The atmospheres contribution to stormwater pollution: a Christchurch context

Louise U. Murphy

Thomas A. Cochrane

Aisling O' Sullivan

Department of Civil and Natural Resources Engineering
Hydrological and Ecological Engineering Group

Report No: 2015-3
ISSN: 1172-9511

ABSTRACT

Understanding the dynamics of atmospheric pollutant build-up and wash-off is essential for stormwater quality modelling. Atmospheric deposition loads in stormwater can be influenced by different land-use activities, meteorological conditions, and pavement types. To understand the dynamics influencing atmospheric deposition loads in stormwater, impermeable concrete boards were deployed in an industrial, residential, and airside land-use area in Christchurch for almost one year to determine the spatial and temporal variability of airborne pollutant loads (TSS, Cu, Pb, and Zn) in runoff. Additionally, atmospheric pollutant loads in runoff from different pavement types (impermeable and permeable concrete and asphalt) were quantified. Results showed that all three land-use areas exhibited similar patterns of varying metal and TSS loads, which indicates that atmospherically deposited metals and TSS had a homogenous distribution within the Christchurch airshed. Atmospheric deposition loads were influenced by the number of antecedent dry days and rainfall characteristics. However, the rainfall characteristics that imposed the greatest effect were dependent of the pollutants dominant speciation phase. Additionally, results showed that both permeable and impermeable concrete pavements were efficient at retaining Cu and Zn. However, bitumen leaching from an impermeable asphalt pavement was a significant source of Zn to runoff. Permeable pavements were effective at retaining particulate pollutants.

1. Introduction

Stormwater runoff is one of the primary causes of water quality degradation in New Zealand. Total suspended solids (TSS) and heavy metals in runoff are of principle concern due to their dominance in urban stormwater signatures and their detrimental effects on aquatic ecosystems (1; 2). In most cases, stormwater managers solely focus on *direct* sources of TSS and heavy metals in urban runoff within a catchment (e.g., from vehicular activity, metal roof erosion, and building construction) when implementing stormwater abatement strategies. *Indirect* pollution from atmospheric deposition is rarely considered. This is due to the uncertainty and challenges associated with measuring and managing these contributions. However, atmospheric deposition can contribute substantial pollutant amounts in runoff (3).

Atmospheric deposition is the returning of particles and gases from the atmosphere to the earth's surface. Atmospheric deposition occurs in two ways: dry or wet deposition. Dry deposition is the direct settling of particles and gases onto land or water surfaces during dry days. Wet deposition occurs when pollutants leach from the atmosphere with water droplets. The combination of dry and wet deposition is called bulk deposition. In Christchurch, dry deposition is the greatest contributor of atmospheric pollutant loads due to Christchurch's limited rainfall (≈650 mm annually). The quantity of atmospherically deposited pollutants loads in stormwater will vary with different land-use activities and meteorological conditions. This report discusses now airborne pollutant loads in stormwater varies spatially and temporally in Christchurch. In addition, the influence of different pavement types at retaining atmospheric pollutants is discussed.

2. Materials and Methods

Modular concrete pavement systems were exposed to atmospheric pollutant build-up, and after a rain event, the atmospheric pollutants were washed-off. The wash-off was collected and analysed for the stormwater pollutants of concern: total Cu, total Zn, total Pb, and TSS. The modular pavement systems were deployed in different land-use areas simultaneously from February 2013 to December 2013. The contribution and trends of atmospheric pollutants in stormwater were analysed over varying spatial and temporal conditions. In addition, atmospheric pollutant build-up and wash-off from different pavement materials (impermeable and permeable asphalt and concrete) were quantified (at the residential land-use area only) to determine how pavement-pollutant interactions influence pollutant retention (Figure 1). The impermeable concrete and asphalt boards had a collection area (Figure 1) incorporated into the board design to minimise pollutant loss via splash and spray. This assumed that the splash and spray leaving the collection area equaled the splash and spray entering into it. The permeable boards had the same dimensions as the collection area of the impermeable boards. Data analysis from the resulting experiments was conducted using the statistical programme R (4).

