Christchurch City Council

MEMORANDUM

27 August 2020

By: **Winsome Marshall (Environmental Consultant, Aquatic Ecology Limited)**
Dr Belinda Margetts (Principal Waterway Ecologist, Christchurch City Council)

Subject: **Literature review of potential effects of leaching from instream structures on waterways**

Introduction

A number of temporary and permanent instream structures are used within waterways to allow the construction of things such as bridges, culverts, linings and retaining walls. Some of these structures have the potential to leach contaminants into waterways, negatively affecting both water quality and biota. To understand the potential effects of using instream structures, this memorandum assesses the information in the literature on the effects of three commonly used materials: copper-chrome-arsenate (CCA) treated timber, galvanised steel, and concrete. This review does not include literature pertaining to runoff from manmade structures outside of waterways, such as galvanised roofs, due to other processes not present within waterways, such as oxidisation from contact with atmospheric carbon dioxide (Pacific Northwest Pollution Prevention Resource Center, 2014).

Literature review

CCA Treated Timber

The leaching of CCA treated timber and subsequent environmental effects is well documented in both laboratory and field studies (34 papers; Table 1). These indicate that leachates from CCA treated timber may have negative impacts on biota, such as algae, barnacles, mussels, oysters, snails, sea urchins, fiddler crabs and fish (Table 1). These include effects on fertilisation and larval development, with some studies also recording mortality (Weis, Weis and Coohill, 1991; Weis *et al*., 1992; Sreeja, 2008). There is also evidence that exposure to CCA treated timber may cause damage to the DNA of resident biota (Weis, Weis and Couch, 1993; Weis *et al.*, 1995). Trophic transfer of copper, chromium and arsenic through the ecosystem may occur, although results are inconsistent (Weis and Weis, 1992b; Weis and Weis, 1993; Weis and Weis, 1999; Chan, Wang and Ni, 2003). Metal concentrations in benthic organisms near bulkheads have also been shown to lower species richness, total abundance and species diversity (Weis and Weis, 1992a; Weis and Weis, 1994; Wendt *et al*., 1996; Weis, Weis and Proctor, 1998). The most harmful effects on biota appear to be due to copper (Chan, Wang and Ni, 2003; Weis and Weis, 2004). However, the form of chromium (Cr(VI)) used in CCA treated timber is also highly genotoxic (Weis and Weis, 2004).

Four literature reviews investigating the leaching of CCA treated timber were identified. One of these reviews by Hingston *et al*. (2001) concluded that insufficient data existed to allow accurate quantification of leaching rates from CCA treated timber. However, another review considered that properly treated CCA timber presents little hazard to the aquatic environment (Brooks, 1993 *in* Hedley, 1997). Hedley (1997) concluded that leaching does occur from freshly treated wood, but most studies indicate it adds little to background water and sediment levels of copper, chromium and arsenic, with issues typically arising when the wood is used before it is properly fixed. However, there are abundant field-based studies which indicate that CCA treated timber leaches into the environment, with copper, chromium and arsenic assimilated by biota (Weis and Weis, 1992b; Weis and Weis, 1993; Weis, Weis and Couch, 1993; Weis, Weis and Lores, 1993). Assimilation rates in environments with CCA treated timber were typically highest for copper, followed by arsenic and then chromium (Weis and Weis, 1992b; Weis and Weis, 1993; Weis, Weis and Couch, 1993; Weis, Weis and Lores, 1993). In addition to dissolved contaminants leaching into the water column, metals from CCA treated timber can accumulate in sediment (Weis, Weis and Proctor, 1993; Wendt *et al*., 1996; Rice, Conko and Hornberger, 2002).

Leaching may be more severe in field experiments due to increased physical stress, such as abrasion, cracking and borer (Merkle, Gallagher and Soldberg, 1993 in Hingston et al., 2001), which allow water to penetrate further into the wood. Leaching rates are typically impacted by pH, temperature, salinity, surface area-to-volume ratio, fixation method, quality of wood, time since fixation, and flushing of water in the environment, as discussed further below.

Maximum leaching of chromium and arsenic has been shown to occur under neutral conditions and initial loss of copper has been shown to increase with higher acidity (Van Eetvelde *et al.*, 1995b in Hingston et al., 2001; Van Eetvelde *et al.*, 1995a in Hingston et al., 2001). Christchurch waterways are typically neutral or slightly alkaline (Marshall and Noakes, 2019). This suggests optimal conditions for leaching of chromium and arsenic, but not copper. The effect of temperature on leaching appears to be variable, with some studies reporting lower leaching rates for copper, chromium and arsenic at lower temperatures, while other studies indicate that arsenic leaching may be lower at higher temperatures (Van Eetvelde *et al.*, 1995b in Hingston et al., 2001; Van Eetvelde *et al.*, 1995a in Hingston et al., 2001; Breslin and Adler-Ivanbrook, 1998). Increasing salinity appears to increase leaching rates, although one study found that brackish water did not increase copper loss (Irvine, Eaton and Jones, 1972 in Hingston et al., 2001; Plackett, 1984 in Hingston et al., 2001). This suggests that leaching rates are likely to be highest in coastal waters, followed by estuarine environments and then freshwater. The surface area-to-volume ratio (i.e. the amount of timber in contact with the water) also appears to be an important factor in leaching rates, with large blocks leaching less than small ones (Hayes, Curran and Hynes, 1994). Sreeja (2008) also found panels that were dip treated leached more quickly than those that were pressure treated.

Newly treated CCA timber leaches the fastest and is therefore the most toxic (Weis and Weis, 2004). Breslin & Adler-Ivanbrook (1998) reported that metals leached continuously throughout a 90-day study, but at a decreasing rate with time. One study found that barnacles growing on one-year-old CCA treated timber had copper concentrations 80 times higher than the reference site, compared to the aged wood which was 10 times higher than the reference site (Weis, Weis and Lores, 1993; Weis and Weis, 2004). Environmental impacts could be substantially lessened if wood was soaked for several months prior to use in aquatic environments (Weis and Weis, 2004; Weis and Weis, 1996). The fixation process is both time and temperature dependant and therefore wood should never leave the treatment site for at least two weeks (Hedley, 1997). However, if wood is stored outside in winter, complete fixation may take months (Hedley, 1997). Poor quality timber can also leach substantially more than higher quality timber (Hayes, Curran and Hynes, 1994). The quality of timber, and its suitability for treatment is complex; however, dense wood is generally of higher quality and fast grown wood of lower quality, due to a higher proportion of earlywood compared to latewood (Hayes, Curran and Hynes, 1994; Jane, 1970 *in* Hayes, Curren and Hynes, 1994; Wise and Jahn, 1952 *in* Hayes, Curren and Hynes, 1994). Conifers (e.g. pine) are likely to have high leaching rates due to the form of their earlywood (i.e. more preservative may be absorbed but not properly fixed, and therefore would be more readily leached) (Hayes, Curran and Hynes, 1994). This highlights the need for New Zealand based research, as it is possible this use of pine/conifers is greater than overseas.

