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Management & treatment of stormwater quality effects in estuarine areas

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Abstract

Long term monitoring of the coastal aquatic environment is one of the key management tools used by the ARC to manage point and diffuse source stormwater pollution from urban areas. There are strong linkages between the state of the environment (estuarine water and sediment quality), the pressures or causes (urban stormwater, waste water overflows) and management responses (catchment management, waste water management, public education). These linkages can be quantified by monitoring marine sediment contamination (copper, zinc, lead, PAH, organochlorines), benthic invertebrate communities, water quality and pathogenic indicators. Monitoring assesses the state of the environment, which then allows informed decisions to be made on priorities for investigations and management.

Once priorities for catchment investigation are identified, contaminant loads and sources, and in turn options for the reduction of contaminant inputs can be assessed. This technical publication assesses the effectiveness of stormwater treatment ponds of a range of sizes, to reduce copper and zinc contaminant loadings and predicts the long term accumulation of those contaminants in three estuarine settling zones. The results can be used by practitioners guide catchment management planning based on a knowledge of receiving environment effects.

Results show that ponds can reduce the rate of contaminant accumulation in estuaries. However the levels of treatment currently feasible will not completely prevent adverse effects in the long term. In highly contaminated estuaries, it is unlikely that traditional stormwater treatment ponds alone will prevent further receiving environment degradation. In more urbanised catchments, where the opportunities to retrofit traditional treatment technologies are limited, more innovative treatment options will need to be considered and source control will need to play an integral role in reducing contaminant generation.

While current treatment pond technology is unable to totally prevent long term adverse effects from occurring in the settling zone of an estuary, it is still a useful tool in the mitigation of sediment quality contamination. This is because any reduction in the rate of increase of contaminant concentrations in the estuaries reduces the risk of those contaminants spreading into the wider harbour. Ponds therefore provide time for new technology and source controls to be developed and implemented. In this publication lead is cited as an example of how successful source control can dramatically reduce contaminant concentrations in estuaries.

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1 Introduction

1.1 General

The Auckland Regional Council (ARC) has recently carried out sediment quality and benthic ecology monitoring at a number of Auckland's urbanised estuaries. This monitoring shows that in 29% (n=97) of estuarine locations sampled, zinc exceeds the "amber" (or initial threshold for investigations and action) Environmental Response Criteria (ERC) set out in the Proposed Regional Plan: Coastal (PRP:C). Levels of copper, lead and PAH also exceed the ERC "amber" levels in a number of locations. Under the PRP:C, exceedance of the amber ERC initiates investigations into the source of contaminants so that options can be assessed for reducing contaminant inputs to the estuary. The background to the ERC trigger levels and the recent monitoring results are summarised in the papers: "Auckland's Regional Discharges Project: The tools used to monitor the state of the coastal environment", Becker (2003) and "Auckland's Regional Discharges Project: The current and future state of Auckland's coastal receiving environment", Williamson (2003). The methodology behind the establishment of the ERC is set out in TP168 and the resulting of monitoring at ERC monitoring sites is set out in TP203.

The ARC is currently managing the consent process for discharges from approximately 80% of urban stormwater catchments across Auckland under the Regional Discharges Project framework. The maintenance or enhancement of estuarine ecological values is one of the key drivers for the consent process, and heavy metal contamination is a primary adverse effect on those values. However, the long term effectiveness of typical stormwater treatment technologies in terms of metal removal needs to be assessed so that stormwater treatment and management works can be designed to adequately meet receiving environment objectives and catchment management is planned on the basis of reasonably likely receiving environment benefits.

Hydrodynamic harbour modelling is one tool that takes land-use contaminant loadings and predicts the areas where those contaminants will settle in the receiving environment. However, a harbour model is unable to effectively predict the long term contaminant accumulation in estuarine settling zones due to the large number of model iterations required and potential model instability. The ARC is therefore using the Urban Stormwater Contaminant (USC) spreadsheet model for making these long term predictions. This simple model has been shown to predict present concentrations reasonably well (Williamson et al. 1999). Its use in this study, to predict concentrations far into the future, is subject to uncertainty, so the model outputs can only be regarded as indicative. The wider use of the USC model is promoted by the

ARC and NSCC, for example, is now using it as part of its catchment management planning process.

This publication assesses the effectiveness of stormwater treatment ponds of various sizes to reduce copper and zinc contaminant loadings in stormwater discharges and predicts the long term accumulation of those contaminants in three estuarine settling zones. This illustrates how future catchment management planning can be guided by the knowledge of treatment effectiveness and receiving environment benefits. Where "standard" levels of treatment are able to achieve "acceptable" contaminant reduction (as determined through the consent process) no further investigations are generally required. However, where standard levels of treatment are inadequate (after considering environmental, technical and financial constraints under a BPO framework) additional contaminant reduction techniques will need to be developed or the catchment management objectives reviewed. Additional contaminant reduction techniques that could be considered are: advanced or innovative treatment methods such as stormwater flocculation, high efficiency street sweeping and contaminant source control. Source control will require a multi-party approach and may need to include central government involvement to effectively implement. In the long term the effectiveness of stormwater treatment and management controls will be assessed by the ARC through further monitoring of estuarine sediment quality.

1.2 Regional Discharges Project

Network operators throughout the Auckland Region have applied to the ARC for resource consents to allow the continued operation and ongoing development of their wastewater and stormwater networks.

The network operators are primarily the territorial local authorities of the Auckland region and Watercare Services Ltd. Their applications are all made on a catchment, super-catchment or whole network basis. Combined, the applications represent approximately 80% of stormwater catchments in the urbanised Auckland area and all major urban wastewater networks

These consent applications are being processed under an ARC initiative called the Regional Discharges Project (RDP). The issues involved in the RDP are complex, with the potential to have a major effect on all residents and ratepayers in the Region.

The scale and extent of the applications presents a unique opportunity for the Auckland regional community to better manage stormwater and wastewater discharges. The overall strategic aim of the RDP is to ensure that, taking into account public expectations and affordability, discharges from stormwater and wastewater networks are managed so as to minimise adverse effects on the environment.

1.3 State of the Environment

1.3.1 Regional Picture

The present state of the Auckland marine receiving environment is summarised in Figures 1-3. Highest concentrations of the three primary heavy metals (copper, lead and zinc) are found in the settling zones of catchments with the longest history of urbanization (e.g., Motions, Meola, Coxes, Whau, Upper Tamaki, Mangere Inlet). Nevertheless, even relatively recently developed catchments, such as those developed at the start of the Auckland's rapid population expansion in the 1950's to 1970's, experience relatively high concentrations of zinc and lead (e.g., Pakuranga, Henderson).

In contrast, and not surprisingly, most settling zones and outer zones away from the main urban areas that have catchments predominantly in rural land use, have low concentrations of those metals (e.g., Orewa, Puherehere Inlet, Waiuku). Small sheltered muddy estuaries are also susceptible to rapid metal contamination (e.g., Deep Creek at Torbay) as they have relatively large urban catchments which provide more contaminants.

Zinc clearly stands out as the metal most likely to exceed the "red" ERC. Copper is least likely to exceed the "red" status. Both copper and lead fall within the amber status much more frequently than zinc, in about equal numbers. Lead concentrations are decreasing, while zinc and copper are generally increasing (see below).

1.3.2 Future Trends

The ARC operates a Long Term Baseline Marine Sediment Monitoring Programme that involves collecting composite samples of sediment from 27 estuarine and harbour sites, mostly close to urban areas, throughout the Auckland region. (ARC 1998a, ARC 1999, Mathieson et al. 2002). Trends over 1998-2001 were examined for zinc, copper and lead in the mud fraction (<63 µm) of the sediment and for high molecular weight polycyclic aromatic hydrocarbons (PAH) in the <500 µm sediment fraction (Timperley and Mathieson, 2002).

Trend analysis of the ARC Long Term Baseline monitoring programme demonstrates that zinc and copper concentrations are clearly increasing at many sites, while lead concentrations are decreasing.