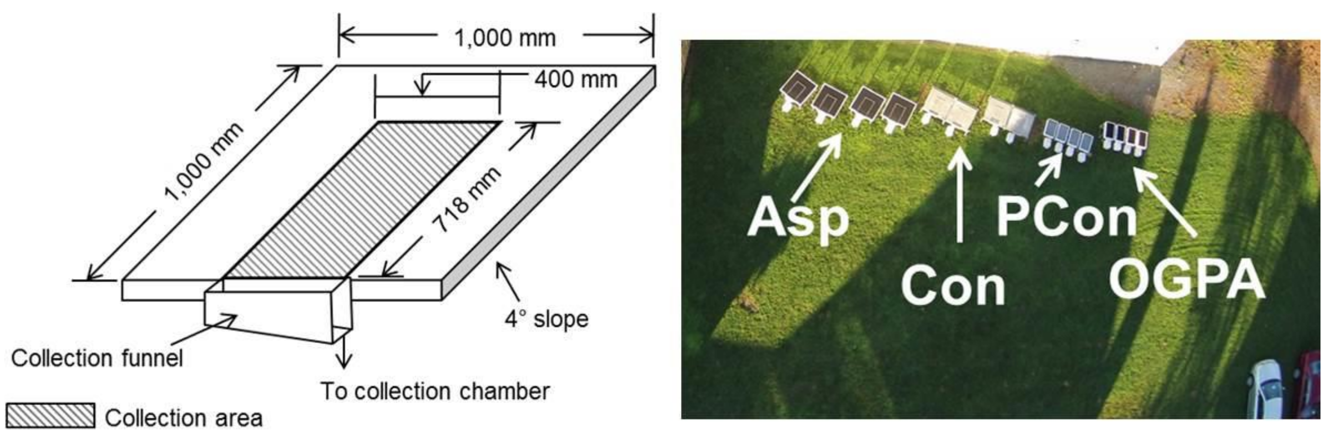

Figure 1 Left: dimensions of the impermeable asphalt and concrete boards. Right: aerial photograph of the pavement board experimental setup.

3. Results and Discussion

3.1. Spatial variability of atmospheric pollutant loads in stormwater

Atmospheric pollutant loads in stormwater were quantified from three varying land-use areas in Christchurch: residential (Res), light industrial (Ind), and airside of Christchurch International Airport (Air). The results are reported in Table 1. TSS loads varied significantly in each land-use area. Atmospheric Cu, Zn, and Pb loads in stormwater from the Res and Air areas were similar; however, the Ind area had significantly higher Cu, Zn, and Pb loads than the other areas. Surprisingly, over the duration of the sampling campaign, all three land-use areas studied showed similar trends of atmospheric metal loads in stormwater. This suggested that atmospheric metal deposition had a similar distribution within Christchurch City, which was due to the metal pollutants originating from a similar source. It was found that, in Christchurch, land-use area was not a primary factor for influencing pollutant loads in stormwater runoff. The source of atmospheric metal pollutants remains unknown in Christchurch. Vehicular activity, which is commonly identified as an important source of atmospheric metals in other locations, is likely not the main source of atmospheric metal pollution because different traffic and road conditions in each site would have resulted in varying pollutant trends if vehicular activity was the predominate source of atmospheric metal pollutants.

The reason Ind had higher metals loads in stormwater was due to topography. The industrial sampling site was located at the base of a hill range (Port Hills). During a northerly and easterly wind (the predominate winds), the Ind experimental site was located on the windward side of a slope where dry deposition is promoted, unlike the other areas (Res and Air) that were on a flat terrain. When implementing stormwater abatement strategies it is important to target the areas where most pollution occurs. Therefore, managing atmospherically deposited pollutants on windward side slopes should be of greater importance as it will provide greater stormwater quality benefits.

Table 1 Pollutant loads in runoff from impermeable concrete boards in each area studied.

	Cu (µg/m^2)	**Zn (µg/m^2)**	**Pb (µg/m^2)**	**TSS (mg/m^2)**
Air	30 ± 3	180 ± 24	7 ± 1	140 ± 18
Res	37 ± 3	177 ± 21	11 ± 1	69 ± 5
Ind	88 ± 7	505 ± 63	47 ± 5	364 ± 34