Tidal inundation can influence metal concentrations in sediments, with concentrations higher in areas that are more frequently inundated (Weis and Weis, 2002). In reasonably flushed areas, leachates from new pilings have been shown to have negligible effects on estuarine ecology, while those from new bulkheads or those in poorly flushed areas may have impacts that can be detected for several years (Weis, Weis and Proctor, 1998). In poorly flushed areas and/or those with a high surface area of CCA treated timber, elevated metal concentrations have been seen in algae, barnacles, mussels, oysters, fiddler crabs and fish (Weis and Weis, 1992b; Weis and Weis, 1993; Weis, Weis and Couch, 1993; Weis, Weis and Lores, 1993).

Galvanised steel

Galvanised steel is coated in zinc to prevent corrosion of the structure (Yadav, Nishikata and Tsuru, 2004), and is frequently used in construction due to its resistance to corrosion and biofouling (Ilhan-Sungur, Cansever and Cotuk, 2007). However, there is little research available on the effects of leaching from instream steel structures (4 papers; Table 2). One detailed study of culvert durability and erosion from South America recorded the most important factors affecting corrosion to be water chemistry (pH, TSS, hardness and alkalinity), degree of water agitation, temperature, and time of water contact (Bednar, 1989). Galvanized steel pipe was considered sufficiently durable to be used in most soft waters; however, care should be taken in very soft, low conductivity water, where little dissolved salts are present in the water (Bednar, 1989). This is because the prevention of corrosion of galvanised steel is partially dependent on appropriate water hardness to form a protective scale over the metal (Bednar, 1989). This study does not investigate leachate; however, if a correlation is drawn between durability (i.e. resistance to corrosion) and the potential source of instream zinc contamination, then galvanised steel installed in waters with low corrosive potential are likely to contribute little to instream pollution. Based on the conclusions in Bednar (1989), it would seem plausible that Christchurch waterways are of appropriate water chemistry (hardness, pH) to prevent high corrosion. However, other regions, such as the West Coast that has some naturally acidic and/or soft streams (Winterbourn and McDiffett, 1996; Greig *et al.*, 2010; Horrox, Chaney and Eaves, 2015), may not have appropriate water chemistry to prevent corrosion.

There is also some indication that treated timber may corrode the galvanised steel angle/plates and nails that hold the timber in place (Kear, Wú and Jones, 2009; Zelinka, Sichel and Stone, 2010; Baker, 1992). In which case, pre-soaking H5 and H6 timber to reduce environmental damage may also substantially reduce galvanised steel corrosion rates.

Sulphur Reducing Bacteria (SRB) reduce inorganic sulphate to hydrogen sulphide, which can increase corrosion of steel (Costello, 1974; Ilhan-Sungur, Cansever and Cotuk, 2007). A study by Mor, Beccaria and Poggi (1974) found that in artificial seawater with a pH >7.2, corrosion of zinc was accelerated in the presence of sulphides. SRB are considered widespread in nature and are found in anoxic marine environments with excess sulphate and from freshwater lake sediments (Widdel and Bak, 1992 in Nielsen, Liesack and Finster, 1999; Jørgensen and Bak, 1991; Bak and Pfennig, 1991). Anoxic sediment refers to sediment that has been depleted of oxygen, as typically occurs in slow waterways with little flushing flows and high detrital inputs. Given the above, corrosion of galvanised steel structures could be expected to be accelerated when in contact with anoxic, sulphate rich sediments, which could lead to an increase in zinc sulphide released to the environment.

Concrete

All the literature on concrete was based on laboratory studies investigating direct concentrations of leachates (5 papers; Table 3). The main risk posed by concrete is the increase of water pH to a highly alkaline state, via the release of calcium hydroxide (Taylor, 1997 *in* Setunge, 2009). Concrete wash and dust should never enter a waterway or stormwater system, with 100,000 litres of water required to dilute 1 litre of concrete wash, with filtering having no effect (Environment Canterbury, undated). Velocity appears to have a substantial impact on peak pH, with lower velocities causing higher pH peaks and for longer durations (Setunge *et al.*, 2009; Law *et al.*, 2013).

For fresh cast concrete, both Law *et al.* (2013) and Setunge *et al*. (2009) found that the time between casting and immersion in water did not materially affect changes in pH, with Setunge *et al*. (2009) finding that all samples followed the same pattern of peaking around pH 11, and slowly falling over the following 30–35 days. However, fresher concrete typically had slightly higher pH peaks and declines were slightly more protracted (Setunge *et al.*, 2009; Law *et al.*, 2013). After immersion, peak pH may occur around one day in very slow water, but in around 15–30 minutes in faster water (Setunge *et al.*, 2009; Law *et al.*, 2013). Aggressiveness of the water (soft water, or water containing corrosive substances, such as those high in carbonic acid) can increase leaching (Ekström, 2003). This may mean that concrete in soft water catchments, such as the Styx and Ōtūkaikino Rivers (Marshall and Noakes, 2019) may leach more readily than other river catchments in Christchurch. Seawater typically has more carbonic acid than freshwater, therefore marine grade concrete should be used in coastal areas (Paul Woods, CCC, personal communication, 27 May 2020). Bulk leaching can also occur in porous concrete (Ekström, 2003).

Basar and Aksoy (2012) found that nickel, zinc and chromium concentrations in eluate from various concrete types were typically lowest in slightly acidic conditions (pH 5.5). The results of this study were compared to the Canterbury Land and Water Regional Plan 90% species protection levels for these metals (Environment Canterbury, 2018) and the following exceedances were found (Table 3):

- at pH 5.5, zinc eluate occasionally exceeded the guideline level and chromium eluate always exceeded the guideline
- at pH 9.0, zinc and chromium eluate from all concrete types were above the respective guideline levels
- at pH 4.0, nickel and zinc eluate exceeded the respective guidelines for most concrete types, and chromium eluate always exceeded the guidelines

Christchurch waterways typically record pH values between 6.5–8.0 (Marshall and Noakes, 2019). Therefore, leaching effects on biota from zinc and chromium may occur in these waterways, although dilution within the streams may reduce or eliminate this effect.

A study by Tippler *et al.* (2014) found that in an acidic sandstone catchment, changes in stream geochemistry were attributable to urban development, particularly the concrete stormwater infrastructure. A similar phenomenon was found by Kaushal, McDowell and Wollheim (2014) when they conducted a literature review assessing urban impacts on ecosystem services. They concluded that widespread coverage of concrete and aging cement infrastructure can contribute to river alkalinisation (Kaushal, McDowell and Wollheim, 2014). Given the urban nature of Christchurch city, there may be similar effects. However, New Zealand based experiments may be important as Christchurch waterways are circumneutral or slightly alkaline (Marshall and Noakes, 2019).

Conclusions and recommendations

The greatest environmental threat appears to be from CCA treated timber, with this risk increased through the use of newly treated timber, timber with a high surface area, and the use of timber within poorly flushed waterways, or estuarine and coastal waters. This draws attention to the high number of timber lined drains in Christchurch waterways, particularly those in estuarine areas and those with ‘threatened’ or ‘at risk’ sediment living biota, such as kākahi/freshwater mussels (*Echyridella menziesii*) and kanakana/lamprey ammocoetes (*Geotria australis*) (Dunn *et al*., 2018; Grainger *et al*., 2018). Christchurch waterways likely have appropriate water chemistry to prevent accelerated corrosion and therefore leaching of galvanised steel, so the environmental risks of using these structures are low. There are some risks with the use of concrete structures, but as with CCA treated timber, it is possible to reduce these risks by following design standards and considering whether the environment the structure is to be used in is more likely to cause leaching.