Figure 1: Copper Sediment Quality ERC

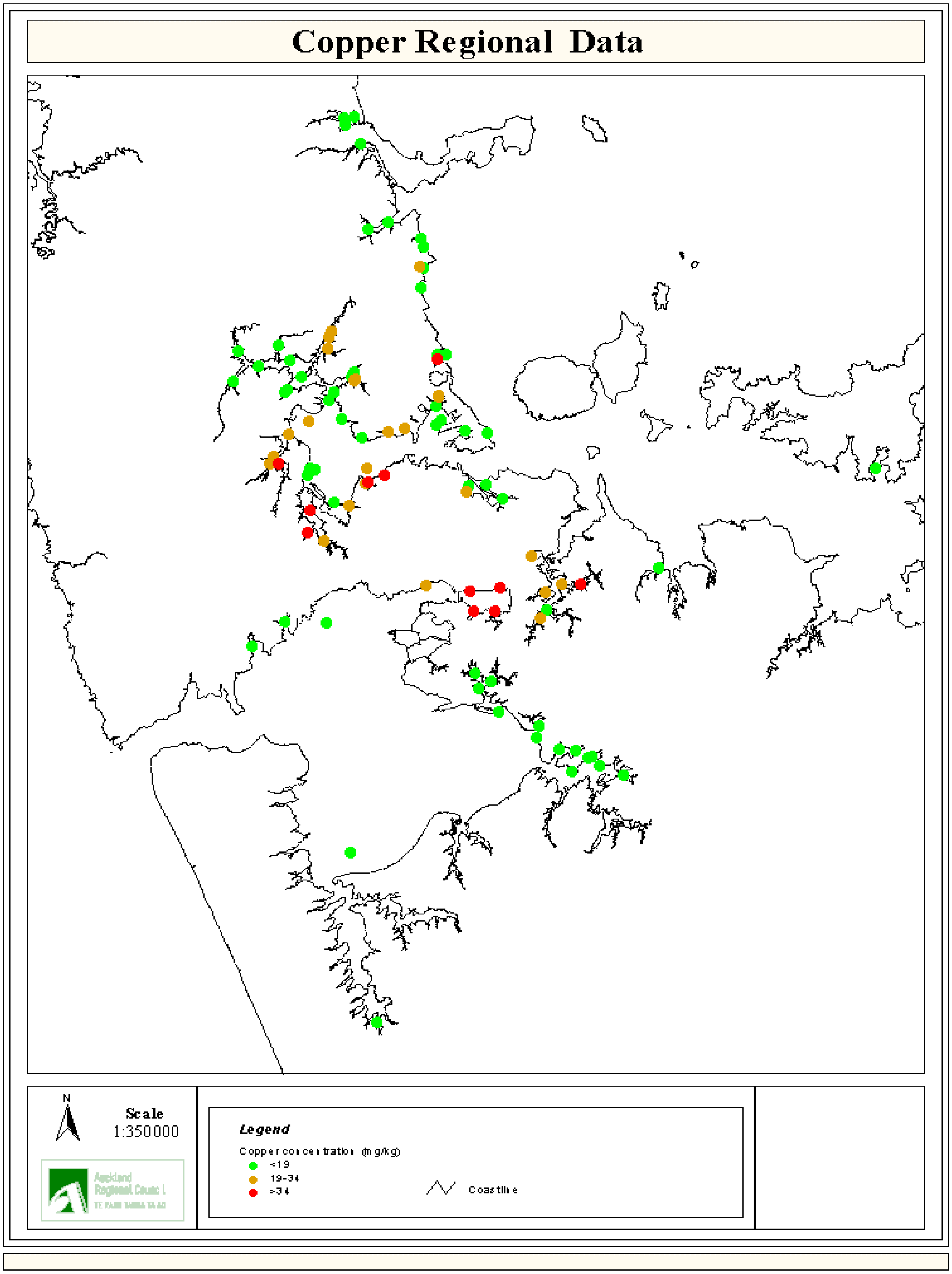


Figure 2: Lead Sediment Quality ERC

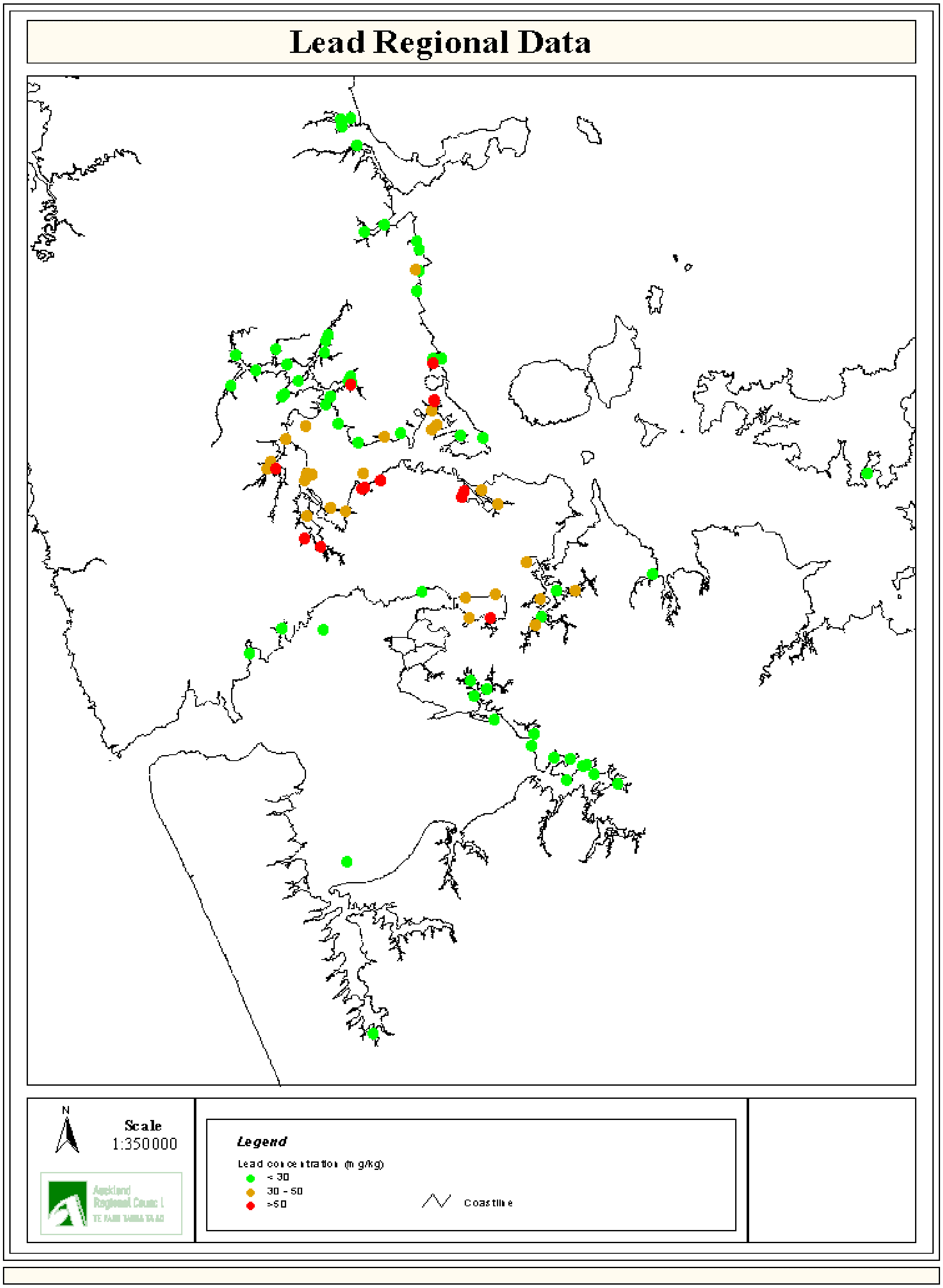
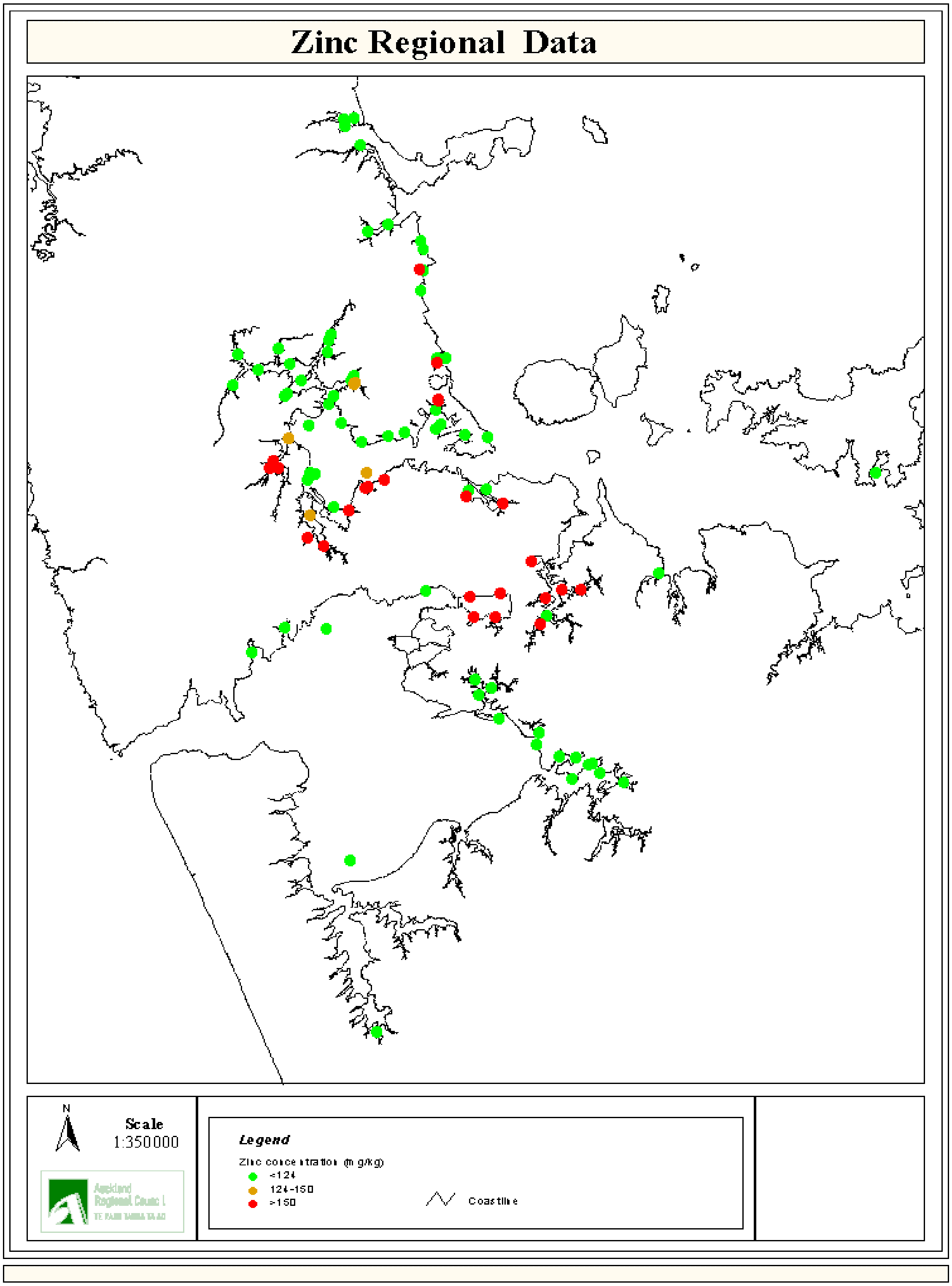


Figure 3: Zinc Sediment Quality ERC



The sites with the highest rates of zinc accumulation, about 24 mg kg^{-1} yr^{-1}, are those in the upper Whau River estuary. If these trends continue, concentrations will double in 15 years. Copper concentrations are also generally increasing at rates about 1/8th of those for zinc, but at many sites, little change is discernable over the short period of monitoring conducted to date. Lead concentrations are decreasing at all sites, no doubt because of the gradual removal of lead in petrol from 1986 - 1996. Note that even sites with small urban areas, such as Big Muddy estuary, are showing decreasing trends in lead levels.

Stratigraphic information from cores taken in urban estuaries confirms the increase in copper, lead and zinc with change in land use from rural to urban. It also confirms the more recent decrease in lead (ARC 1994, Swales et al. 2002, Williamson et al. 2003).

Despite the recent reduction in lead concentrations, modelling of estuarine sediment contamination suggests that there will still be an ongoing deterioration in sediment quality in many of Auckland's urbanised estuaries through the accumulation of zinc and copper if present stormwater discharges continue unabated (ARC 1998b, Williamson et al. 1999).

1.3.3 The Importance Of Particle Size On Bioavailability And Fate

Heavy metals can be added to the environment by either being bound to sediment particles or as dissolved species. For example, one of the major sources of zinc is tyre wear. It can therefore be found on street surfaces in particles of rubber, and be transported via stormwater runoff to the aquatic receiving environment in this form. However, much of the zinc is present as zinc oxide (ZnO), which is sparingly soluble, so it can dissolve in rainwater and be transported to the aquatic receiving environment in solution. Another major source of zinc is galvanised iron on roofs. Electrolytic dissolution of the zinc coating on galvanised iron adds zinc to rainwater as the dissolved form. Paints contain zinc – often ZnO – so particulate zinc can also be found in roof runoff as paint particles. ARC has released a separate Technical Publication on the effects of roof runoff – TP213 A Study of Roof Runoff Quality in Auckland NZ.

In its dissolved form, zinc is quite reactive and easily adsorbed onto particulate matter. In urban streams, zinc concentrations may be high enough to exert toxicity on some organisms.

The following conceptual picture emerges on the changes in the form of zinc in urban stormwater runoff. At source, a high proportion of the zinc is in the dissolved form. As it is carried through the drainage network, dissolved zinc gradually decreases as zinc adsorbs to particles (Timperley 2003).

The sources of copper in the urban environment are probably particles from the abrasion of vehicle brake linings, naturally occurring copper in soils, cement and roading materials, and dissolved copper from spouting and potable water (e.g., from car washing). In contrast to zinc, little is known on the dynamics of copper speciation as it is carried through the stormwater system.

In an estuary, most of the zinc and copper is particulate, because dissolved zinc or copper tends to adsorb to particles.

The impact on aquatic life in the ultimate receiving water depends on the bioavailability of the contaminants. Bioavailability depends on the form of the heavy metal present in the estuarine sediments. In sediments with high metal concentrations, dissolved metal concentrations can build up in pore water (interstitial water) from chemical reactions in the sediment. They can affect some animals living in the sediments through this media. Alternatively, metals may affect animals through the digestion of metal-contaminated particles. In this case, smaller (silt-sized) particles are more important than larger particles, because they are more commonly ingested by animals living in the sediment. However, estuarine sediments are dynamic, and the chemical, biological and physical processes that occur in the estuary can cycle the metals through many different forms over a long time period.

1.4 Policy Framework

1.4.1 Environmental Response Criteria

In early 2002, the ARC introduced measurable Environmental Response Criteria (ERC) for the urban coastal marine area (CMA) into the statutory regional planning framework. The policy direction and support for doing that was contained within the Auckland Regional Policy Statement (ARPS) and the Proposed Auckland Regional Plan: Coastal. The ERC are monitoring benchmarks that quantify sediment and water quality concentrations at which adverse environmental effects may arise. Understanding whether or not particular parts of the urban CMA are contaminated will allow stormwater and wastewater contaminant discharges to be managed in a prioritised and cost effective manner. This in turn will help to achieve the vision for coastal water quality in the Auckland region set out in the ARPS.

The policy framework for discharges to the CMA is set out in Chapter 20 of the Coastal Plan. Policies 20.4.3 and 20.4.4 of that chapter are the main policies to be considered for stormwater and wastewater discharges. Policy 20.4.3(d) of the Plan refers to degraded areas shown on maps contained in the ARPS, providing some indication of areas within the urban CMA that may be contaminated above guideline values. Policy 20.4.3(j) of the Plan allows the use of "relevant, appropriate and accepted international or national Codes of Practice and Environmental Guidelines" to gauge environmental quality. However, no direction was given as to the specific criteria that should be used.

Variation 1 to the Coastal Plan provides a specific means of measuring the extent to which the ARPS and Coastal Plan vision for urban coastal water quality has been achieved by setting ERC for the urban coastal marine area. The ARC does not assume that the ERC will be "achieved" as such, but rather that they will serve as measures of environmental quality so that progress toward the vision can be monitored over time and, where appropriate, the need for environmental enhancement can be balanced against other social and economic considerations.

The sediment quality and water quality criteria have been derived using the process recommended in ANZECC for taking the ANZECC guidelines values and making them specific to a local region.

The Variation to the Coastal Plan includes the following items:

(a) Maps of settling zone and outer zone[1] areas;

(b) ERC for sediment quality, water quality and contact recreation.

No numerical criteria are proposed to represent ecological communities, fishing and shellfish gathering, cultural or aesthetic values.

The ARC has set an ERC for microbiological contamination from wastewater discharges as the number of contact recreation beach closures.

The following sets out how the ERC will be used, the key decisions to be made when using them and provides guidance for their use and implementation.

The ERC for sediment and water quality will be used as surrogates for ecological quality and will generally be used as follows:

(a) Areas will be assessed for sediment quality through robust field monitoring;

(b) The ARC will co-operate with any organisations discharging to degraded areas to identify the most likely sources of contamination. This will involve an assessment of the physical pathways for discharges to contribute to the degraded area (for significant discharges this may require the use of a computerised hydrodynamic model of the harbour – such as the "Hauraki Regional Harbour model");

(c) Areas not meeting the "green" primary contaminant sediment criteria will have a benthic ecology assessment undertaken and may be further investigated for secondary contaminants, bioavailability, and/or toxicity to determine if there are significant adverse effects likely to be occurring within the receiving environment;

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[1]These are primarily planning boundaries. The settling zone (SZ) is a specific area where catchment derived contaminants settle and accumulate. It is defined in size and location. Originally, it was envisaged that a SZ would trap 75% of the suspended sediment, however the SZ concept has been modified to take into account less efficient settling encountered in Auckland intertidal estuaries. The outer zone (OZ) is the area beyond the SZ, which is still impacted by stormwater runoff, but to a lesser extent.

(d) Generally, discharges to estuarine settling zones within the urban area that have "amber" or "red" levels of sediment contamination should be managed to ensure that contamination of outer zones and the wider harbour does not occur. However, the ARC acknowledges that in some cases the maintenance or reduction of a receiving environment's contamination status may not be practicable or affordable, or may only be possible over a long period of time;

The ERC for contact recreation (or indicators of microbiological contamination) will be used as assessment criteria in consent processing.

Ideally steps (a) through to (d) would occur as part of the investigations undertaken by the network operators who have applied to renew their existing network discharge consents that expired in March 2001. As such, the identification of degraded areas and the assessment of the appropriate BPO approach for dealing with discharges to those areas would form part of the risk based approach being adopted by most (if not all) network operators. The ARC completed stage (a) of the process in March 2003 and is currently working with some applicants (including ACC and NSCC) on step (b).

It is important that all parties have certainty and clarity regarding how the ERC will be used. Figure 4 sets out a flow chart which describes the process of monitoring, evaluation and investigation set out by the ERC process in relation to sediment quality monitoring for ecological values. Refer to ARC TP168 for more details of this process.