3.2. Temporal variability atmospheric deposition

The relationship between meteorological conditions and atmospheric pollutant build-up and wash-off was modelled using mixed-effect models. The results are represented in Table 2. Atmospheric pollutant loads in stormwater did not vary seasonally. However, atmospheric pollutant build-up and wash-off varied with different meteorological conditions. Number of antecedent dry days was an important influencer on Cu, Zn, Pb, and TSS loads in stormwater runoff in all three land-use areas. As the antecedent dry period increased, atmospheric pollutant build-up also increased asymptotically. Pollutant build-up ultimately plateaued after 7-9 days as pollutant deposition and resuspension stabilised. The relationship between pollutant wash-off and rainfall characteristics (i.e. rain depth, intensity etc.) was dependent on the pollutant of concern. Cu and Zn had a significant relationship with rain depth (mm); Pb and TSS had a significant relationship with rain intensity (mm/h) and duration (h). Therefore, it was assumed that pollutant speciation phase (i.e. particulate or dissolved) plays an important role in surface wash-off. Rain intensity and duration had a greater influence on pollutants that were predominately in the particulate phase, i.e. Pb and TSS. As the rain intensity increased, more particulates had the ability to be mobilised from the impermeable surface. Conversely, rain depth had a greater influence on pollutants that had a high portion (≈ 40 - 50%) in the dissolved phase, like Cu and Zn. Thus, as rain depth increased, more dissolved pollutants desorbed from the pavement surface. In all cases, pollutant wash-off was the greatest at the start of a rain event, but the rate of pollutant wash-off declined as the rain event continued (i.e. rain intensity, duration, and depth increased). Therefore, stormwater treatment systems that are implemented for removing atmospheric pollutants should target large rain events. Larger rain events (>10 mm) will have greater pollutant loads in runoff than smaller rain events; thus, capturing and treating larger rain events will provide better improvements to urban waterway quality.

Table 2 Model summary of the best fitted values for total Cu, Zn, Pb, and TSS for the Ind, Res, and Air land-use areas and the percentage error between the measured data and modelled 'validation' data (mean ± S.E.).

Area	Pollutant	Intercept a	atan(ADD) b	log(RD) c	log(RI) d	log(Dur) e	R^2 of cal.	E of cal.	% Error of val.
Air	Total Cu	0.467	0.257	0.685	-	-	0.66	0.47	21.6 ± 3.9
	Total Zn	1.182	0.108	0.872	-	-	0.60	0.29	15.7 ± 2.6
	Total Pb	-0.457	0.276	-	0.663	0.597	0.62	0.11	31.4 ± 5.0
	TSS	0.844	0.330	-	0.816	0.484	0.69	0.43	13.2 ± 2.2
Ind	Total Cu	1.068	0.414	0.394	-	-	0.64	0.39	14.2 ± 2.9
	Total Zn	1.708	0.305	0.578	-	-	0.59	0.23	11.0 ± 1.8
	Total Pb	0.918	0.215	-	0.802	0.166	0.62	0.45	17.4 ± 4.1
	TSS	1.669	0.312	-	0.679	0.217	0.64	0.40	10.6 ± 3.5
Res	Total Cu	0.448	0.516	0.423	-	-	0.64	0.40	14.3 ± 2.7
	Total Zn	1.041	0.244	0.788	-	-	0.59	0.42	13.8 ± 2.1
	Total Pb	0.087	0.317	-	0.679	0.198	0.53	0.22	32.2 ± 2.1
	TSS	0.849	0.416	-	0.616	0.191	0.64	0.35	11.7 ± 2.8

Note: R^2 = variance explained by the fixed and random factors, E = Nash Sutcliffe efficiency. Example: log(tCu) = a + b*atan(ADD) + c*log(RD); log(TSS) = a + b*atan(ADD) + d*log(RI) + e*log(Dur).

3.3. Pavement retention of atmospheric pollutants

From a stormwater management perspective, not all pavement types are equivalent. In fact, pavement type can have a strong influence on a pollutants ability to be washed-off. Pollutant loads from pavement runoff are affected by the pavements surface roughness and composition. The greater the surface roughness of a pavement, the more particulate pollutants that can be trapped within the pavements cavities. Pavement composition affects the movement of pollutants by different physiochemical processes, i.e. adsorption and desorption, whereby, adsorption describes the adhesion of a pollutant to the pavement surface and desorption describes the pollutants release.

