Effective monitoring and assessment of pollution types and loads entering the drainage system from commercial areas

Melbourne Water

EPA VICTORIA

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Executive summary

Today, the main source of pollution in urban estuaries and coastal waters, and a leading source for both lakes and river systems, is stormwater generated from urban surfaces during wet weather periods (Novotny and Olem, 1994; Burton and Pitt, 2002). Characterising pollutant levels from urban stormwater drains during dry and wet weather periods is important for understanding their impact on these downstream systems. However, to properly characterise pollutant loads and concentrations, accurate monitoring methodologies must be employed. **This report identifies the temporal variability of pollutants in urban stormwater runoff from two commercial precincts that feed into Melbourne's Yarra River. The collected data was then used to help assess and improve (via recommendations) current sampling methodologies used to estimate pollutant loads.**

The average pollutant levels were found to vary significantly between the two wet weather catchments, with the Abbotsford catchment generally being more polluted than the Fitzroy catchment. Pollution differences are large between catchments, considering both are of the same primary land-use and are within close proximity of one another (i.e. similar climatic characteristics). One possible explanation for these differences in pollutant levels is that the Fitzroy catchment has a slightly higher level of residential land-use when compared to the Abbotsford catchment (both still <20%). Furthermore, the Abbotsford catchment is known to have a small percentage of industrial land-use and a different social behaviour (i.e. habits and practices which may influence stormwater runoff – e.g. street cleaning, dumping of waste, etc) than that found within the Fitzroy catchment. These slight variations meant the sources of stormwater within each could differ enough to cause dissimilar pollutant levels. In spite of these differences, both catchments' pollutant levels still compared favourably with the range found in the literature for commercialised catchments.

It is not uncommon to assume information from one catchment is adequate to use for another, as long as the land-use characteristics for both catchments are similar. **However, the large differences in average pollutant levels observed in this report pose a problem for the transferability of information between different catchments.** There are three solutions to this problem:

1. understanding the stormwater pollutant levels exported from any catchment through intensive monitoring;
2. collecting enough data from an array of different commercial catchments to understand the true underlying probability distribution of pollutant levels; this distribution could then be used to help inform what the likely pollutant levels are in an unmonitored catchment; and,
3. collect enough data (both on pollutant levels and catchment information) from an array of commercial catchments to help determine relationships between more site specific characteristics and pollutant levels.

In any case, the current understanding of pollutants in urban systems implies that monitoring of stormwater is necessary for correctly estimating true pollutant loads. Hence, developing accurate and cost-effective monitoring regimes is critical.

The variability of pollutants within each catchment was also considerably different, with the Fitzroy catchment consistently having more constant pollutant levels than the Abbotsford catchment. Some of this variability was shown to be during the first flush (i.e. pollutant levels are higher at the beginning of an event than at the end), indicating that for some pollutants their source was being depleted during wet weather events. Other pollutants were found to depend heavily on flow rates, indicating that their variability was caused mainly by the variability in flow rates. However, for other pollutants there was no first flush present or any relation with flow and the high variability for these constituents could be caused by intermittent sources acting between, or within, wet weather events. Furthermore, this high variability could also be related to catchment drainage layout, in that the variability is inevitably dependent on the pollutant's time of concentration for each contributing sub-catchment (i.e. each area within the catchment may contribute at different times during the event, possibly adding to this variability).

The variability in pollutant levels within each catchment determines monitoring requirements for estimation of wet weather loads, with those pollutants which vary considerably requiring a large number of samples, and those which remain fairly constant requiring fewer samples for the same level of accuracy. The report found that the accuracy of a random grab sampling methodology for wet weather load estimation was directly related to the variability of the pollutant's concentrations during each event. For example, nitrogen loads for both catchments could be estimated using the results of just one grab sample during each event and this corresponded with nutrients having a low relative level of variability.

For monitoring, the best outcome would be that a given pollutant requires the same sampling regime no matter the catchment selected (e.g. sampling for lead at one catchment would require a similar sampling frequency at another catchment). However, while the results suggest that for nutrients and *E. coli* this may be applicable (since both showed similar variance and hence monitoring requirements at both catchments), this is not the case for heavy metals (which showed different variance and hence monitoring requirements at each catchment). **This means that, according to the current dataset, having one sampling regime for each pollutant type is not a feasible solution.** The best solution to this problem is to continue to invest in detailed monitoring regimes across a range of similar catchments to understand how sampling requirements vary. This data could then be used to identify the typical sampling requirement for each pollutant type. For example, if ten catchments were monitored in detail, it would be possible to calculate the number of samples required for accurate estimation of loads from each of the ten catchments. The maximum (or maybe the 95 percentile) sampling requirement for each pollutant from the ten catchments could then be used to inform future monitoring regimes across any similar catchment.

Estimated annual wet weather loads from each catchment were high, with the Abbotsford catchment again producing the highest loads because of its larger runoff rates and higher average pollutant concentrations. In fact, this catchment exports, on an annual basis, *E. coli* levels which equate to an equivalent of over 750kg of human faeces into the Yarra River. Furthermore, this same catchment releases 256kg of nitrogen and 43kg of phosphorus into the river and eventually to Port Phillip Bay.

Dry weather flows were rarely detected in either catchment, but some intermittent high flow periods occurred without rainfall (possibly caused by illegal discharges). However, the total measurable dry weather volume was 0.2% of the wet weather volume for the Abbotsford catchment (0.07% for Fitzroy). Unless concentrations of pollutants during dry weather flows are much greater than that found in wet weather flows, these results imply that **dry weather loads are insignificant when calculating total pollutant loads for these catchments**.

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1 Introduction

Characterising pollutant levels from urban stormwater drains during dry and wet weather periods is important for: assessing and improving WSUD treatment technologies, assessing the impacts of stormwater runoff on downstream systems and for modelling purposes. However, in order to accurately characterise pollutant loads and concentrations, accurate monitoring methodologies must be used.

The sampling of stormwater flows is often conducted using a 'grab' sampling methodology (e.g. Eleria and Vogel, 2005; Leecaster et al., 2002; Fletcher & Deletic, 2007; Soonthornnonda and Christensen, 2008; Francey et al, *in press*). Most bacterial and toxicant sampling in rivers and drains is from a single sampling point using a 'grab' sample methodology. The adequacy of such a sampling methodology is dependent on a number of factors, including: the pollutant's variability (both spatially and temporally), the frequency of the sampling and the corresponding time period which is being characterised (i.e. are daily, weekly, monthly or annual loads being characterised?). As such, the representativeness of this form of sampling, in terms of quantifying pollutant levels, is inaccurate under certain conditions.

Discharges of faecal contamination from many stormwater drains into to the Yarra River were found to be highly variable (Melbourne Water and EPA Victoria, 2007a). An independent scientific review of the above investigation supported the recommendation to further characterise the degree of spatial and temporal variability of pollutant loads within the system (Melbourne Water and EPA Victoria, 2007b). Melbourne Water and EPA Victoria are now conducting research to understand the spatial and temporal variability of pollutants entering the Lower and Middle Yarra.

1.1 Background information

The initial aim of this project was to determine the temporal variability of pollutant loads in stormwater pipes draining from commercial areas during both dry and wet weather flows. To achieve this aim, the following was to be conducted:

- monitor flow rates and typical water quality parameters (temperature, pH, dissolved oxygen, electric conductivity) in three stormwater pipes (Swan St, Richmond; Walmer St, Richmond; Smith St, Fitzroy);
- take three samples each day from the three catchments during dry weather flows for a consecutive seven day period and assay samples for key pollutants known/thought to originate from commercial catchments; and,
- collect up to 60 wet weather (high flow event) samples using automatic samplers from one catchment and assay samples for key pollutants known/thought to originate from commercial catchments

However, after setting up all flow and water quality monitoring equipment, it was observed that, for all catchments, the dry weather flows were too low to be measured by the flow and water quality devices. This low flow hindered the collection of dry weather samples where water depth was often 1mm, making it impossible to withdraw samples. After monitoring these catchments for four weeks, it was determined that the dry weather flows were not just intermittent but were never present at high enough levels to consider dry weather sampling. Furthermore, these low flows meant that the water quality probes were never inundated with stormwater and therefore needed to be removed, as leaving them in dry conditions can cause major damage to their components. The data collected during these four weeks is presented in Appendix A.

