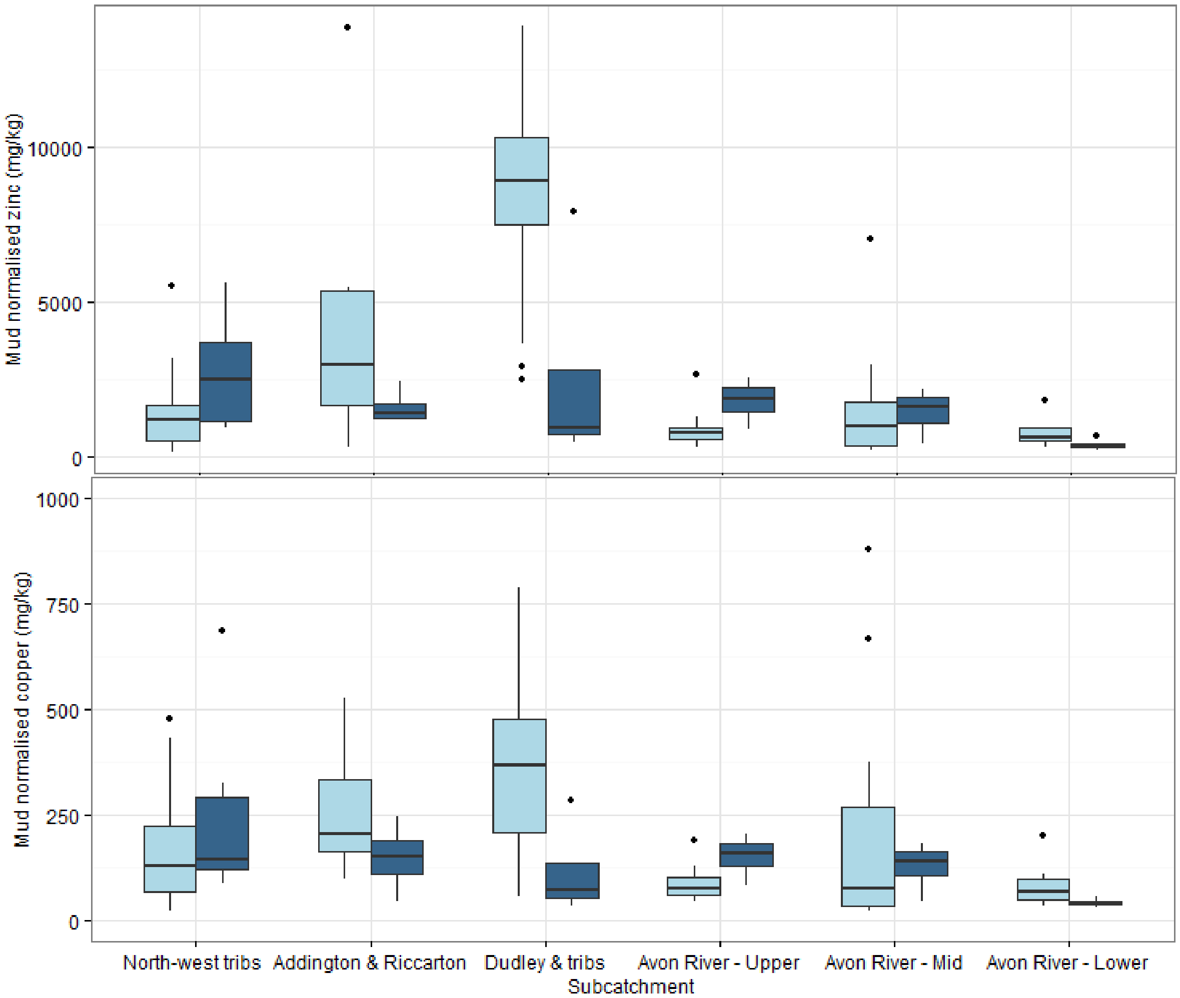

Figure 6-4: Comparison of mud-normalised zinc and copper concentrations from each subcatchment in 1981 and 2013. Note three outliers for copper are not shown: ~2900 in Addington & Riccartion sub-catchment; 2400 and 1900 in Dudley sub-catchment.

6.2 PAHs

PAHs were measured in sediments from 8 locations in the Avon River / Ōtākaro by Lee (1982) as part of a PhD thesis. A different suite of PAH compounds was analysed in that survey, only 7 of which are the same as the current survey. These results are compared in Table 6-1 and indicate that at most sites the PAHs were similar in 1982 than in 2013. However, with only eight sites, and differences in sampling and analytical methodology, it cannot be said whether there has been a change in PAHs in the Avon River / Ōtākaro catchment. To investigate whether PAHs are changing over time, monitoring of PAHs should be undertaken again in 5 to 10 years time, at the same sites and using the same analytical methods as this current survey.

Table 6-1: Comparison of PAH concentrations at sites in the Avon River catchment.

		1982 results (Lee 1982)		2013 results (this study)	
2013 Site No.	**Site**	**Total PAHs measured**	**Sum of 7 PAHs**	**Sum of 7 PAHs**	**Total PAHs measured**
3	Source - Nortons Rd	1.9	0.9	0.8	1.4
6	Okeover Stream	5.0	3.1	1.4	2.9
7	Straven Rd	2.3	1.5	1.3	2.5
36	Harper Ave	3.7	2.4	5.6	10.6
27	Antigua St	15.0	8.8	4.6	8.7
30	Fitzgerald Ave	22.1	13.4	17.3	30.8
31.1 / 31.2	Gloucester St North	33.9	20.7	5.0-5.6	8.6-10.2
34	Owles Terrace	2.8	1.9	1.0	1.7

7 What are the Main Influences on Sediment Quality of the Avon River Catchment?

7.1 Are the Contaminants Correlated?

Correlations between contaminants in the sediment samples can indicate common sources, which can assist stormwater managers in their catchment planning. If sources are the same, stormwater mitigation methods may be applied to reduce inputs of several contaminants at once. Correlations between different metals/metalloids in the sediment samples are examined in Figure 7-1. The top right of the plot shows scatter plots for each variable against each other, as indicated at the start of the row and bottom of the column. The bottom left of the plot shows correlation coefficients, with a value close to 1 representing a high positive correlation between the two variables indicated at the top of the column and the right of the row. An outlier for lead of 780 mg/kg (found in Riccarton Main Drain at Clarence St, downstream of Riccarton Mall) was excluded from this plot.

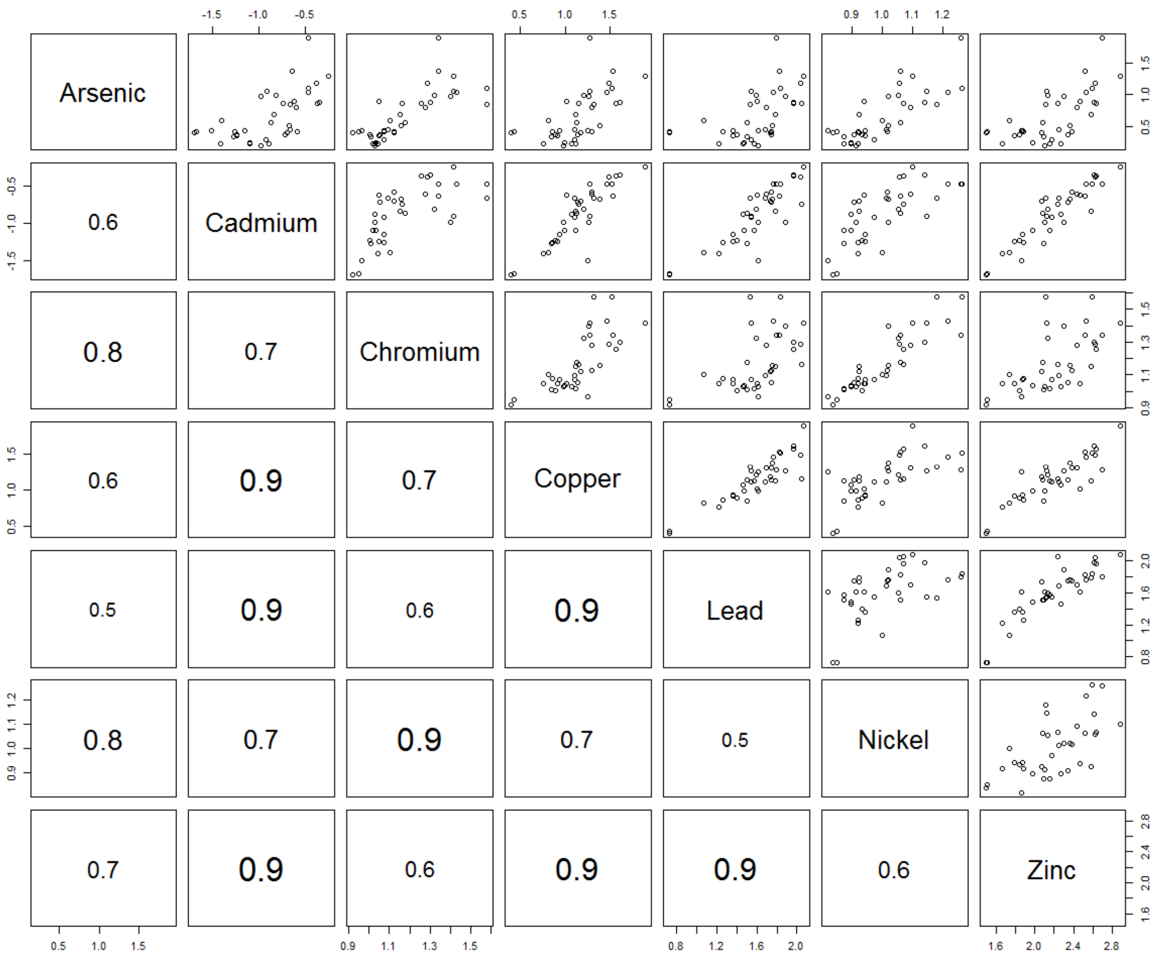

Figure 7-1: Correlations between metals in sediments. Note: Named variable at left of each row of scatter plots is y-axis. Named variable at bottom of each column of scatter plots is x-axis. All metals plotted on log10 scale. Correlation coefficients are presented in lower left side of matrix. Font size for correlation coefficient indicates strength of relationship. Excludes lead outlier of 780 mg/kg.

The plot indicates clear relationships between cadmium, copper, lead and zinc, with each pair having a correlation coefficient of 0.9. Chromium and nickel are closely related to each other (correlation coefficient 0.9) and have a slightly weaker relationship to arsenic (correlation coefficient 0.8), but have weaker relationships to the other four metals (0.7 or less). This suggests that the sources of cadmium, copper, lead and zinc may be the same, whereas arsenic, chromium and nickel may be from an alternative source (or several alternative sources).

The plot also reveals some outliers and extreme values that were not immediately apparent in the earlier figures. There are two values with low copper concentrations (seen at the bottom left of the scatter plots for copper) which also have low concentrations of lead, zinc and cadmium compared to the other sites. These values are both from site 24, the No.2 drain in Christchurch Golf Course, where duplicate samples were collected.

A similar correlation plot was constructed for the PAHs (not shown) and this indicated that all PAHs were very closely correlated, with coefficients of 0.9-1.0. The one exception to this was naphthalene, which was below the detection limit in 18 out of 38 samples measured (this includes duplicates).

The correlations between TOC, phosphorus, selected metals/metalloids and PAHs are examined in Figure 7-2. Pyrene is used as an indicator PAH to represent the relationship with all PAHs (as they are all closely correlated). Similarly, lead is included in this plot and also represents the relationship with cadmium, copper and zinc; and chromium represents nickel. TOC is closely correlated with chromium (and therefore nickel), and weakly correlated with the other parameters except pyrene (correlation coefficient of 0.2). In fact, pyrene is not correlated to any parameters (all 0.2) except lead, where there is a weak relationship of 0.7. The relationship of pyrene with other metals was investigated (not shown here) and was weaker for cadmium, copper and zinc at 0.6, 0.5 and 0.5. Phosphorus has a strong correlation with arsenic, a slightly weaker relationship with chromium (0.7) and only a very weak relationship with lead (0.5). Figure 7-2 also reveals some apparent outliers in the data that were not apparent earlier. There is a high value of 2400 mg/kg for phosphorus measured at site 22, Addington Brook in Hagley Park. Possible causes for this are discussed further in Section 7.

In summary, this analysis suggests that the source (or sources) of cadmium, copper, lead, and zinc may be the same, and that this source is different from that for organic carbon, phosphorus, arsenic, chromium, nickel and PAHs.

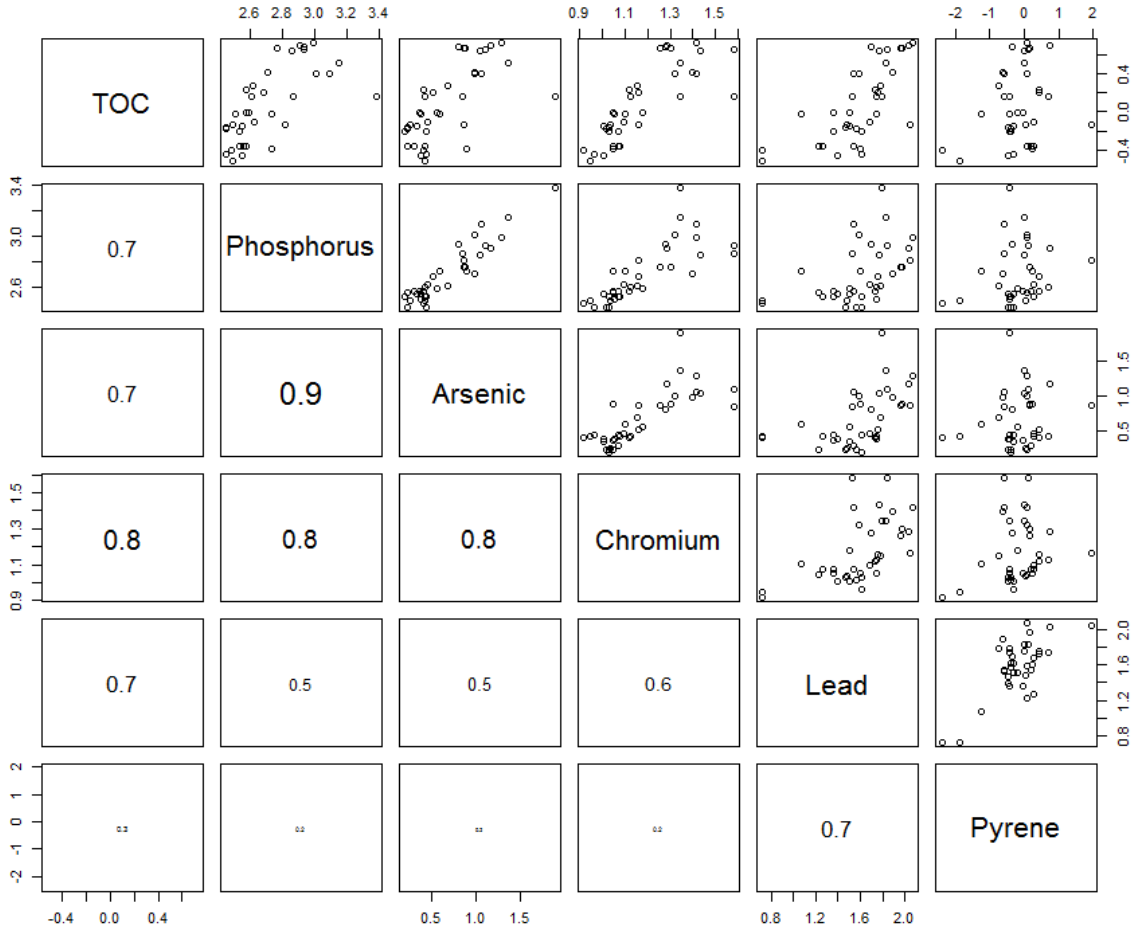

Figure 7-2: Correlations between selected contaminants in sediments. Note: Named variable at left of each row of scatter plots is y-axis. Named variable at bottom of each column of scatter plots is x-axis. All metals plotted on log10 scale. Correlation coefficients are presented in lower left side of matrix. Font size for correlation coefficient indicates strength of relationship (minimum 0.2 in this case). Excludes lead outlier of 780 mg/kg.