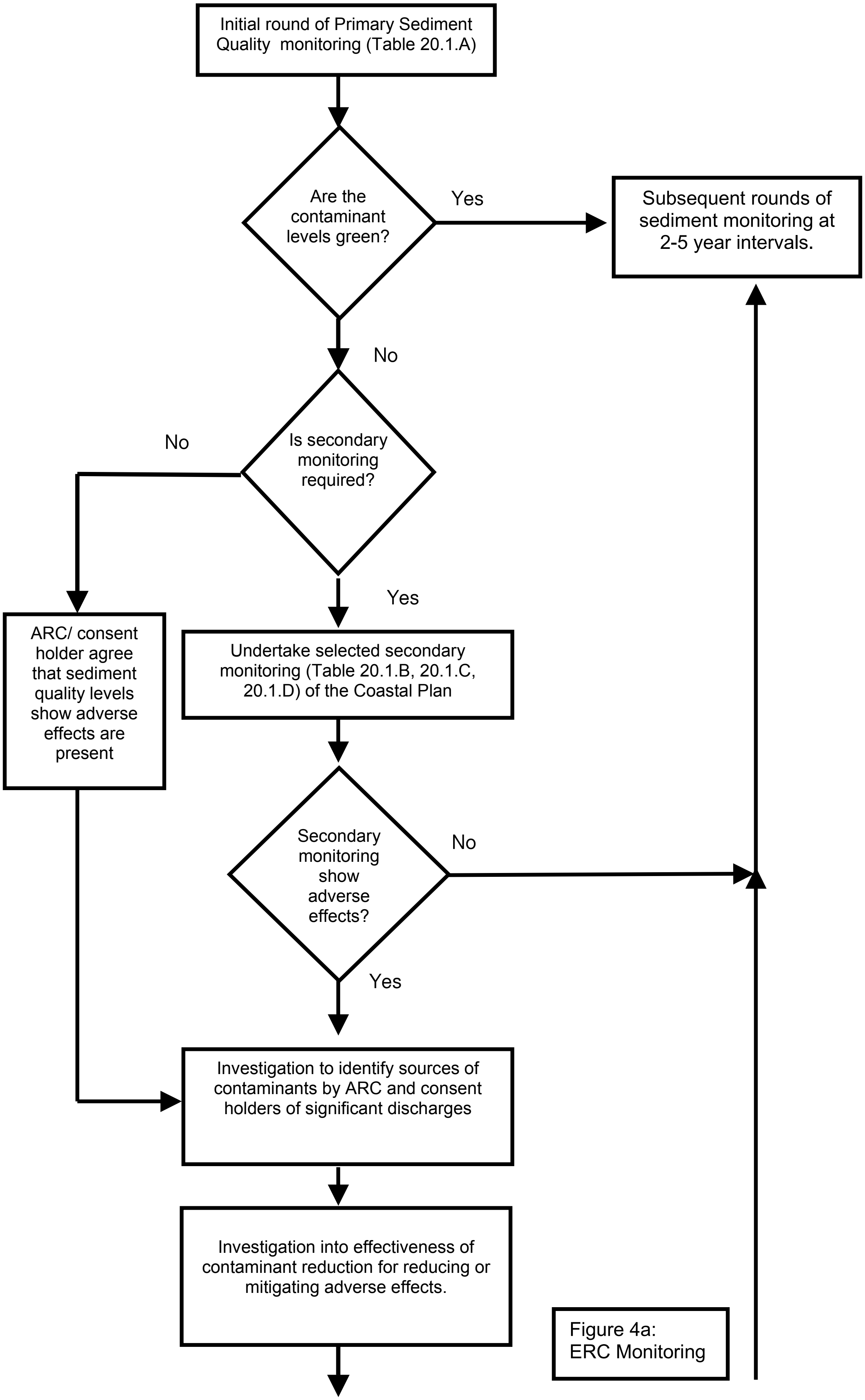

Figure 4a:
ERC Monitoring

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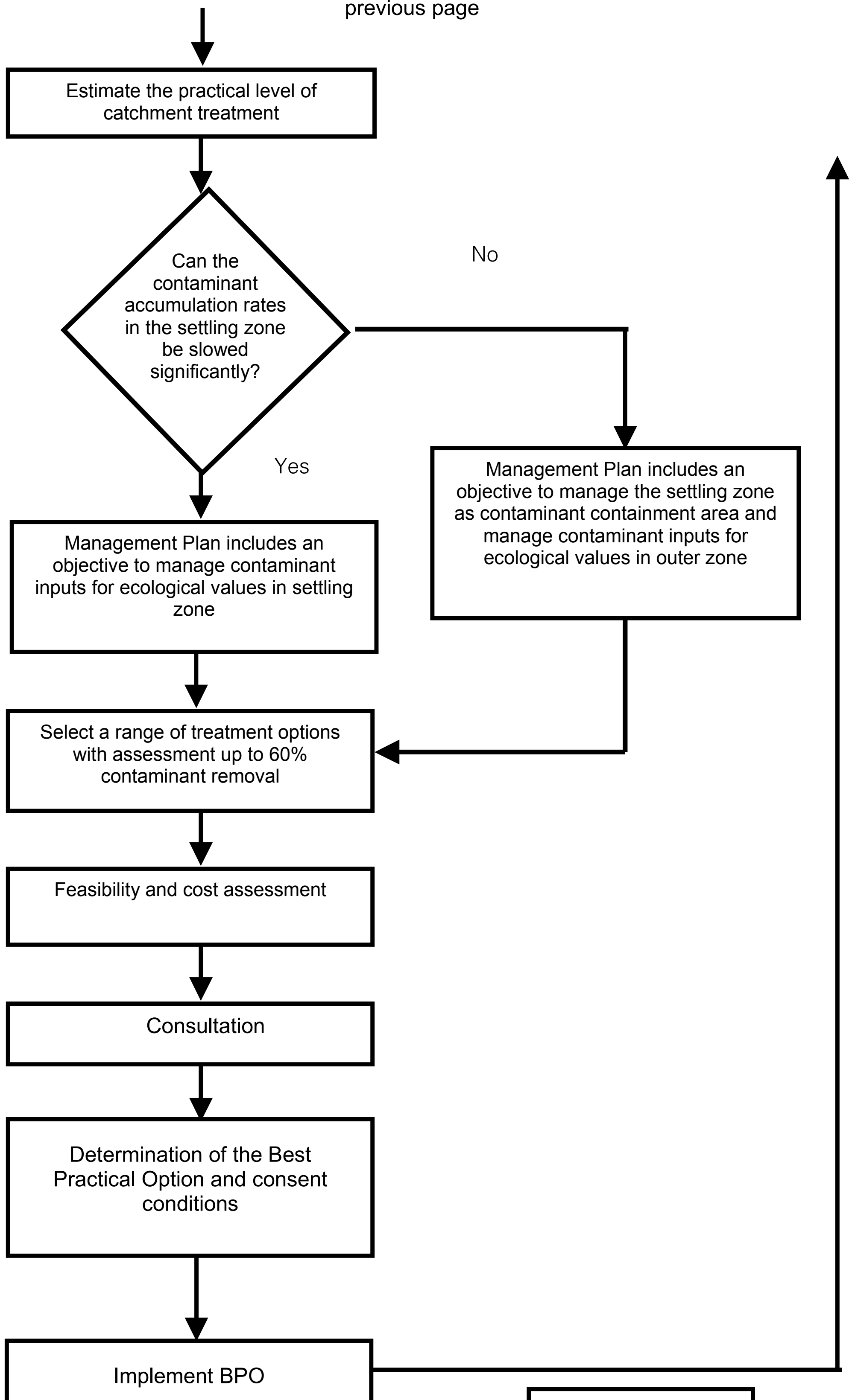


Figure 4b:
ERC Monitoring

1.5 Secondary Monitoring

Additional monitoring may be required to confirm whether or not there are adverse effects on marine ecology in the receiving environment. The trigger levels for the primary sediment contaminants have been correlated with the health of benthic ecology and ARC therefore expects adverse effects to be present for the red trigger levels in Table 20.1.A of the Coastal Plan. However, in individual cases, either the ARC or consent applicants may initiate additional monitoring to confirm the presence of adverse effects. This may be either in terms of further sediment quality monitoring (Table 20.1.B), water quality monitoring (Table 20.1.C) or benthic ecology monitoring (Table 20.1.D).

If no secondary monitoring is undertaken and the primary contaminant trigger levels have exceeded the red or amber levels, the ARC will generally consider that there are adverse effects occurring . Investigations would therefore proceed to the assessment of practicalities of contaminant input reduction.

No secondary monitoring is required where the settling zone has been graded green by the primary sediment quality monitoring parameters in Table 20.1.A.

The decision to carry out further monitoring should be guided by the following criteria:

1. The purpose of secondary monitoring should be in relation to ecological values only. Secondary monitoring is not required to support investigations into contact recreation effects;
2. Benthic ecology monitoring will be carried out in all settling zone sites, adjacent to the location of the site where primary sediment samples were taken from;
3. Benthic ecology monitoring will be carried out in the outer zone when the primary sediment quality monitoring in the outer zone has been graded as amber or red;
4. Sediment quality monitoring for the parameters set out in Table 20.1.B will be carried out where benthic ecology monitoring shows adverse effects to a red grading;
5. Water quality monitoring for the contaminants set out in Table 20.1.C will be carried out, adjacent to the location of the settling or outer zone site, where a long term water quality issue may exist, such as:
    - i) the site has limited tidal water flushing; and,
    - ii) there are significant wastewater overflows (or other human derived nutrient sources) potentially degrading water quality at the site.

Interpretation of the primary sediment quality monitoring should be undertaken using the tables contained in the Appendices to TP 168.

Confirmation of toxicity is optional. The ANZECC guidelines allow for the confirmation of adverse effects by toxicity testing and this step is therefore identified here.

ARC has avoided this step by generally correlating contaminant levels directly to benthic ecology. However, if desired by the applicant, additional monitoring of the toxicity of contaminants in the settling zone and outer zone may be undertaken to confirm the bio-availability of contaminants and the toxicity of contaminants to organisms.

2 Methodology

2.1 Study Catchments

The Motions, Wairau (to Whau Creek) and Kaipatiki catchments have been chosen for the analyses reported in this publication.

Catchment	Area (ha)	Imperviousness (%)
Motions	430	52
Wairau, (to Whau Creek)	410	33
Kaipatiki	905	31

2.1.1 Motions Catchment – History

The Motions catchment is located within the central Auckland isthmus and contains a central section of the North-western motorway, the Zoo, Western Springs park and Seddon fields as well as residential areas (established in the early 1900s), giving an area of 391 ha. The catchment will have a further 42 ha added to it from the Basque Park (landlocked) catchment to the north east. The upper catchment is a natural valley with reasonably steep sides (approx 7%) through which the north-western motorway runs. Lower parts of the catchment are reasonably flat (< 0.1% stream gradient). The catchment is primarily serviced by combined sewers but there are plans for these to be separated. Seddon fields is an old rubbish dump and a possible source of contaminants. The estuary sides are well defined by cliffs to the east and the Meola reef to the west. The extent of the settling zone out into the harbour is less clear. ARC long term baseline monitoring of sediment quality in the estuary indicates high levels of zinc (about 280ppm), copper and PAHs. The PAH exceed Effects Range – Low and is the highest monitored level of PAH from all the LTB and RDP sites in the region.

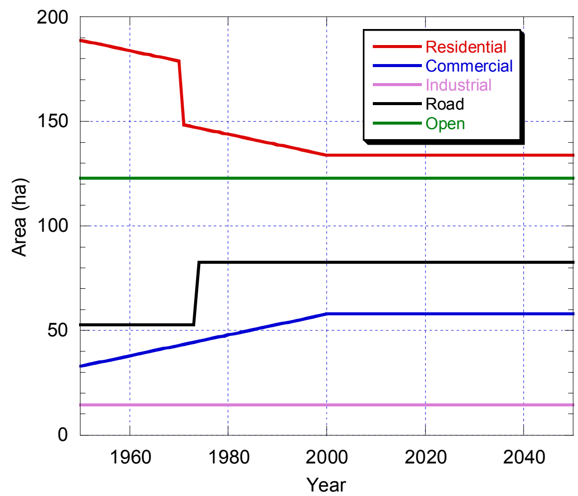
The land use history for the catchment was extracted from the ARC GIS database (T. Batistich, pers. comm.). Unfortunately, both the information on history and land use was sketchy and there was a lot of missing or ambiguous data. From the existing and historical data, and information on the North Western motorway construction, the following history was constructed.

Prior to 1950, the catchment was fully developed but contained large open spaces (Chamberlain Golf Course, Auckland Zoo, Western Springs and Sir Keith Park). In

1970, 30 ha of predominantly residential land was taken for development of the NW motorway. It is assumed that this took place over two years during which time 30 ha of soils were exposed. It is also assumed that there was a gradual conversion of residential land to commercial land since the 1950s in the Newton area.

The land use pattern assumed in the modelling is shown in Figure 5.

Figure 5. Assumed land use history for Motions Creek catchment.

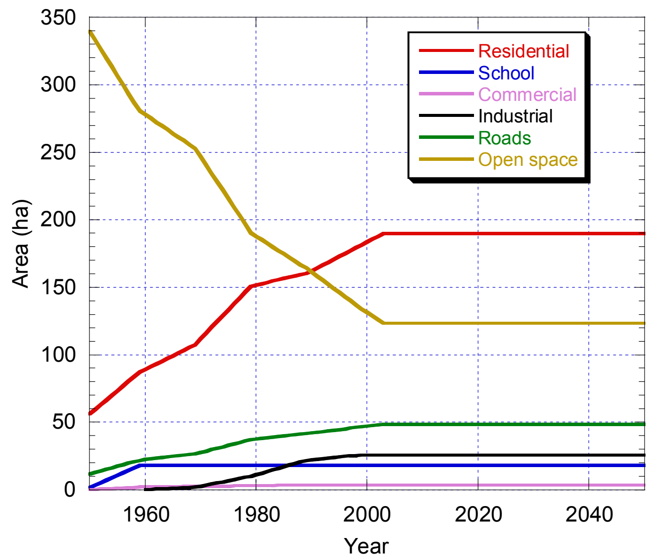


2.1.2 Wairau (to Whau Creek)

The Wairau catchment drains to the Wairau Creek, an arm of the Whau estuary and has two sub-catchments (Gabbens and Porters). There was no significant development in the catchment until the 1950s. The catchment is primarily residential with some light industrial and limited commercial land-use and contains the Waikumete cemetery (approximately 100 ha). Monitoring indicates that the sediment quality concentrations of zinc are about 280ppm and are expected to double to 600ppm within 12 to 15 years. This is a very high rate of increase and is of significant concern.

Land use was obtained from Waitakere City Council (K. Fan, pers. comm.) and from the ARC GIS database (T. Batistich, pers. comm.). The catchment with its history is shown in Appendix B. The Waitakere City data was adjusted slightly with reference to the ARC data, to obtain the following land use history (Fig 6).

Figure 6. Assumed land use history in the Wairau (to Whau Creek) catchment.

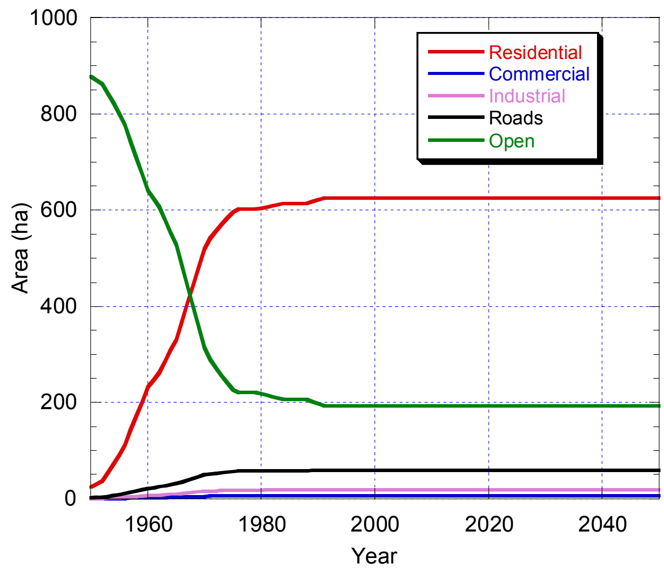


2.1.3 Kaipatiki

The Kaipatiki catchment is again primarily residential with limited industrial and commercial uses. Development is less intense due to the topography which comprises a series of valleys. Monitoring has identified estuarine zinc concentrations of about 140 ppm.

The present day Kaipatiki land use was obtained from North Shore City Council. Historical land use was obtained from Technical Publication 139 (ARC, 1998) – this history was based on records supplied by the North Shore City in map form, showing approximate locations and dates on consent application for development. This data was used to construct the following picture of land development. A small adjustment was made to the historical data reported in ARC (1998) to fit the recent land use information.

Figure 7. The assumed land use history of Kaipatiki Creek catchment.



2.2 Study Methodology

The aim of this study is to quantify the expected degree of contaminant removal from different levels of stormwater treatment and predict the resulting sediment quality concentrations in estuarine settling zones.

The treatment is provided by a theoretical single pond at the bottom of the catchment prior to discharge into the settling zone. The treatment levels assessed are: no treatment; 1m deep ponds designed in accordance with ARC TP10 (1992) for 30%, 50% and 75% TSS treatment levels; typical wet pond contaminant reduction percentages from pond monitoring data and typical contaminant concentrations in wet pond effluent from monitoring data. Monitoring data has been taken from New Zealand and overseas investigations into pond efficiency.

The three catchments selected for this study assessment are Kaipatiki, Motions and Wairau (to Whau Creek). Kaipatiki sediment quality is marginally below the red ERC trigger level and represents a situation where severe adverse ecological effects are not expected for some time. It therefore provides an opportunity to implement treatment prior to more severe effects occurring. Motions sediment quality has significantly exceeded a number of the ERC trigger levels within the settling zone and provides an example of treatment for a more severely impacted environment. Zinc concentrations are rapidly increasing in the Wairua (to Whau Creek) catchment.

The study methodology is summarised as follows:

1. Gather New Zealand contaminant land-use loading data, and contaminant and particle sizes associations.

- Collate stormwater quality data (Event Mean Concentrations) for various land-uses for input to the Urban Stormwater Contaminant (USC) model;
- Determine the typical split between dissolved and particulate contaminants for copper, lead, zinc;
- Determine the percentage of particulate contaminants associated with the five particle size groups used in the ARC TP10 stormwater treatment pond design methodology.