When considering the use of these instream structures, the following is recommended:

- CCA treated timber
    - After treating, timber should be free of any extraneous surface deposits ('sludge’) (Hedley, 1997) and held on the Timber Treatment Pad until it is drip free, then moved to a storage area until such time as fixation is achieved (Jeff Ilott, New Zealand Timber Preservation Council, personal communication, 26 June 2020). Storage time should also be provided by suppliers.
    - Fixation should be determined as per the relevant New Zealand Standards and the Best Practice Guideline for the safe use of Timber Preservatives and Anti

  Sapstain Chemicals[1], and using a Merck test or equivalent (Hedley, 1997; Standards New Zealand, 2003; New Zealand Timber Preservation Council Inc, 2005; Standards Australia and Standards New Zealand, 2006). Fixation time can vary, as this is a function of time and temperature. Therefore, baseline testing should be undertaken to ascertain fixation times at various times of the year (Jeff Ilott, New Zealand Timber Preservation Council, personal communication, 26 June 2020). In summer, fixation may take as little as two weeks; however, if wood is stored outside in winter this may take months (Hedley, 1997).
  - Timber is treated to Hazard Class 5 (H5) for freshwater environments, or to Hazard Class 6 (H6) for use in sea water or estuarine ground (Standards New Zealand, 2003).
  - Timber intended for use in aquatic environments is pressure treated to minimise potential adverse environmental effects (Sreeja, 2008). This currently occurs for H5 and H6 timber (Jeff Ilott, New Zealand Timber Preservation Council, personal communication, 17 June 2020).
  - Timber is soaked for several months prior to installation in aquatic environments. This is particularly important in areas where CCA treated timber will be used in coastal or estuarine waters, in waterways that are poorly flushed, or where a large volume of timber is required relative to the size of the waterbody (Weis and Weis, 1992b; Weis and Weis, 1993; Weis, Weis and Couch, 1993; Weis, Weis and Lores, 1993). Exactly how long timber should be soaked to prevent environmental effects is not defined in the literature. This practice may also be difficult to achieve on site. As such, research is required to determine whether this is necessary in the context of Christchurch and Banks Peninsula environments, and if so, how long timber should be soaked for, and how this soaking would be achieved.
- Galvanised steel
  - Galvanised steel should not be used where there is highly anoxic sediment.
  - Where galvanised steel is used with H5 and H6 CCA treated timber, the timber should be pre-soaked to reduce corrosion of the steel.
- Concrete
  - Given the peak in pH observed after immersion of concrete in water, prefabricated concrete structures should be used where possible and washed/soaked for at least 24 hours before installation in waterways (Setunge *et al.*, 2009; Law *et al.*, 2013). Particular care should be taken to pre-soak concrete to be used in waterways with low velocity. It is unlikely that soaking is currently a standard practice in New Zealand and this could potentially be difficult to achieve with large structures. Research should be carried out to determine whether this is necessary for Christchurch and Banks Peninsula streams and how this could be achieved if so.
  - If concrete can only be poured, cured and soaked in-situ, this must occur in isolation from the waterway (e.g. within a dry cofferdam). Soakage water should be pumped out and removed. Research is recommended to investigate the effects of different water to concrete ratios and how often soakage water should be replaced - as well as how this could be practically achieved.
  - Storage time should be provided by suppliers.
  - Bulk leaching is high in porous concrete (where pores are interconnected) (Ekström, 2003); therefore, dense concrete (i.e. concrete with low porosity) should be used. In New Zealand, concrete pipes are typically machine made, producing dense, high strength concrete with low permeability (Concrete Pipe Association of Australasia, 2013). As such, soaking may only be required for other concrete structures, such as headwalls.

---

[1] At the time of publication, this is a best practice guideline and not a compliance requirement specified in any Standard. However, the New Zealand Timber Treatment Standard (NZS 3640) is currently being revised and the issue of fixation will become a compliance matter (Jeff Ilott, New Zealand Timber Preservation Council, personal communication, 26 June 2020).

    - Heavily cracked and damaged concrete should be replaced to minimise leachates released into the environment, and to ensure the functionality and integrity of the structure.
- Additional research to that mentioned in the recommendations above is carried out to assess the effects of leaching from these instream structures on surface water quality and biota of Christchurch and Banks Peninsula waterways. In particular:
    - To establish what timber type should be used to address the issue of more leaching from fast grown wood of lower quality.
    - To determine whether the high use of pine in New Zealand means that the risks of leaching from CCA treated timber is greater than that recorded overseas and whether other wood products can be used to reduce environmental effects.
    - A survey (likely with anonymous participants) is carried out of current practices, comparisons between expected industry practice, what practices installers actually carry out and whether they believe they are following the guidelines, as well as an assessment of how difficult the recommendations in this memo would be to achieve.
    - Research into changes in stream geochemistry and whether this is attributable to urban development and concrete infrastructure.
    - Quantification, assessment and remediation prioritisation of old, heavily cracked and damaged concrete structures (e.g. pipes, outlets, piers), due to the increased risk they provide of leaching.
- The recommendations in this memo and from future research are incorporated into relevant Christchurch City Council (CCC) documents (e.g. Infrastructure Design Standard and Waterways Wetlands and Drainage Guide) and disseminated to other interested parties (e.g. industry and Regional Council’s).

Table 1 Summary of each study investigating the leaching of Copper-Chrome-Arsenate (CCA) treated wood, including country where the study was undertaken, year of study, reference details, focus of the study and the main points from the study

Country of Origin	Year	Reference	Focus	Main Points
Germany (?)	1972	(Irvine, Eaton and Jones, 1972) *in* (Hingston *et al.*, 2001)	Leaching of CCA timber in marine water	• Marine water was found to increase copper and chromium loss compared to freshwater and sewage effluent. • Salinity from 0–24 ppt had no increased loss of copper.
Sweden	1984	(Plackett, 1984) *in* (Hingston *et al.*, 2001)	Laboratory study of leaching of CCA timber in salt solutions	• Wood soaked in salt solutions leached more copper than in deionized control water. • Leaching rates increased with higher salt concentrations.
Canada	1990	(Warner and Solomon, 1990)	Laboratory study of leaching of CCA timber in acidic conditions	• Low pH solutions resulted in very high leaching rates. • At pH 3.5, up to 100% of copper was leached.
United States of America	1991	(Cooper, 1991)	Laboratory study of leaching of CCA timber in acidic conditions	• In response to Warner & Solomon (1990), the strong result of leaching in acidic conditions was due to the citric acid buffer, and when a mineral acid was used, no consistent effect was found at pH 3.5–5.5.
United States of America	1991	(Weis, Weis and Coohill, 1991)	Laboratory study on the effect of CCA wood on aquatic biota	• Fiddler crabs (*Uca pugilator*) had their limbs removed and were placed in containers with variously sized treated wood or control wood. The rate of limb regeneration was inhibited in a dose-dependent manner and mortality occurred with the treated wood, reaching 100% in the tank with the largest piece of wood. • Mortality was recorded in mummichog (*Fundulus heteroclitus*) embryos that developed in culture dishes with CCA-treated timber. Mortality was recorded to a smaller extent in those with untreated wood.