7.2 Catchment Soils

Previous studies of sediment contaminants in the Christchurch waterways have compared the concentration of contaminants to ‘background concentrations’ in soils, based on a study by Tonkin and Taylor (2007). The level 1 concentration is the maximum concentration found in the soils sampled. This is useful only as a rough comparison as sediments below the level 1 concentration (Table 7-1) are not necessarily ‘background’ sediment concentrations, in terms of being unaffected by urban runoff. Christchurch soils had considerably higher concentrations of lead and zinc than soils collected outside of the urban centre, for the same soil type (Tonkin & Taylor 2007). This is expected as all the soils are affected by atmospheric deposition which can be expected to have higher concentrations of lead and zinc in Christchurch than outside the city.

Table 7-1: Background concentrations of trace elements in Christchurch urban soils.

	Soil concentrations (mg/kg)						
Soil type	**As**	**Cd**	**Cr**	**Cu**	**Pb**	**Ni**	**Zn**
Level 1							
Gley	10.6	0.2	18.5	23.3	34.9	15.6	138
Organic	13.2	0.11	12.4	13.3	40.9	11.7	63.3
Recent	15.3	0.2	19.0	17.7	101	16.6	149
Saline Gley Recent	7.5	0.06	22.1	10.2	31.2	14.1	87.7
Yellow Brown Sand	5.6	0.1	15.4	8.8	22.3	11.7	54.9

For the majority of the Avon River / Ōtākaro catchment, that is, from the headwaters to Avondale, the soils are predominantly recent, with some small patches of gley and organic (Figure 7-3). The eastern part of the catchment from Avondale downstream including the tributaries of No.2 Drain and Corsers Stream are dominated by yellow brown sand. The soil type in the catchment of Riccarton Main Drain and Addington Brook is predominantly gley.

Figure 7-5 and Figure 7-4 compare the contaminant concentrations in sediments to the level 1 soil concentrations for recent, gley and yellow brown sand, as these are the dominant soil types in the various subcatchments. This shows numerous sites (13-18) where cadmium, copper and zinc concentrations in the sediments are higher than the soils suggesting that these metals are influenced by other factors, which are discussed in the sections that follow.

Apart from some outliers, arsenic, chromium, lead and nickel concentrations in the sediments are very similar to soil concentrations. This suggests that these metals (and metalloids) may be predominantly derived from soils. As mentioned, lead concentrations are much higher in the Christchurch soils than in soils outside the urban area. This is likely to be due to the historical use of lead as a fuel additive, as it accumulated in roadside soils. Although lead is no longer in fuel, it appears that these contaminated soils are now the primary source of lead in the catchment.

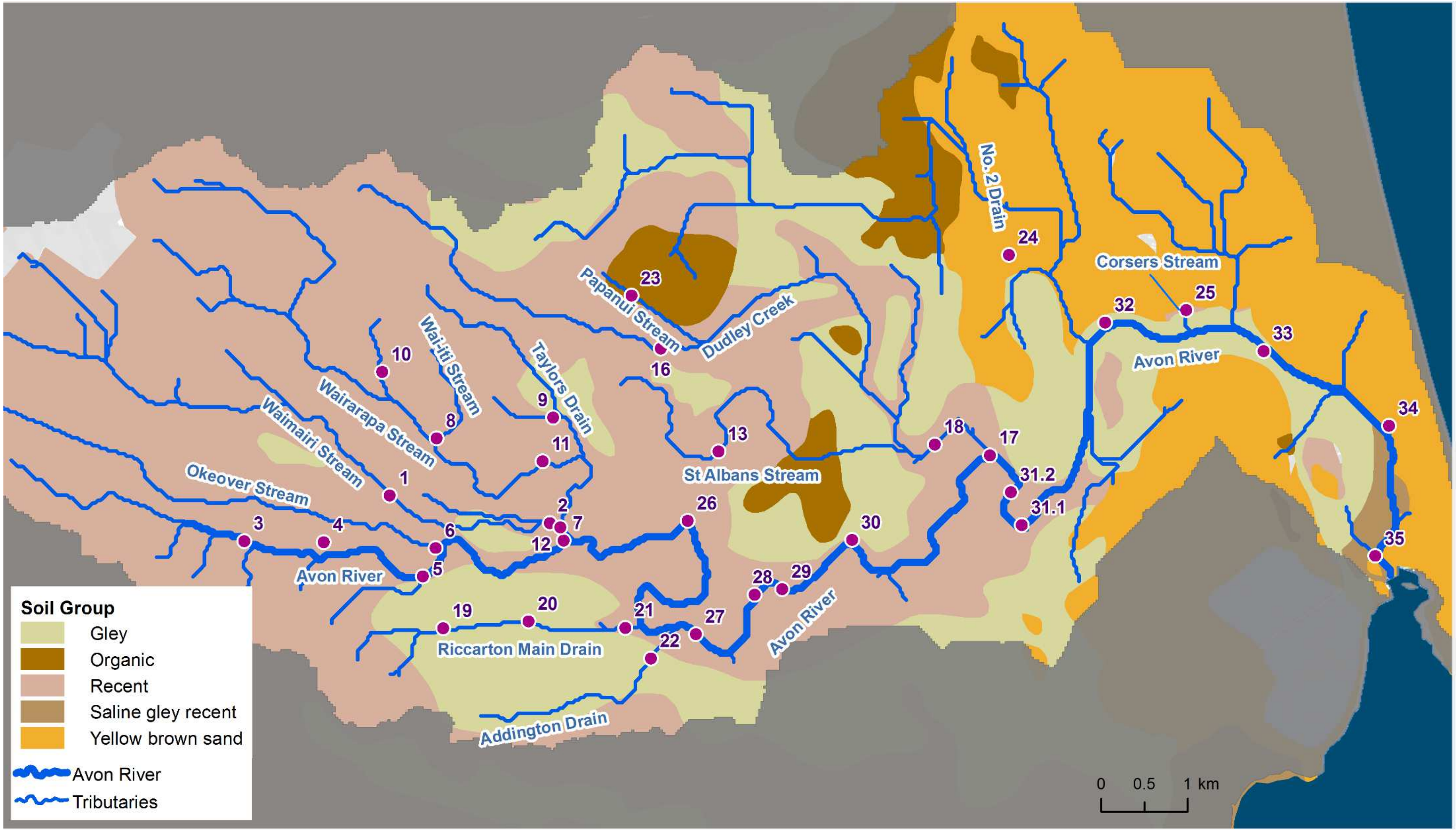

Figure 7-3: Soil groups in the Avon River / Ōtākaro catchment. Note: Soil map layer from Environment Canterbury GIS portal.

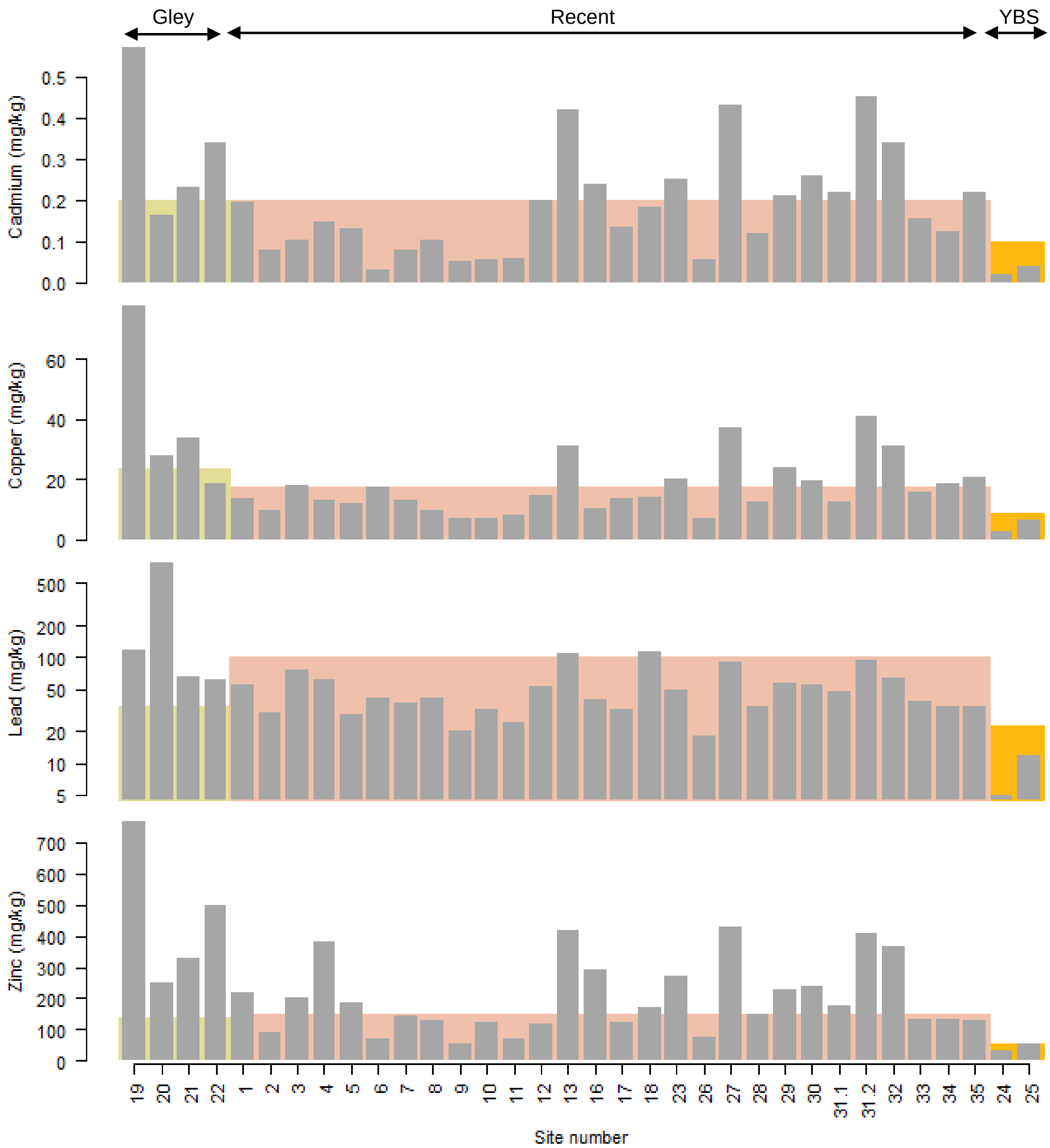

Figure 7-4: Comparison of sediment concentrations for cadmium, copper, lead and zinc at each site to level 1 soil concentrations for gley, recent and YBS (yellow brown sand) soils.
Note: Level 1 soil concentrations from Tonkin & Taylor (2007).

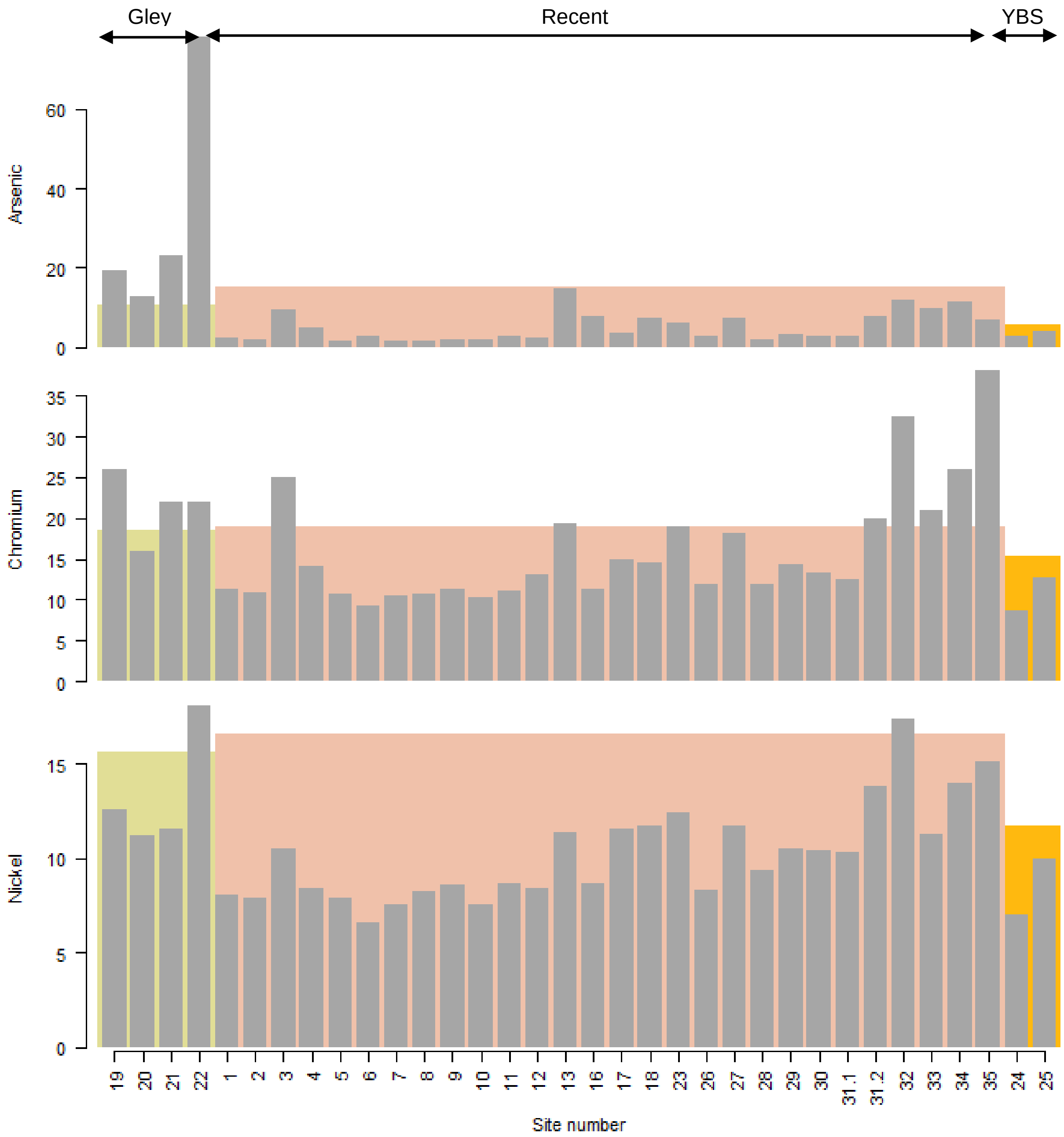

Figure 7-5: Comparison of arsenic, chromium and nickel sediment concentrations at each site to level 1 soil concentrations for gley, recent and YBS (yellow brown sand) soils. Note: Level 1 soil concentrations from Tonkin & Taylor (2007).