Because of these outcomes, the project was refined to remove all dry weather monitoring and to solely focus on rain event sampling from two of the three catchments. The following outlines the new project objectives.

1.2 Project objectives

This project aims at identifying the temporal variability of pollutants in urban stormwater feeding into the Yarra River. The outlet pipes of two commercial catchments (Walmer St, Abbotsford; Smith St, Fitzroy) were monitored during wet weather periods. Results will provide information to help increase understanding of the temporal variability for bacterial, heavy metal, hydrocarbon, oil and grease, surfactant and nutrient contaminants leaving commercial drainage systems during rainfall events. This information can be used to help improve the sampling design of future bacterial and toxicant pollutant investigations and guide the correct installation of structural solutions to mitigate the impact on receiving waters.

More specifically, there were a number of smaller aims/objectives:

1. Identify and report the variability of each pollutant during *wet* weather periods to help understand this variability in commercial catchments. This variability includes:
    - how the pollutant varies between different study catchments and within each study catchment; and,
    - how the pollutant varies within each wet weather event.
2. Identify and report significant correlations between all wet weather pollutant levels and flow rates to help determine whether the behaviour and or source of a pollutant is explained by flow rates
3. Determine the errors associated with using just one, two, three or four randomly taken samples during rainfall events to characterise a pollutant's wet weather event load
4. Estimate and compare the relative pollutant loads from each catchment to determine their relative impact on the Yarra River

2 Methods

2.1 Study catchments & equipment

2.1.1 Study catchments

The two catchments were carefully selected based upon a number of different criteria, including:

- the selected catchments must have a good representation of a commercial land-use;
- the catchment selection should be based on prior knowledge of key drains that have been shown to be influenced by microorganisms, heavy metals, hydrocarbons, surfactants and/or oil and grease;
- the catchments were relatively close to the base location of the sampling team (i.e. Monash University, Clayton) and were easily accessible from this location;
- the catchments and the equipment needed to be installed in a location that was safe to access by sampling staff and in a location where the likelihood of vandalism was minimal;
- the catchments needed sampling equipment and other sampling stations to be installed and, as such, approval from the local government was required; and,
- established catchments were chosen to ensure that construction and remediation works were not likely during the sampling period.

After careful consideration of the criteria above, two study catchments were selected for use in this project. Table 1 shows a summary of the characteristics of the catchments, followed by a brief explanation of each catchment. An aerial photograph is shown in Figure 1, which shows the relative location of each catchment to Melbourne's Central Business District (CBD). It should be noted that the bolded names shown in Table 1 will be used to refer to each catchment.

Table 1. Catchment descriptions and catchment characteristics.

Catchment Name	Melways reference of outlet pit	Primary land-use	Total catchment area (ha)	Estimated total imperviousness (% of area)	Catchment's outlet pipe dimensions [m]	Latitude, Longitude
Walmer Street, **Abbotsford**	44 H7	Commercial, with a small proportion of residential (<5%)	24	90%	Circular – 0.76 rad	37°48'39.42"S 145° 0'35.62"E
Smith Street, **Fitzroy**	44 B3	Commercial, with a small proportion of residential (<20%)	18	85%	Egg shape – max depth – 94cm, max width – 60cm @ 65cm from invert	37°47'47.92"S, 144°59'4.46"E

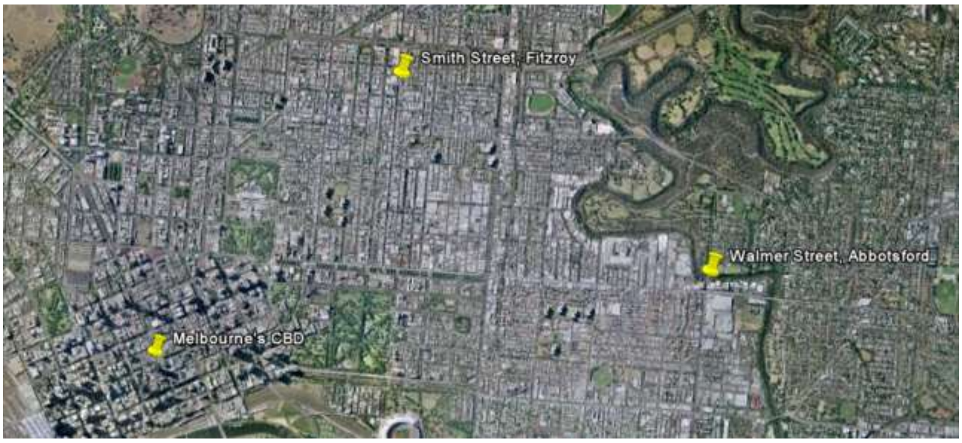

Figure 1. Location of the two study catchments, in respect to Melbourne's Central Business District.

Walmer Street, Abbotsford

This long, narrow catchment comprises an area of 18ha and is predominantly a commercial precinct (although there is also a very small proportion of residential development < 5%). The catchment is highly impervious, with an estimated total imperviousness of over 90%. The catchment also includes a busy roadway and tram lines. Figure 2 shows an aerial photograph of the catchment indicating the boundaries of the catchment (left) and also shows a typical streetscape of Abbotsford (right).

Figure 2. Aerial photograph of the Abbotsford catchment showing the approximate stormwater boundaries (left) and a photograph of the typical streetscape found within this catchment (right). × represents the location of the catchment outlet pipe/access pit used for sampling and installation of equipment.

Smith Street, Fitzroy

Again, this is a long and narrow catchment with an area of around 26ha. The catchment is highly urbanised, with an estimated imperviousness of 85% and is mainly comprised of commercial properties, with a small percentage of residential development (<20%). The catchment also includes a busy roadway (both in terms of vehicular and pedestrian traffic) and tram lines. Figure 3 shows an aerial photograph of the catchment, indicating the boundaries of the catchment (left) and a typical streetscape of Fitzroy (right).

Figure 3. Aerial photograph of the Fitzroy catchment showing the approximate stormwater boundaries (left) and a photograph of the typical streetscape found within this catchment (right). ×represents the location of the catchment outlet pipe/access pit used for sampling and installation of equipment.

2.1.2 Equipment installation

Once each catchment was selected, it was necessary to consult with local councils and water authorities to obtain permits for the installation of the equipment at the two study catchments (EPA Victoria conducted this consultation). Each catchment was equipped with instruments to measure flow rates. This equipment needed to be fixed to the inside of the stormwater pipe and, as such, confined space entry permits were required. In these catchments, the local council (City of Yarra) was the authorising body for the installation of monitoring huts on the surface for automatic sampling equipment (see Figure 4).

Figure 4. An example of the monitoring huts located at both the catchments. These huts contain the autosampling equipment required to conduct wet weather sampling at the catchments.

Flow measurement

Each catchment was equipped with a flow meter and a flow probe installed in the invert of the outlet pipe (HACH – see Figure 5). These flow meters measure stormwater depths using pressure transducers to calculate the 'wetted area' of the flow using the measured pipe radius or cross section (see Table 1). They also employ two ultrasonic transducers to estimate the average velocity of the flow by converting Doppler shifts in returned ultrasounds to velocity readings (see HACH, 2005 for more information).