Country of Origin	Year	Reference	Focus	Main Points
				• Within a few days of immersion in containers with CCA treated timber, chlorophyll content of algae (*Ulva lactuca*) reduced, and snails (*Nassarius obsoletus*) became moribund and died. In the controls containing untreated wood or no wood, no such effects were seen. • Copper was primarily responsible for algal bleaching and snail mortality. • Toxic effects from wood that had previously leached for several weeks were much less severe.
United States of America	1992	(Weis and Weis, 1992a) *in* (Weis and Weis, 2004)	Field study on the effect of CCA wood on aquatic biota	• CCA treated timber that was submerged in an estuary had lower species richness and diversity, and barnacles were less common and had reduced growth. • One species of bryozoan (*Bugula turrita*), was found in higher density on the treated wood.
United States of America	1992	(Weis and Weis, 1992b)	Laboratory and field study on the effect of CCA wood on aquatic biota	• Green algae (*Enteromorpha intestinalis* and *U. lactuca*) from CCA treated wood (c. 3 year old bulkheads and floating docks) had approximately four and three times as much copper respectively, two and three times as much chromium, and four and nine times as much arsenic, as algae from nearby rocks. • Snails (*N. obsoletus*) were fed green algae from CCA treated wood and after four weeks all snails were either retracted into their shells or dead. All control snails fed algae from nearby rocks remained active. • However, snails fed on algae collected from CCA treated timber did not have elevated metal concentrations in their tissue. • Metal concentrations were higher in older parts of the plant and lowest in the fast-growing tips. • Oysters (*C. virginica*) collected from a reference site, open water dock and a CCA timber lined canal. Compared to the reference site, copper levels were elevated in both the dock (two times) and canal (12 times) populations, but only the canal population had elevated arsenic. Chromium was below detection in all oysters. • Benthic living fiddler crabs (*Uca panacea* and *U. pugilator*) were also found to have elevated copper and arsenic concentrations in areas with CCA treated timber. Chromium levels in *U. panacea* did not vary across sites; however, levels in *U. pugilator* were elevated in association with CCA treated timber.
United States of America	1992	(Weis *et al.*, 1992)	Laboratory study on the effect of CCA	• Limb regeneration was depressed in fiddler crabs (*U. pugilator*) exposed to CCA treated timber.

Country of Origin	Year	Reference	Focus	Main Points
			wood and recycled plastic on aquatic biota	• One- and three-day leachate from CCA treated timber reduced sea urchin (*Arbacia punctulata*) fertilisation by 90% and completely inhibited larval development in the remaining 10%. A smaller piece of wood did not have significant effect of fertilisation or development. • With 1–3 weeks of leaching from the smaller piece of CCA treated timber, no fertilisation was seen in sea urchins. • Snails (*N*. *obsoletus*) and algae (*U*. *lactuca*) were exposed to CCA leachates for two months, and this caused 100% mortality in snails and chlorosis of the algae.
N/A	1993	(Brooks, 1993) *in* (Hedley, 1997)	Literature review of CCA and ACZA wood	• "Even with this very conservative approach to assessing the risks involved, this analysis indicates that the levels of contaminants associated with the use of properly treated CCA and AZCA [ammoniacal zinc copper arsenate] wood products are well below regulatory standards and will produce concentrations far below those causing acute or chronic stress in even the most sensitive taxa".
United States of America	1993	(Merkle, Gallagher and Soldberg, 1993) *in* (Hingston *et al.*, 2001)	Leaching of CCA timber	• Leaching may be more severe in field experiments due to increased physical stress, such as abrasion, cracking and borer.
United States of America	1993	(Weis and Weis, 1993)	Laboratory and field study on the effect of CCA wood on aquatic biota	• Copper concentrations in carnivorous snails (*Thais haemastoma*) fed oysters (*C*. *virginica*) collected from a CCA treated wood lined canal increased approximately four-fold compared to snails fed oysters collected from the reference site. These snails attained levels comparable to snails collected from a CCA bulkhead in open water. Snails were not found within the canal. • Snails fed oysters collected from CCA wood grew and gradually ate less than the control snails. • Fish (*Leiostomus xanthurus* and *Lagodon rhomboides*) collected from inside a CCA lined canal had five and seven times as much copper and arsenic than reference fish. *L*. *xanthurus* collected from the canal had elevated levels of chromium, however L. *rhomboides* had lower levels compared to the reference site. • Fish fed worms collected from adjacent to a CCA bulkhead facing open water had a non-significant trend of lower survival than those fed reference worms, and there was no significant difference in growth or CCA body burdens.

Country of Origin	Year	Reference	Focus	Main Points
United States of America	1993	(Weis, Weis and Couch, 1993) *in* (Weis and Weis, 2004)	The effect of CCA wood on aquatic biota	• Copper concentrations in oysters collected from within a CCA timber lined canal were 12 times higher than the reference site, while arsenic was about double the reference site. • Oysters collected from within a CCA timber lined canal were often greenish in colour. • A negative correlation between oyster weight and copper concentration indicates that levels dilute as they grow, which may have negative implications for predators that preferentially feed on smaller oysters. • Oysters collected from within a CCA timber lined canal had an elevated incidence of a pathological condition of the digestive diverticula. This condition did not appear in control oysters that were transplanted into the canal for three months.
United States of America	1993	(Weis, Weis and Lores, 1993)	Field study on the effect of CCA wood on aquatic biota	• Algae (*Ceramium* sp.) growing on a CCA treated timber dock in open water had approximately double the copper and arsenic concentrations of the reference site. Algae was not found in the canal. • Barnacles (*Balanus eburneus*) growing on a CCA treated dock had copper concentrations approximately three times higher than those on nearby rocks, while those in a CCA timber treated canal had levels approximately 10 times that of the reference site rocks. Barnacles attached to new wood in the canal had concentrations approximately 80 times higher than the reference. Chromium and arsenic were also elevated in the canal, particularly in barnacles attached to the new wood. • Mussels (*Brachydontis recurvis*) collected from the canal had elevated copper concentrations (c. 7 times) compared to the reference site. It is likely that the increase in chromium (from below to above detection) is biologically significant.
United States of America	1993	(Weis, Weis and Proctor, 1993)	Field study of CCA timber leaching in estuarine sediment	• Metals were found to accumulate in fine sediment, such as silt or clay. • Metals were found in higher concentrations in the newest bulkhead. • Poorly flushed areas had higher metal concentrations than in more open water environments. • Copper concentration was always much higher than chromium or arsenic.
United States of America	1994	(Cooper, 1994) *in* (Hingston *et al.*, 2001)	Leaching of pressure treated CCA wood	• Studies typically use small blocks of wood, which have a high surface area available for leaching. • High concentrations of humic acid in surface water may increase leaching.