7.3 Catchment Landuse and Stormwater Quality

Stormwater is influenced by the landuse and types of impervious surfaces within a catchment. The land cover source areas was calculated for various subcatchments by Golder as part of their contaminant load modelling of the Avon SMP and was provided for comparison to the sediment data (K. How, pers comm.). This is not reported in terms of landuse type (as in residential vs commercial vs industrial) but as the land cover: grassland, paving, roof and roading.

The proportion of source areas in key subcatchments relevant to the sediment monitoring sites are presented in Table 7-2. Thisshows that most of the subcatchments in the Avon River / Ōtākaro catchment are dominated by urban land covers, with the exception of No. 2 Drain, which has 75% rural grassland in its catchment. Paved areas, roofing and roading have been summed to provide the total impervious surface for each sub-catchment. Riccarton Main Drain and Addington Brook have the highest percentage of impervious surfaces at 68% and 67%, followed by Dudley Creek at 59% and other sub-catchments at 52% or less. No.2 Drain has the lowest proportion of impervious land cover, at 18%.

Table 7-2: Landuse source areas for key subcatchments of the Avon River. Data provided by Golder (K. How, pers comm.)

Sub-catchment	Grassland		Paved areas	Roof	Roads	Total of impervious surfaces
	Rural	Urban				
Wairarapa Stream	21%	41%	12%	14%	13%	38%
Riccarton Main Drain	0%	32%	30%	21%	17%	68%
Addington Brook	0%	33%	39%	16%	12%	67%
Dudley Creek	0%	41%	22%	19%	19%	59%
No. 2 Drain	75%	7%	10%	3%	5%	18%
Avon River at Curators house	16%	41%	16%	15%	13%	44%
Avon River at Gayhurst Road Bridge	11%	37%	20%	17%	15%	52%
Avon River at Bridge Street	10%	38%	22%	15%	15%	52%

The total impervious area is often used as an indicator for effects of urban landuse on streams (e.g., Paul & Meyer 2001). The influence of this on sediment quality is examined in Figure 7-6 and shows that while, in general, metal and PAH concentrations in the sediment do tend to increase with an increase in impervious area, the relationship is fairly weak, with R 0.40-0.52. This indicates that while catchment management should address issues of increasing imperviousness, other factors are important influences on sediment quality.

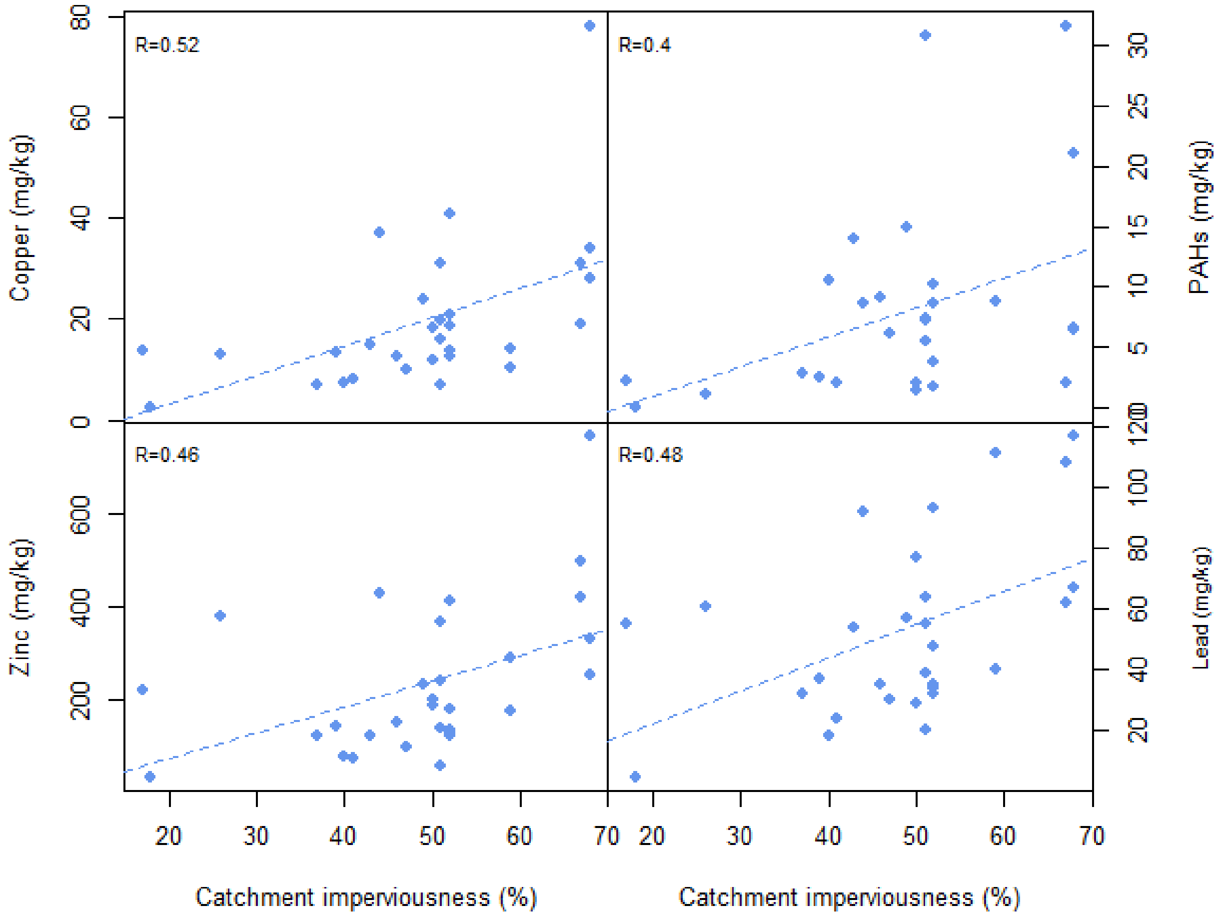

Figure 7-6: Relationship between metal concentrations in sediments and impervious area.

One of these factors may be the actual landuse in the catchment, rather than the land cover. The landuse based on the District Plan Zones are shown in Figure 7-7. The predominant landuse in the Avon River / Ōtākaro catchment is residential, with a much smaller proportion zoned as Business (which includes commercial and industrial landuses), mainly around the CBD and Addington Brook. Most of the landuse in the Addington Brook catchment that is marked as Business Zone is industrial (light and heavy industry, processing and warehousing) whereas the Business Zone around the CBD is mainly commercial. Although Addington Brook has the greatest proportion of commercial and industrial landuse, the highest concentrations of copper, lead and zinc were found in Riccarton Main Drain (see Section 5.3), which has a much smaller proportion of commercial/industrial. Landuse in the No.2 Drain catchment is predominantly rural and there is some rural landuse in the upper catchments of Papanui, Waimairi and Wairarapa Streams.

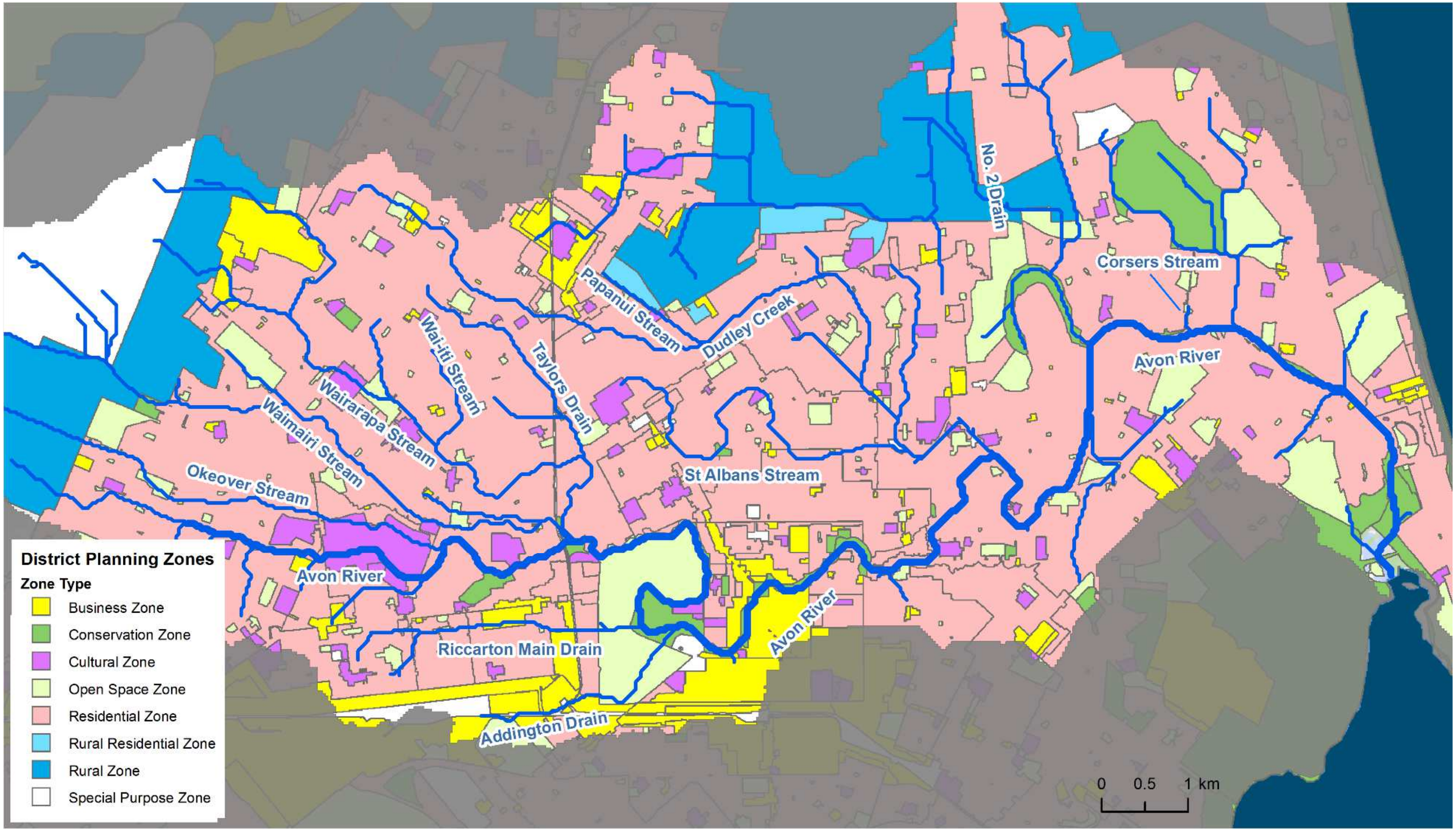

Figure 7-7: Landuse in the Avon River catchment based on current District Planning Zones.

The major landuse in each sub-catchment has been approximated from Figure 7-7 for the tributaries and upper reaches of the Avon River / Ōtākaro. The assessment of major landuse becomes difficult to estimate further down the catchment and has not been attempted. The major landuse is used to compare the sediment quality in Figures 7-4 and indicates that in general, copper, zinc and lead concentrations increase from rural to residential to commercial/industrial landuses. For chromium there is less difference between the landuse types which is expected as its concentration is close to that of soils and is related to the grain size of the sediment particles.

This assessment is limited by the fact that there is only one site with predominantly rural landuse in the catchment (No.2 Drain) and few sites with commercial or industrial land use (Riccarton Main Drain and Addington Brook only).