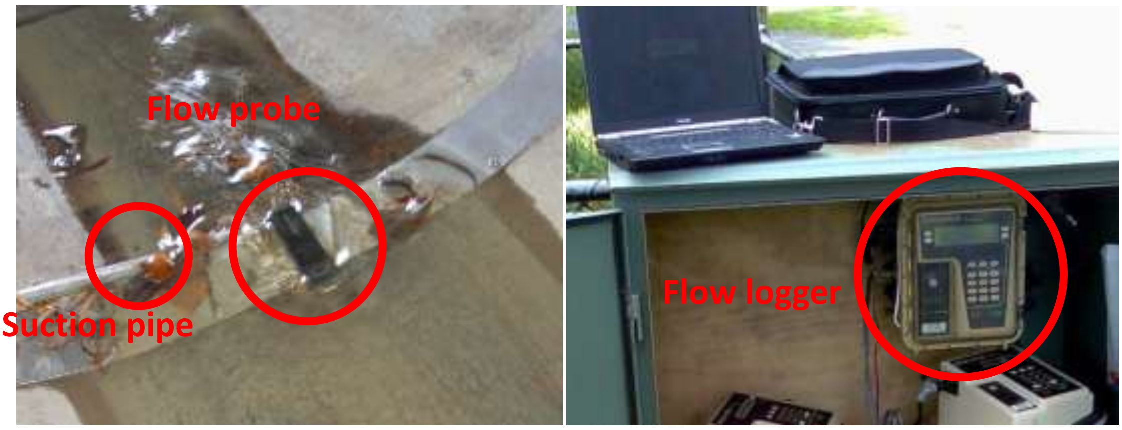

Figure 5. Typical installation of the flow sensor (left) and the above ground logger (right) installed at the catchments.

Prior to installation within the pipe, these flow probes and meters were calibrated using a flume within Monash University's hydraulics laboratory. Each probe (and associated meter) was placed within the flume and water with three known flows (measured using a magnetic based flow meter), velocities (measured using a velocity probe) and depths (measured using a ruler) was passed through the flume. These known parameters were then compared to the parameters estimated by the probe, and any discrepancies were minimised by the calibration of the device.

Once installed, the accuracy of the depth measurement was checked on a regular basis (every week) and if any discrepancy was detected, the meter and probe were calibrated in-situ to ensure an accurate reading was obtained. The calibration of the velocity measurement in-situ was not possible, however the checking of the probe prior to use showed that the probe's velocity measurement did not drift from calibration.

The meters were set to log water depth, water velocity and calculated water flow rates at six minute intervals for Abbotsford and five minute intervals for Fitzroy. The meters were downloaded on a weekly basis. These flow meters are often able to measure water depths to a reasonably low level. However, for depths less than 1-2cm, the measurement is often inaccurate. Velocity measurement is not usually possible at low water depths because the device measuring the Doppler shift is not submerged. Furthermore, they have limited velocity measurement accuracy, and so velocities of less than 0.01m/s are not recorded. As such, during low flow periods it was hard to achieve conditions whereby an accurate flow measurement is obtained. In actual fact, the low flow depth was so small that the depth measurement was inaccurate and the velocity was often not recorded since the device was not properly submerged. As a result, Monash has previously trialled many different weir formations to alleviate this problem. However, even a very small weir downstream of the probe resulted in problems. Increasing the depth of the water often meant creating a dam, which therefore reduced water velocity to levels below detection (i.e. <0.01m/s). Furthermore, the creation a weir leads to blockages which, even when cleaned on a weekly basis, mean that the probe is inundated with sediment and litter, rendering it useless for accurate measurements. As such, weirs were not installed at either catchment since it was decided that the measurement of higher flow rates (which could be detected without a weir) was better than having no measurements.

Wet weather sampling equipment.

To facilitate wet weather sampling, two automatic water samplers were installed near the outlet of each catchment (Figure 6). These autosamplers were programmed to collect up to 24 1L samples according to flow weighted intervals (these intervals are discussed in Section 2.2, below) during any one event. Clean, reinforced sampling tubes were installed from each autosampler to the outlet pipe's invert (Figure 5). The tubes were installed 3cm above the invert of the pipe to avoid debris and sediment causing blockages. Before and after withdrawing the stormwater sample, the autosamplers go through a purge process designed to clean the suction pipes. The purge process involves withdrawing water from the pipe until this water reaches the pump located on the sampler. Water is then pushed back out of the suction pipe and the process is repeated.

Figure 6. An example of the autosamplers used for wet weather water quality sampling. Two samplers were required for the samples analysed.

Rainfall data

Rainfall data for the two catchments were obtained from Melbourne Water (www.melbournewater.com.au) and includes recorded rainfall totals in six minute intervals from the beginning of 2009 until the 14th June 2010. The gauge selected to be representative for both catchments was Burnley (Melbourne Water gauge 229621).

2.2 Wet weather sampling

Samples were drawn from a number of wet weather events at the Abbotsford and Fitzroy catchments using two automatic samplers. These samplers were programmed to take samples using flow weighted intervals and were arranged so that each autosampler would trigger simultaneously. One autosampler was dedicated to collecting samples for microbiological, heavy metal and nutrient analyses, while the other dedicated to collecting samples for hydrocarbon, oil and grease and anionic and non-ionic surfactant analyses. The former autosampler contained cleaned and sterilised plastic bottles (1L), while the latter contained cleaned glass bottles (375mL). Each plastic bottle sample was analysed for all microbiological, heavy metal and nutrient pollutant levels. However, due to volume requirements by the laboratories, each consecutive glass bottle sample was assayed for one of the following: hydrocarbons, oil and grease, anionic and non-ionic surfactants (i.e. the first sample was tested for hydrocarbons, the second for oil & grease, etc). This means that, due to volume constraints, a different number of samples were assayed for different pollutant types.

The sampling intervals used for the two catchments were different, because of their varying degree of impervious areas and hence runoff volumes. However, each catchment was programmed so that a 30mm rainfall event could be captured without having to refill the autosamplers (i.e. 30mm rainfall event would be characterised by 24 sample bottles). However, it should be noted that the collection of samples was skewed so that the initial portion of the event was characterised by more samples than the end of the event, so as to more properly ascertain whether a first flush effect was present.

It was initially proposed that four wet weather events, with around 15 samples in each, would be collected from these two catchments (i.e. 60 samples from each catchment). However, it was decided that the collection of events would continue until a total of 60 samples was reached, meaning that more or less than four events could be monitored, depending on the size of these events. Five events, with a total of 66 plastic bottle samples, were taken from the Fitzroy catchment and only 29 plastic bottle samples (4 events) from the Abbotsford catchment due to sampling constraints. This was mainly due to problems with flow measurement equipment and lack of rainfall events (during the working week).

2.3 Laboratory analyses

NATA accredited laboratories were used to analyse the collected wet weather samples. Samples were analysed using standard laboratory techniques and, as such, these techniques are not explicitly described, so the reader is asked to refer to standard laboratory manuals for more information on these methods. Table 2 shows the water quality parameters quantified for each collected sample using the named laboratories with their associated detection limits.

2.4 Analysis & presentation of collected data

2.4.1 Between- and within-catchment variability

Summary descriptive statistics are provided in the main body of the report for pollutants which were regularly above their corresponding detection limits. Mean pollutant concentrations, together with Relative Standard Deviations (RSD is the coefficient of variation expressed as a percentage), were calculated for each catchment, using all wet weather samples collected. If the pollutant was not detected, samples were removed from the calculation of the mean and RSD for that pollutant and the final number of samples used in the analysis was presented. Boxplots were used for visual comparisons of results. Each boxplot contains the pollutant concentrations measured in all wet weather samples. If samples had levels less than the detection limit, they were not included in the boxplots.

Table 2. Water quality parameters assayed on each sample showing detection limits and laboratory used to conduct the analysis.