Atmospheric pollutant loads in stormwater were quantified from four different pavement types: impermeable asphalt (Asp), impermeable concrete (Con), permeable asphalt (OGPA), and permeable concrete (PCon). The results are shown in Table 3. In addition, the pollutant loads from each pavement were compared to pollutant loads in bulk deposition (BD) (see Figure 2). Concrete, especially PCon, provided the greatest retention of Cu and Zn because the hydroxides and the carbonates in the concrete were effective at adsorbing Cu and Zn ions. Conversely, Asp provided no retention of Cu and it leached high quantities of Zn into the runoff. This Zn leaching was assumed to be from the bitumen binder. However, not all Asp pavements will leach Zn as the Zn content in bitumen will vary from batch to batch depending on the source of the original bitumen product. Asp was better at retaining particulate pollutants (Pb and TSS) than Con because Asp had a rougher surface and was able to trap more particulates. The permeable pavements, PCon and OGPA, were more effective at retaining particulate pollutants as particulates were filtered out by the pavements. The OGPA, however, was found to provide very little retention of Cu and Zn due to the low pH of the infiltrate (pH = 3.55). Modifying pavement design to improve stormwater quality can be an effective indirect method at treating atmospheric pollutants in stormwater.

Table 3 Pollutant load ranges from the different pavement types.

	Cu (μg/m^2)	**Zn (μg/m^2)**	**Pb (μg/m^2)**	**TSS (mg/m^2)**
Asp	46 ± 7	2459 ± 372	5 ± 1	65 ± 9
Con	23 ± 6	107 ± 11	9 ± 1	78 ± 10
PCon	14 ± 2	37 ± 6	1 ± 0.1	18 ± 3
OGPA	28 ± 2	196 ± 16	4 ± 0.3	10 ± 2