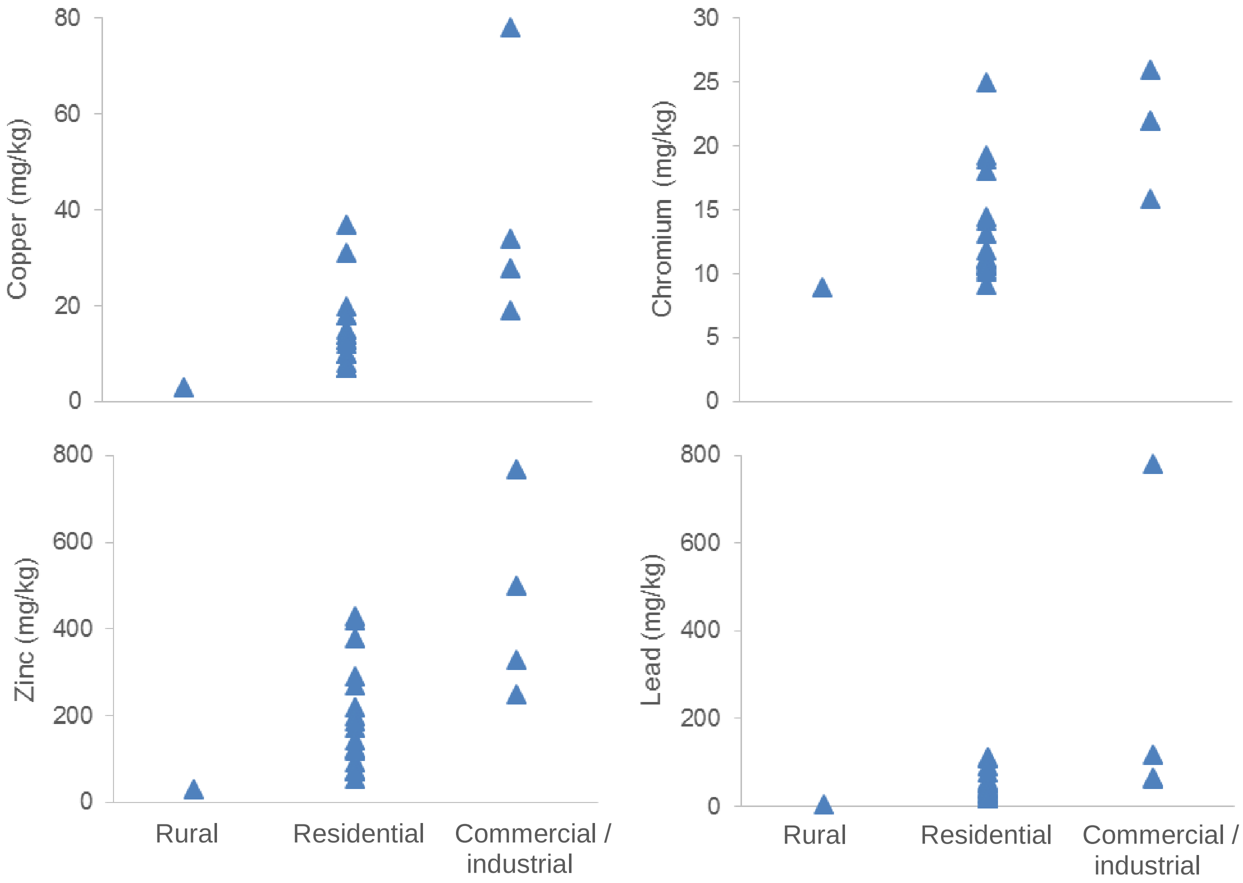

Figure 7-8: Comparison of metal concentrations in sediments for different landuses (based on estimated sub-catchments and District Planning Zones).

Stormwater studies in the Avon River / Ōtākaro catchment have previously focussed on the commercial and industrial catchments of Riccarton Main Drain and Addington Brook. These studies showed that these waterways have elevated concentrations of some metals compared to those expected in typical urban stormwater, which may be the cause of the elevated zinc found in these drains compared to many other tributaries and the mainstem. However, there have been no similar studies in other tributaries such as Wairarapa Stream or Dudley Creek to assess the relative water quality there. The contaminant load modelling being undertaken as part of the Avon Catchment SMP should provide more information on the specific sources of zinc within these sub-catchments.

7.4 Specific Land Use Activities as Contaminant Sources

There are several historic and current activities in the Addington Brook catchment which may be a source of the elevated arsenic: an old sheep-dip on the Canterbury Saleyards site; and the former Railway Workshops.

Firstly, arsenic contaminated soils have been reported adjacent to the old sheep dip in the Canterbury Saleyards site on Deans Ave, opposite Hagley Park and upstream of the sampling site in Addington Brook (Royds Garden 1993). Arsenic was used for sheep dips from ~1840 to 1980 (MfE 2006) and the saleyards were in use from approximately 1875 to 1997/98 (MWH 2013). The contamination around the sheep-dip has not yet been fully investigated.

The Addington Railway Workshops have also been identified as a potential source of land, groundwater and surface water contamination. Stormwater drains on the site discharged into the Addington Brook. Elevated concentrations of arsenic were measured in groundwater at this site during contaminated site investigations, as described in Environment Canterbury's audit of the site in the Listed Landuse Register.

Arsenic is also used in timber treatment, as a herbicide and has been found at elevated concentrations in some phosphate fertilisers (Hartley et al. 2013), all of which are potential sources of the observed arsenic in Addington Brook.

Figure 7-9: Historic landuse activities in the Addington Brook catchment that may have resulted in elevated arsenic (1946 aerial photo). Note: Aerial photo from Environment Canterbury.

Fertiliser use on the cricket oval and other sports grounds may be the cause of the high phosphorus concentration (2400 mg/kg) measured in Addington Brook. A high phosphorus concentration of 1400 mg/kg was also measured in Riccarton Main Drain upstream of Riccarton Avenue, also within Hagley Park. This was approximately double the concentration further upstream in Riccarton Main Drain.

There are several historic and closed landfills in the Avon River / Ōtākaro catchment, particularly to the north of the CBD, around Edgeware. Old landfills have been identified as sources of lead and PAHs in surrounding groundwater and surface waters (Conor Parker, Environment Canterbury, pers. comm).

7.5 Historic Roading Materials

The use of coal tar in roading materials has been identified as a major source of PAHs, particularly in older areas of Christchurch (Depree and Ahrens 2005) as discussed in Section 3.1. There was one site in the current study (Dudley Creek at North Parade) where PAHs were extremely elevated, measuring 506 mg/kg, well above that measured at other sites in this study and previously in stream sediments. In repeat analyses of the collected sample, total PAHs measured 22 and 112 mg/kg, indicating the PAHs were not well-mixed through the sample.

This site had been recently dredged to remove sand and silt from earthquake liquefaction. It is highly unlikely that such a high result could be due to stormwater, as PAHs are usually at much lower concentrations than this in stormwater particulates. PAHs are substantially lower even in sediments collected from stormwater treatment devices (e.g., 11-13 mg/kg in the Grafton Gully sediment retention tank; Depree & Ahrens 2007) or catchpits on industrial sites excluding that from a service station (Gadd et al. 2009). Such a high concentration suggests there may have been a small fragment of coal tar from roading material included in the sediment analysed by the laboratory. This is quite possible as there was substantial damage to roading in this area from the earthquakes (visible on aerial photographs taken 24 February 2011).

Although other samples in the Avon River / Ōtākaro catchment contained much lower PAH concentrations, they may still be influenced by coal tar roading materials. The use of coal tar binder and primers was widespread in the Christchurch urban area, particularly in the older streets. It is estimated that up to 50% of Christchurch's urban roads still have coal tar in subsurface layers. Frittering of the seal edge (roads and footpaths) enables these subsurface seal layers (containing between 7,000 and 12,000 mg/kg) to be subject to weathering and abrasion and subsequently transported into streams through the stormwater system. The earthquakes have also caused additional breakup of the road surface, which may have resulted in small fragments of material entering the stormwater system and would also enable faster weathering than expected.

Whilst the total PAH concentration was very high in Dudley Creek and well in excess of the ANZECC ISQG-high, toxicity testing on similar samples showed no acute or chronic effects on aquatic biota (Ahrens et al.; 2007) even at concentrations higher than this. This lower toxicity was attributed to weathering which depleted mobile and more toxic components and the strong sorption to organic matter in the soils and sediments (Ahrens et al.; 2007).

7.6 Earthquake-related Liquefaction and Dredging

The Christchurch earthquakes in September 2010 and particularly in February 2011 caused considerable physical change to the streams, by adding liquefaction sands and silt material; causing bank slumping and collapse; and lifting of the stream bed in some locations. Liquefaction can affect stream sediment quality as sediments are expected to have lower concentrations of metals than the stream sediments, as shown for the Avon-Heathcote Estuary (Zeldis et al. 2011). In samples collected from liquefaction mounds, the concentrations of copper, lead and zinc were approximately half those found in samples from the adjacent inter-tidal flats (Zeldis et al. 2011). Furthermore, several stream reaches were dredged where liquefaction was extensive.

Areas where liquefaction is known or suspected to have added sand and silt material to the streams are shown in Figure 7-10, based on previous reports in the catchment (Golder Associates 2012; James & McMurtrie 2012; Taylor et al. 2012) and observations made during the field work for this study. This is not a complete record and there are likely to be many more reaches where liquefaction sediments entered the streams. Relevant locations where dredging was undertaken to remove liquefaction sediments (pers. comm. Kirsty Patton, CCC) are also shown in Figure 7-10. Note, as for liquefaction, this is unlikely to be a complete record of dredged reaches as information on dredging was only obtained for areas related to the sediment sampling sites.

It is noted that liquefaction would have an influence on the sediment metal concentrations at affected sites, however contaminant concentrations vary considerably by site due to other factors, as shown in surveys conducted in Christchurch prior to the earthquake; and the effect of liquefaction on the stream sediment quality would be best assessed on a site-by-site basis. This was attempted using data from the previous catchment-wide survey (Robb 1988) and suggested that for the 14 sites with known liquefaction, there were 12 sites where zinc concentrations were lower in the present than previous survey and only two sites where the zinc concentrations were higher (see Appendix D, Figure 12-3). However as the previous survey was over 30 years prior to this present survey, there are multiple reasons for any decrease in the contaminant concentrations from that time, including liquefaction. The extent and magnitude of any effects from liquefaction on sediment quality are therefore not possible to confirm.

Dredging of the river and tributaries to remove silt material generated from the earthquakes appears to have reduced the concentrations of many contaminants at the dredged sites compared to nearby sites that have not been dredged. For example, the Avon River was dredged to remove silts near Gayhurst bridge (site 31.1), but not just upstream at site 31.2. The concentrations of TOC, metals and metalloids are clearly lower at the dredged site compared to the one just a few hundred metres upstream (Figure 7-10). This finding suggests that the dredging has not only removed sediments from liquefaction, but has also removed sediment that has previously built up in the stream from diffuse sources, including stormwater.

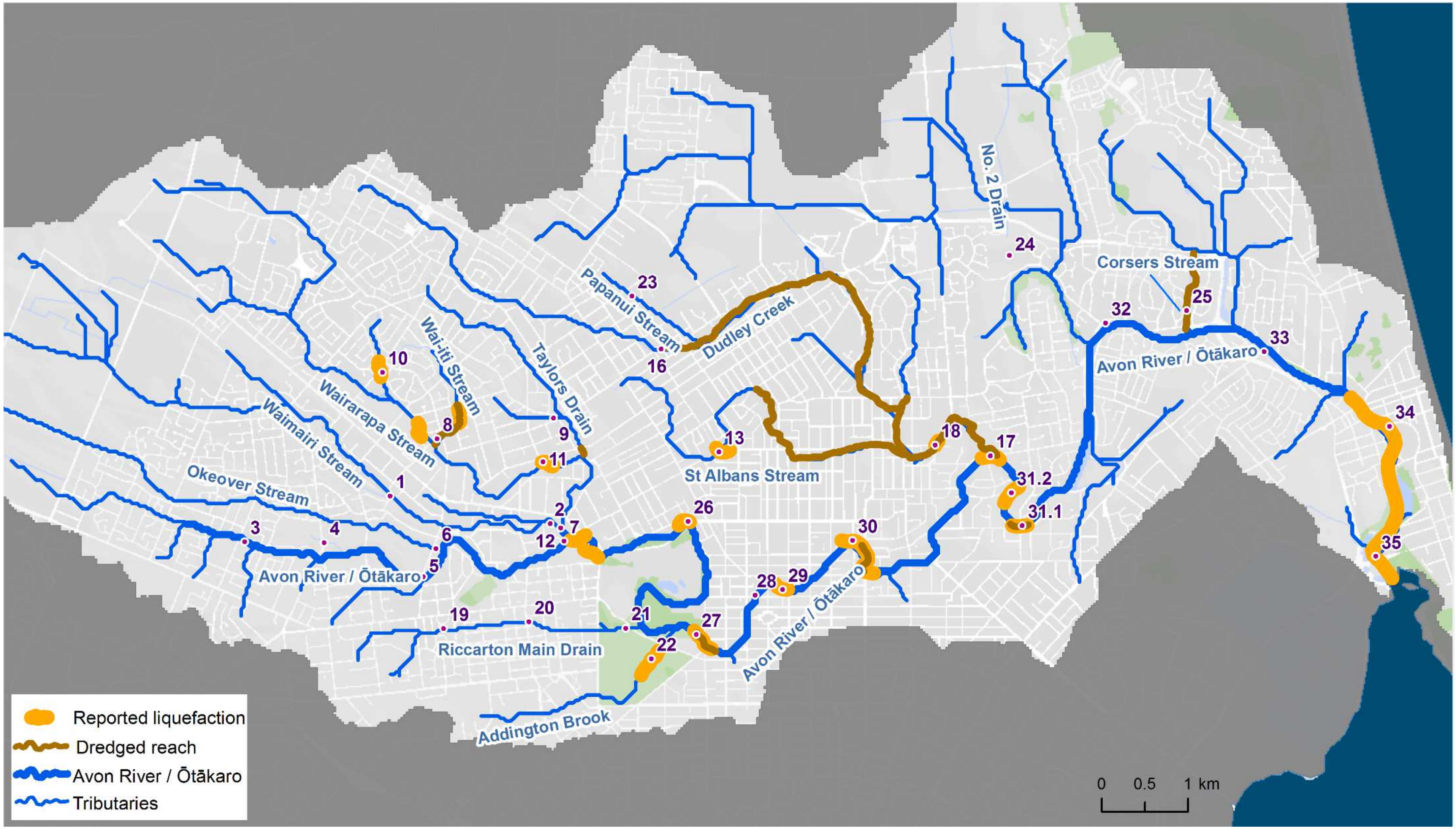

Figure 7-10:Reaches where there was known to be liquefaction caused by the Christchurch earthquakes; and reaches dredged to remove liquefaction sediments.

Table 7-3: Comparison of contaminant concentrations at two nearby sites in the Avon River, one dredged and the other not.

Site No.	31.1 Dredged	31.2 Not dredged
Mud (%)	9.2	29.4
Fine sand (%)	71.8	33.8
Medium-coarse sand (%)	14.2	6.7
Gravel (%)	4.8	30.1
TOC (%)	0.77	4.6
Phosphorus (mg/kg)	420	580
Arsenic (mg/kg)	2.9	7.6
Cadmium (mg/kg)	0.22	0.45
Chromium (mg/kg)	12.4	20
Copper (mg/kg)	12.8	41
Lead (mg/kg)	48	93
Nickel (mg/kg)	10.3	13.8
Zinc (mg/kg)	178	410

7.7 Earthquake-related Wastewater Overflows

Following the February 2011 earthquake, untreated wastewater was released into the Avon River / Ōtākaro (and other rivers) due to the major damage to infrastructure. Many of these discharges continued for a number of months, with over 2 million cubic metres discharged into the Avon River / Ōtākaro between February and June 2011.

Although the primary issues with untreated wastewater discharges are related to water quality, the discharges also have potential to affect sediment quality by increasing the amount of fine material; increasing the phosphorus and organic carbon content of sediment due to the highly enriched wastewater material; increasing metal concentrations as wastewater can contain metals at concentrations greater than stormwater; and increasing concentrations of a range of organic contaminants that can be found in wastewater (some of these measured in the SVOC suite).