	Pollutant	Detection Limit
Heavy metals [mg/L] Ecowise Environmental, Scoresby, Victoria	Aluminium	0.01
	Antimony	0.001
	Arsenic	0.001
	Barium	0.001
	Beryllium	0.001
	Boron	0.02
	Cadmium	0.0002
	Chromium	0.001
	Cobalt	0.001
	Copper	0.001
	Iron	0.02
	Lead	0.001
	Manganese	0.001
	Mercury	0.0001
	Molybdenum	0.001
	Nickel	0.001
	Selenium	0.001
	Strontium	0.001
	Thallium	0.001
	Tin	0.001
	Titanium	0.001
	Vanadium	0.001
	Zinc	0.001
Microbes [MPN/100mL] Ecowise	*E. coli*	1
	Enterococci	1
Nutrients [mg/L] Water Studies Centre, Monash University	TN	0.01
	NH3	0.01
	TP	0.01
Other [mg/L] Ecowise	TPHs	0.1
	Oil & grease	5
	Anionic surfactant	0.1
	Non-ionic surfactant	0.1

2.4.2 Within-event variability of pollutants

In order to understand whether the pollutants at the two catchments experienced a first flush, plots of pollutant concentrations against cumulative rainfall depth were created for select pollutants. These plots contain the results from all samples collected from all wet weather events. If samples were below detection, then they were included on the plot, for illustrative purposes only, at half of their detection limit. It was not possible to present a plot of wet weather concentrations against cumulative rainfall depths for each pollutant (i.e. too many graphs). Instead, a linear correlation analysis was conducted to determine whether any significant trends were present. Only statistically significant correlation coefficients are presented in the results section (i.e. $p<0.05$). Furthermore, this correlation analysis was not performed on pollutants that had less than five data points for the analysis due to non detection (less than five points is considered not accurate for a correlation analysis).

An analysis was also performed comparing instantaneous flow rates with pollutant concentrations to determine whether flow rate had a large influence on the concentration of a pollutant at any time during rainfall events. Both scatter plots and a correlation analysis are again presented (only statistically significant correlations were reported; $p<0.05$).

2.4.3 Errors in event loads using a few samples in each event

A boot strapping methodology was employed to determine the impact of randomly taking a 'grab' sample during a wet weather event to estimate wet weather event loads. This method was used to determine the accuracy of using one, two, three and four randomly selected samples to estimate the total wet weather pollutant load. Using the 'three samples per event' as an example, three samples were randomly selected from each wet weather event using a uniform distribution (i.e. each sample had the same probability of being selected). The concentrations in these three samples were then averaged and multiplied by the total event volume to achieve the event's total 'estimated' pollutant load. This was repeated for each event which was monitored at the specific catchment. The summed loads from all events (known as the 'estimated' total load) were then compared with the loads calculated using all of the samples collected within the events (referred to as 'actual' wet weather event load). This 'actual' event load is estimated using a flow-weighted approach. The process was repeated 1000 times to ensure that most possible combinations were captured.

Boxplots of ratios between 'estimated' and 'actual' total wet weather loads are presented. Since it was not possible to present all pollutants using boxplots, it was decided to represent the spread of these boxplots using the 95% confidence interval from the 1000 ratios calculated for each pollutant at each catchment. However, the calculation of this confidence interval was not possible for some pollutants, where there were a number of samples below its detection limit. Where pollutants had more than 5 samples below detection, the confidence interval was not reported.

Please see Appendix B for more information about this method and a discussion on its accuracy when applied to the current dataset.

2.4.4 Comparison of pollutant loads

Using the 'actual' wet weather loads calculated for each catchment (see Section 2.4.3), it was possible to extrapolate this data to estimate the approximate contribution of each to total annual pollutant loads. To obtain annual wet weather pollutant loads, it was assumed that the monitored rainfall events taken at each catchment were representative of the pollution levels found in typical events. As such, the total 'actual' load from the monitored events was divided by the total rainfall in these events and then subsequently multiplied by the catchment's average annual rainfall to achieve an approximate annual wet weather pollutant load. There are obviously huge issues related to such an assumption, therefore the results from this section of the report are for indicative purposes only.

The report estimates the contribution of dry weather flows to total loads. For this report, the total amount of measurable flow not associated with rainfall was considered dry weather flow. However, this is an underestimate since some dry weather flows were not detectable (as discussed above). Using total dry and wet weather volumes, the report shows the differences required in dry and wet weather concentrations, so that both dry and wet weather loads contribute equally to the total load exported from each catchment (e.g. if the dry and wet volumes from the catchment were 100L and 1000L, respectively, then dry weather concentrations would need to be 10 times higher than wet weather concentrations).

3 Results and discussion

In total, four wet weather events were monitored from the Abbotsford catchment and five from the Fitzroy catchment. Each event varied in the number of samples withdrawn, since the spacing between samples was flow weighted. In total, 29 plastic bottle and 37 glass bottle samples were taken at the Abbotsford catchment. As explained in Section 2.2, lack of rainfall and problems with the flow meter meant that this catchment did not meet the objective of 60 collected samples. However, at the Fitzroy catchment 66 plastic and 69 glass bottle samples were taken, thus exceeding the objective.

The range of rainfall events was adequate, although the maximum amount of rainfall for any monitored event was around 10mm. A larger event would have been good to capture, but this was not possible due to the short duration of investigation and because samples could not be collected on weekends (because laboratories were closed and microbiological samples need to be assayed within 24hrs of collection). The range of rainfall intensities was also adequate, with both catchments experiencing events which had low (0.4mm/6min) and high (1.4mm/6min) rainfall intensities. Again, a longer monitoring period may have allowed a larger range to be captured. Comparing runoff volumes and maximum runoff rates it is clear that the Abbotsford catchment has a higher connected impervious area than the Fitzroy catchment, which is evident by the differences in outlet pipe sizes between the two catchments (see Table 1 for pipe sizes; note both catchments have similar slopes).

Table 3. Summary of event data for the wet weather events collected at the Abbotsford and Fitzroy catchments.

	Abbotsford	Fitzroy
Number of plastic samples per event (glass samples)		
Event 1	8 (12)	22 (22)
Event 2	8 (12)	6 (9)
Event 3	9 (9)	9 (9)
Event 4	4 (4)	10 (10)
Event 5	NA	19 (19)
Total Event Rainfall Depth (mm)		
Event 1	6.4	9.8
Event 2	7.4	2
Event 3	4.2	4
Event 4	1.8	1.8
Event 5	NA	4.2
Maximum Event Rainfall Intensity (mm/6min)		
Event 1	1.4	1.4
Event 2	1.2	0.6
Event 3	0.6	0.6
Event 4	0.4	0.4
Event 5	NA	0.6
Total Event Runoff (kL)		
Event 1	221	63
Event 2	253	26
Event 3	117	44
Event 4	50	30
Event 5	NA	56
Maximum Runoff rate (L/s)		
Event 1	410	101
Event 2	404	63
Event 3	127	60
Event 4	73	45
Event 5	NA	56

The monitored events are presented in Figure 7 and Figure 8 for the Abbotsford and Fitzroy catchments, respectively. These graphs indicate runoff rates [L/s] and sample collection times (for both plastic and glass bottles). Coverage of samples for the Abbotsford catchment was adequate for three of the events, but was poor for one of the events where only the first peak in the hydrograph was monitored (Figure 7, bottom left). The poor coverage at the Abbotsford catchment was mainly attributed to flow meter faults, which caused velocity to cut out during events thus not triggering autosamplers properly. However, all the events were still accepted for analysis because collected samples covered the majority of each event. The coverage of samples in all events from the Fitzroy catchment was very good, with all samples being assayed for the listed pollutants.