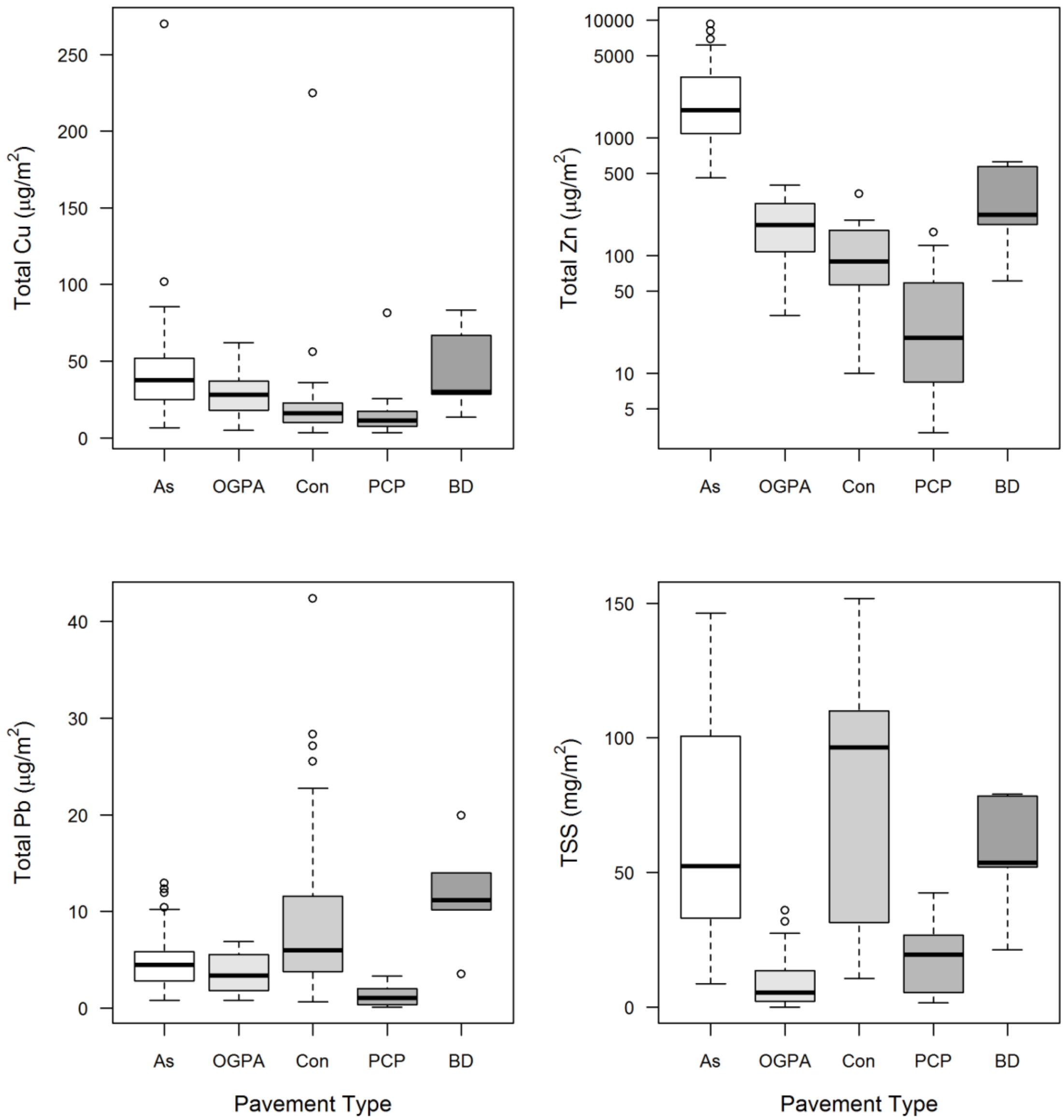

Figure 2 A comparison of total Cu, Zn, Pb and TSS loadings in wash-off from different pavement surfaces and from BD. The box represents the 25th (lower) percentile, median, and 75th (upper) percentile; the whiskers represent the 5th and 95th percentiles. Note the varying scales for each pollutant.

4. Concluding remarks

Atmospheric deposition is known to be an important indirect source of pollutants to stormwater runoff; however, it is rarely considered by stormwater managers when implementing stormwater abatement strategies. This is principally due to the uncertainty and challenges associated with measuring and managing these contributions. This uncertainty was amplified by the dearth of knowledge on the major controllers influencing the contribution of atmospheric deposition to stormwater pollution. This research has contributed to the greater understanding of atmospherically derived pollutant build-up and wash-off dynamics in Christchurch. Some key findings from the research are the following:

- Land-use activities do not exhibit a strong influence on total Cu, Zn, and Pb deposition in the Christchurch airshed, instead, orographic features of an area were found to greatly influence the rate of deposition.
- Antecedent dry days were found to exert the most influence on pollutant loads in stormwater runoff.
- Rainfall intensity, duration, and rainfall depth may also have an influence, although this is dependent on the speciation phase of the pollutant. Particulate pollutants are likely to be controlled by rainfall intensity and duration as more particulates have the potential to be mobilised from a surface. Rain depth seems to influence pollutants that have a high proportion in their dissolved phase because more pollutants have the ability to dissociate from a surface.
- The type of pavement used can reduce the quantities of atmospheric pollutants are washed-off; in particular, utilising concrete in the pavement design for greater Cu and Zn retention through chemical adsorption processes.
- Increasing pavement roughness will also promote greater particulate pollution attenuation as more particulates are trapped within the pavements cavities. Further research is warranted to quantify the long-term effect of the pollution attenuation. Additionally, permeable pavements are effective at removing particulate pollutants (i.e. TSS and Pb).

For more information on this topic, see Murphy et al. (2014, 2015a and 2015b) (5; 6; 7).

Acknowledgements

The authors would like to thank; Leila Chrystall from Christchurch International Airport Limited for enabling us to conduct research on airside; Lily Smith for allowing the use of her property as a testing site; and Fulton Hogan for providing the asphalt studied in this research; the Department of Civil and Natural Resources technical staff, in particular Peter McGuigan, for their help in constructing and deploying out the experimental setup. Additionally, thank you to the Department of Civil and Natural Resources for meeting the financial costs of the resources used in this research.

References

[1] Auckland Regional Council, Technical publication 10, design guideline manual: stormwater treatment device, Auckland Regional Council, 2003.

[2] CCC, Waterways, wetlands and drainage guide = Ko te anga whakaora mō ngā arawai rēpō: Part B, Christchurch, Christchurch City Council, 2003.

[3] L.D. Sabin, J.H. Lim, K.D. Stolzenbach, K.C. Schiff, Water Research 39 (2005) 3929-3937.

[4] R Core Team, R: A language and environment for statistical computing, Vienna, Austria, http://www.R-project.org/, 2014.

[5] L.U. Murphy, A. O'Sullivan, T.A. Cochrane, Water, Air, & Soil Pollution 225 (2014) 1-13.

[6] L.U. Murphy, T.A. Cochrane, A. O'Sullivan, Science of the Total Environment 508 (2015) 206-213.

[7] L.U. Murphy, T.A. Cochrane, A. O'Sullivan, Water, Air, & Soil Pollution 226-232 (2015) 1-14.