2. Identify contaminant removal rates for various stormwater treatment ponds.
    - Determine the theoretical particle removal rates for the five settling velocity groups (used in the TP10 underlying pond sizing methodology) for three real catchments with 1m deep ponds (1m deep taken as a typical pond depth) sized in accordance with TP10 for 30%, 50%, 60% and 75% TSS removal;
    - Apply the various particle size removal rates to the contaminant versus particle size association data to get the copper and zinc removal rates. Assume that treatment is only by sedimentation and therefore no dissolved contaminants are removed;
    - Review stormwater treatment pond monitoring data and select typical total metal removal rates and average total metal effluent concentrations.
3. Predict sediment concentrations in the settling zone of the estuaries for the three catchments for the range of contaminant removal rates.
    - Run the Urban Stormwater Contaminant (USC) model for the land use loading rates and no treatment;
    - Run the USC model with the land-use loading rates with treatment from the 30%, 50% and 75% TSS ponds, the total metal removal rates and effluent concentrations identified from the monitoring data;
    - Compare the time it takes for contamination in the settling zone to reach the sediment quality guideline where widespread biological effects are anticipated "Probable Effects Level" or "Effects Range-Median" under the different levels of stormwater treatment.

The study aims to put a number of catchment management techniques together to show how land-use planning and structural stormwater controls can be integrated and tested to guide catchment management planning. It also provides an indication of the overall usefulness of stormwater treatment and identifies the needs for future investigations by the ARC. The study is not designed to determine the appropriate level of treatment for any of the three catchments studied or replace more detailed investigations required for those catchments. Overall the level of accuracy is at a "planning" level. To take it to the stage required by a resource consent application would require further assessment of the potential for sub-catchments to deliver contaminants and assessment of treatment and management options within those sub-catchments.

The removal of suspended solids has been calculated using the method developed by Beca Carter Hollings and Ferner which was used in the determination of the Water Quality Volume for the original TP10 (ARC, 1992).

3 Contaminants

3.1 New Zealand loading rates

The following tables summarise the Event Mean Concentration (EMC) data collated for this study.

Table 1: NZ EMCs for total copper, g/m^3

All land-uses	Residential	Commercial	Industrial	Heavily trafficked	Source
Median EMC of events monitored					
0.028	0.009	0.0265	0.0475		Hamilton, NIWA, 2001
0.007	0.0066				Hamilton, new residential, NIWA, 2001
0.050			0.05		Pacific Steel, Leersnyder, 1993
0.035		0.035			Hayman Park, Leersnyder, 1993
0.008		0.008			Unitech sand filter, ARC TP48, 1994
0.013	0.013				Unitech 2002 data, Larcombe, 2002
0.042	0.042				Pakuranga, ARC TP5, 1989, Table A5.4
0.013	0.013				Pakuranga, ARC TP5, 1991, Table A5.5
0.042			0.042		Southdown, ARC TP5, Table A5.4
0.026	**0.017**	**0.023**	**0.047**		**Average of median EMCs**
Table 1 continued, Mean EMC of events monitored					
0.061	0.061				Wairau, North Shore, Williamson, 1986
0.025	0.25				Chartwell, Williamson, 1986
0.01	0.01				Pakuranga, ARC TP49, 1994
0.017	0.0115	0.0083	0.031		Rotorua, NIWA, 2002
0.0258	0.0258				Unitech, 1994 data, Larcombe, 2002
0.03				0.03	Swale study, 100m, Larcombe, 2002
0.03				0.03	Swale study, 50m, Larcombe, 2002
0.028	**0.027**	**0.008**	**0.031**	**0.030**	**Average of mean EMCs**
Literature Values					
0.040					Mean, Urban runoff data book, NIWA (1993)
0.047					NURP average, Fundamentals of Urban Runoff Management, Horner et al (1994)
	0.036	0.054	0.054	0.076	Median, Urban Stormwater Quality: a statistical overview, CRCCH (1999)

Note that lead was removed from petrol in New Zealand over the period 1986 to 1996. The pre 1986 lead EMCs listed here average approximately 0.2 g/m^3 , while they average 0.1 g/m^3 during the transition period. The post 1996 lead EMCs are approximately 5 to 10% of the pre 1986 values. The literature values for lead are from overseas or older studies and are therefore not consistent with the recent New Zealand monitoring data.

Table 2: NZ EMCs for total lead, g/m^3

All land-uses	Residential	Commercial	Industrial	Heavily trafficked	Source
Median EMC of events monitored					
0.086	0.086				Pakuranga, ARC TP5, 1991, Table A5.5
0.055	0.055				Pakuranga, ARC TP5, 1992, Table A5.4
0.082			0.082		Southdown, ARC TP5, 1992, Table A5.4
0.170			0.17		Pacific Steel, Leersnyder, 1993
0.110		0.11			Hayman Park, Leersnyder, 1993
0.0339		0.0339			Unitech sand filter, ARC TP48, 1994
0.004	0.0036				Hamilton, new residential, NIWA, 2001
0.021	0.0095	0.0197	0.0335		Hamilton, NIWA, 2001
0.017	0.017				Unitech 2002 data, Larcombe, 2002
0.064	**0.034**	**0.055**	**0.095**		**Average of median EMCs**
Mean EMC of events monitored					
0.192	0.192				Wairau, North Shore, Williamson, 1986
0.200	0.200				Chartwell, Williamson, 1986
0.200	0.200				Hamilton, Williamson, 1986
0.08	0.08				Pakuranga, ARC TP49, 1994
0.0947	0.0947				Unitech, 1994 data, Larcombe, 2002
0.012	0.015	0.0078	0.013		Rotorua, NIWA, 2001
0.004				0.004	Swale study, 100m, Larcombe, 2002
0.008				0.008	Swale study, 50m, Larcombe, 2002
0.093	**0.123**	**0.008**	**0.013**	**0.006**	**Average of mean EMCs**
Literature Values					
0.110					Mean, Urban runoff data book, NIWA (1993)
0.180					NURP average, Fundamentals of Urban Runoff Management, Horner et al (1994)
	0.04	0.18	0.18	0.25	Median, Urban Stormwater Quality: a statistical overview, CRCCH (1999)

Table 3: NZ EMCs for total zinc, g/m^3

All land-uses	Residential	Commercial	Industrial	Heavily trafficked	Source
Median EMC of events monitored					
0.641	0.199	0.684	1.04		Hamilton, NIWA, 2001
0.101	0.101				Hamilton, new residential, NIWA, 2001
0.645			0.645		Pacific Steel, Leersnyder, 1993
0.171		0.171			Hayman Park, Leersnyder, 1993
0.0518		0.0518			Unitech sand filter, ARC TP48, 1994
0.182	0.182				Unitech 2002 data, Larcombe, 2002
0.444	0.444				Pakuranga, ARC TP5, 1989, Table A5.4
0.33	0.33				Pakuranga, ARC TP5, 1991, Table A5.5
0.466			0.466		Southdown, ARC TP5, Table A5.4
0.337	**0.251**	**0.302**	**0.717**		**Average of median EMCs**

Mean EMC of events monitored					
0.380	0.380				Wairau, North Shore, Williamson, 1986
0.300	0.300				Chartwell, Williamson, 1986
0.200	0.200				Hamilton, Williamson, 1986
0.160	0.062	0.111	0.307		Rotorua, NIWA, 2002
0.379	0.379				Pakuranga, ARC TP49, 1994
0.225	0.225				Unitech, 1994 data, Larcombe, 2002
0.09				0.09	Swale study, 100m, Larcombe, 2002
0.117				0.117	Swale study, 50m, Larcombe, 2002
0.220	**0.242**	**0.111**	**0.307**	**0.104**	**Average of Mean EMCs**
Literature Values					
0.260					Mean, Urban runoff data book, NIWA (1993)
0.176					NURP average, Fundamentals of Urban Runoff Management, Horner et al (1994)
	0.17	0.31	0.31	0.47	Median, Urban Stormwater Quality: a statistical overview, CRCCH (1999)

3.2 Adopted EMCs

The following EMCs have been adopted for use in the USC model for the purposes of this study. They have been varied to reflect catchment conditions and allow outputs from the model to match the monitoring data available. Consequently these values should not be used for other purposes or catchments. The adopted EMCs also do not make allowance for changes in future loading due to factors such as increased impervious area or increased traffic volumes. This means that the resulting settling zone contaminant concentrations are likely to be higher in reality and the time to reach trigger levels shorter.

A completely different approach was used for lead. Because lead concentrations are decreasing from 1986 to the present day and into the future, only the untreated case was considered. This case is equivalent to full source control from 1996. The gradual decline in lead EMC since its complete removal from petrol probably reflects its gradual removal from storage in the catchment.

3.2.1 Kaipatiki

Lower concentrations have been chosen to reflect relatively low traffic densities and narrow roads, relatively large residential lots and relatively light industrial activities.

Table 4: Adopted EMCs for Kaipatiki catchment, g/m³

Contaminant	Residential	Commercial	Industrial	Heavily trafficked	Open space
copper	0.020	0.025	0.041	0.040	0.002
zinc	0.110	0.200	0.300	0.200	0.010

3.2.2 Motions

Higher values for the roads have been adopted to reflect the approximately 40ha of the North-western motorway which runs through the catchment. The industrial values have been reduced to reflect relatively light industrial areas.

Table 5:Adopted EMCs for Motions catchment, g/m³

Contaminant	Residential	Commercial	Industrial	Heavily trafficked	Open space
copper	0.020	0.025	0.041	0.040	0.002
zinc	0.140	0.200	0.300	0.260	0.010

3.2.3 Wairau (to Whau Creek)

These values are the same as for the Kaipatiki catchment, reflecting similar catchment characteristics. A new land-use for "schools" was added as a number were identified in the catchment.

Table 6 :Adopted EMCs for Wairau catchment, g/m³

Contaminant	Residential	School	Commercial	Industrial	Heavily trafficked	Open space
copper	0.020	0.010	0.025	0.041	0.040	0.002
zinc	0.110	0.055	0.200	0.300	0.200	0.010

4 Treatment Factors

4.1 Methods

4.1.1 General

The treatment ponds considered in this report were sized as wet ponds (retention ponds). No live storage was used. It is assumed treatment is provided by a single 1m deep wet pond at the bottom of the catchment.

The National Urban Runoff Programme (carried out in the United States in the early 1980s) collated data on stormwater particle settling characteristics from a set of 46 settling column tests. The data was collated into five groups of settling velocities-containing a range of particle sizes. The groups with slower settling velocities do not operate as discrete particles under Stoke's Law (as they have different densities, shapes and are electrostatically charged) and are subject to flocculent settling characteristics. This means that they are more susceptible to external conditions such as through velocity, currents and wind. There is less certainty in their predicted removal rates.

The USEPA "Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality" (1986) is based on the above settling experiments. It is used as the conceptual basis for sizing devices in TP10 and has been used here to predict long-term TSS removal rates. It accounts for dynamic settling (during storm events) and quiescent settling (during the dry period between storm events). An estimate of the particles removed for each of the five settling velocity groups is made for both types of settling and then combined to give an overall removal efficiency rate. This process was modeled for the Auckland region during the development of the original TP10.

The method used in this work utilizes estimates of particulate removal for each of the five settling velocity groups as described above and combines these with estimates of the contaminant distribution over those five groups to give estimates of particulate metal removal. The method only calculates the removal of particulate contaminants. The dissolved component of each contaminant is assumed to remain in the flow. The method therefore gives the maximum theoretical level of treatment due to sedimentation of particulate metals. Values of expected maximum contaminant removal through sedimentation have been similarly calculated by USEPA and are set out in Table 7 for comparison.

Table 7:Literature values of maximum pond treatment by sedimentation

Source	Maximum contaminant removal, %			
	TSS	copper	lead	zinc
USEPA, (1986), figure 14	97	47	88	47
Scheuler, (1987), figure 4.6	98	45	95	45

4.1.2 Contaminant vs Particle Size Association

To estimate the metal contaminant removal characteristics of ponds, the USEPA assumed an equal distribution of contaminants across the four slowest settling velocity groups. The coarsest fraction was excluded (for which no reason was given). This was inadequate for this present study, so the association of metal contaminants versus the settling velocity groupings was reassessed using local contaminant particle size distribution data and the proportion of dissolved versus particulate contaminants.

Contaminants are also associated with particles larger than those contained in the fastest settling velocity group. These particles are not considered by the USEPA and TP10 methodologies, which only consider particles "suspended" in stormwater. TP10 assumes that these larger particles are either too heavy to mobilize and they remain near the source, or they become part of the stormwater "bedload" and are removed in pre-treatment devices (such as cesspits or a sediment forebay). The same assumption is made for this study.

The contaminant distributions used here were derived from particles in stormwater rather than "road dust" distributions. Dust distributions include particles removed by mechanical means such as brushing or vacuuming - which may be different particles to those removed by stormwater "wash-off" mechanisms. Consequently, they may contain a proportion of particles that are not mobilised by stormwater and/or are normally caught in cesspits, or contained in stormwater bedload.

Lead removal in ponds was not considered in this study, but the projected theoretical removal is presented here for comparison purposes with copper and zinc.

The percentages of contaminants in different particle sizes in Table 8 are averaged from three measured Auckland contaminant distributions: Pacific Steel, Pakuranga and Hayman Park. (Leersnyder (1993) and ARC TP49 (1994)).

Table 8: Contaminant association with particle size

Particle Size, μm	Percentage of sediment mass in stormwater (suspended and bedload) by particle size	Percentage of particulate copper mass by particle size	Percentage of particulate lead mass by particle size	Percentage of particulate zinc mass by particle size
< 20	38.3	67	71.7	80
20 – 63	29.6	21.5	19.8	12.9
63 – 125	11.1	4.9	4.4	3.4
125- 250	7.5	2.7	2.0	1.7
250 – 500	5.6	2.8	1.1	1.2
500 – 1000	3.1	0.5	0.4	0.5
> 1000	4.8	0.6	0.6	0.7

To use the particle sizes shown in Table 8 with the TP10 settling velocity groups, an estimate was made of the equivalent particle size for the maximum and minimum settling velocity for each group. This was taken from the study by Leersnyder 1993 and reading from the settling column test results. This estimated particle size range then allowed the proportion of contaminant mass to be assigned to a settling velocity group. The estimated particle size range of the five settling groups are shown in Table 9. These estimates are approximate at the slower settling velocities due to the variations in particle characteristics and increased relevance of other physical environmental factors. Table 9 also includes the mean equivalent particle size based on Stokes Law for comparison.

Also as noted above, the TP10 treatment pond design method assumes that larger particles are part of "bedload" and are inherently removed. The 125 μm particle size is taken as the upper bound of the fastest settling velocity group. Leersnyder (1993) also gives a breakdown of the particle sizes within the <20 μm group and these are used to estimate percentages split between the three slowest settling velocity groups. Table 9 shows the results of declining particle size for Auckland monitoring data and the proportion of the total particulate metal mass associated with that particle size.

Table 9:Estimated approximate particle size versus the proportion of associated copper, lead and zinc associated with that particle size

Group	Settling velocity mean (m/hour)	Equivalent diameter mean (μm)	Equivalent diameter range (μm)	copper, % of total particulate contaminants	lead, % of total particulate contaminants	zinc, % of total particulate contaminants
5 (fine)	0.009	2	<3	22	24	27
4	0.1	5	3-7	22	24	27
3	1.5	12	7-20	22	24	27
2	2.0	35	20-60	22	20	13
1 (coarse)	20.0	82	60 –125	5	4	4

Note that the resulting spread of contaminants in Table 9 is close to that originally assumed in the USEPA (1986) methodology- i.e. few contaminants attach to particles in the coarsest fraction and the rest are spread evenly across the other four groups.

4.1.3 Dissolved and Particulate Contaminants

Table 10 identifies the proportions of contaminants in the dissolved and particulate classes for Auckland data. Average percentages of particulate contaminants in stormwater were 66% of total copper, 92% of total lead and 52% of total zinc. It is therefore assumed that these values are the maximum amount of these contaminants that can be removed by sedimentation in a wet pond.