Figure 7-11 shows the locations of the major wastewater discharges and indicates the concentrations of phosphorus and organic carbon in the sediments. It is difficult to assess whether there is any effect from the wastewater discharges. Within the mainstem of the Avon River / Ōtākaro, the TOC is highest near the Curators House (site 27) however this is upstream of the major discharges. TOC is considerably lower than this at the sites downstream of the first discharges. The highest TOC concentrations in the Avon River / Ōtākaro catchment were measured upstream of the wastewater discharges, in Riccarton Main Drain (5.3 g/100g) and St Albans Stream (5.0 g/100g). TOC and phosphorus concentrations will also be influenced by liquefaction (lowering the concentrations) and dredging; inputs from tributaries; and differences on a reach-scale, such as the inputs of leaves and other organic matter like macrophytes.

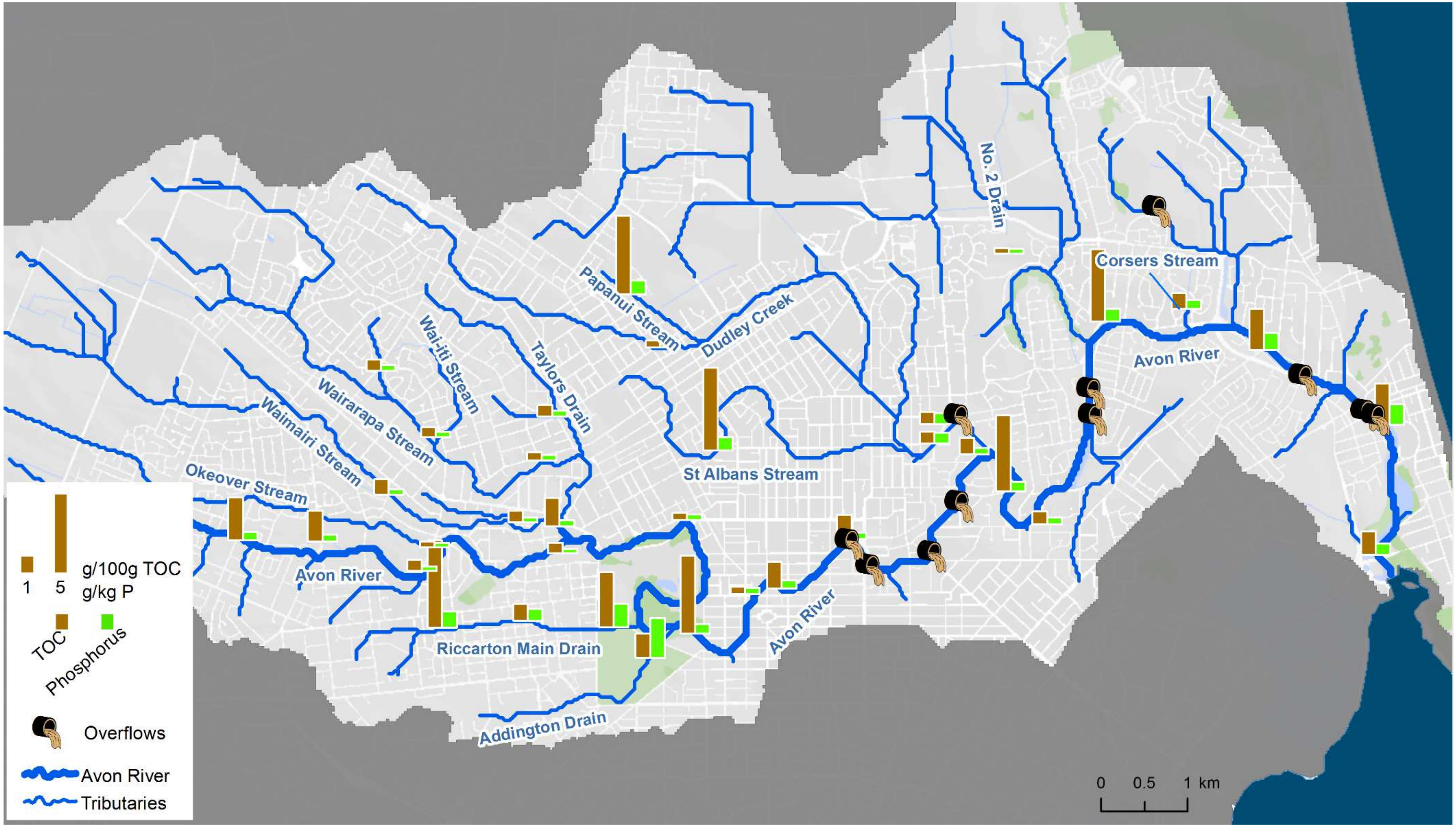

Figure 7-11:Total Organic Carbon and Phosphorus concentrations in sediments in relation to major wastewater overflows following the Christchurch earthquakes. Note: Units for TOC and phosphorus differ to ensure both are visible on this map.

8 Summary of Sediment Quality, Issues and Influences

8.1 Sediment Quality

The survey of sediment quality in the Avon River / Ōtākaro catchment has shown that arsenic, cadmium, copper, lead, zinc, PAHs and phosphorus concentrations are variable across the catchment; with a 10-20x difference between the lowest and highest concentrations measured. By contrast, there was little variation in the concentrations of chromium and nickel. The sediment texture was also variable, with samples from some sites dominated by gravel and coarse sand, many sites by fine sands and some sites by mud, particularly within the lower, tidal reaches around the Avon River / Ōtākaro mouth. In general, higher concentrations of metals were measured in Riccarton Main Drain, Addington Brook, Dudley Creek and its tributaries and the middle reaches of the Avon River / Ōtākaro. Metal concentrations were usually lower in the Avon River headwaters, tributaries to the north-west (Ilam, Wairarapa, Waimairi, Wai-iti Streams), No.2 Drain and Corsers Stream. Table 8-1 provides a summary for the contaminants measured in this study of their concentrations, guideline exceedances, trends and major sources.

Table 8-1: Summary of sediment contaminants.

Contaminant	Measured conc. (mg/kg)	Exceedance of sediment quality guidelines	Change since previous survey	Likely sources	Urban stormwater as major source?
Zinc	32 - 770 mg/kg	15 sites exceed ISQG-low (200 mg/kg) 5 sites exceed ISQG-high (410 mg/kg)	Not clear, poss. higher in fine sediments	Urban stormwater	Likely
Lead	5 - 780 mg/kg	15 sites exceed ISQG-low (50 mg/kg) 1 site (780 mg/kg) exceeds ISQG-high (220 mg/kg)	Lower	Legacy, contaminated soils	Likely through transport of legacy contaminated soils
PAHs	0.4 - 506 mg/kg	15 sites exceed ISQG-low (4 mg/kg) 1 site (693 mg/kg) exceeds ISQG-high (45 mg/kg)	Insufficient historical data for comparison	Coal tar in roading materials	Likely through transport of coal tar residues in road material and roadside soils
Arsenic	1.7 - 78 mg/kg	2 sites (23 & 78 mg/kg) exceed ISQG-low (20 mg/kg) 1 site exceeds ISQG-high (70 mg/kg)	No historical data for comparison	Hotspot contamination from historical sheep-dip	Unlikely but may be transported through stormwater
Copper	3 - 78 mg/kg	1 site (78 mg/kg) exceeds ISQG-low (65 mg/kg) No sites exceed ISQG-high (270 mg/kg)	Not clear, poss. higher in fine sediments	Urban stormwater and soils	Possibly
Cadmium	0.02 – 0.57 mg/kg	No sites exceed ISQG-low (1.5 mg/kg)	Not clear	Urban stormwater	Likely as concentrations closely correlated to copper and zinc
Chromium	9 - 38 mg/kg	No sites exceed ISQG-low (80 mg/kg)	Higher	Soils, with generally similar concentrations	Unlikely, concentrations related to sediment grain size
Nickel	7 - 18 mg/kg	No sites exceed ISQG-low (21 mg/kg)	Higher	Soils, with generally similar concentrations	Unlikely, concentrations related to sediment grain size
Phosphorus	280 - 2400 mg/kg	Not applicable	No historical data to compare to	Mixture	Unlikely

8.2 Changes in Sediment Quality Over Time

Metals were measured in Avon River / Ōtākaro sediments in 1980/1981 during a major survey of sediments in Christchurch waterways, with samples collected at 89 sites and analyses using similar methods. Almost all of the sites in the present survey were located near a site previously investigated. A comparison of the metal concentrations from the two studies shows that lead concentrations in sediments are now considerably lower than they were in the 1980s, as can be expected due to the removal of lead additives from petrol. Chromium and nickel concentrations were higher in the current survey compared to the 1980/81 survey. For the other metals (zinc, copper, cadmium) there was no clear difference between the surveys. This contrasts with results for other Christchurch catchments where zinc concentrations appear to be higher in recent surveys. Further analysis of the data mud-normalised metal concentrations to circumvent issues with differences in sample texture suggested that in the north-western tributaries the fine sediments may be becoming more enriched with these metals.

PAHs were also measured in the 1980s, but only at eight sites, and with differences in sampling and analytical methods. At most of these sites the PAHs were very similar now and in 1982; however the data set was very limited for assessing any change in concentrations over time.

8.3 Influences on Sediment Quality

Correlations between contaminants in the sediment samples indicated that the sources of cadmium, copper, lead, and zinc may be the same. The correlations also suggested that this source is different from that for organic carbon, phosphorus, arsenic, chromium, nickel and PAHs.

Metals are naturally-occurring in soils though their concentrations can be somewhat different between soils. Soils in the catchment are predominantly recent, with some small patches of gley and organic. For arsenic, chromium, lead and nickel the sediment concentrations are similar to the soil concentrations. Lead concentrations in the soils of urban Christchurch are higher than outside the urban centre as a result of lead additives in petrol. These historically contaminated soils are likely to be the primary source of lead on a catchment-wide basis. For cadmium, copper and zinc, many of the sediment concentrations were higher than the soils, suggesting that these metals are influenced by factors other than soil.

Urban land use is a major influence on sediment quality identified in other studies, as is impervious surface cover to a lesser extent. For sites in the Avon River / Ōtākaro catchment, a greater proportion of impervious surfaces in the sub-catchment appears to result in higher concentrations of copper, lead, zinc and PAHs, although this is a relatively weak relationship. Lowest concentrations of contaminants were found in the stream with a rural catchment, however there was only one such stream in the study area. Higher concentrations of contaminants were measured in streams with commercial and industrial land use in the catchment compared to residential, though there was considerable overlap between land uses.

Specific activities within each land use can also influence sediment quality. A hotspot of arsenic contamination was found in Addington Brook. This is not a typical contaminant in urban stormwater and may be related to a historical sheep dip site in the old saleyards, upstream of the sampling site. A hotspot of PAH contamination was also noted, in Dudley Creek. This is highly likely to be derived from coal tar residues that were used for roading materials in this part of Christchurch, and in other areas. General wear of the roading material and the additional damage caused by the earthquakes are likely to have mobilised fragments of material with coal tar residues into the stormwater and stream network. Although the concentrations were greatly in excess of sediment quality guidelines, previous toxicity studies have suggested that these types of residues are less bioavailable and contain less of the more toxic components than fresh tars.

The Canterbury earthquakes of 2010 and 2011 resulted in large amounts of liquefaction sediments entering the Avon River / Ōtākaro and many of its tributaries. These sediments are expected to have lower concentrations of contaminants than stormwater derived sediments. Although a clear difference in concentrations was not noted between sites with and without liquefaction, such an assessment is difficult in streams where the concentrations are extremely variable. The presence of liquefaction sediments may contribute to a lack of increase in zinc concentrations in this catchment, unlike the other Christchurch urban catchments (where sediment studies were undertaken prior to the earthquakes). In some locations liquefaction sediments have been removed by dredging, resulting in low concentrations of contaminants, presumably as stormwater-derived sediments were also removed. The earthquake-related wastewater discharges do not appear to have had any effect on the sediment quality in terms of the contaminants measured in this study.

Based on the results from this, and previous studies, a range of recommendations for stormwater contaminant catchment management are presented in the next section.

9 Recommendations for Stormwater Management

9.1 Recommendations for Catchment-wide Management

This sediment quality survey has identified zinc, lead and PAHs as the primary contaminants of concern due to the large number of locations where guidelines were exceeded. Because these locations were distributed through the catchment, a catchment-wide approach would be appropriate to reduce sediment contaminant concentrations.

Source control may be a potential method to manage zinc. Results of the contaminant load modelling will provide more information as to whether roofing or roading is the major source of zinc in the catchment. Roofing types could potentially be regulated to reduce inputs from galvanised steel roofs; however control of the roading related source (tyre wear) is unlikely to be feasible. Treatment devices distributed throughout the catchment, such as swales and rain-gardens would be of benefit in reducing zinc concentrations in stormwater close to the source. Alternatively, stormwater treatment devices could be located at the bottom of sub-catchments. This may prove to be difficult in practise as most sub-catchments have open streams with multiple small discharges from a relatively short piped network. As part of an integrated strategy for stormwater management, non-structural best management practices such as optimised street sweeping and sump cleaning maintenance (e.g., Depree 2011) may reduce stormwater contaminant loads in priority catchments.

The likely source of PAHs in sediments is roading materials and roadside soils rather than vehicle or combustion sources. There has been extensive damage to roading throughout Christchurch including in the areas where coal tar was used (St Albans, Shirley etc). A management plan should be developed to reduce the loss of contaminated material into the stormwater network and streams during the roading reconstruction. This management plan could also apply to future roading renewals.

Whilst lead concentrations are an issue at many locations, the concentrations of lead in the sediment are lower than when measured in the 1980s and they are expected to decline further. Therefore there are no catchment-wide recommendations for dealing with lead.

9.2 Recommendations for Individual Subcatchments

When individual sub-catchments are considered, Riccarton Main Drain and Addington Brook have the overall poorest quality sediment compared to other tributaries and sections of the Avon River. Based on this, the following actions are recommended for these subcatchments:

1. **Sediment toxicity testing to elucidate whether current concentrations are resulting in adverse effects on biota:** There were two sites in Riccarton Main Drain, and one in Addington Brook where sediment concentrations of either zinc, lead or arsenic exceeded the ANZECC ISQG-high. These exceedances suggest that adverse effects on biota may occur. The ecological survey in the catchment confirms that freshwater biota are depauperate in these locations. Sediment toxicity testing is an option to provide further evidence as to whether sediment quality, or other factors (water quality, habitat) are the cause. This would be most easily undertaken by collecting a large sediment sample at each site and submitting to an appropriate laboratory for chronic (>4 days) toxicity testing with a New Zealand invertebrate or fish species.