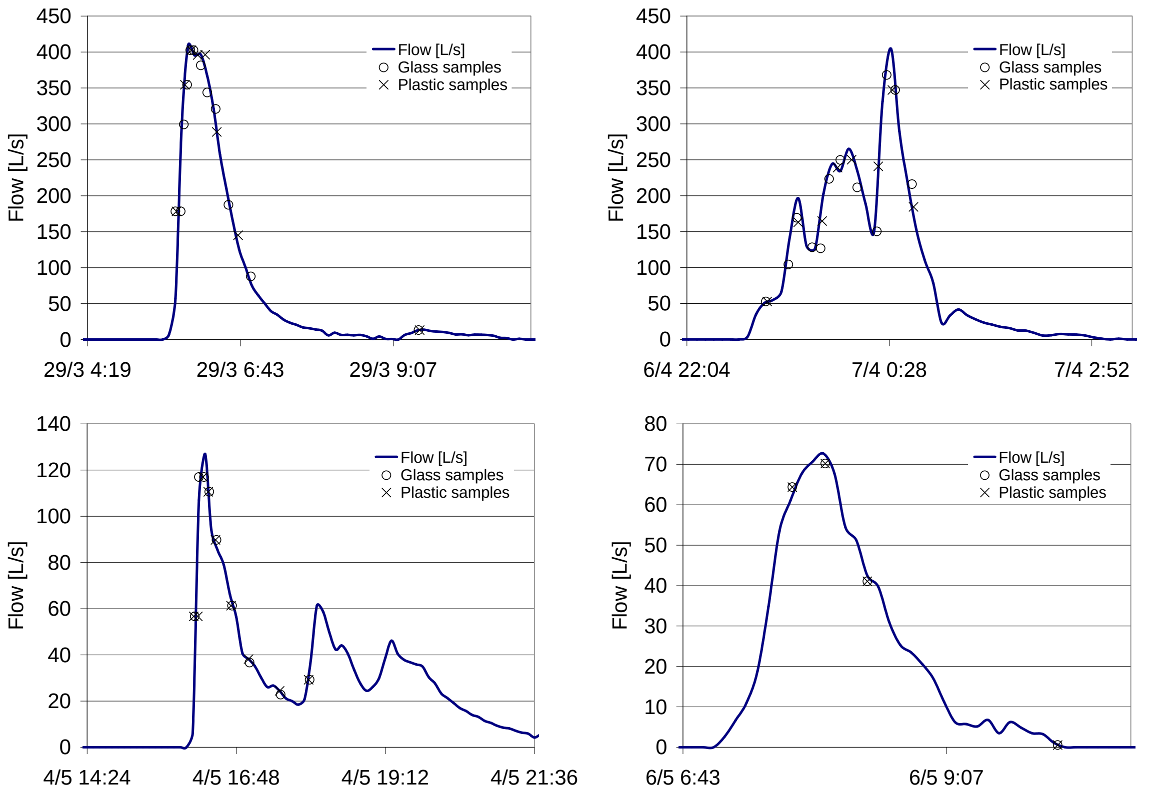

Figure 7. Hydrographs and sample times for the four events monitored at the Abbotsford catchment (top left – 29h March 2010, top right – 6th April 2010, bottom left – 4th May 2010, bottom right – 6th May 2010).

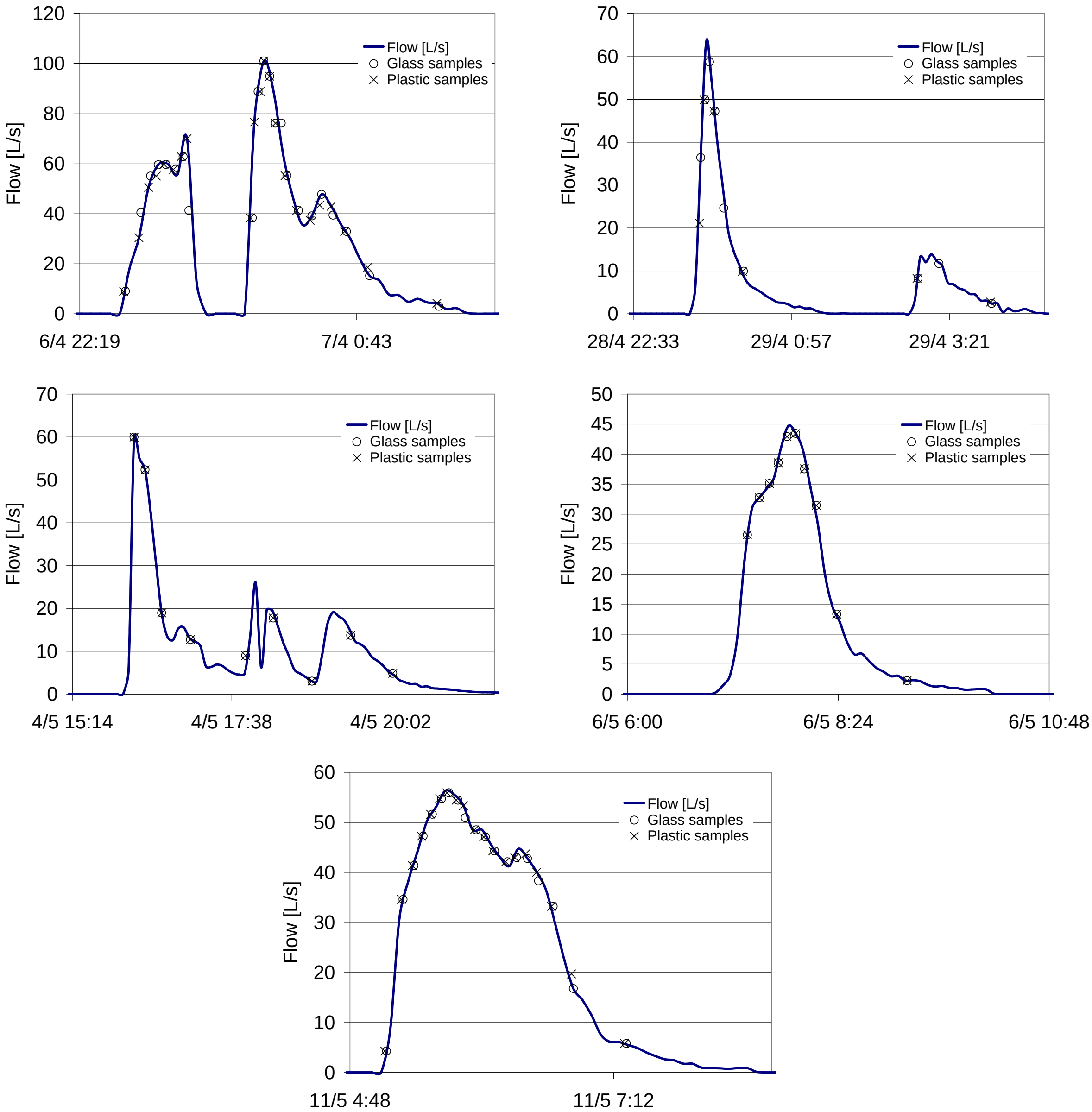

Figure 8. Hydrographs and sample times for the five events monitored at the Fitzroy catchment (top left – 6th April 2010, top right – 28th April 2010, middle left – 4th May 2010, middle right – 6th May 2010, bottom – 11th May 2010).

The following is divided into four separate subsections, each addressing one of the key questions outlined in Section 1.2:

1. Between- and within-catchment variability – to attempt to provide details about how each pollutant is varying between, and within, each different catchment
2. Within-event variability – to provide information about how each pollutant varies within the events, and whether first flushes exist at the monitored catchments
3. Errors in load estimations – to assess the accuracy of random grab sampling methodologies during wet weather events to estimate total wet weather loads
4. Comparison between wet weather pollutant loads – to assess the relative contribution of pollutants to the Yarra River system from each of these catchments

3.1 Between- and within-catchment variability

Table 4 provides a summary of the water quality constituents found in the wet weather samples taken from both catchments. The mean and RSD for each pollutant was calculated using all samples collected from the catchments. Boxplots in Figure **9** displays how select pollutants vary, both within each study catchment and between the two catchments.