It is noted earlier that the contaminants appear to change from the dissolved to the particulate phases as they travel through the catchment. The proportions presented here are taken from a range of sites in different parts of catchments. Their mean represents an average split between the dissolved and particulate phases.

Table 10: Dissolved and particulate contaminant association

copper		lead		zinc		Sources
Dissolved %	Particulate %	Dissolved %	Particulate %	Dissolved %	Particulate %	
		2	98	23	77	Urban Runoff Data book, 1993
				47	53	ARC TP49, 1994
46	54			54	46	Pakuranga, 1989 ARC, TP5, 1992
20	80	0.2	99.8	34	66	Pakuranga, 1991 ARC, TP5, 1992
Nd	>86	Nd	>83	12.6	87.4	Pacific Steel, Leersnyder, 1993
Nd	>50	Nd	>60	35.2	64.8	Hayman Park, Leersnyder, 1993
31	69	7.1	92.9	39.6	60.4	ARC, TP48, 1994
21.7	78.3	2.5	97.5	43.1	56.9	Unitech pond 1994, Larcombe, 2002
35.2	64.8	2.8	97.2	52.5	47.5	Unitech Pond 2002, Larcombe, 2002
41.1	58.9	7.3	92.7	45.7	54.3	Hamilton, old residential, NIWA, 2001
44.9	55.1	8.6	91.4	79.5	20.5	Hamilton, commercial, NIWA, 2001
12	88	0.6	99.4	47.7	52.3	Hamilton, industrial, NIWA, 2001
56.1	43.9	5.6	94.4	46.5	53.5	Hamilton, new residential, NIWA, 2001
31.3	68.7	15.3	84.7	58.1	41.9	Rotorua, residential, NIWA, 2002
45.8	54.2	17.9	82.1	77.5	22.5	Rotorua, commercial, NIWA, 2002
32.3	67.7	15.4	84.6	73.3	26.7	Rotorua, industrial, NIWA, 2002
33.8%	**66.2%**	**7.1%**	**92.9%**	**48.1%**	**51.9%**	**AVERAGE PERCENTAGES**

4.2 Treatment

4.2.1 USEPA (1986) Method

Table 11 sets out the calculated metal reduction percentages based on the Beca methodology for estimating the removal of suspended solids (ARC 1992), the dissolved /particulate contaminant split in Table 10 and the contaminant association data in Table 9. The efficiencies may vary depending upon the pond geometry and therefore these rates should be treated as indicative. The following assumptions have been used in calculating the TSS removal efficiencies in the USEPA method:

- Pond sizes are calculated for 30%, 50%, 60% and 75% TSS removal based on the TP10 1992 design methodology for wet ponds;
- No allowance is made for rainfall variation across Auckland (to allow some comparison between the ponds);
- The NURP particle size groups have been used to be consistent with the TP10 design methodology;
- The pond is assumed to be 1m deep and the pond surface area is therefore equivalent to the water quality volume;
- The pond is assumed to be of "average" performance (as used in the design method).

Calculations were originally carried out using a graphical method set out in the USEPA (1986) manual. However, these were then repeated using the "Pond" model developed by Beca for the ARC when developing TP10 (ARC, 1992). The Pond model results alone are used in this report, because they are more consistent with the pond sizes used in Auckland through the application of TP10 and are more accurate than the graphical method used from USEPA (1986). The full set of Pond model results are included with this report as Appendix C.

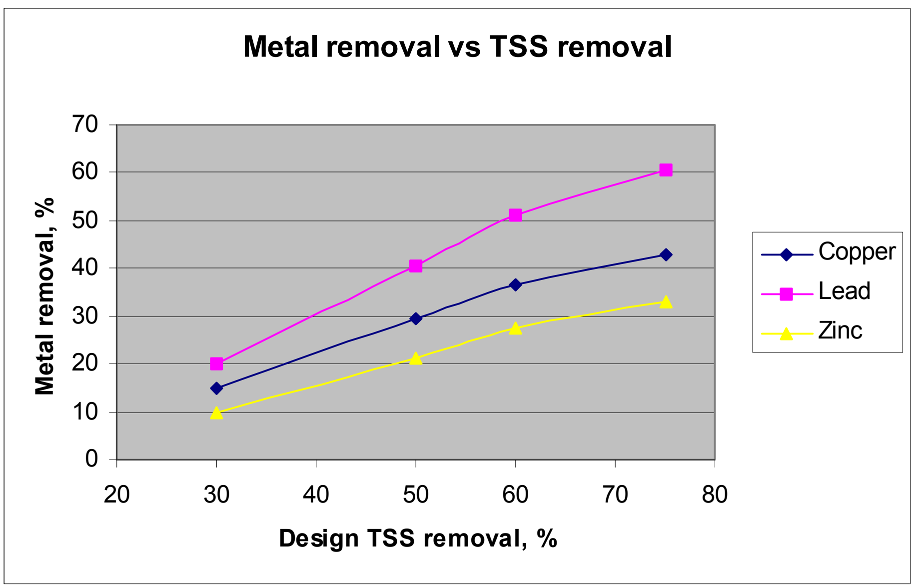
The model results are for 10,000 iterations and are representative of long term pond performance. For different model runs, the quoted predicted treatment efficiency varied by +/- 3% for the same input factors.

Lead removal rates and the 60% TSS removal rate are presented here for comparison purposes. They are not used in the subsequent USC modelling.

Table 11: Contaminant removal factors vs TSS removal, Pond model

Catchment	Design TSS removal, %	Modelled TSS removal, %	Total copper removal, %	Total lead, removal, %	Total zinc, removal, %
Kaipatiki	30	37	15	21	10
Motions	30	34	14	20	10
Wairau (Whau)	30	35	15	20	10
Kaipatiki	50	56	29	40	20
Motions	50	56	29	41	21
Wairau (Whau)	50	57	30	42	22
Kaipatiki	60	65	36	50	27
Motions	60	64	36	52	27
Wairau (Whau)	60	65	37	52	28
Kaipatiki	75	76	43	61	33
Motions	75	75	43	61	33
Wairau (Whau)	75	74	42	60	33

Figure 8: Average contaminant removal factors vs TSS removal, Pond model



4.2.2 Pond Performance Monitoring

Monitoring data from the USEPA/ASCE Best Management Practice database was reviewed to obtain real contaminant reduction factors for wet (retention) ponds. Data for a range of treatment practices is available through the database at www.bmpdatabase.org. In this case, a search for retention ponds with monitoring data for metals yielded 13 ponds. Four Auckland ponds were added to this data set. The catchment characteristics, pond details and monitoring data were analysed to determine if there were indications of improving performance with mean storm volume / pond volume. The results of this review are set out in Table 12. From a review of this information, maximum removal rates were selected so as to represent a "best case" scenario for the reduction in contaminant inflows to estuarine settling zones.

Duncan (1997), in his review of stormwater treatment processes, puts suspended solids, total zinc and total lead together in a stormwater pond "settling group" where the output concentration is proportional to the square root of the input concentration. He notes that the pond area to catchment area ratio is the best indicator of pond performance for removal of these contaminants followed by the pond volume. Pond surface area / catchment area was not included in this review due to a lack of data.

Strecker (2003) has also analysed stormwater treatment practices on the BMP database and found a significant difference for suspended solids removal between devices where the ratio of pond volume to mean storm volume (Vb/Vr) is less than or greater than 1. He notes for devices where Vb/Vr >1 that the effluent quality of a stormwater treatment practice is much less variable than the fraction of contaminant removed. This is probably due to the increased retention volume, reduced opportunity for short-circuiting and the unquantified effects of aquatic vegetation affecting dissolved contaminants. In recognition of this, the average outflow total metal (effluent) concentrations were also used as a direct contaminant removal efficiency scenario in the USC model runs. A "maximum removal rate" has then been qualitatively estimated from the above cases to estimate the best case treatment scenario.

Table 12: Treatment monitoring data

Treatment	Total Suspended Solids removal, %	Total copper removal, %	Total lead removal, %	Total zinc removal, %
Average removal, all ponds	55 (16)	57 (9)	59 (13)	44 (17)
Average removal, volume permanent pond / volume mean runoff < 1	19 (5)	46 (2)	27 (5)	26 (6)
Average removal, volume permanent pond / volume mean runoff > 1	71 (11)	61 (7)	79 (8)	62 (11)
Average effluent concentration (g/m^3)		0.008 (9)	0.019 (13)	0.06 (16)
Selected maximum removal		60	80	60

Note: the number of pond monitoring records used is given in brackets.

The above information indicates that contaminant removal rates may be greater than those estimated using the theoretical settling rates quoted in USEPA (1986) and Scheuler (1987). This may be due to the influence of non-settling characteristics such as vegetative adsorption and filtering.

4.2.3 Adopted Treatment Factors

The final pond treatment factors adopted are summarised in Table 13.

Table 13: Adopted pond treatment factors

Catchment	Design TSS removal, %	Total copper removal, %	Total zinc removal, %
Kaipatiki	30	15	10
Motions	30	14	10
Kaipatiki	50	29	20
Motions	50	29	21
Kaipatiki	75	43	33
Motions	75	43	33
Effluent concentration, (g/m^3)		0.008	0.060
Selected maximum removal rates from monitoring data		60	60

5 Urban Stormwater Contaminant Model

5.1 Model Description

The USC model is described in this extract from ARC TP 139 (1998):

"The model broadly describes the processes occurring within the estuary and predicts the distribution of contaminants throughout the estuarine sediments. Published information on the amounts of contaminants exported in runoff from areas of land under different uses was combined with information on the historical sequence of development. The resulting estimates of the cumulative inputs of these variables are combined with estimates of the volume of sediment already present in the estuary, and the concentrations of contaminants in it, to generate predictions of the concentrations of contaminants in the estuary in increasing times after the start of catchment development. The model assumes furthermore, that 75% of the sediment entering the upper estuary will be deposited in a settling area near the freshwater input to the estuary and equivalent in area to about 4% of the area of the catchment. There was good agreement between the observed average concentrations of metals and those predicted by the model" Thus, the model predicts the average concentration of contaminants in the surface sediments of urbanized estuaries quite well, but it does not predict the concentrations at specific locations. The model is generally applicable for planning purposes".

As part of the RDP project, the settling zone criteria have been refined and defined for each urbanised Auckland estuary (Diffuse Sources Ltd (2002)). For this study, the model input parameters have been expanded to account for varying land-uses within the catchment and the application of treatment factors to the contaminant loading rates. The model uses the "Simple method" (refer Scheuler (1997)) to generate contaminant loads from the EMCs inputted.

As well as the assumptions described in the model formulation (ARC 1998), it was noted above that the modelling carried out in this study did not include future changes in impervious area and traffic density, mostly because these are not known. The model also does not include some estuarine self-cleansing mechanisms because their rate is small and unknown. While these mechanisms are small and unimportant in predicting accumulation associated with untreated runoff, over the very long modelling times, they may be significant in slowing the rate of accumulation at high levels of treatment.

5.2 Model inputs

The model has been comprehensively described in ARC (1998).

Contaminant loads to the estuary were calculated by multiplying flow-weighted means (Tables 4-6) and annual mean flows. Annual mean flows were calculated using the rational formula method from Shaver, 1994. Flows calculated with this method were compared with those calculated using the catchment annual runoff volume method (Beca Carter for ARC, 2000). The two methods were in excellent agreement. Impervious areas inputted to the rational formula for the different land uses in each catchment were estimated from consideration of likely paved areas and literature values, and are listed in Table 14.

Table 14 Proportion of impervious area (%) used in calculating mean annual flows.

Land use	Kaipatiki	Motions	Wairau
Residential	40	50	40
School	n/a	n/a	20
Commercial	70	70	70
Industrial	70	70	70
Road	70	80	70
Open space	5	5	5

Loads were adjusted by the desired treatment factors (Table 13).

The contaminant loads were input into the USC model using values in Tables 4 to 6. Other model input parameters are given in Table 15.

Table 15 Values for parameters used in the USC model.

Parameter	Kaipatiki	Motions	Wairau
Proportion of sediments and metals deposited in SZ	0.42	0.4	0.70
SS specific yield from urban construction (tonnes ha^{-1} yr^{-1})	110	55	55
SS specific yield from urban land-use (tonnes ha^{-1} yr^{-1})	0.4	0.4	0.4
SS specific yield from rural land-use (tonnes ha^{-1} yr^{-1})	0.9	0.9	0.9
Zinc			
Background concentration ($\mu g\ g^{-1}$)	35	35	35
Subsoil concentration ($\mu g\ g^{-1}$)	7	7	7
Lead			
Background concentration ($\mu g\ g^{-1}$)	5	5	5
Subsoil concentration ($\mu g\ g^{-1}$)	5	5	5
Copper			
Background concentration ($\mu g\ g^{-1}$)	2	2	2
Subsoil concentration ($\mu g\ g^{-1}$)	2	2	2

5.3 Measures of Treatment Success

Sediment quality guidelines (SQG) were used as a yardstick for evaluating treatment options, refer Table 16. These are additional to those used to grade sediment concentrations according to the Environmental Response Criteria. They reflect concentrations above which many sediment dwelling animals are expected to be adversely affected. Two such SQG have been reported, Effects Range-median (ER-M) (Long et al 1995) and the Probable Effects Level (PEL) (Smith et al 1996). They differ because of the different ways they are derived. The ER-M is favoured by the ANZECC guidelines, while the PEL is more conservative and probably more robust. For each treatment scenario, the length of increase in the time before the PEL or ER-M was reached was recorded. This gives a simple measure of the relative effectiveness of each treatment scenario.

Table 16:Marine Sediment Quality guidelines

Contaminant	Environmental Response Criteria, amber	Environmental Response Criteria, red	Probable Effects Level	Effects Range-Median
copper, mg/kg	19	34	108	270
lead, mg/kg	30	50	112	218
zinc, mg/kg	124	150	271	410

The ERC adopted by the ARC in the PRP:C have been set at relatively low levels of sediment contamination and adverse effects compared to the PEL and ER-M. This is to allow investigations, treatment option analysis and catchment management decisions to be made while the levels of effects are still relatively low and there is still time available to investigate management options and avoid more severe effects such as those represented by the PEL and ER-M.

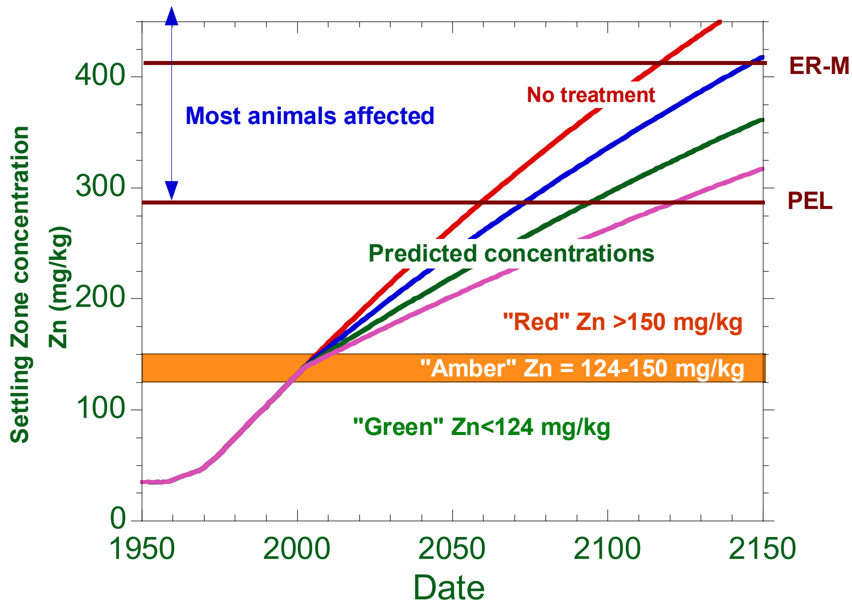
5.4 Results

Terminology

Figure 9 shows the terminology used in the results of the model runs shown in Figures 10 through 16. In each case the contaminant concentration in the sediment is shown from 1950 through to 2150. The model starts in 1950 to replicate the development of the catchment over time and correlate the contaminant loading rates to sediment quality monitoring results. The various lines shown on the graph after 2003 indicate the various levels of treatment as options for reducing the amount of contaminant inflow to the settling zone. The various treatment levels shown on each graph are from those summarised in Table 13. It is re-emphasized that the model predictions are indicative only.