Country of Origin	**Year**	**Reference**	**Focus**	**Main Points**
Ireland	1994	(Hayes, Curran and Hynes, 1994)	Field study of leaching of CCA timber in coastal waters	• The poor-quality timber (Lodgepole pine: *Pinus contorta*) leached more metals than the better-quality timber (Douglas fir: *Pseudotsitga menziesii*). • Arsenic was more readily leached than copper or chromium. • Larger blocks leached less than smaller blocks.
United States of America	1994	(Weis and Weis, 1994)	Field study on the effect of CCA wood on aquatic biota	• Metals were elevated in subtidal benthic worms living adjacent to CCA treated bulkheads and decreased with distance from the bulkhead. • Compared to reference sites, the benthic community adjacent to the bulkheads had lower species richness, total abundance and species diversity.
Belgium/ Sweden	1995	(Van Eetvelde *et al.*, 1995b; Van Eetvelde *et al.*, 1995a) *in* (Hingston *et al.*, 2001)	Leaching of CCA timber in acidic conditions	• Maximum leaching of chromium and arsenic was recorded under neutral conditions; however, initial loss of copper increased with higher acidity. • Leaching rates were lower at lower temperatures.
United States of America	1995	(Weis *et al.*, 1995)	Field study on the effect of CCA wood on aquatic biota	• Oysters (*Crassostrea virginica*) living inside a canal lined with CCA treated timber bulkheads had twice as many micronuclei in gill cells as reference oysters and had significantly more metaplastic degeneration in digestive gland diverticula. • The number of micronuclei in control oysters transplanted into the canal significantly increased after three months; however, they did not show increased digestive gland metaplasia. • Other possible stressors in the canal (e.g. boat exhaust, gardening chemicals) could be involved.
United States of America	1996	(Weis and Weis, 1996)	Field study on the effect of CCA wood on aquatic biota	• When the epibiota from the CCA treated timber was removed after one month and the timber returned to the water, the subsequent epibiota differed less compared to the control. On the third submersion, there was no statistically significant difference between the treatment and control. This indicates that toxicity reduced after a period of soaking. • However, growth of algae (*Enteromorpha* sp.) and a bryozoan (*Conopeum* sp.) was still impacted. • Study provides evidence that timber would have reduced environmental impact if it were soaked prior to leaving the treatment facility.

Country of Origin	Year	Reference	Focus	Main Points
United States of America	1996	(Wendt *et al.*, 1996)	Field study on the effect of CCA wood on aquatic biota	• In some cases metal concentrations were higher in sediments and oysters (*C. virginica*) immediately adjacent to docks; however, sediments from most sites had concentrations below the level reported to cause biological effects. • No significant difference was seen in sediments between creeks with high numbers of docks compared to those without docks. • Copper concentrations were significantly higher in oysters growing directly on dock pilings than those at least 10 m away; however, there was no significant difference in the physiological condition. • In a four day experiment, there was no significant difference in percent survival of mummichogs (*F. heteroclitus*), mud snails (*Ilyanassa obsoleta*), juvenile red drum (*Sciaenops ocellatus*), and juvenile white shrimp (*Penaeus setiferus*) between sites near to and distant from newly constructed docks. • There was no significant difference in percent survival, growth, or bioaccumulation of metals in oysters (*C. virginica*) after six weeks of exposure to newly constructed docks (4–12 months old). • The results indicate that in estuarine environments (tidal range 1.5-2.0 m) CCA leachates from dock pilings do not have acutely toxic effects on four common estuarine species, nor do they affect the short-term survival or growth of juvenile oysters.
N/A	1997	(Hedley, 1997)	Literature review of CCA wood	• Some leaching occurs from freshly treated wood, but most studies indicate this adds little to background levels. • The fixation process is time and temperature dependant, and CCA wood should never leave the treatment site for at least two weeks. • Issues tend to arise when quality assurance requirements are not complied with. •
United States of America	1998	(Breslin and Adler-Ivanbrook, 1998)	Laboratory study of Leaching of CCA timber in estuarine water	• Metals leached continuously, but at a decreasing rate throughout the 90-day study. • Leaching rates of arsenic were lower at higher temperatures (4℃ and 20℃). • Studies where the leachate solution is replaced infrequently may inhibit the diffusion of elements from the wood.

Country of Origin	Year	Reference	Focus	Main Points
United States of America	1998	(Weis, Weis and Proctor, 1998)	Field study of CCA timber leaching on estuarine the benthos	• Leachates from new pilings have negligible ecological effects in reasonably flushed areas. • Leachates '…from bulkheads, particularly new ones and those in poorly flushed regions, have effects that can be seen in some cases out to 10 m and for a number of years'. • Metal concentrations in benthic organisms generally paralleled levels within the surrounding sediment. • Concentrations were typically elevated 0-1 m from the bulkheads; however, in some cases extended to 10 m. The inconsistent reduction up to 10 m out was attributed to a variety of factors such as age of the bulkhead, energy of the environment and the nature of the sediments.
United States of America	1999	(Weis and Weis, 1999)	Field study on the effect of CCA wood on aquatic biota	• In a three month caged field experiment, epibiota from CCA treated timber had elevated copper and arsenic, while amphipods also had elevated copper when compared to the control. • Caged grass shrimp (*Palaemonetes pugio*), naked gobies (*Gobiosoma bosci*) and mummichogs (*F. heteroclitus*) did not have elevated metals. • Trophic transfer was not demonstrated to the consumers, indicating that the treated wood did not present a hazard to higher trophic levels.
United Kingdom	2000	(Tupper, Pitman and Cragg, 2000)	Field study on the effect of CCA wood on aquatic biota	• A marine isopod (*Limnoria* spp.) was able to bore through CCA treated timber by storing copper in inert granules in their digestive caecae and therefore did not suffer toxic effects. • Neither chromium nor arsenic were elevated in granules or the digestive caecal cells.
United Kingdom	2001	(Brown and Eaton, 2001)	Field study of leaching of CCA timber on aquatic biota in coastal waters	• After 6, 12 and 18 months, epibiotic communities on CCA treated timber were similar to untreated wood.
N/A	2001	(Hingston *et al.*, 2001)	Literature review of CCA wood	• Insufficient data exists to allow accurate quantification of leaching rates and there is a need for standardised leaching protocols. • Factors affecting leaching rates included pH, salinity, surface area-to-volume ratio, treatment and leaching test protocols.

Country of Origin	Year	Reference	Focus	Main Points
England	2001	(Prael, Cragg and Henderson, 2001) *in* (Weis and Weis, 2004)	Laboratory study on the effect of CCA wood on aquatic biota	• Early veliger stage of larval oysters (*Crassostrea gigas*) avoided concentrated leachate. • Three- and seven-day old larvae swam faster in leachate than in clean sea water, they also moved up and down more in the leachate.
United States of America	2002	(Rice, Conko and Hornberger, 2002)	Field study of anthropogenic sources of metals in a lake	• Metal concentrations in lake sediment from CCA treated lumber accounted for 50% of the arsenic and 4% of the copper present.
United States of America	2002	(Weis and Weis, 2002)	Field study of CCA timber leaching on saltmarshes	• Metal concentrations were highly elevated up to 10 m away, the maximum extent of the sampled area. • Concentrations were more elevated under the new (3 years) walkway than the old (15 years) walkway but had not dispersed as far. • Accumulation was generally highest in the low marsh, where tidal inundation was most frequent. • Accumulation patterns in saltmarsh plants were similar to sediments; however, elevated levels did not disperse as far and did vary depending of the age of the walkway.
Hong Kong	2003	(Chan, Wang and Ni, 2003)	Laboratory study of cadmium, chromium and zinc assimilation through trophic levels	• Macroalgae (*Enteromorpha crinita*) with various elevated levels of chromium were fed to the herbivorous marine rabbitfish (*Siganus canaliculatus*). Metals were assimilated at appreciable levels regardless of metal concentration within the algae.
United States of America	2004	(Weis and Weis, 2004)	Literature review of effects of CCA wood on biota	• CCA treated timber contains Cr(VI), which is highly genotoxic. • Newly treated CCA timber leaches the fastest and is therefore the most toxic. • Environmental impacts from the use of CCA treated timber could be considerably reduced if timber was soaked for a few months before being released to the market.