Table 4. Mean and Relative Standard Deviations (RSD = standard deviation divided by mean, expressed as a percentage) of detected constituents in the wet weather events monitored at each catchment. Superscript numbers indicate the number of samples used to calculate the mean and RSD/number of samples taken for analysis (the difference giving the number of samples below detection). Values in right column are taken from Duncan (1999) and represent the average and the range found within the reviewed literature for commercial runoff. Bolded values indicate means which lie outside this range.

		Abbotsford	Fitzroy	Duncan (1999)
Heavy metals [mg/L]	Aluminium	2.02 (169%)$^{29/29}$	0.66 (71%)$^{66/66}$	
	Antimony	0.002 (48%)$^{29/29}$	0.002 (40%)$^{30/66}$	
	Arsenic	0.003 (158%)$^{29/29}$	0.001 (36%)$^{38/66}$	
	Barium	0.05 (120%)$^{29/29}$	0.02 (57%)$^{66/66}$	
	Boron	0.03 (31%)$^{22/29}$	0.03 (28%)$^{40/66}$	
	Cadmium	0.001 (141%)$^{17/29}$	**0.0004** (44%)$^{28/66}$	0.003 (0.0006-0.012)
	Chromium	0.007 (120%)$^{29/29}$	**0.003** (74%)$^{62/66}$	0.02 (0.005-0.07)
	Cobalt	0.003 (127%)$^{16/29}$	0.002 (44%)$^{21/66}$	
	Copper	0.04 (102%)$^{29/29}$	**0.02** (58%)$^{66/66}$	0.8 (0.02-0.3)
	Iron	3.44 (102%)$^{29/29}$	**1.03** (81%)$^{66/66}$	4 (1.06-10.2)
	Lead	0.10 (297%)$^{29/29}$	**0.02** (80%)$^{66/66}$	0.15 (0.04-0.65)
	Manganese	0.08 (151%)$^{29/29}$	0.03 (71%)$^{66/66}$	
	Molybdenum	0.002 (41%)$^{29/29}$	0.002 (52%)$^{38/66}$	
	Nickel	0.007 (153%)$^{29/29}$	0.003 (64%)$^{66/66}$	
	Selenium	0.002 (54%)$^{6/29}$	ND$^{\#}$	
	Strontium	0.03 (56%)$^{29/29}$	0.02 (37%)$^{66/66}$	
	Tin	0.002 (56%)$^{22/29}$	0.002 (39%)$^{22/66}$	
	Titanium	0.06 (102%)$^{29/29}$	0.02 (63%)$^{66/66}$	
	Vanadium	0.004 (107%)$^{29/29}$	0.002 (51%)$^{60/66}$	
	Zinc	**0.98** (138%)$^{29/29}$	**0.96** (43%)$^{66/66}$	0.33 (0.14-0.9)
Microbes [MPN/100mL]	*E. coli*	22700 (110%)$^{29/29}$	11100 (101%)$^{66/66}$	3000 (220-32000)
	Enterococci	13100 (58%)$^{27*/29}$	8300 (62%)$^{66/66}$	
Nutrients [mg/L]	TN	3.02 (58%)$^{29/29}$	2.88 (59%)$^{66/66}$	2.05 (1.5-3.3)
	NH3	0.33 (78%)$^{29/29}$	0.39 (46%)$^{66/66}$	
	TP	0.57 (123%)$^{29/29}$	0.35 (58%)$^{66/66}$	0.31 (0.2-0.8)
Other [mg/L]	TPHs	0.70 (85%)$^{11/11}$	0.81 (73%)$^{14/23}$	
	Oil & grease	**10.0** (0%)$^{1/11}$	13.3 (84%)$^{3/21}$	13 (9-26)
	Anionic surfactant	0.19 (30%)$^{10/11}$	0.18 (45%)$^{20/20}$	
	Non-ionic surfactant	2.30 (43%)$^{7/7}$	1.78 (48%)$^{20/20}$	

Beryllium was never detected at either catchment (<0.001mg/L), mercury was only detected once at the Abbotsford catchment at 0.0005mg/L with the rest of the samples at both catchments being <0.0001mg/L, silver was never detected at either catchment (<0.001mg/L), thallium was not detected at either catchment (<0.001mg/L), #selenium was not detected at the Fitzroy catchment (<0.001mg/L), *two samples had enterococci concentrations greater than the detection limit of 24000/100mL at the Fitzroy catchment

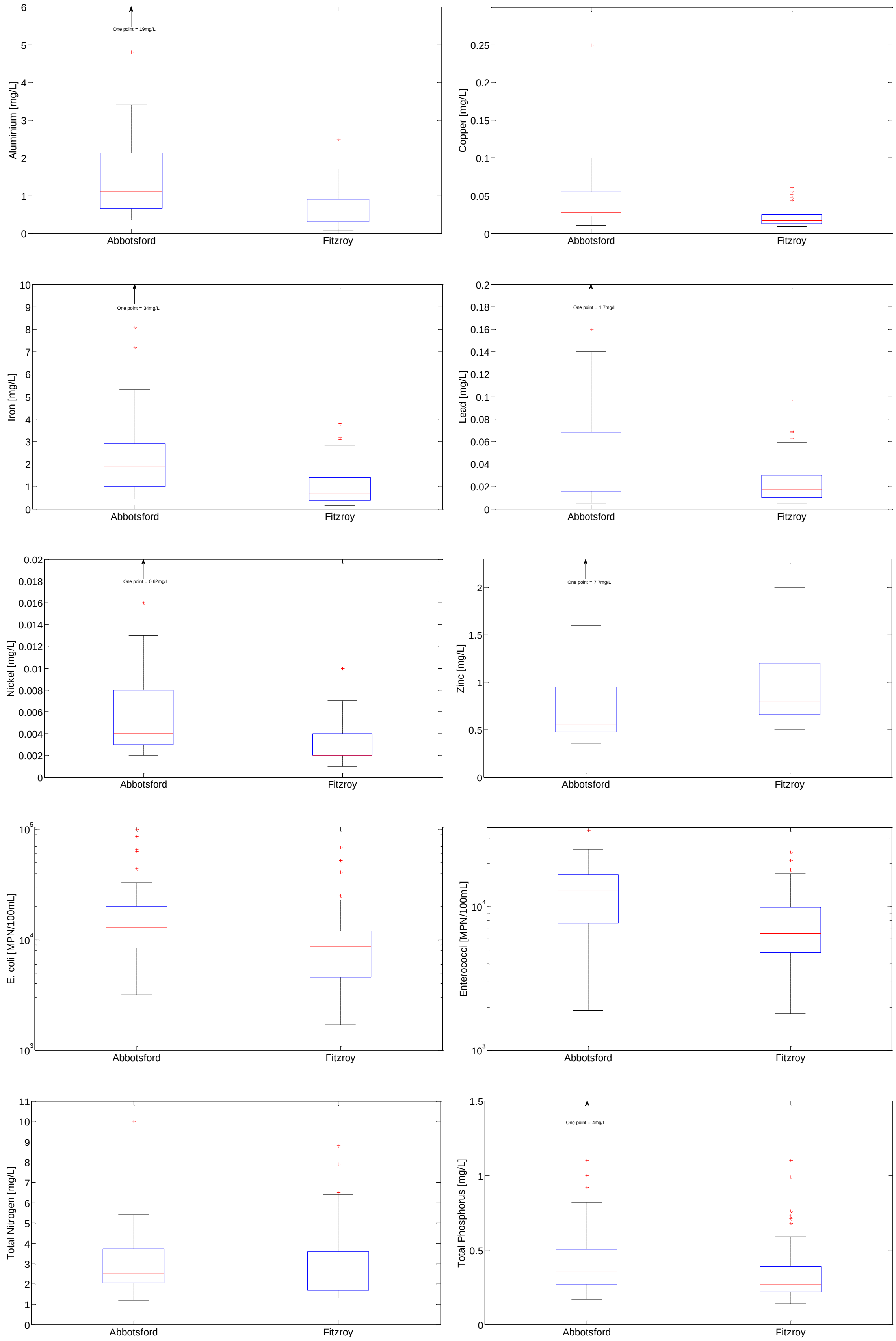

Figure 9. Boxplots showing the distribution of aluminium, copper, iron, lead, nickel, zinc, *E. coli*, enterococci, total nitrogen and total phosphorus concentrations during all wet weather events at Abbotsford and Fitzroy.