Each graph also shows the contaminant ERC levels from the PRP:C and the PEL and ER-M which are shown to provide a yardstick to assess the performance of the various treatment options.

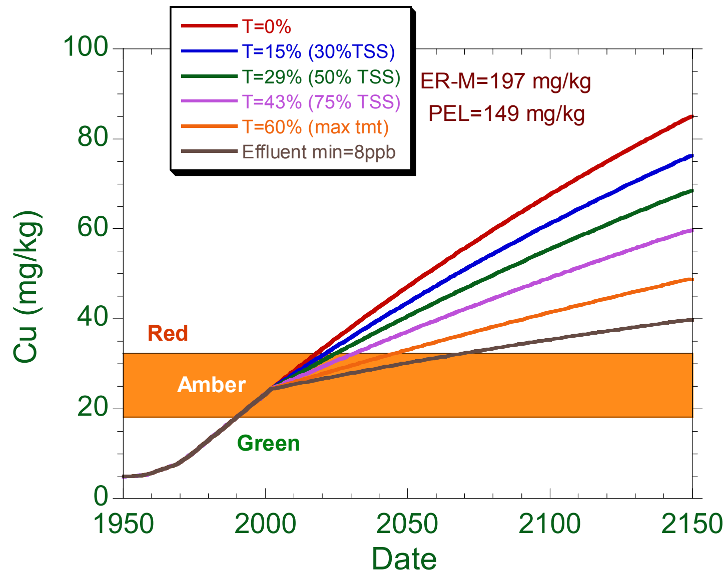
Figure 9: Description for figures 10 to 16. The upper diagonal line is the predicted concentration with no treatment and the lower diagonal lines are the predicted concentrations for various treatment options.



Results

Current copper concentrations for Kaipatiki are above the ERC amber concentration. Figure 10 shows the accumulation of copper in the Kaipatiki settling zone. Compared to no treatment, treatment levels, T=15% (30% TSS removal) and T=29% (50% TSS removal) show a slight reduction in the rate of contaminant concentration accumulation. The T=34% line (75% TSS pond) indicates a much slower rate of accumulation and is close to the maximum assessed sedimentation based copper removal rate. The effluent concentration level indicates that still better treatment is possible, but this includes the effects of treatment on the dissolved component. Predicted copper concentrations are not predicted to exceed PEL or ER-M levels for more than 150 years.

Figure 10: Kaipatiki Creek settling zone copper accumulation



Figures 11 and 13 show the accumulation of zinc in the Kaipatiki and Motions settling zones. Current zinc concentrations exceed the ERC amber level in the Kaipatiki settling zone and exceed the ERC red level for the Motions settling zone. If no treatment is implemented for the Kaipatiki catchment, zinc concentrations are predicted to exceed PEL and ER-M within the 150 year timeframe of the predictions, under the assumptions used in this modelling. In the case of Motions, the PEL for zinc is already exceeded and it is estimated to be only a short time before the ERM is reached. Under the PRP:C process, in marine receiving environments where sediment quality exceeds the amber or red ERC levels, investigations are required into methods to reduce the level of contamination. Figures 11 and 13 show the effects of various levels of stormwater treatment from a single pond at the bottom of each catchment. The length of time before the sediment quality metal concentration in Kaipatiki Creek exceeds PEL increases with treatment. However, ponds sized for 30% and 50% TSS removal only increase this time slightly.

The removal of 75% TSS gives a theoretical zinc removal due to sedimentation of about 33%, but expected removal rates based on actual pond performance monitoring are closer to 60%. This indicates that contaminant removal processes apart from sedimentation are occurring in the actual ponds which improves their performance.

It is likely that significant adverse effects are already occurring in the settling zone of Motions Creek. The model indicates that lower levels of treatment do not reduce the rate of contaminant accumulation significantly and therefore prevent these further effects from occurring.

Figure 11: Kaipatiki Creek settling zone zinc accumulation

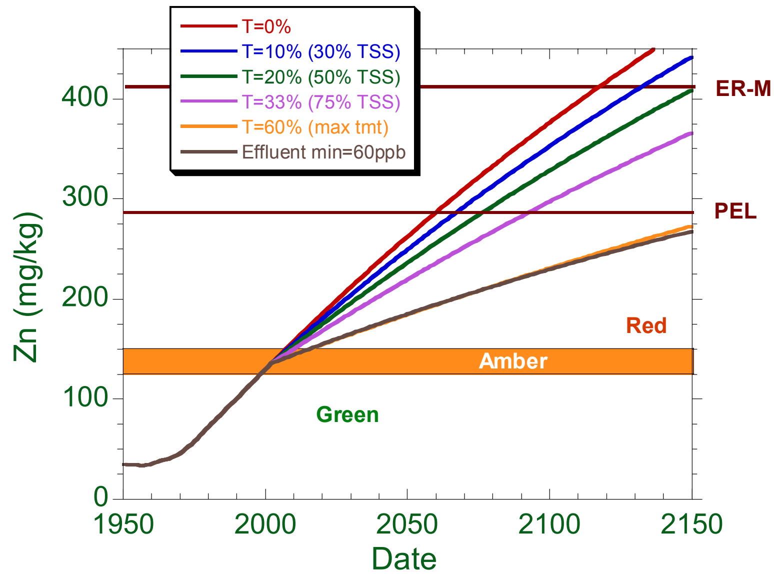


Figure 12: Motions Creek settling zone copper accumulation

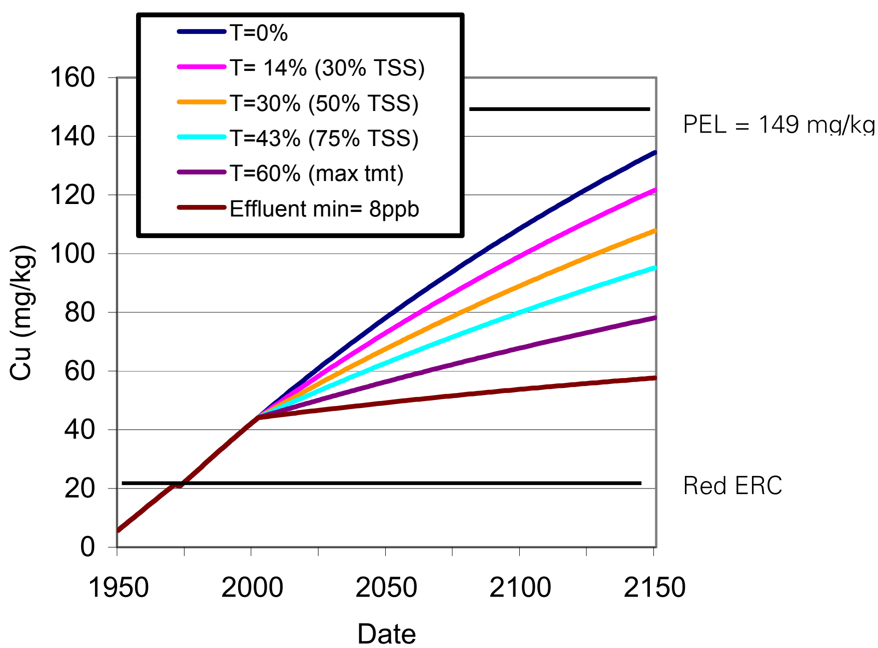


Figure 13: Motions Creek settling zone zinc accumulation

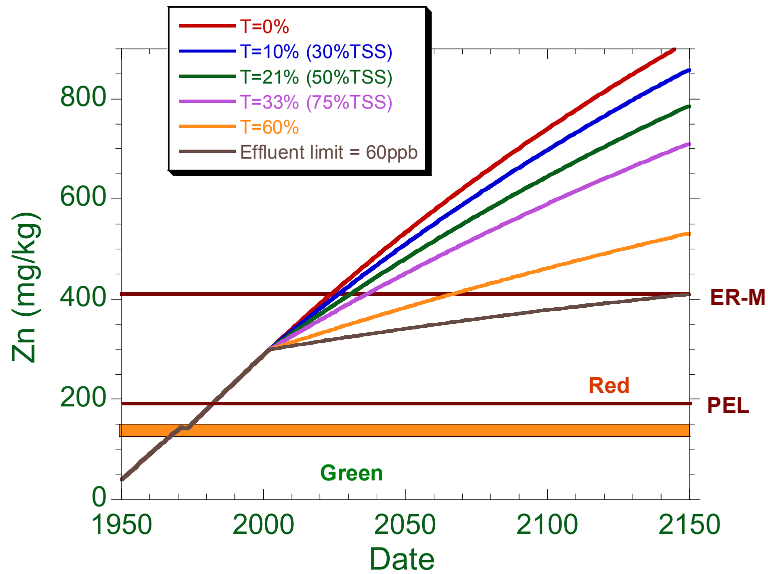
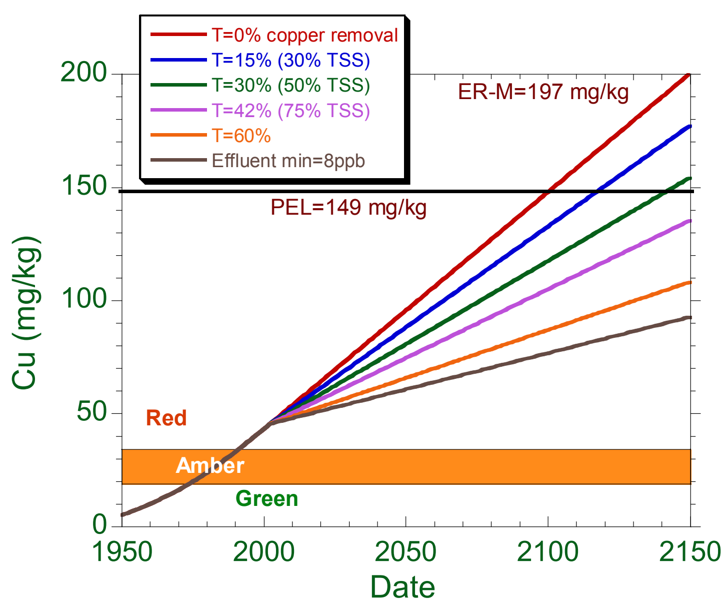


Figure 14: Wairau (to Whau Creek) settling zone copper accumulation



Figures 14 and 14 show the concentrations of copper and zinc in the Wairau (to Whau) creek. This settling zone is subject to rapid rates of contaminant increase. It is possible also that point sources may be contributing to this contaminant load. However, based on the land-use loading rates adopted, contaminant accumulation is still increasing significantly. The response of the catchment to treatment is similar to Motions with the smaller 30% and 50% TSS ponds only reducing the time to reach more severe effects levels slightly. In the case of copper, Wairau is predicted to exceed the PEL level before Motions. The maximum treatment option and effluent concentration option from the monitoring data indicates that a significant benefit to the contaminant accumulation rate is possible.

Figure 15: Wairau (to Whau Creek) settling zone zinc accumulation

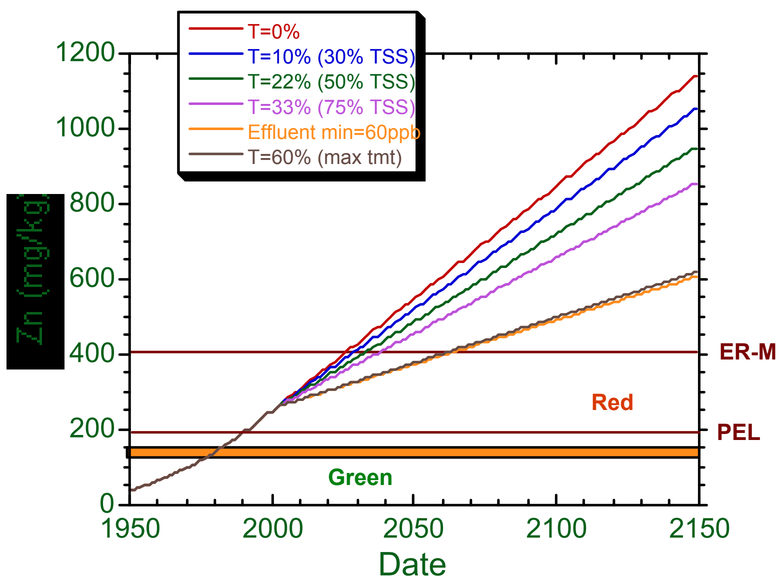


Figure 16 shows the dramatic effects of source control. Recall that lead was removed gradually from petrol between 1986 and 1996. The rate of contaminant accumulation decreases during this transition period. Then after 1996 the model predicts that rate of incoming lead is less than the natural removal processes (export to the wider harbour, incoming sediment dilution, bioturbation) and the settling zone concentrations actually decrease. The comparison of EMC before, during and after this period indicates that removal of lead from petrol equated to a 90 to 95% reduction in lead levels in stormwater.

Figure 16: Kaipatiki Creek settling zone lead accumulation

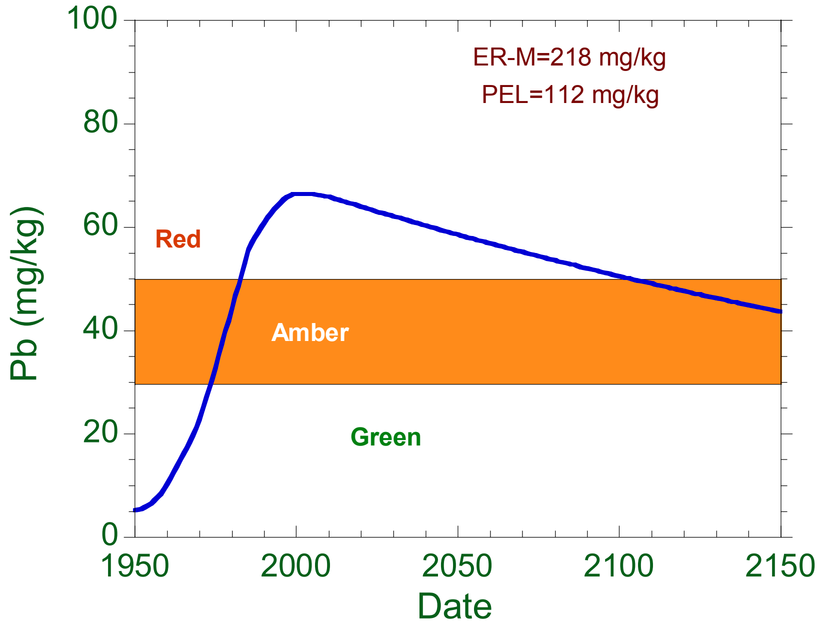


Table 15 summaries the effects of treatment, assuming no other intervention, in terms of the time that it takes to reach PEL or ERM in the settling zone. PEL has been used for copper as the concentrations are less overall and the PEL is lower than the ERM concentrations.