2. **Further investigations to identify contaminant sources (current and historic):** These should include sediment and stormwater quality measurements and reconnaissance surveys. Measurement of sediment quality at additional locations could confirm the results found in this current survey (particularly the lead concentration of 780 mg/kg in Riccarton Main Drain at Clarence Street) and provide greater information to localise the sources of contaminants. Event-based water sampling for metals at multiple locations, including within the stormwater network as well as the streams, would provide information on the on-going sources at different locations. This information is not currently provided by Christchurch City Council's monthly monitoring of metals (which may be at baseflow or event-flow); or by Environment Canterbury's event-based Addington Brook study, which sampled only at one location. Such an investigation has been previously undertaken in the Haytons Stream catchment to identify sources of poor water quality. Reconnaissance surveys in these catchments could identify sites that may be contributing excessive loads of contaminants (some of this information may be available already through the HAIL study for the Avon SMP).

3. **On-site stormwater management to prevent on-going degradation:** If sources of contaminants can be identified through the further investigations outlined above, then stormwater management options could be implemented to reduce contaminant inputs. These may include on-site management practices within industrial sites to reduce spills and improve stormwater quality being discharged, or installing stormwater treatment devices at key locations.

4. **Remediation of the sediments:** If toxicity testing shows that sediment is a major factor in limiting the biota at these sites, dredging to remove the contaminated sediment may be an option to reduce the metal concentrations, particularly of lead and arsenic. There are however several issues that need to be considered in relation to this: a) the effect of the dredging process on the in-stream biota; and b) whether this will have a long-term effect or not. Ecological specialists should be consulted to establish the potential effects of any dredging in this area. To ensure that dredging will mitigate this issue, the contaminant sources need to be identified and managed (as outlined in 2 and 3) otherwise contaminants will accumulate to toxic concentrations again.

The survey also identified metal concentrations in the Dudley Creek catchment which exceeded the ANZECC ISQG-high. In St Albans Stream, zinc concentrations exceeded the ANZECC ISQG-high as did PAHs in the lower Dudley Creek. These exceedances suggest that adverse effects on biota may occur. The ecological survey showed an absence of the caddisflies here, suggesting these streams may not be suitable for sensitive species (Blakely, pers. comm). Sediment toxicity testing is also recommended for these sites, as outlined above.

The survey showed that contaminants were generally at lower concentrations in the sediments of the Wairarapa, Waimairi and Wai-iti Stream and the ecological survey showed macroinvertebrate communities were slightly healthier here than at other sites in the catchment (Blakely, pers. comm). However, there is some evidence that the metal concentrations may be increasing in these areas, at least within the fine sediments. Stormwater management in the Wairarapa, Waimairi and Wai-iti Stream catchments should focus on ensuring sediment quality does not degrade to levels in the remainder of catchment and can continue to support sensitive macroinvertebrate species such as caddisflies. This would require stormwater management throughout the sub-catchment, and not just at the bottom of each stream, as the aim is to protect these streams, not the Avon River mainstem (this may differ from management aims for Addington Brook and Riccarton Main Drain). To achieve this, stormwater treatment systems should be installed close to the contaminant source or near upstream reaches of the streams. Any future urban development in these catchments, including greenfields development of the rural areas at the top of the catchment, should incorporate stormwater treatment systems that are capable of removing fine sediment and metals.

9.3 Recommendations for Future Monitoring

Stormwater managers are very interested in understanding whether metal concentrations in stream sediments have changed over time. However, this is difficult to assess using the methodology of this study. This sediment survey, and others in Christchurch streams, have shown that sediment quality is inherently variable in streams, due to catchment and reach-scale differences. Furthermore the grain size of collected samples can vary, and subsequently metal concentrations vary too.

Despite these complications, decreases have been noted between recent and historical sediment lead concentrations; and some studies have found increases in zinc concentrations. However, such changes are only apparent when they occur across the catchment and with sufficient magnitude. It is not possible to distinguish more subtle changes.

If understanding changes in sediment quality over time are considered important to Christchurch City Council, then the methodology for future studies should be amended to include analysis of individual replicates at each site, or at a subset of sites where change is assessed (e.g., five sites distributed throughout the catchment). Replication at each site would enable statistical comparisons between sites, which would enable stormwater managers to have more confidence in the results.

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11 Glossary of abbreviations and terms

ANOVA	Analysis of variance
ANZECC	Australian and New Zealand Environment and Conservation Council
CBD	Central Business District
CCC	Christchurch City Council
ECan	Environment Canterbury
IANZ	International Accreditation New Zealand
IQR	Inter-quartile range
ISQG	Interim sediment quality guideline
NIWA	National Institute of Water and Atmospheric Research Ltd
PAHs	Polycyclic aromatic hydrocarbons
SMP	Stormwater management plan
SVOCs	Semi-volatile organic compounds
TP	Total phosphorus
TOC	Total Organic Carbon
USEPA	United States Environmental Protection Agency

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Appendix A Proposed Sampling Sites

The 35 sampling sites proposed by CCC in the Request for Proposals are listed below.

Table 12-1: Sampling sites proposed by CCC in RFP.

No.	Location description	Easting	Northing	CDB Sample ID
1	Waimairi Stream – confluence of two branches	2476274	5743174	7
2	Waimairi Stream – upstream of railway line	2478123	5742854	13
3	Avon River – at Avonhead Road	2474518	5742697	14
4	Ilam Stream - Waimairi Road	2475509	5742636	21
5	Avon River - at Clyde Road	2476657	5742235	24
6	Clarksons Drain / Okeover Stream – 30 m d/s of Clyde Rd	2476804	5742565	C15
7	Avon River – confluence with Wairarapa	2478282	5742655	31
8	Wai-iti Stream – Clyde Road	2476816	5743832	45
9	Taylors Drain – Heaton Street	2478474	5743761	52
10	Wairarapa Stream – Greers Road Bridge	2476161	5744620	54
11	Wairarapa Stream – Idris Road	2478039	5743568	68
12	Wairarapa Stream – above confluence of Waimairi & Wairarapa	2478246	5742806	78
13	St Albans Creek - Abberley Park	2480075	5743683	
14	St Albans Creek – Hills Road	2481860	5743767	91
15	Shirley Stream - Stapletons Road	2482185	5744223	
16	Dudley Creek – downstream of Jameson Ave	2480363	5745381	99
17	Dudley Creek – Julius Tce, upstream Shirley Stream	2482137	5744184	105
18	Dudley Creek - North Parade (McKillop College)	2482575	5743763	108
19	Riccarton Main Drain – Matipo St (upstream of mall)	2477320	5741676	
20	Riccarton Main Drain – Clarence St (downstream of mall)	2477879	5741716	
21	Riccarton Main Drain – upstream Riccarton Ave	2478997	5741643	118
22	Addington Brook – Hagley Park	2479291	5741289	131
23	Papanui Stream - Erica Reserve	2479069	5745479	
24	No. 2 Drain - Christchurch Golf Club	2483431	5745954	
25	Corsers Stream - Brooker Reserve	2485480	5745312	
26	Avon River – Carlton Mill Bridge	2479764	5742834	138
27	Avon River – Antigua Boatsheds	2480018	5741393	146
28	Avon River – downstream Armagh Street	2480490	5742024	149
29	Avon River – opposite Chch Drainage Board	2480810	5742089	151
30	Avon River – upstream Fitzgerald Ave	2481738	5742301	154
31	Avon River – Gayhurst Road Bridge	2483538	5742819	168
32	Avon River - Avondale Bridge	2484776	5745167	181
33	Avon River – 10 m downstream of Wainoni Rd Bridge	2486375	5744840	187
34	Avon River – New Brighton Power Boat Club House	2487775	5744006	193
35	Avon River – 30 m upstream of Bridge Street	2487666	5742474	204

Appendix B Sampling and Analytical Variation

Duplicate samples were collected in the field at four of the sites to assess the variation due to sampling and analysis. As described in Section 4.2, the duplicate consists of two separate samples collected in the same manner at the same site. The duplicates are compared to the 'primary samples' in Tables B.1 to B.4.

The variation, in terms of relative difference between the two samples, ranged from no difference to greater than 100% difference. However, for the majority of the parameters measured, in most samples the variation was less than 50%. The greatest variation was observed in PAHs at site 24. This site had very low concentrations of PAHs, with some compounds below the detection limit. At these very low concentrations even minor differences between the samples results in a high relative difference. Total Organic Carbon (TOC) also had relatively high variability in most samples, being over 50% for samples from site 9 and 11. This may be related to the variation in the proportion of mud in these samples which varied by a similar amount and was low at only 3-7% (compared to approximately 50% for site 32).

Overall, the variation was lowest for the metals, being less than 20% for samples 11, 24 and 32 (with the exception of chromium at site 32). There was greater variation in metal concentrations at site 9, typically 30-40% difference between duplicates.

Table 12-2: Results for duplicate samples from site 9 (Taylors Drain at Railway Line). Parameters with a greater than 50% variation are highlighted in red.

	9	9 (2)	Average	Difference	Relative difference (%)
Dry Matter	77	72	74.5	5	7%
Grain size analysis					
Fraction ≥ 2 mm	7.2	6.2	6.7	1	15%
Fraction < 2 mm, ≥ 1 mm	2.6	3	2.8	0.4	14%
Fraction < 1 mm, ≥ 500 µm	6.6	6.5	6.55	0.1	2%
Fraction < 500 µm, ≥ 250 µm	40.9	44.6	42.75	3.7	9%
Fraction < 250 µm, ≥ 125 µm	33	26.9	29.95	6.1	20%
Fraction < 125 µm, ≥ 63 µm	6	5.7	5.85	0.3	5%
Fraction < 63 µm	3.7	7.1	5.4	3.4	63%
TOC, TP and metals					
Total Organic Carbon	0.44	0.98	0.71	0.54	76%
Phosphorus	360	370	365	10	3%
Arsenic	1.7	2.3	2	0.6	30%
Cadmium	0.039	0.057	0.048	0.018	38%
Chromium	11.1	11.2	11.15	0.1	1%
Copper	5.7	8.3	7	2.6	37%
Lead	16.6	23	19.8	6.4	32%
Nickel	8.3	8.8	8.55	0.5	6%
Zinc	46	62	54	16	30%
PAHs					
Acenaphthene	0.022	0.018	0.020	0.004	20%
Acenaphthylene	0.022	0.018	0.020	0.004	20%
Anthracene	0.116	0.107	0.112	0.009	8%
Benzo[a]anthracene	0.4	0.38	0.39	0.02	5%
Benzo[a]pyrene (BAP)	0.46	0.37	0.42	0.09	22%
Benzo[b]fluoranthene + Benzo[j]fluoranthene	0.48	0.52	0.5	0.04	8%
Benzo[g,h,i]perylene	0.34	0.29	0.32	0.05	16%
Benzo[k]fluoranthene	0.22	0.21	0.22	0.01	5%
Chrysene	0.39	0.36	0.38	0.03	8%
Dibenzo[a,h]anthracene	0.062	0.076	0.069	0.014	20%
Fluoranthene	1.17	1.00	1.09	0.17	16%
Fluorene	0.049	0.034	0.042	0.015	36%
Indeno(1,2,3-c,d)pyrene	0.37	0.22	0.30	0.15	51%
Naphthalene	0.014	<0.010	0.0095 [a]	0.009 [a]	95% [a]
Phenanthrene	0.67	0.57	0.62	0.1	16%
Pyrene	1.15	0.92	1.04	0.23	22%
Sum of PAHs	5.94	5.10	5.52	0.84	15%

Notes: [a] Average, difference and relative difference calculated using half the detection limit where result was below the detection limit.

Table 12-3: Results for duplicate samples from site 11 (Wairarapa Stream at Idris Road). Parameters with a greater than 50% variation are highlighted in red.

	11	11 (2)	Average	Difference	Relative difference (%)
Dry Matter	72	73	72.5	1	1%
Grain size analysis					
Fraction ≥ 2 mm	5.5	12.2	8.85	6.7	76%
Fraction < 2 mm, ≥ 1 mm	2.4	1.7	2.05	0.7	34%
Fraction < 1 mm, ≥ 500 µm	7.2	5.8	6.5	1.4	22%
Fraction < 500 µm, ≥ 250 µm	39.1	40.9	40	1.8	4%
Fraction < 250 µm, ≥ 125 µm	26.9	27.6	27.3	0.7	3%
Fraction < 125 µm, ≥ 63 µm	11.6	8.1	9.9	3.5	36%
Fraction < 63 µm	7.3	3.6	5. 5	3.7	68%
TOC, TP and metals					
Total Organic Carbon	0.63	0.35	0.49	0.28	57%
Phosphorus	340	350	345	10	3%
Arsenic	2.8	2.4	2.6	0.4	15%
Cadmium	0.07	0.058	0.064	0.012	19%
Chromium	11.8	10.1	11.0	1.7	16%
Copper	8.6	7.8	8.2	0.8	10%
Lead	23	25	24	2	8%
Nickel	8.8	8.6	8.7	0.2	2%
Zinc	74	70	72	4	6%
PAHs					
Acenaphthene	0.003	0.005	0.004	0.002	50%
Acenaphthylene	0.014	0.015	0.015	0.001	7%
Anthracene	0.042	0.029	0.036	0.013	37%
Benzo[a]anthracene	0.171	0.187	0.179	0.016	9%
Benzo[a]pyrene (BAP)	0.20	0.199	0.200	0.001	1%
Benzo[b]fluoranthene + Benzo[j]fluoranthene	0.20	0.26	0.23	0.06	26%
Benzo[g,h,i]perylene	0.15	0.136	0.143	0.014	10%
Benzo[k]fluoranthene	0.084	0.096	0.090	0.012	13%
Chrysene	0.167	0.166	0.167	0.001	1%
Dibenzo[a,h]anthracene	0.025	0.036	0.031	0.011	36%
Fluoranthene	0.39	0.37	0.38	0.02	5%
Fluorene	0.008	0.011	0.0095	0.003	32%
Indeno(1,2,3-c,d)pyrene	0.163	0.104	0.134	0.059	44%
Naphthalene	< 0.010	< 0.010	<0.010	0	0%
Phenanthrene	0.135	0.188	0.162	0.053	33%
Pyrene	0.38	0.35	0.37	0.03	8%
Sum of PAHs	2.14	2.16	2.15	0.02	0.9%

Table 12-4: Results for duplicate samples from site 24 (No. 2 Drain at Christchurch Golf Club). Parameters with a greater than 50% variation are highlighted in red.