Average concentrations

Some of the pollutants measured were either never detected, or were only occasionally above detection limits (e.g. beryllium, mercury, selenium, silver, thallium, oil and grease) (Table 4). With the exception of very few pollutants, the most consistent trend found in the dataset was that Abbotsford always had higher average pollutant concentrations than Fitzroy. In some instances the average levels found at the Abbotsford catchment were more than three times that found in Fitzroy, clearly indicating the different sources of pollutants (or relative magnitude) within each catchment. This demonstrates that even catchments with the same land-use can have very different stormwater quality. An explanation for the observed differences between catchments might be the fact that Fitzroy was known to have a slightly higher proportion of residential land-use when compared with the Abbotsford catchment. Furthermore, the Abbotsford catchment is known to have a small percentage of industrial land-use and a different social behaviour (i.e. habits and practices which may influence stormwater runoff – e.g. street cleaning, dumping of waste, etc) than that found at the Fitzroy catchment. Such characteristics could mean that the sources of stormwater from these systems are different enough to cause these varying pollutant levels. However, it is noted that while some average pollutants' concentrations varied considerably between catchments, others remained largely similar (e.g. TN, NH_3, Zn, anionic surfactants) possibly indicating similar sources or transported pathways for these pollutants in both catchments.

The average nutrient and microbe concentrations from both catchments are consistent with the range of concentrations found by Duncan (1999) for commercial stormwater. However, average heavy metal concentrations at Fitzroy were often outside of these ranges, as compared with the Abbotsford catchment which generally had comparable concentrations with those in the literature. Whilst these differences between the Fitzroy catchment and the literature values were small, it still indicates that this catchment is classified as a relatively clean commercial catchment compared with other catchments around the world.

Pollutant variability

The variability of the pollutants within each catchment is also interesting, especially since this variability is generally larger at the Abbotsford catchment (Table 4 and Figure 9). In fact, with the exception of just five pollutants, all pollutants behaved in this manner. The variability of a pollutant can indicate an array of possible catchment characteristics. Firstly, a high variability could mean there is an intermittent source of pollution within the catchment. These intermittent sources can either appear within a single wet weather event (causing concentration variability during an event), or they could also occur between events (causing concentration variability between events). The large variability could also suggest that the pollutant source is limited within the catchment, thus resulting in a fast decay of pollutant concentrations during wet weather events because the watershed is depleted of the pollutant (i.e. a strong first flush is present – see Section 3.2 for more information). This depletion may also occur between wet weather events (i.e. if the antecedent dry weather period varies between events, so may the pollutant concentrations).

3.2 Within-event variability

The first flush phenomenon has been noted in urban stormwater runoff for many years. However, whilst the first flush does occur for many stormwater pollutants, its presence is not consistent between wet weather events, between different pollutants and between different catchments. In any case, it is often informative to investigate whether there is a general trend for pollutant concentrations to decrease as the event progresses.

Figure 10 is shown to assist in identifying trends between cumulative rainfall depth of wet weather events (x-axis) and concentrations of copper, zinc, *E. coli* and ammonia (other pollutants are not shown here, but general trends can be seen for all pollutants in Table 5). It is evident that copper, zinc and ammonia concentrations generally decrease as events progress at both catchments (i.e. the concentrations are higher at the start of the event as compared to the end of the event). However, *E. coli* concentrations either have no trend at all or tend to increase as events progress.

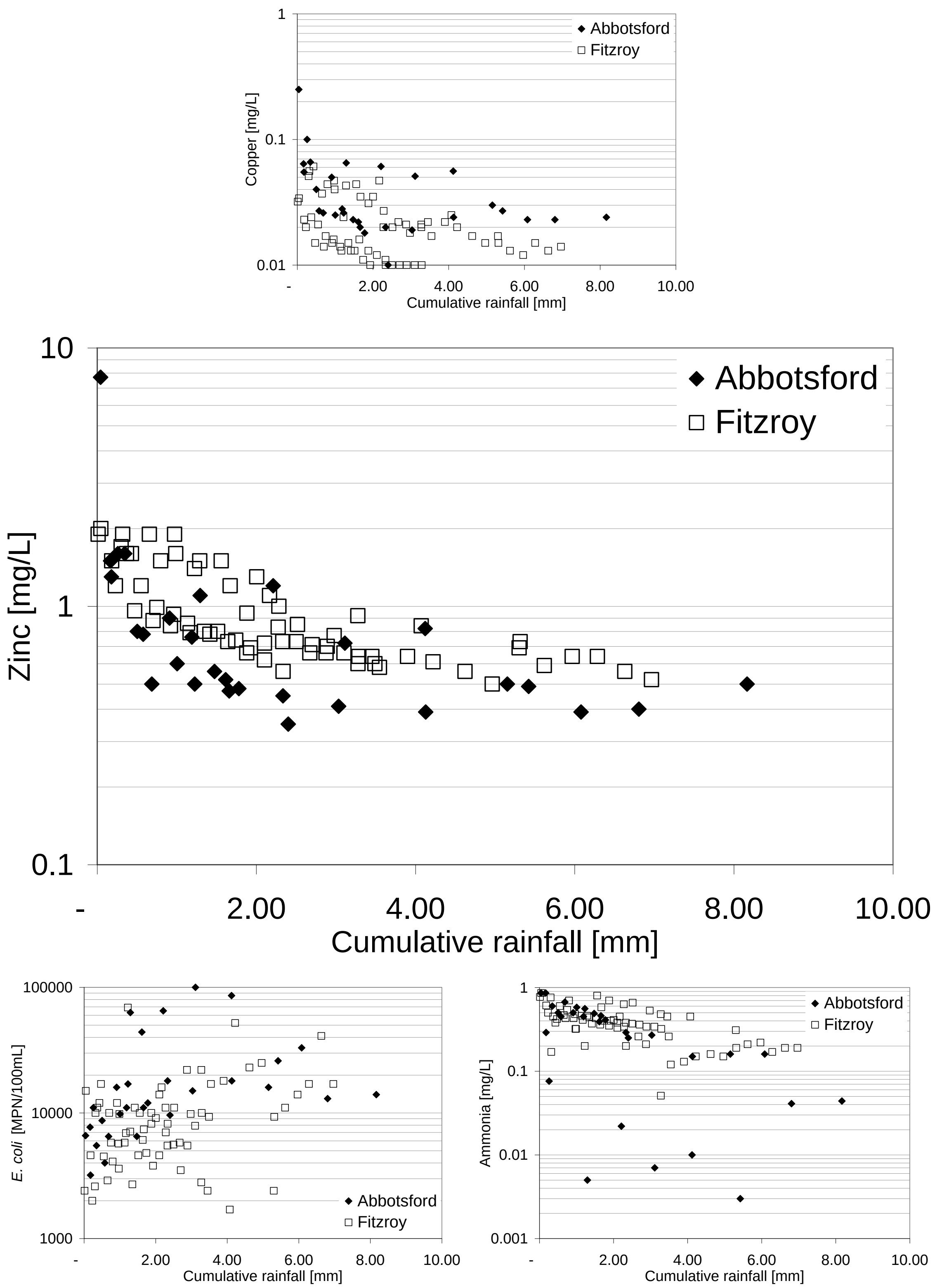

Figure 10. Pollutant concentrations found in the wet weather events at the Abbotsford and Fitzroy catchments plotted against cumulative rainfall depth [mm] for copper (top left), zinc (top right), E. coli (bottom left) and ammonia (bottom right).