Table 17: Comparison of treatment options

	Time from 2003 to PEL, years			Time from 2003 to ERM years		
Treatment	**Total copper, Kaipatiki**	**Total copper, Motions**	**Total copper, Wairau (Whau)**	**Total zinc, Kaipatiki**	**Total zinc, Motions**	**Total zinc, Wairau (Whau)**
No treatment	>150	95	59	114	21	24
30% TSS pond	>150	115	69	128	24	27
50% TSS pond	>150	147	83	>150	27	31
75% TSS pond	>150	>150	101	>150	33	36
Effluent quality, (g/m^3)	>150	>150	>150	>150	146	63
Selected maximum removal rate	>150	>150	145	>150	63	61

6 Implications

6.1 General

The model predictions presented here do not allow for intensification of development or increased traffic volumes. In this sense the model predictions are therefore likely to under-predict the actual level of contaminant build-up within the settling zone. However, in the higher levels of treatment, the model may also overestimate the accumulation by not allowing for some settling zone self-cleansing mechanisms.

6.2 Identification of Catchment Contaminant Sources

This report has focused on the contribution of non- point source contaminants to estuarine environmental degradation. However, it should be recognised that there are also potential point source contaminant sources in a catchment and that these need to be proactively managed.

There are two possibilities for tracking contaminant sources. Either there is i) a significant point source discharge of contaminants such as from an industrial site or spill; or ii) general urban land-use, or non point source pollution, is contributing to the contaminant build-up in the marine settling or outer zone. A two pronged approach is therefore required to track contaminant sources.

6.2.1 Point Sources

Firstly in the case of point sources, it is necessary to identify any possible significant point sources of contaminants, including (but not necessarily limited to):

- High risk industrial activities as per Schedule 3 of the ALW plan;
- Old landfills;
- Contaminated sites;
- Sewer overflows which occur more than twice per year.

Industrial

The USEPA document "Proposed re-issuance of National Pollutant Discharge Elimination System Storm Water Multi-sector General Permit for Industrial Activities" lists contaminants commonly found for various types of industrial activities. Table 4.6 of TP10 also lists common industry types and associated contaminants. Comparison of the receiving environment contaminants of concern identified and the industries identified in the catchment, may identify a correlation.

However, correlation does not automatically equate to the existing industry being responsible for those contaminants. Historical discharges of contaminants to groundwater for example can cause continuing discharges for many years following removal of the source. The ARC pollution control team carry out a programme of industrial audits proactively and in response to complaints to audit environmental performance and prevent discharges of contaminants. Some high risk industries, such as electroplaters, have been audited over recent years.

If high contaminant levels are found and a correlation to existing industry is suspected, then the stormwater network would need to be inspected or monitored at significant discharge points upstream and downstream of the industrial sites' connection points to the network.

Should existing industrial sites be identified as contaminant sources, then either the ARC or the relevant territorial authority should audit the industries and act as required to ensure the reduction of contaminants discharged from those sites.

Landfills And Contaminated Sites

As an initial screening, registers of contaminated sites are available from the ARC and historic landfills from territorial authorities.

Wastewater Overflows

Key contaminants associated with wastewater overflows are ammonia, BOD and pathogens. There is also potential however for trade waste discharges to contribute to the levels of heavy metals investigated in this report.

It is likely that significant point source industrial discharges into wastewater networks will already have Trade Waste Permits authorising their connections to the wastewater network. The potential for these discharges to contribute contaminants to the environment via wastewater overflows should be considered by territorial authorities and LNOs when furthering their RDP wastewater network consents.

6.2.2 Non Point Source Contaminants

If no significant correlations between the ERC contaminants of concern and the industrial activities within the catchment are found, then it should be assumed that the contaminants are generated from non point source contaminants. Even if industrial point sources are found to be contributing significant contaminant loads to the receiving environment, general land uses should still be examined to check their relative contribution.

In all urban catchments, the general urban land-use will be contributing to the accumulation of contaminants in settling and outer zones. Different land-uses contribute different proportions of contaminants.

The methodology set out in Section 2 of this publication provides a means of assessing the effects of non-point source contaminants. The method can easily be extended to combine the different loading rates with land-use areas to determine the key areas or sub-catchments which contribute the most contaminants and which should therefore be the focus for the assessment of treatment opportunities.

To identify particular sub catchments that are contributing higher proportions of contaminants it is suggested that the catchment pipe network is overlain on a map of the catchment land use to identify sub-catchments and significant discharge points (say for all pipes 600mm diameter or larger). Discharge points from heavily trafficked roads and significant industrial zones should also be identified (as likely key land-use sources).

Land-use contaminant loading data from local monitoring (or from literature), can then be applied to each sub catchment area to identify the likely contaminant load contributions from the sub-catchments and to identify areas of significant contaminant sources.

From this analysis, identify and rank (say the top five) sub-catchments for the catchment for each of the primary sediment contaminants which exceed the Table 20.1.A trigger levels. The sub catchment areas can then be prioritised for treatment based on their relative contaminant contribution.

It is suggested that within the roading network, those areas that have significant vehicle movements (and in particular those areas where vehicles brake) should be targeted for treatment. Key areas would therefore be heavily trafficked arterial roads, motorway off-ramps and arterial road intersections.

6.3 Levels of Treatment

6.3.1 General

When carrying out the assessment of treatment options, no allowance has been made for the physical space or funds required to construct stormwater treatment practices. In many urbanized catchments the actual constraints may prevent higher treatment levels being achieved. The level of treatment available is often only between 30% to 50% TSS removal. In some catchments this may be deemed sufficient through the consent process. Where greater levels of treatment are desired and traditional treatment is not feasible, it will be necessary to carefully examine innovative treatment technologies and source controls. Innovative technologies could include high efficiency street sweepers and stormwater flocculation. Source controls could include the removal or immobilization of contaminants from building products and vehicles.

It is also necessary to consider the skills and programme elements required to construct, maintain and operate effective treatment devices. The construction, operation and maintenance of devices must be carried out correctly or the treatment efficiency may be significantly reduced. The RDP consents programme will be addressing this issue to ensure that both existing and additional devices are effective.

6.3.2 Treatment Levels

Smaller ponds, such as those sized for 30% and 50% TSS removal, only slightly reduce the rate of long term contaminant accumulation. A pond sized for 75% TSS removal removes close to the maximum amount of particulate contaminants. Pond monitoring data results indicate that actual contaminant removal rates may be greater than that predicted by the pond sized for 75% TSS removal. Treatment ponds have greater effect where the current level of contaminant accumulation is lower. In the case of the Kaipatiki catchment, the implementation of treatment measures for the management of zinc levels within the settling zone should minimise wider harbour effects for a longer period of time. In the Motions catchment, higher levels of treatment would be required to achieve the same result.

The USC model predicts contaminant concentrations in the settling zone. For Motions and Kaipatiki, about 40% of contaminants from the catchment will settle in this zone. Catchment objectives which manage settling zone effects, also inherently manage wider harbour effects. Beyond the settling zone, contaminants are more widely dispersed and the accumulation of contaminants is much slower and therefore associated adverse ecological effects are less severe. Thus, the reduction of contaminant accumulation in the settling zone also protects the wider harbour. Sediment quality contaminant levels within the settling zone significantly exceeding the ERC triggers are indicative of effects extending into the wider harbour. Careful assessment of the extent of effects is required for these catchments. Given that smaller treatment ponds have limited effect in catchments with higher settling zone contaminant levels, the catchment management regime may need to implement a range of innovative technologies to prevent wider scale effects. It may also be necessary to adopt catchment objectives managing effects beyond the settling zone instead of managing effects in the settling zone itself.

6.4 Catchment Management Planning

This study has important implications for integrated catchment management planning. Planning needs to:

- recognise the results of monitoring which identify contaminated areas and the extent of effects both within the settling zone and wider harbour;
- consider the use of treatment to meet both short and long term contaminant reduction needs;

- acknowledge that stormwater ponds should be installed early in the land use development phase to achieve the greatest benefit- i.e. before the contaminant levels in the receiving environment become high;
- where effects in the settling zone are already high, consider the need for implementing measures to prevent harbour effects;
- consider the development and implementation of innovative treatment technology and source controls to achieve higher levels of contaminant reduction;
- in the context of the wider harbour, integrate the effects of contaminant loads and treatment for all catchments. It may also be necessary to consider the use of priority catchments so that catchments that contribute the highest contaminant loads receive the highest levels of treatment.

The use of smaller treatment ponds may still be an important component of catchment planning, even if higher settling concentrations are present. Even small ponds remove contaminants and hence delay the onset of effects giving time during which alternative technologies and source controls can be developed and implemented.

6.5 Recommendations for Further Work

Zinc is recognised as a key contaminant. The relative contributions of zinc need to be identified from each of the range of sources within a catchment. It is suggested that loadings from each key source be identified and a revised catchment contaminant budget be made to identify the sources which contribute the greatest amount of zinc.

The means of removing zinc also needs to be identified. Two approaches need to be developed:

- Firstly, treatment technologies that specifically target zinc need to be developed and their performance assessed;
- Secondly, assessments need to be made of the potential for removing zinc from the identified key sources.

7 Conclusions

Marine receiving environment monitoring indicates zinc is a key contaminant of concern in Auckland. Stormwater treatment ponds are able to remove 60% of copper and 60% of zinc at best. In urbanized catchments the actual quantum of treatment able to be implemented may be significantly less than this due to physical constraints.

None of the treatment options assessed reduced the predicted concentration of contaminants in the settling zones. However, some treatment scenarios such as the 75% TSS removal pond and the average effluent quality concentrations indicate that a significant increase in time can be achieved before more severe effects occur. In other words, high levels of conventional treatment can significantly slow the rate at which contaminants accumulate in marine receiving environments.

Reducing contaminants entering settling zones will have the greatest benefit in catchments which have only just exceeded the ERC "red" trigger levels. Catchments with a longer history of contaminant build-up, such as Motions, will need very high levels of contaminant reduction to prevent significant effects in the settling zone. Consequently, it may be necessary to adopt objectives for managing ecological effects in the wider area beyond the settling zone of these catchments, rather than in the settling zone itself.

It is important to recognise that, while current treatment ponds may be unable to reverse accumulation sufficiently to prevent PEL or ERM contaminant levels being exceeded, their implementation still provides significant benefits such as managing wider harbour effects and providing a period of time for innovative technologies and source controls to be developed and implemented.

It is necessary to investigate additional treatment technologies to achieve higher rates of contaminant reduction and the ways in which the production of contaminants can be minimized at their source. The effects of source control can be dramatic. The removal of lead from petrol has reduced the average EMC values to approximately 5 to 10% of their previous values. In Kaipatiki, the red ERC for lead is currently exceeded but based on existing land-use loadings it is expected that over approximately the next 100 years the concentration will reduce to below the red ERC concentration. ARC recognises the importance of source control and this will be an increasingly important part of the stormwater programme and the Stormwater Action Plan to be funded with ex-Infrastructure Auckland money now held on behalf of ARC by Auckland Regional Holdings.

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Appendix A: Catchment Maps

Figure A1: Wairau Catchment Land-use

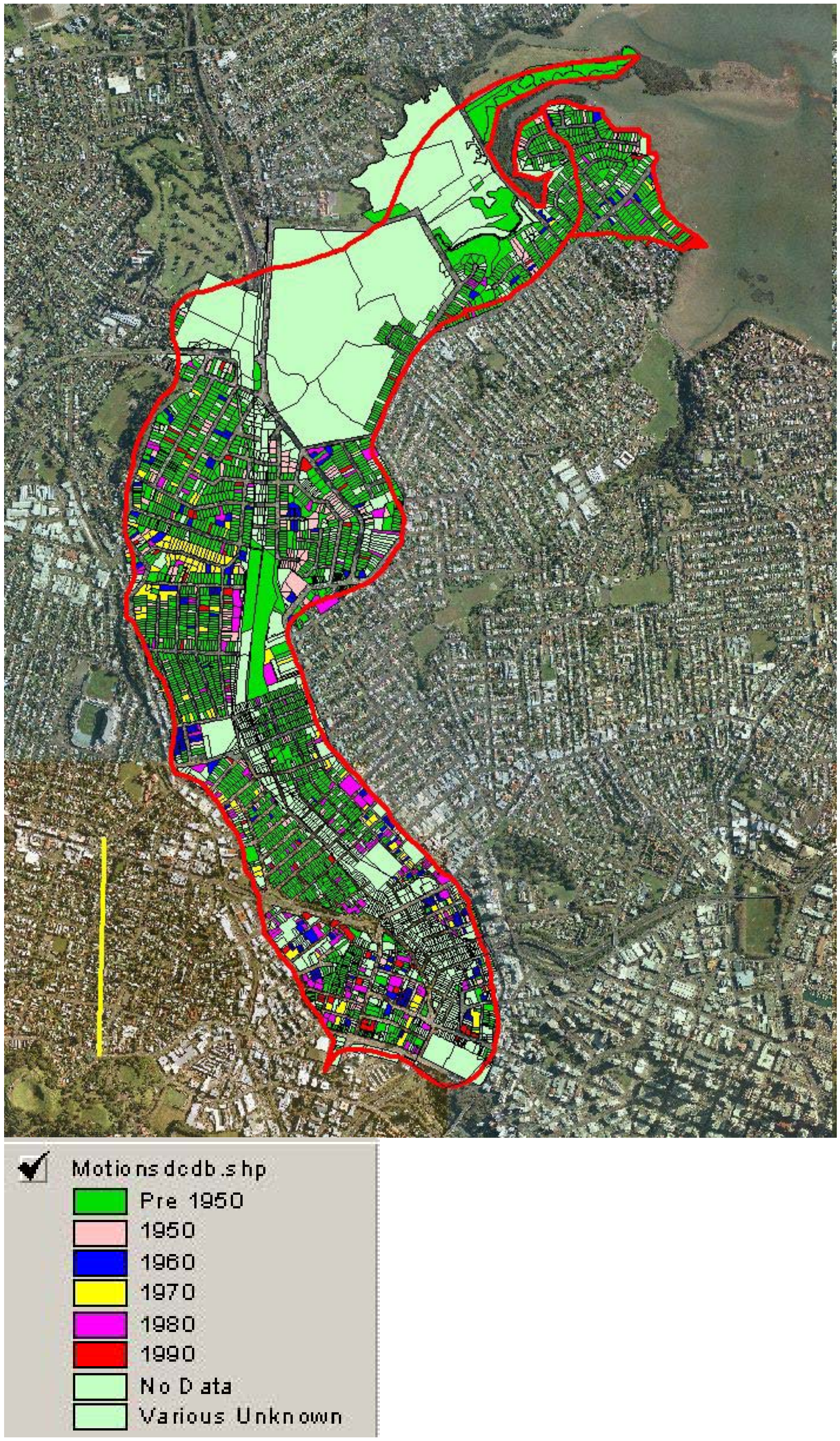


Table W1. Land use history for the Wairau catchment.