	24	24 (2)	Average	Difference	Relative difference (%)
Dry Matter	75	73	74	2	3%
Grain size analysis					
Fraction ≥ 2 mm	< 0.1	< 0.1	<0.1	0	0%
Fraction < 2 mm, ≥ 1 mm	< 0.1	< 0.1	<0.1	0	0%
Fraction < 1 mm, ≥ 500 µm	< 0.1	< 0.1	<0.1	0	0%
Fraction < 500 µm, ≥ 250 µm	1.4	2.3	1.85	0.9	49%
Fraction < 250 µm, ≥ 125 µm	91.7	89.3	90.5	2.4	3%
Fraction < 125 µm, ≥ 63 µm	4.5	5.6	5.05	1.1	22%
Fraction < 63 µm	2.2	2.6	2.4	0.4	17%
TOC, TP and metals					
Total Organic Carbon	0.39	0.3	0.345	0.09	26%
Phosphorus	300	310	305	10	3%
Arsenic	2.6	2.7	2.65	0.1	4%
Cadmium	0.02	0.021	0.021	0.001	5%
Chromium	8.3	8.9	8.6	0.6	7%
Copper	2.5	2.7	2.6	0.2	8%
Lead	5.3	5.3	5.3	0	0%
Nickel	6.9	7.1	7	0.2	3%
Zinc	31	32	31.5	1	3%
PAHs					
Acenaphthene	< 0.002	< 0.002	<0.002	0	0%
Acenaphthylene	< 0.002	< 0.002	<0.002	0	0%
Anthracene	< 0.002	< 0.002	<0.002	0	0%
Benzo[a]anthracene	0.002	0.006	0.004	0.004	100%
Benzo[a]pyrene (BAP)	0.003	0.007	0.005	0.004	80%
Benzo[b]fluoranthene + Benzo[j]fluoranthene	0.003	0.009	0.006	0.006	100%
Benzo[g,h,i]perylene	0.002	0.004	0.003	0.002	67%
Benzo[k]fluoranthene	< 0.002	0.004	0.003 [a]	0.003 [a]	120% [a]
Chrysene	< 0.002	0.005	0.003 [a]	0.004 [a]	133% [a]
Dibenzo[a,h]anthracene	< 0.002	< 0.002	<0.002	0	0%
Fluoranthene	0.004	0.014	0.009	0.01	111%
Fluorene	< 0.002	< 0.002	<0.002	0	0%
Indeno(1,2,3-c,d)pyrene	< 0.002	0.003	0.002 [a]	0.002 [a]	100% [a]
Naphthalene	< 0.010	< 0.010	<0.010	0	0%
Phenanthrene	0.003	0.009	0.006	0.006	100%
Pyrene	0.004	0.014	0.009	0.01	111%
Sum of PAHs	0.034	0.085	0.06	0.05	86%

Notes: [a] Average, difference and relative difference calculated using half the detection limit where result was below the detection limit.

Table 12-5: Results for duplicate samples from site 32 (Avon River upstream of Avondale Bridge). Parameters with a greater than 50% variation are highlighted in red.

	32	32 (2)	Average	Difference	Relative difference (%)
Dry Matter	39	37	38	2	5%
Grain size analysis					
Fraction ≥ 2 mm	10.4	7.5	8.95	2.9	32%
Fraction < 2 mm, ≥ 1 mm	0.6	2.3	1.45	1.7	117%
Fraction < 1 mm, ≥ 500 µm	1.3	3.6	2.45	2.3	94%
Fraction < 500 µm, ≥ 250 µm	4.3	4.5	4.4	0.2	5%
Fraction < 250 µm, ≥ 125 µm	17.4	11.4	14.4	6	42%
Fraction < 125 µm, ≥ 63 µm	19.7	16.7	18.2	3	16%
Fraction < 63 µm	46.3	53.9	50.1	7.6	15%
TOC, TP and metals					
Total Organic Carbon	4.3	4.5	4.4	0.2	5%
Phosphorus	720	850	785	130	17%
Arsenic	11	12.7	11.9	1.7	14%
Cadmium	0.34	0.34	0.34	0	0%
Chromium	27	38	33	11	34%
Copper	29	33	31	4	13%
Lead	58	69	64	11	17%
Nickel	16.4	18.3	17.4	1.9	11%
Zinc	340	390	365	50	14%
PAHs					
Acenaphthene	0.012	0.019	0.016	0.007	45%
Acenaphthylene	0.047	0.048	0.048	0.001	2%
Anthracene	0.061	0.083	0.072	0.022	31%
Benzo[a]anthracene	0.51	0.59	0.55	0.08	15%
Benzo[a]pyrene (BAP)	0.62	0.7	0.66	0.08	12%
Benzo[b]fluoranthene + Benzo[j]fluoranthene	0.91	0.97	0.94	0.06	6%
Benzo[g,h,i]perylene	0.53	0.56	0.55	0.03	6%
Benzo[k]fluoranthene	0.32	0.39	0.36	0.07	20%
Chrysene	0.51	0.59	0.55	0.08	15%
Dibenzo[a,h]anthracene	0.137	0.142	0.140	0.005	4%
Fluoranthene	1.08	1.35	1.22	0.27	22%
Fluorene	0.038	0.056	0.047	0.018	38%
Indeno(1,2,3-c,d)pyrene	0.4	0.42	0.41	0.02	5%
Naphthalene	<0.018	<0.019	0.0093 [a]	0.0005 [a]	5% [a]
Phenanthrene	0.42	0.59	0.51	0.17	34%
Pyrene	1.02	1.25	1.14	0.23	20%
Sum of PAHs	6.62	7.77	7.20	1.14	16%

Notes: [a] Average, difference and relative difference calculated using half the detection limit where result was below the detection limit.

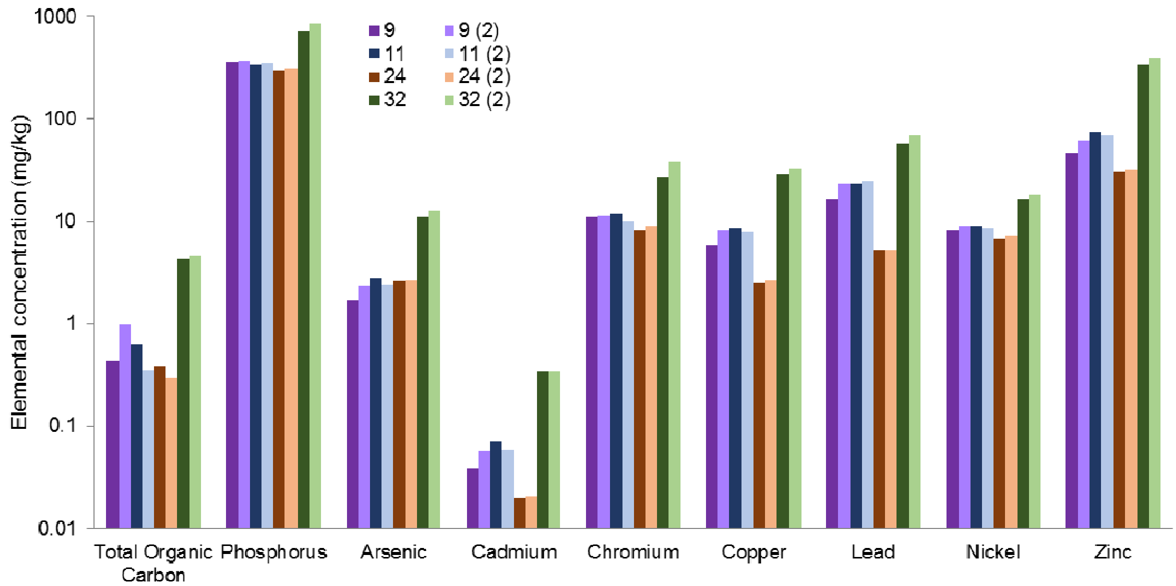

Figure 12-1:Difference in elemental concentrations between sample duplicates.

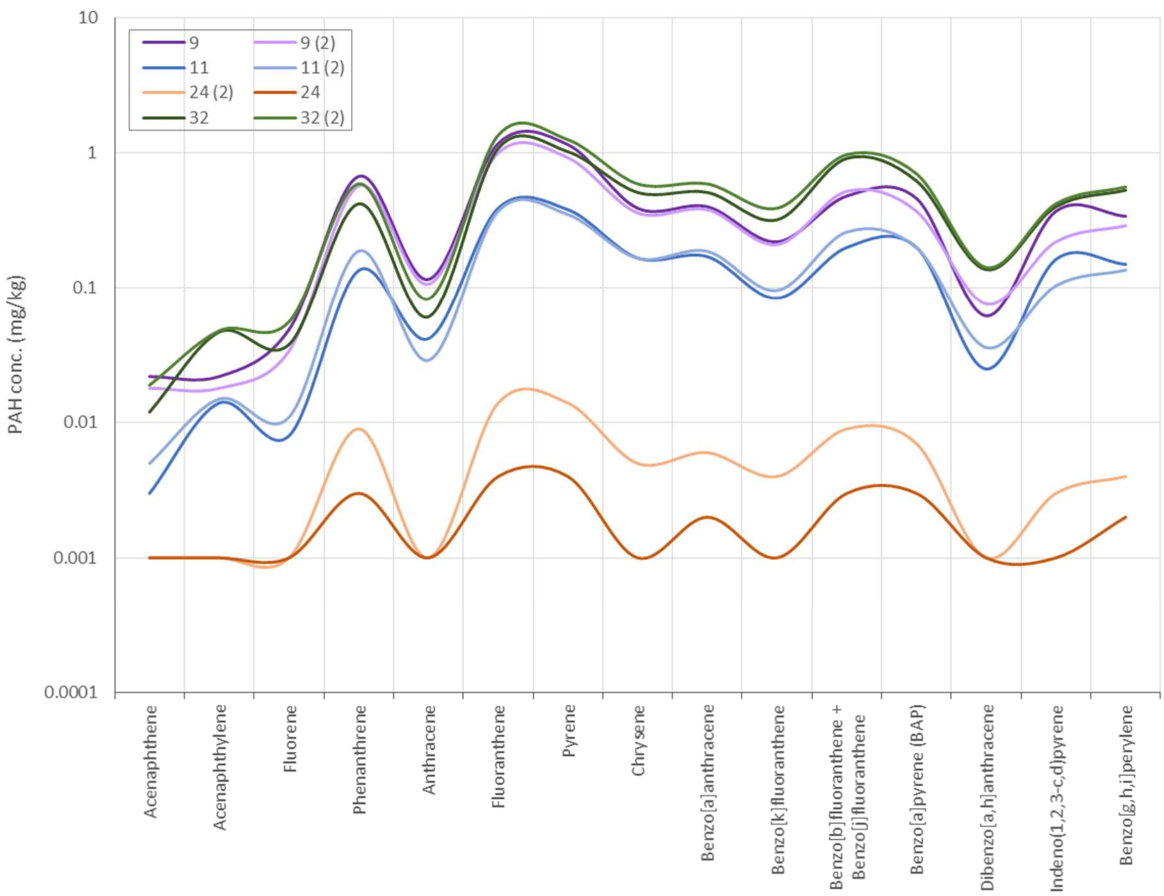

Figure 12-2:Difference in individual PAHs concentrations between sample duplicates.

Appendix C Tables of Results

The results for all analyses are presented in Tables 11-6 to 11-12.

Table 12-6: Stream bed substrate and depth of soft sediments at each site.

Site No.	Percentage of stream substrate that is:							Soft sediment depth (cm)
	Clay / silt	Sand	Gravel	Cobble	Boulder	Artificial	Leaves/veg.	
1	40		20	40				20-40
2	30		30	40				30-250
3	5	15	70	10				30-100
4	30		10				60	20-40
5	20	30	40	10				10-120
6			100					20-30
7	30		60	10				60-130
8	10	25	5				60	30-110
9	5	5	30				60	10-60
10	90				10			20-100
11	5	10	65	20				20-50
12	100							60-100
13	50					50		>200
16	10	30	60					10-20
17	20						80	>200
18	20	5	10	65				10-30
19	20					80		90->200
20	20		30	50				10-20
21						100		0
22	*Unable to measure as could not see into water*							*Not measured*
23	60		20	10	10			10-100
24	10	20	40	20	10			20-60
25	70	10	20					30-80
26	10		50	40				20-40
27	20						80	60-200
28		10	30	60				10-60
29	30	70						30-100
30	80	10					10	>250
31.1	20	80						30-260
31.2	2					98		>250
32	100							150-500
33	90		10					30-170
34	100							25-60
35	50	50						200

Table 12-7: Percentage of material in each particle size range.

Site No.	Gravel > 2 mm	Very coarse sand 1 – 2 mm	Coarse sand 0.5 – 1 mm	Medium sand 0.25 – 0.5 mm	Fine sand 0.125 – 0.25 mm	Very fine sand 0.063 – 0.125 mm	Mud (silt & clay) <0.063 mm
1	9.5	0.6	1.0	6.9	62.5	15.2	4.3
2	0.3	<0.1	0.2	6.6	57.2	27.1	8.6
3	52.1	4.6	3.9	8.5	11.8	8.6	10.6
4	10.3	1.1	2.1	15.3	40.8	16.7	13.7
5	4.0	0.3	0.5	7.0	61.7	19.5	7.1
6	4.0	1.0	1.8	42.9	43.5	4.4	2.5
7	0.3	0.1	0.3	8.5	61.5	22.8	6.4
8	3.5	0.9	3.4	44.3	38.7	5.9	3.3
9	6.7	2.8	6.6	42.8	30.0	5.9	5.4
10	8.0	1.1	4.8	48.9	31.0	4.3	2.0
11	8.9	2.1	6.5	40.0	27.3	9.9	5.5
12	2.3	0.6	2.8	27.3	29.8	27.0	10.2
13	7.5	1.2	2.2	2.8	12.2	24.7	49.3
16	1.5	2.0	2.4	20.6	60.3	9.7	3.6
17	2.8	0.2	0.7	2.2	23.3	41.3	29.5
18	19.2	4.2	4.4	22.8	27.7	8.7	12.9
19	12.0	2.5	2.8	7.9	25.5	21.6	27.7
20	29.3	10.6	8.4	16.0	18.0	5.9	11.8
21	1.0	11.4	4.5	10.2	30.5	16.9	25.5
22	45.2	12.2	4.5	4.6	5.5	4.9	23.2
23	2.7	0.8	0.7	4.3	8.5	23.4	59.6
24	<0.1	<0.1	<0.1	1.9	90.5	5.1	2.4
25	0.4	0.5	0.4	3.6	46.6	25.3	23.2
26	0.5	0.5	3.5	40.8	45.2	5.4	4.0
27	7.7	1.1	1.4	2.8	28.5	31.6	26.9
28	<0.1	<0.1	0.2	14.7	58.6	18.9	7.5
29	0.4	0.2	0.4	3.1	45.0	34.6	16.2
30	2.1	0.7	1.2	9.1	45.6	30.6	10.7
31.1	4.8	0.6	1.6	12.0	54.9	16.9	9.2
31.2	30.1	0.6	0.7	5.4	16.4	17.4	29.4
32	9.0	1.5	2.5	4.4	14.4	18.2	50.1
33	8.4	1.6	4.2	11.5	20.9	15.2	38.2
34	16.0	4.4	3.2	9.2	23.7	8.3	35.2
35	0.3	1.3	2.1	10.0	9.4	11.9	65.1

Table 12-8: Results for phosphorus, TOC, metals and metalloids.