Country of Origin	Year	Reference	Focus	Main Points
				• There have been no studies investigating ecosystem level impacts in the aquatic environment. • Most harmful effects appear to be due largely to copper. •
India	2008	(Sreeja, 2008)	Laboratory study on the effect of CCA wood on aquatic biota	• Six types of CCA treated timber ('treatments') were submerged into still freshwater tanks for six months and the effects on fish were assessed. A control tank with untreated timber was also used. • Highly acidic CCA treated wood did not cause a significant change in pH. • In all treatments fish showed excess mucus secretion, but not the control. • The highest accumulation of all three metals was in the liver, while the lowest was in muscle. • All three metals were detected in the gills of the control group. • Fishes exposed to CCA timber showed an increase in metal concentrations when compared to the control samples, although there was some overlap. • Laboratory studies may overestimate the impacts of metals due to limited dilution. • Dip treated panels leached more quickly than pressure treated.

Table 2. Summary of each study investigating corrosion of galvanised steel, including country where the study was undertaken, year of study, reference details, focus of the study and the main points from the study

Country of Origin	**Year**	**Reference**	**Focus**	**Main Points**
South Africa	1974	(Costello, 1974)	Laboratory study on sulphur reducing bacteria	• The production of hydrogen sulphide by sulphur reducing bacteria may be causing corrosive effects rather than sulphur reducing bacteria themselves, as has been proposed elsewhere.
Italy	1974	(Mor, Beccaria and Poggi, 1974)	Laboratory study on impact on corrosion of annealed zinc bars	• In artificial seawater with a pH >7.2, corrosion of zinc was accelerated in the presence of sulphides.
South America	1989	(Bednar, 1989)	Field study on corrosion of galvanised steel pipes/culverts	• Most issues are around durability and accelerated waterside corrosion. • Most important factors in corrosion are water chemistry (pH, TSS, hardness and alkalinity), degree of agitation, temperature and time of water contact. • “Hardness and alkalinity salts common to natural waters tend to form partially protective mineral scales or films that hinder corrosion of reactive metals like zinc and steel which otherwise would tend to corrode excessively”. • “Soft, pure low-conductivity waters containing very little of any type of dissolved salt, including hardness/alkalinity salts, tend to be fairly corrosive because they possess no scaling tendency and they lack the buffering capacity that leads to pH lowering.” • “The balance between hardness and alkalinity on one hand versus acidity and chloride/sulfate salts on the other is critical in determining whether protective scaling or excessive corrosion will occur”. • Soft water in drier temperate climates is less harsh than soft water in warm, wet tropical climates.

Country of Origin	Year	Reference	Focus	Main Points
				• Galvanized steel pipe is sufficiently durable to be used in most soft waters, and certainly for limited life requirements. • “Excessive free CO_2 suppresses scaling and directly accelerates corrosion, and the combined effect of excess CO_2 and higher conductivity can be very severe. Slow flowing streams in areas with somewhat impeded drainage are more likely to be rich in free C02 because higher velocity greatly aerates the water and drives off C02”. • Physical steel erosion processes can be worsened as high velocities slough off the protective scale.
Turkey	2007	(Ilhan-Sungur, Cansever and Cotuk, 2007)	Laboratory study on galvanised steel corrosion by sulphur reducing bacteria	• Galvanized steel is frequently used in construction due to its resistance to corrosion and biofouling. • Sulphur reducing bacteria reduce inorganic sulphate to hydrogen sulphide. • Study demonstrated that sulphur reducing bacteria are able to corrode galvanized steel.

Table 3. Summary of each study investigating concrete effects, including country where the study was undertaken, year of study, reference details, focus of the study and the main points from the study

Country of Origin	Year	Reference	Focus	Main Points
Sweden	2003	(Ekström, 2003)	Thesis on durability and strength of concrete	• Corrosion can be caused by water itself, or by matter dissolved in the water. • Calcium-silicate-hydrate (a product in concrete) is soluble in water, and the most important factors influencing leaching are aggressiveness of the water and permeability of the concrete. • Bulk leaching is high in porous concrete (where pores are interconnected), but low through cracks. However, localised leaching (e.g. in a crack) is often very high. Permeability is considered the most important property affecting concrete durability.
Australia	2009	(Setunge *et al.*, 2009)	Laboratory study on leaching of fresh cast concrete	• Early contact with water after casting (up to the study maximum of 120 hours) can result in pH levels of up to 11, which is similar to levels in pore water of freshly cast concrete. • Time since casting (20, 48 and 120 hours) did not materially affect changes in pH, with all samples following the same pattern of peaking around pH 11, and slowly falling over the following 30–35 days. • Even after 35 days, pH did not reduce below 8.5. However, the experiment was conducted in low velocity water. • For normal concrete to water ratios as observed in bridges and culverts, peak pH can be expected to occur about one day from initial contact.
Turkey	2012	(Basar and Aksoy, 2012)	Laboratory study on leaching of cast concrete	• Eluate concentrations for all three tested metals (nickel, zinc and chromium) were typically lowest at pH 5.5. • To provide context for CCC waterways, metal concentrations in eluate from this paper were compared to the Canterbury Land and Water Regional Plan (Environment Canterbury, 2018) guideline concentrations as below: o Nickel: All eluate at pH 5.5 and 9.0 were below the 90% and 99% Species Protection Level (SPL) of 0.013 mg/L, but not at pH 4.0. o Zinc: Generally, eluate at pH 5.5 was just below the 90% SPL of 0.015 mg/L. However, levels were above the SPL at pH 4.0 and 9.0. o Chromium: No value was recorded below the 90% SPL of 0.006 mg/L. • It is unclear whether metals given are totals or dissolved – if totals, comparisons to the SPL will be conservative.
Australia	2013	(Law *et al.*, 2013)	Laboratory study on	• Concrete either one or four days after casting was immersed in water and exposed to two velocities.

Country of Origin	Year	Reference	Focus	Main Points
			leaching of fresh cast concrete in slow flowing streams	- Velocity was the most significant factor in peak pH and the time until peak pH. The volume of the sample was also a significant factor in peak pH. - Slower velocity resulted in pH peaking higher, later and for longer. - In slower velocities, peak pH was recorded at over an hour after immersion, while at the faster velocity peak pH was recorded between 15–30 minutes. - Although not significant, concrete immersed one day after casting had a higher mean peak pH than those immersed after four days.
New Zealand	N/A	(Environment Canterbury, undated)	Planning document on concrete wash and dust	- Concrete wash and dust is trade waste and must be disposed of correctly, and never into a waterway. - 100,000 L of water would be required to dilute 1 L of concrete wash, and filtering has no effect on toxicity.