From WCC	Road (ha)	School (ha)	Community (ha)	Industrial (ha)	Residential (ha)	Urban (ha)	ΣUrban (ha)	Open (ha)
pre-1950	10.82		0.00	0.00	52.80	63.62	63.62	346.38
1950-1960	11.17	18.00	2.00	0.00	34.50	65.67	129.29	280.71
1960-1970	4.67		0.50	2.00	20.30	27.47	156.77	253.23
1970-1980	10.64		0.50	8.00	43.40	62.54	219.30	190.70
1980-1990	4.49		0.50	12.00	9.40	26.39	245.69	164.31
1990-2003	6.91		0.00	4.00	29.70	40.61	286.30	123.70
Sum	48.70	18.00	3.50	26.00	190.10	286.30		

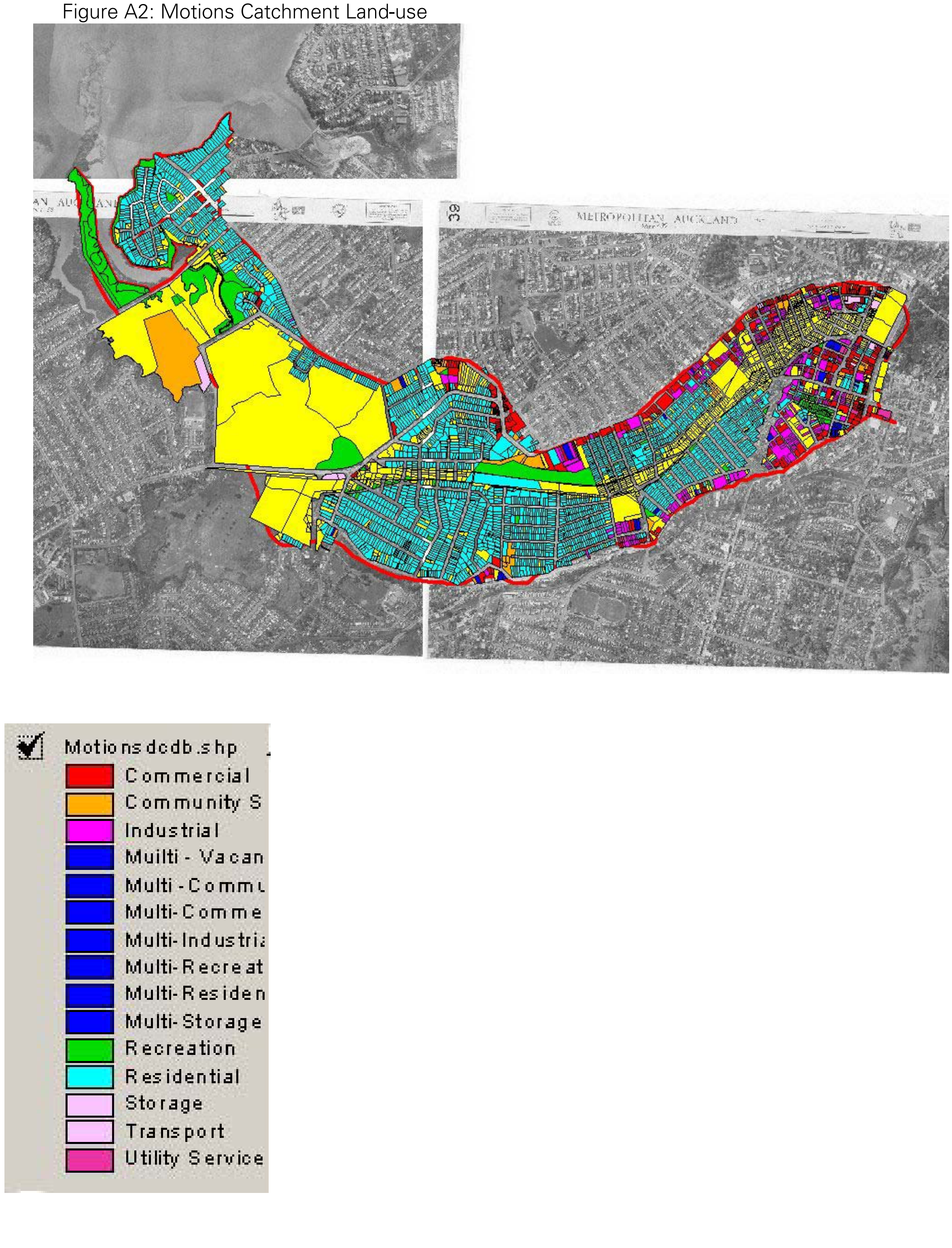
Current land use was obtained from Figure A1. The six sub-catchments identified in this figure had the following land use characteristics (Table W2).

Table W2. Current land use (ha) for the Wairau catchment.

Block No. (see Figure W2)	Dominant Land use	Area	Building	Road	Living	Working	Open space	Total impervious
1	Working	26.3	6.1	3.4	0.0	13.5	3.3	16.4
2	Living	70.3	13.4	12.0	40.0	0.2	4.6	28.6
3	Living	8.4	1.3	0.5	3.2	0.0	3.4	2.2
4	Cemetery	98.6	0.3	4.0	0.1	0.0	94.0	2.9
5	Working	13.1	4.6	1.9	0.1	6.5	0.0	9.8
6	Living & working	171.2	28.2	26.9	99.7	5.7	10.1	67.0
	SUM	387.8	53.9	48.7	143.2	25.9	115.4	126.9

From this data an assumed development history was derived for the catchment (Figure 6).

Figure A2: Motions Catchment Land-use



Appendix B: Urban Stormwater Contaminant Model

The Urban Stormwater Contaminant model (a variation of the Auckland Strategic Plan [ASP] model) (ARC 1998, Williamson 1999, Williamson and Morrisey 2000, Morrisey et al. 2000) is used in this report to predict average concentrations of copper, lead and zinc in the "settling zone" of estuaries. The model was developed to predict contaminant accumulation in upper reaches of estuaries where most stormwater is discharged. Figures B1 and B2 show schematics of the model.

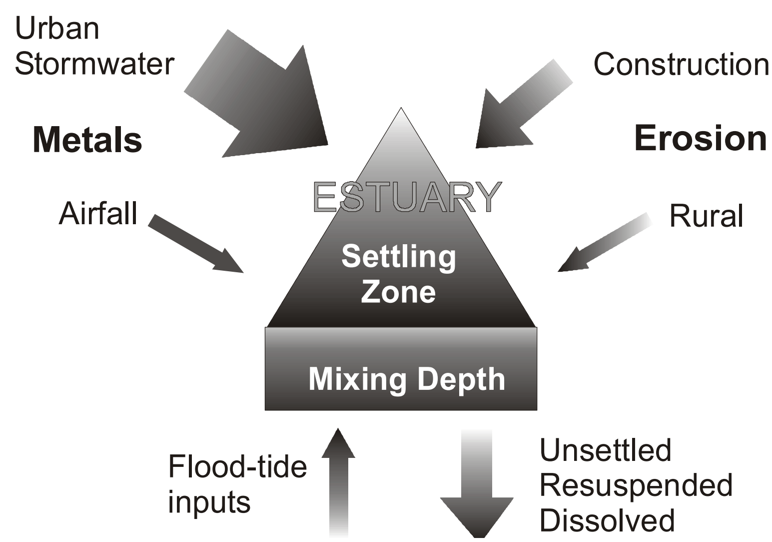


Fig. B1 Conceptual underpinning of USC model.

The USC model has been successfully tested in the settling zones of estuaries, which is where fine sediments accumulate because of low tidal currents and small waves (Williamson et al., 1998a; Williamson and Morrisey, 2000; Morrisey et al., 2000). The model worked reasonably well in predicting spatial-average concentrations, but does not predict vertical profiles well, nor does it predict the overall distribution of contaminants down the estuary.

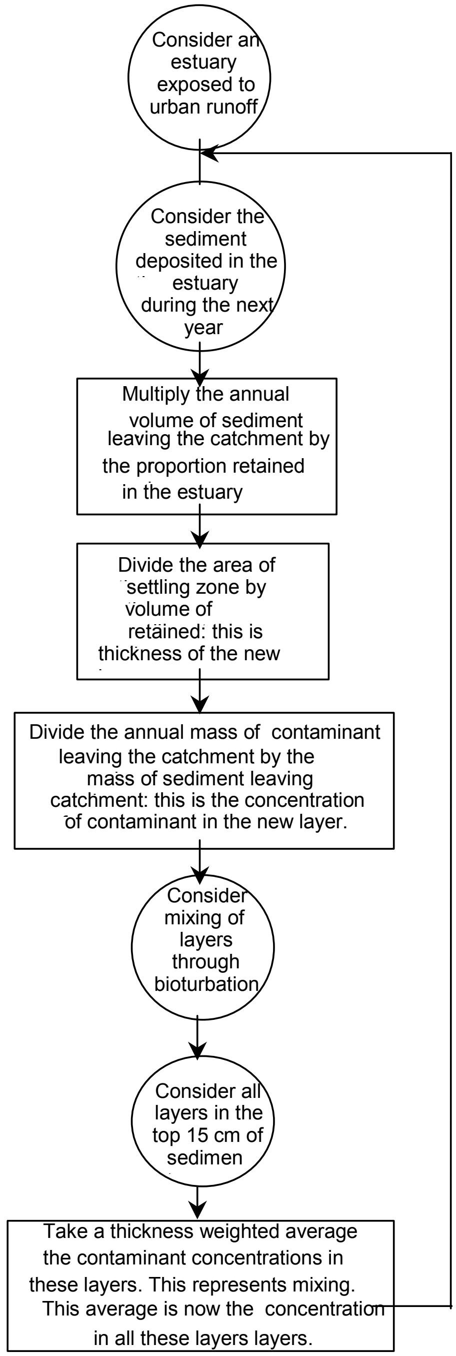


Figure B2 Flow chart of the computational steps within the USC model (from ARC 2000).

Conceptual Understanding Behind the USC Model

General Considerations

Many Auckland catchments discharge into small estuaries that are infilled stream valleys. The USC model was developed to address accumulation in these small estuaries. Key considerations in understanding the probable fate of sediment and contaminants discharged by stormwater runoff into sheltered estuaries are as follows:

- Auckland watersheds are relatively steep, and flow velocities are decreased substantially after discharge into estuaries.
- A large proportion of stormwater particulates are silt-sized or greater (Leersnyder, 1993; ARC, 1992), which will settle quickly.
- Stormwater discharges occur at many points around estuaries.
- Estuaries are shallow, with extensive intertidal areas.

Contaminant Settling in Estuaries

Contaminants primarily adsorb to fine particulate matter in stormwater discharges (Williamson, 1993; Leersnyder, 1993). Upon arrival at the estuary, the coarser fine particles settle by gravity because there is a large drop in the velocity of the water carrying these particles when the stormwater is discharged to the estuary. Finer particles are flocculated and the resulting larger particles settle to the bed. Therefore, the immediate fate of a large proportion of the contaminants after entering the estuary is deposition by settling in the upper reaches of the estuary.

Some particles and dissolved contaminants will be carried through the estuary, especially during large storms, and especially during low tide when storm flows are carried right down the estuary in central incised flow channels.

Dissolved contaminants in stormwater are substantially diluted when discharged into estuaries, and thus are not expected to exert toxic effects in the water column. Any dissolved metals tend to adsorb on particles in the estuary.

Accumulation or Dispersal?

Once settled, particulate-associated contaminants can be resuspended from the seabed into the water column by waves and/or currents. Resuspended sediments may then be dispersed by tidal currents to more quiescent areas, where they settle and are mixed into the underlying sediments by bioturbation. The ultimate fate of sediments and adsorbed contaminants depends on the amount and spatial distribution of hydrodynamic energy in the estuary.

In estuaries with low hydrodynamic energy, contaminants tend to be trapped. In areas of high hydrodynamic energy, contaminants are "moved on". Therefore, it is useful to distinguish within an estuary three zones based on three types of processes (Hakanson, 1982):

1. Areas of accumulation, where fine materials are being continuously deposited. Wave and current energies are very low here.
2. Areas of transportation, where periods of accumulation are interrupted by periods of remobilisation (generally of short duration and associated with storms).
3. Areas of erosion, where there is little deposition of fine materials. Wave and/or current energies are high here.

Fine materials tend to be shunted from erosional and transportation zones to sheltered arms and embayments. Thus, according to Hakanson's view, the ultimate repositories of contaminants associated with fine particles are depositional zones.

Some of the sediment resuspended by waves will escape from the estuary on the ebb tide. However, since many estuarine arms discharge into effectively enclosed basins (e.g., Pakuranga Estuary, which discharges into Tamaki Estuary), much of the "escaped" material will return on the next flood tide. Because the flood tide is more energetic than the ebb tide, fine sediments tend to march up-estuary, which means that the ultimate fate of the bulk of contaminants discharged into small estuarine arms will be accumulation in the upper reaches.

Processes that 'Average' Contaminant Concentrations in Estuarine Sediments

Small catchments in Auckland generally discharge small stormwater flows into relatively large estuarine areas. At high tide, the relatively low-volume, low-energy freshwater discharge spreads out over the submerged intertidal area. Within a short distance of the outfall, currents will be low enough to provide ideal settling environments (Hume and McGlone, 1986). As the tide retreats, stormwater will flow in channels incised within intertidal flats. Scouring of existing estuarine sediments and deposition of coarse, urban-derived sediments occurs within these channels. On reaching the tide water line, stormwater will be mixed and spread out over lower intertidal and subtidal areas, with the mixing/settling field therefore tending to spread down-estuary. A similar picture holds for the rising tide, except the mixing/settling field moves up-estuary.

In larger catchments, greater discharges will push stormwater further down main channels. At high tide, the discharge field will tend to spill out over the top of the adjacent intertidal areas, which provide ideal settling areas. As the tide ebbs, this intertidal area will become smaller, until most of the flow is concentrated in the channel. Settling will occur only where channels widen significantly.

Once settled, contaminated sediment is intermittently resuspended and redispersed. Direct observations of the action of small waves (5–20 cm) show very high turbidity in shallow waters behind the tidal front (ARC, 1994; Green and Bell, 1995). Very fine sediments (clays and fine silts) can be transported in suspension for large distances (100's m) until reaching quiescent areas, whereas the coarser fraction of the suspended material (medium silts to fine sands) settles within short distances (e.g., <10 m) of the point of resuspension. The continual advance and retreat of the tide means that contaminants can be spread widely over the intertidal zone.

The 75% and 4% Rules

The USC model assumes that 75% of contaminants discharged to an estuarine arm are retained in that arm and settle in an area that is nominally 4% of the catchment area. The values of 75% and 4% were adopted on the basis of settling-pond theory (Vant et al., 1993) and because 4% approximately equates to the intertidal area in many estuarine arms.

The model assumes that 25% of contaminants are lost from the estuary, either during the storm, or at a later date from resuspension and dispersal.

In practice, the two rules are adjusted to site-specific circumstances.

The 75% rule is applicable to situations where 4% of the catchment area approximately equals the intertidal estuary area. In a number of estuary arms, this is not so, and the '75%' value is adjusted by tidal excursion. For example, in the Kaipatiki arm of the Hellyers Creek estuary, tides drain well below the mouth of this arm. Tides reach the arm only 56% of the time on average. Therefore the 75% value is adjusted to 75 x 0.56 = 42%.

Sediment Mixing

Vertical mixing of deposited contaminants is a very important process. If freshly deposited contaminated sediments were not mixed into the underlying estuarine sediments, then concentrations would be very high (e.g., 1000 mg/kg zinc) on the surface of the sediments. This is not observed to occur because sediment mixing – mostly due to activities of sediment dwelling animals – mixes and dilutes the incoming contaminants with the underlying, relatively uncontaminated sediments.

The USC model assumes a 2-layer mixing sub-model, where the top 15 cm of the sediments is completely mixed. Below this, the sediments are assumed to be unmixed and 'buried'.

Appendix C: Results of modelling of TSS removal from ponds