Site No.	TOC	Phosphorus	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc
1	0.94	320	2.4	0.193	11.3	13.9	55	8.1	220
2	0.72	310	1.8	0.079	10.8	9.8	30	7.9	94
3	2.60	510	9.6	0.104	25.0	18.3	77	10.5	200
4	1.86	410	4.9	0.147	14.2	13.1	61	8.4	380
5	0.68	280	1.7	0.130	10.7	11.8	29	7.9	187
6	0.36	280	2.8	0.031	9.2	17.8	41	6.6	73
7	0.67	280	1.7	0.080	10.4	13.2	37	7.5	143
8	0.62	340	1.6	0.104	10.7	9.6	41	8.2	126
9	0.71	365	2.0	0.048	11.2	7.0	20	8.6	54
10	0.70	350	2.2	0.053	10.2	7.1	32	7.5	122
11	0.49	345	2.6	0.064	11.0	8.2	24	8.7	72
12	1.72	370	2.6	0.200	13.2	14.9	54	8.4	119
13	5.00	810	14.9	0.420	19.3	31.0	108	11.4	420
16	0.41	540	7.8	0.240	11.2	10.4	40	8.7	290
17	0.99	390	3.7	0.134	15.0	13.6	32	11.5	121
18	0.73	650	7.3	0.181	14.5	14.2	111	11.7	172
19	5.30	980	19.5	0.570	26.0	78.0	117	12.6	770
20	1.01	720	12.6	0.163	15.9	28.0	780	11.2	250
21	3.30	1420	23.0	0.230	22.0	34.0	67	11.5	330
22	1.47	2400	78.0	0.340	22.0	18.9	62	18.1	500
23	4.80	860	6.3	0.250	19.0	20.0	49	12.4	270
24	0.35	305	2.7	0.021	8.6	2.6	5	7.0	32
25	0.96	540	4.0	0.040	12.7	6.6	12	10.0	55
26	0.44	340	2.7	0.055	11.9	7.3	18	8.3	76
27	4.70	580	7.4	0.430	18.1	37.0	92	11.7	430
28	0.44	370	2.0	0.120	11.8	12.7	35	9.4	149
29	1.60	480	3.3	0.210	14.4	24.0	57	10.5	230
30	1.46	400	2.7	0.260	13.3	19.9	55	10.4	240
31.1	0.77	420	2.9	0.220	12.4	12.8	48	10.3	178
31.2	4.60	580	7.6	0.450	20.0	41.0	93	13.8	410
32	4.40	785	11.9	0.340	32.5	31.0	64	17.4	365
33	2.50	1020	9.9	0.153	21.0	16.1	39	11.3	136
34	2.50	1240	11.5	0.122	26.0	18.6	35	14.0	134
35	1.43	730	7.1	0.220	38.0	21.0	34	15.1	128

Table 12-9: Results for PAHs.

Site No.	Acenaph-thene	Acenaph-thylene	Anthra-cene	Benzo[a]-anthra-cene	Benzo[a]-pyrene	Benzo[b]-+Benzo[j]-fluoran-thene	Benzo[k]-fluoran-thene	Benzo-[g,h,i]-perylene
1	0.014	0.010	0.046	0.192	0.210	0.220	0.096	0.135
2	0.010	0.039	0.075	0.490	0.590	0.630	0.280	0.420
3	0.005	0.011	0.020	0.098	0.128	0.156	0.064	0.102
4	0.004	0.008	0.021	0.072	0.090	0.112	0.046	0.080
5	0.011	0.014	0.036	0.144	0.178	0.210	0.088	0.136
6	0.007	0.021	0.069	0.240	0.220	0.240	0.110	0.124
7	0.009	0.015	0.033	0.176	0.220	0.250	0.109	0.157
8	0.007	0.016	0.035	0.173	0.220	0.250	0.105	0.164
9	0.020	0.020	0.112	0.390	0.415	0.500	0.215	0.315
10	0.005	0.032	0.092	0.280	0.230	0.250	0.116	0.124
11	0.004	0.015	0.036	0.179	0.200	0.230	0.090	0.143
12	0.033	0.072	0.158	0.980	1.400	1.550	0.730	0.760
13	0.043	0.144	0.220	2.100	3.100	3.700	1.630	2.300
16	0.010	0.044	0.095	0.660	0.880	0.920	0.410	0.560
17	0.013	0.027	0.047	0.270	0.370	0.420	0.175	0.300
18	**0.88**	**5.8**	**14**	**28**	**27**	**53**	**21**	**27**
19	0.021	0.053	0.095	0.420	0.510	0.690	0.280	0.460
20	0.027	0.093	0.360	1.730	2.000	2.200	0.970	1.350
21	0.022	0.056	0.117	0.440	0.610	0.770	0.310	0.530
22	<0.004	0.015	0.034	0.150	0.171	0.230	0.094	0.124
23	0.004	0.015	0.025	0.199	0.260	0.370	0.144	0.250
24	<0.002	<0.002	<0.002	0.004	0.005	0.006	0.003	0.003
25	<0.003	0.003	0.003	0.025	0.035	0.046	0.016	0.030
26	0.026	0.034	0.111	0.920	1.000	1.210	0.550	0.570
27	0.024	0.043	0.091	0.610	0.670	1.110	0.480	0.590
28	0.010	0.039	0.064	0.880	0.960	1.240	0.540	0.550
29	0.022	0.052	0.115	1.440	1.500	1.980	0.880	0.790
30	0.039	0.106	0.370	2.700	2.700	3.400	1.570	2.000
31.1	0.026	0.039	0.097	0.940	0.980	1.260	0.560	0.550
31.2	0.019	0.054	0.076	0.640	0.790	1.180	0.440	0.690
32	0.016	0.048	0.072	0.550	0.660	0.940	0.355	0.545
33	0.011	0.049	0.063	0.550	0.680	0.950	0.370	0.610
34	0.004	0.013	0.019	0.129	0.165	0.250	0.086	0.130
35	0.004	0.013	0.018	0.112	0.159	0.250	0.088	0.138

Table 12-10: Results for PAHs (contd).

Site No.	Chry-sene	Dibenzo-anthra-cene	Fluoran-thene	Fluo-rene	Indeno (1,2,3-c,d)-pyrene	Naphtha-lene	Phenan-threne	Pyrene	Sum of PAHs
1	0.192	0.032	0.400	0.020	0.158	0.043	0.200	0.380	2.3
2	0.520	0.080	1.090	0.027	0.480	0.022	0.410	1.070	6.2
3	0.114	0.018	0.220	0.010	0.112	<0.011	0.117	0.230	1.4
4	0.086	0.013	0.178	0.010	0.080	<0.011	0.110	0.182	1.1
5	0.158	0.024	0.330	0.019	0.145	0.039	0.194	0.330	2.1
6	0.220	0.032	0.540	0.028	0.158	<0.010	0.400	0.490	2.9
7	0.200	0.031	0.430	0.021	0.177	<0.010	0.240	0.410	2.5
8	0.193	0.026	0.430	0.017	0.174	0.014	0.230	0.420	2.5
9	0.375	0.069	1.085	0.042	0.295	0.010	0.620	1.035	5.5
10	0.240	0.036	0.530	0.024	0.157	<0.010	0.300	0.480	2.9
11	0.167	0.031	0.380	0.010	0.134	<0.010	0.162	0.365	2.1
12	0.970	0.139	2.700	0.083	0.800	0.036	0.980	2.600	14.0
13	2.300	0.300	5.900	0.087	1.760	0.066	2.200	5.600	31.5
16	0.700	0.100	1.700	0.023	0.590	0.013	0.600	1.630	8.9
17	0.270	0.051	0.610	0.022	0.330	0.025	0.260	0.620	3.8
18	**49.000**	**3.500**	**90.000**	**3.400**	**20.000**	**2.200**	**73.000**	**88.000**	**505.8**
19	0.480	0.086	1.060	0.061	0.490	0.025	0.550	1.140	6.4
20	1.510	0.178	3.900	0.078	1.030	0.032	1.820	3.800	21.1
21	0.540	0.107	0.960	0.064	0.570	0.030	0.590	1.000	6.7
22	0.146	0.032	0.400	0.011	0.093	<0.02	0.220	0.380	2.1
23	0.192	0.046	0.420	0.010	0.171	<0.017	0.128	0.430	2.7
24	0.003	<0.002	0.009	<0.002	0.002	<0.010	0.006	0.009	0.1
25	0.024	0.006	0.054	0.002	0.020	<0.011	0.023	0.056	0.4
26	0.840	0.130	2.000	0.040	0.430	0.018	0.800	1.930	10.6
27	0.620	0.122	1.600	0.059	0.430	0.030	0.820	1.430	8.7
28	0.770	0.122	1.600	0.022	0.420	0.021	0.430	1.550	9.2
29	1.250	0.199	2.700	0.051	0.610	0.027	0.830	2.600	15.0
30	2.200	0.490	5.200	0.111	2.400	0.067	2.400	5.000	30.8
31.1	0.790	0.139	1.920	0.059	0.410	<0.011	0.610	1.830	10.2
31.2	0.630	0.169	1.440	0.036	0.510	<0.030	0.570	1.380	8.6
32	0.550	0.140	1.215	0.047	0.410	<0.019	0.505	1.135	7.2
33	0.590	0.160	1.230	0.028	0.470	<0.014	0.440	1.160	7.4
34	0.119	0.035	0.270	0.011	0.099	<0.011	0.112	0.260	1.7
35	0.110	0.035	0.270	0.013	0.102	<0.012	0.112	0.260	1.7

Table 12-11: Semi-volatiles detected in five samples selected for additional analysis.

Compound	Site 7 (Avon headwaters)	Site 27 (Avon u/s CBD)	Site 30 (Avon d/s CBD)	Site 33 (Avon mouth)	Site 18 (Dudley Creek)
Bis(2-ethylhexyl)phthalate	0.7	3.6	4.5	In Progress	1.2
Carbazole	< 0.16	< 0.3	0.24	< 0.3	0.9
Dibenzofuran	< 0.16	< 0.3	0.24	< 0.3	0.5

Table 12-12: PAHs in sediment from lower Dudley Creek.

Compound	Initial result	Reanalysed result	SVOC suite result
Acenaphthene	0.88	0.041	0.28
Acenaphthylene	5.8	0.096	1.26
Anthracene	14	0.26	2.3
Benzo[a]anthracene	28	1.47	10.2
Benzo[a]pyrene (BAP)	27	1.62	9.4
Benzo[b]fluoranthene + Benzo[j]fluoranthene	53	1.93	9.4
Benzo[k]fluoranthene	21	0.83	4.2
Benzo[g,h,i]perylene	27	1.23	5.7
Chrysene	49	1.43	8.2
Dibenzo[a,h]anthracene	3.5	0.32	1.8
Fluoranthene	90	5.3	21
Fluorene	3.4	0.086	1.18
Indeno(1,2,3-c,d)pyrene	20	1.04	4.9
Naphthalene	2.2	0.065	< 0.14
Phenanthrene	73	1.55	14.7
Pyrene	88	4.5	17.4
Sum of PAHs	505.8	21.768	111.92

Appendix D Additional Plot

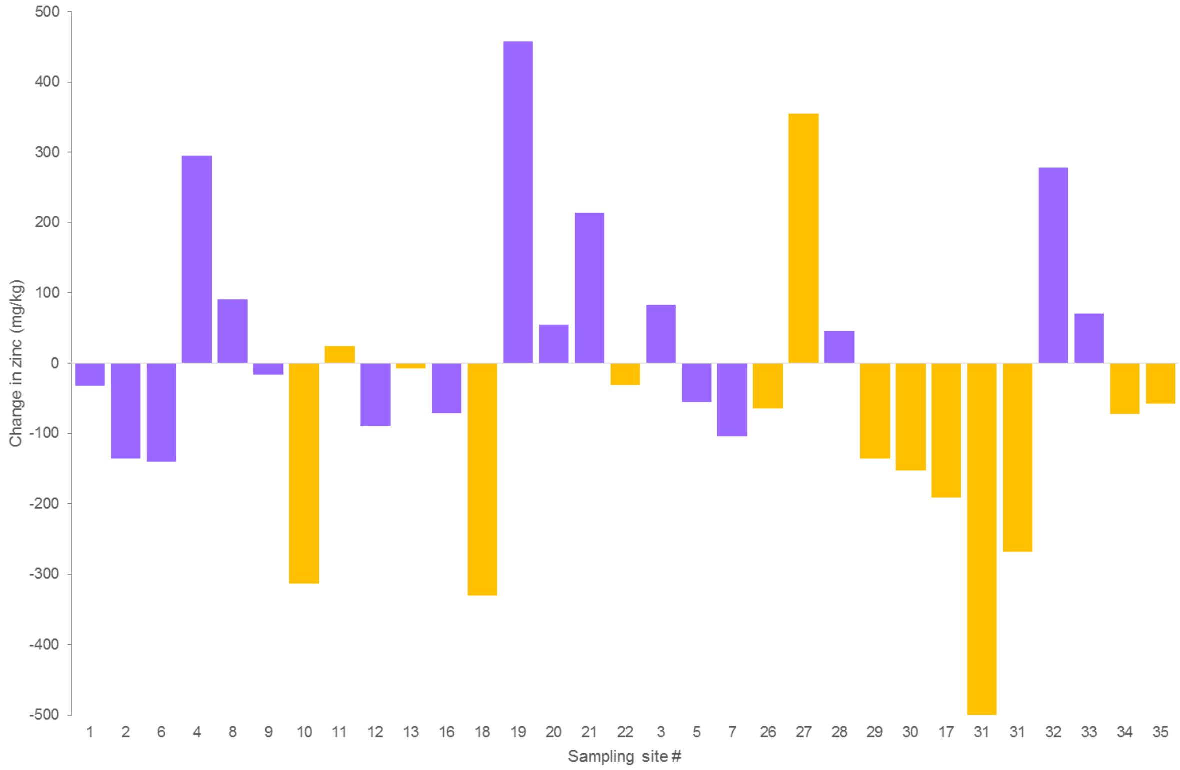

Figure 12-3:Change in zinc concentrations between previous (Robb 1988) and current surveys, showing sites with observed liquefaction in yellow.