References

Bak, F. and Pfennig, N. (1991) 'Sulfate-reducing bacteria in littoral sediment of Lake Constance', *FEMS Microbiology Letters*, 85(1), pp. 10.

Baker, A. J. (1992) 'Corrosion of nails in CCA-and ACA-treated', *Forest Products Journal*, 42(9), pp. 39.

Basar, H. and Aksoy, N. (2012) 'The effect of waste foundry sand (WFS) as partial replacement of sand on the mechanical, leaching and micro-structural characteristics of ready-mixed concrete', *Construction and Building Materials*, 35, pp. 8.

Bednar, L. (1989) 'Durability of plain galvanized steel drainage pipe in South America: criteria for selection', *Transportation Research Record*, 1231, pp. 8.

Breslin, V. and Adler-Ivanbrook, L. (1998) 'Release of copper, chromium and arsenic from CCA-C treated lumber in estuaries', *Estuarine, Coastal and Shelf Science*, 46(1), pp. 15.

Brooks, K. (1993) *Literature review and assessment of the environmental risks associated with the use of CCA and ACZA treated wood products in aquatic environments*, Vancouver, WA, United States of America: Western Wood Preservers Institute.

Brown, C. and Eaton, R. (2001) 'Toxicity of chromated copper arsenate (CCA)-treated wood to non-target marine fouling communities in Langstone Harbour, Portsmouth, UK', *Marine pollution bulletin*, 42(4), pp. 9.

Chan, S., Wang, W. and Ni, I. (2003) 'The uptake of Cd, Cr, and Zn by the macroalga *Enteromorpha crinita* and subsequent transfer to the marine herbivorous rabbitfish, *Siganus canaliculatus*', *Archives of environmental contamination and toxicology*, 44(3), pp. 9.

Concrete Pipe Association of Australasia (2013)*: Guide to Understanding AS/NZ 4058:2007*.

Cooper, P. (1991) 'Leaching of CCA from treated wood: pH effects', *Forest Products Journal*, 41(1), pp. 3.

Cooper, P. (1994) 'Leaching of CCA: is it a problem? Environmental considerations in the manufacture, use and disposal of pressure treated wood', *Forest Products Society*.

Costello, J. (1974) 'Cathodic depolarization by sulphate-reducing bacteria', *South African Journal of Science*, 70(7), pp. 3.

Ekström, T. (2003) *Leaching of concrete: the leaching process and its effects*. PhD, Lund Institute of Technology, Lund, Sweden.

Environment Canterbury (2018) *Canterbury Land and Water Regional Plan*, Christchurch, New Zealand: Environment Canterbury.

Environment Canterbury (undated) *Concrete washwater; what you need to know*.

Greig, H., Niyogi, D., Hogsden, K., Jellyman, P. and Harding, J. (2010) 'Heavy metals: confounding factors in the response of New Zealand freshwater fish assemblages to natural and anthropogenic acidity', *Science of the Total Environment*, 408(16), pp. 11.

Hayes, C., Curran, P. and Hynes, M. (1994) 'Preservative leaching from softwoods submerged in Irish coastal waters as measured by atomic absorption spectrophotometry', *Holzforschung*, 48, pp. 11.

Hedley, M. (1997) *An assessment of risks associated with use of CCA-treated timber in sensitive environments and options for its substitution with alternative timber materials*, Wellington, New Zealand: Department of Conservation154).

Hingston, J., Collins, C., Murphy, R. and Lester, J. (2001) 'Leaching of chromated copper arsenate wood preservatives: a review', *Environmental Pollution*, 111(1), pp. 14.

Horrox, J., Chaney, E. and Eaves, A. (2015) *West Coast surface water quality report*, West Coast, New Zealand: West Coast Regional Council14001).

Ilhan-Sungur, E., Cansever, N. and Cotuk, A. (2007) 'Microbial corrosion of galvanized steel by a freshwater strain of sulphate reducing bacteria (*Desulfovibrio* sp.)', *Corrosion Science*, 49(3), pp. 13.

Irvine, J., Eaton, R. and Jones, E. (1972) 'The effect of water of different ionic composition on the leaching of a water borne preservative from timber placed in cooling towers and in the sea', *Material und Organismen*, 7, pp. 27.

Jane, F. (1970) *The structure of wood. Revised by Wilson, K. and White, D.* London, England: Adam and Charles Black, p. 478.

Jørgensen, B. and Bak, F. (1991) 'Pathways and microbiology of thiosulfate transformations and sulfate reduction in a marine sediment (Kattegat, Denmark)', *Appl. Environ. Microbiol.*, 57(3), pp. 10.

Kear, G., Wú, H.-Z. and Jones, M. (2009) 'Weight loss studies of fastener materials corrosion in contact with timbers treated with copper azole and alkaline copper quaternary compounds', *Corrosion Science*, 51(2), pp. 11.

Law, D., Setunge, S., Adamson, R. and Dutton, L. (2013) 'Effect of leaching from freshly cast concrete on pH', *Magazine of Concrete research*, 65(15), pp. 9.

Marshall, W. and Noakes, K. (2019) *Surface Water Quality Monitoring Report for Christchurch City Waterways: January – December 2018*: Christchurch City Council.

Merkle, P., Gallagher, D. and Soldberg, T. 'Leaching rates, metals distribution and chemistry of CCA treated lumber: implications for water quality monitoring'. *Forest Product Society's Symposium, Environmental Considerations in the Use of Pressure-Treated Wood*, Maddison, Wisconsin, United States of America, 10.

Mor, E., Beccaria, A. and Poggi, G. (1974) 'Behaviour of zinc in sea water in the presence of sulphides', *British Corrosion Journal*, 9(1), pp. 4.

New Zealand Timber Preservation Council Inc, Department of Labour and Zealand, E.R.M.A.N. (2005) *Best practice guideline for the use of timber preservatives & anti-sapstain chemicals.* Wellington, New Zealand.

Nielsen, J., Liesack, W. and Finster, K. (1999) '*Desulfovibrio zosterae* sp. nov., a new sulfate reducer isolated from surface-sterilized roots of the seagrass *Zostera marina*', *International Journal of Systematic and Evolutionary Microbiology*, 49(2), pp. 7.

Pacific Northwest Pollution Prevention Resource Center 2014. Emerging best management practices in stormwater: addressing galvanized roofing Seattle, Washington, United States of America.

Plackett, D. (1984) *Leaching tests on CCA treated wood using inorganic salt solutions (IRG/WP 3310)*, Stockholm, Sweden.

Prael, A., Cragg, S. and Henderson, S. (2001) 'Behavioral responses of veliger larvae of *Crassostrea gigas* to leachate from wood treated with copper-chrome-arsenic (CCA): a potential bioassay of sublethal environmental effects of contaminants', *Journal of Shellfish Research*, 20(1), pp. 7.

Rice, K., Conko, K. and Hornberger, G. (2002) 'Anthropogenic sources of arsenic and copper to sediments in a suburban lake, northern Virginia', *Environmental science & technology*, 36(23), pp. 6.

Setunge, S., Nguyen, N., Alexander, B. and Dutton, L. (2009) 'Leaching of alkali from concrete in contact with waterways', *Water, Air, & Soil Pollution: Focus*, 9(5-6), pp. 381.

Sreeja, A. (2008) *Chromated copper arsenate (CCA) treatment for rubber wood preservation and its impact on the aquatic biota.* Doctor of Philosophy, Cochin University of Science and Technology, Cochin, India.

Standards Australia and Standards New Zealand (2006) *AS/NZS 2843.1:2006: Timber preservation plants. Part 1: timber preservation plant site design*. Jointly published in Sydney, Australia & Wellington, New Zealand: Standards Australia & Standards New Zealand

Standards New Zealand (2003) *NZS 3640:2003: Chemical preservation of round and sawn timber*. Wellington, New Zealand: Standards New Zealand.

Taylor, H. (1997) *Cement chemistry*. Thomas Telford London.

Tippler, C., Wright, I., Davies, P. and Hanlon, A. (2014) 'The influence of concrete on the geochemical qualities of urban streams', *Marine and Freshwater Research*, 65(11), pp. 9.

Tupper, C., Pitman, A. and Cragg, S. (2000) 'Copper accumulation in the digestive caecae of *Limnoria quadripunctata* Holthius (Isopoda: Crustacea) tunnelling CCA-treated wood in laboratory cultures', *Holzforschung*, 54(6), pp. 7.

Van Eetvelde, G., Homan, W., Militz, H. and Stevens, M. 'Effect of leaching temperature and water acidity on the loss of metal elements from CCA treated timber in aquatic conditions. Part 2: semi-industrial investigation'. *The challenge: safety and environment*, Cannes-Mandelieu, France: The International Research Group on Wood Preservation, Stockholm., 13.

Van Eetvelde, G., Orsler, R., Holland, G. and Stevens, M. 'Effect of leaching temperature and water acidity on the loss of metal elements from CCA treated timber in aquatic applications, 1: Laboratory scale investigation', *The International Research Group on Wood Preservation, Sweden*.

Warner, J. and Solomon, K. (1990) 'Acidity as a factor in leaching of copper, chromium and arsenic from CCA-treated dimension lumber', *Environmental Toxicology and chemistry*, 9(11), pp. 7.

Weis, J. and Weis, P. (1992a) 'Construction materials in estuaries: reduction in the epibiotic community on chromated copper arsenate (CCA) treated wood', *Marine Ecology Progress Series*, pp. 9.

Weis, J. and Weis, P. (1992b) 'Transfer of contaminants from CCA-treated lumber to aquatic biota', *Journal of Experimental Marine Biology and Ecology*, 161(2), pp. 11.

Weis, J. and Weis, P. (1993) 'Trophic transfer of contaminants from organisms living by chromated-copper-arsenate (CCA)-treated wood to their predators', *Journal of Experimental Marine Biology and Ecology*, 168(1), pp. 10.

Weis, J. and Weis, P. (1994) 'Effects of contaminants from chromated copper arsenate-treated lumber on benthos', *Archives of Environmental Contamination and Toxicology*, 26(1), pp. 7.

Weis, J. and Weis, P. (1996) 'Reduction in toxicity of chromated copper arsenate (CCA)-treated wood as assessed by community study', *Marine Environmental Research*, 41(1), pp. 11.

Weis, J. and Weis, P. (2002) 'Contamination of saltmarsh sediments and biota by CCA treated wood walkways', *Marine Pollution Bulletin*, 44(6), pp. 7.

Weis, J. and Weis, P. 'Effects of CCA wood on non-target aquatic biota'. *Environmental Impacts of Preservative-Treated Wood.*, Florida Center for Solid and Hazardous Waste Management, Gainesville, FL., 13.

Weis, J., Weis, P. and Proctor, T. (1998) 'The extent of benthic impacts of CCA-treated wood structures in Atlantic coast estuaries', *Archives of Environmental Contamination and Toxicology*, 34(4), pp. 10.

Weis, P. and Weis, J. (1999) 'Accumulation of metals in consumers associated with chromated copper arsenate-treated wood panels', *Marine environmental research*, 48(1), pp. 9.

Weis, P., Weis, J. and Coohill, L. (1991) 'Toxicity to estuarine organisms of leachates from chromated copper arsenate treated wood', *Archives of Environmental Contamination and Toxicology,* 20(1), pp. 7.

Weis, P., Weis, J. and Couch, J. (1993) 'Histopathology and bioaccumulation in oysters *Crassostrea virginica* living on wood preserved with chromated copper arsenate', *Diseases of aquatic organisms,* 17(1), pp. 6.

Weis, P., Weis, J., Couch, J., Daniels, C. and Chen, T. (1995) 'Pathological and genotoxicological observations in oysters (Crassostrea virginica) living on chromated copper arsenate (CCA)-treated wood', *Marine Environmental Research,* 39(1-4), pp. 4.

Weis, P., Weis, J., Greenberg, A. and Nosker, T. (1992) 'Toxicity of construction materials in the marine environment: a comparison of chromated-copper-arsenate-treated wood and recycled plastic', *Archives of Environmental Contamination and Toxicology,* 22(1), pp. 8.

Weis, P., Weis, J. and Lores, E. (1993) 'Uptake of metals from chromated-copper-arsenate (CCA)-treated lumber by epibiota', *Marine Pollution Bulletin,* 26(8), pp. 3.

Weis, P., Weis, J. and Proctor, T. (1993) 'Copper, chromium, and arsenic in estuarine sediments adjacent to wood treated with chromated-copper-arsenate (CCA)', *Estuarine, Coastal and Shelf Science,* 36(1), pp. 9.

Wendt, P., Van Dolah, R., Bobo, M., Mathews, T. and Levisen, M. (1996) 'Wood preservative leachates from docks in an estuarine environment', *Archives of environmental contamination and toxicology,* 31(1), pp. 14.

Widdel, F. and Bak, F. (1992) 'Gram-negative mesophilic sulfate reducing bacteria', in A. Balows, H.T., M. Dworkin, W. Harder, K Schleifer (ed.) *The Prokaryotes*. New York: Springer Verlag.

Winterbourn, M. and McDiffett, W. (1996) 'Benthic faunas of streams of low pH but contrasting water chemistry in New Zealand', *Hydrobiologia,* 341(2), pp. 11.

Wise, L. and Jahn, E. (1952) *Wood Chemistry. American Chemical Society Monograph Series* 2nd edn. New York, United States of America: Reinhold.

Yadav, A., Nishikata, A. and Tsuru, T. (2004) 'Electrochemical impedance study on galvanized steel corrosion under cyclic wet–dry conditions—influence of time of wetness', *Corrosion Science,* 46(1), pp. 13.

Zelinka, S., Sichel, R. and Stone, D. (2010) 'Exposure testing of fasteners in preservative treated wood: gravimetric corrosion rates and corrosion product analyses', *Corrosion Science,* 52(12), pp. 6.