To determine whether or not concentrations for other pollutants follow any trend with cumulative rainfall depth, a correlation analysis was conducted between each pollutant's concentrations and the cumulative rainfall depth (see Table 5). There are a number of significant correlations present at both catchments, with the majority being at Fitzroy; the cause for which is related to the number of samples taken at each catchment (Fitzroy had over 60 samples, but Abbotsford only 29).

With the exception of just one, all significant correlations were negative, such that pollutant concentrations generally decreased during wet weather events. These results indicate that a slight first flush might be present for a number of pollutants. Taking copper as an example, both catchments experienced decreasing copper concentrations with rainfall depth (Figure 10; Table 5). The main source of copper in urban stormwater is thought to be from the wearing of tyres and brake linings (Makepeace *et al*., 1995). Copper deposited on the roads in the catchment could be effectively conveyed to the catchment's outlet during rainfall/surface runoff events. If these events are large enough (in intensity and volume) the deposited copper would be effectively depleted, thus causing a first flush effect. As such, these pollutant sources are thought to deplete during wet weather events, suggesting that these sources are of limited capacity. A similar justification can be made for the remaining pollutants showing these types of correlations.

E. coli was the only pollutant positively correlated with cumulative rainfall, which occurred at the Fitzroy catchment (R = 0.30). Although the correlation is weak, it was still significant suggesting that *E. coli* concentrations increased toward the end of events. This phenomenon for microbes has been shown in several previous studies, including that by McCarthy *et al*. (2009) who showed *E. coli* and enterococci concentrations at a residential catchment generally were greater at the end of the event than at the beginning. This was also suggested by McCarthy (2008), who proposed the 'end-flush' concept for microorganisms, stating that these pollutants could be sourced from leaking sewer and septic systems, thus only contributing to stormwater flows during the end of each event.

Table 5. Linear correlation coefficients between cumulative rainfall depths [mm] and pollutant concentrations taken from the wet weather events at each study catchment. Only correlations which were significant at the 95% level were reported.

	Abbotsford	Fitzroy
Aluminium		-0.33
Antimony		-0.46
Barium		-0.42
Cadmium		-0.48
Chromium		-0.38
Copper		-0.42
Iron		-0.40
Lead		-0.38
Manganese		-0.47
Molybdenum	-0.45	
Nickel		-0.38
Strontium	-0.38	-0.26
Titanium		-0.44
Vanadium		-0.37
Zinc		-0.68
E. coli		0.30
TN	-0.51	-0.49
NH3	-0.67	-0.61
TP		-0.46
Anionic surfactant		-0.48

These correlations between concentrations and cumulative rainfall depth demonstrate that certain grab sampling methodologies could systematically over or under estimate pollutant loads. For example, if a grab sampling methodology was devised that ensured a sample was collected within the initial portion of each event, the total annual load estimated would be much greater than the actual pollutant load because of the presence of a first flush. This should be avoided and pure random sampling methodologies should be employed to avoid this problem (this is tested in Section 3.3).

Pollutant concentrations are often considered to be dependent on flow rates because shear forces from overland flow can mobilise and transport pollutants from their source to the catchment's outlet. Figure 11 and Table 6 show how the monitored pollutants vary with flow rate. Generally, it is expected that as flow rates increase, the pollutant concentrations also increase (since the energy available to transport these pollutants increases). However, there is also a trade-off between this higher energy for transportation and the dilution effect of higher flows. As such, Figure 11 and Table 6 both show that while some pollutants are positively correlated with flow rates, others are negatively correlated.

The results for aluminium, iron, lead and titanium at the Fitzroy catchment and *E. coli* at the Abbotsford catchment all suggest that the transport of these pollutants increases with higher flow rates. However, since these correlations are never present at both catchments, this indicates the different processes, and possibly the different sources, which exist for these pollutants between each of the catchments. Boron, molybdenum, strontium and non-ionic surfactants all indicate a possible dilution effect during higher flow rates, but again these correlations were not consistently present at both study catchments. The only pollutant that exhibited a significant correlation at both catchments was ammonia, which decreased in concentrations as flow rates increased suggesting that this pollutant was not transported by flow related processes but instead maybe is diluted in higher flows.

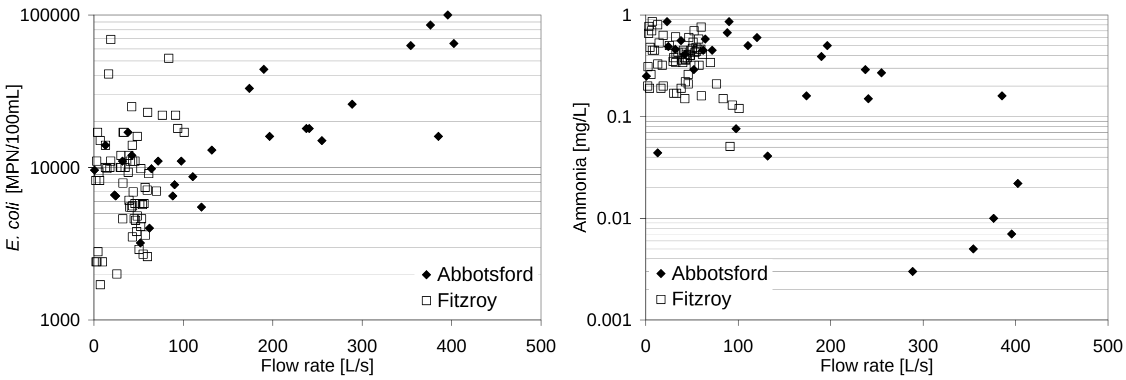

Figure 11. Pollutant concentrations found in the wet weather events at the Abbotsford and Fitzroy catchments plotted against instantaneous flow rate [L/s] for E. coli (left) and ammonia (right).

Table 6. Linear correlation coefficients between instantaneous flow rates [L/s] and pollutant concentrations taken from the wet weather events at each study catchment. Only correlations which were significant at the 95% level were reported.

	Abbotsford	Fitzroy
Aluminium		0.38
Boron	-0.44	
Iron		0.32
Lead		0.32
Molybdenum	-0.40	
Strontium		-0.33
Titanium		0.30
E. coli	0.77	
NH3	-0.61	-0.34
Non-ionic surfactant	-0.75	

Pollutants not presented in Table 6 are not significantly impacted by flow rates, which may indicate that they are more dissolved than particulate and hence do not depend on flow rates for transportation/mobilisation. However, this is not in line with the fact that some pollutants which are known to be associated with particulates are not listed in this table (e.g. total phosphorus). This may infer that pollutant variability in stormwater flows is a function of many different variables, not just flow rates.

3.3 Errors in loads using a small number of samples per event

To understand the impact of taking just one, two, three or four 'grab' samples from a wet weather event to estimate downstream loads, a boot strapping methodology was adopted. Figure 12 shows the results of this, and indicates that as the number of samples used per event to estimate wet weather loads increases from 1 to 4, the spread of the boxplots tends to decrease. This is logical since more samples are being used to estimate the load, hence capturing more of the likely variability in the pollutant.

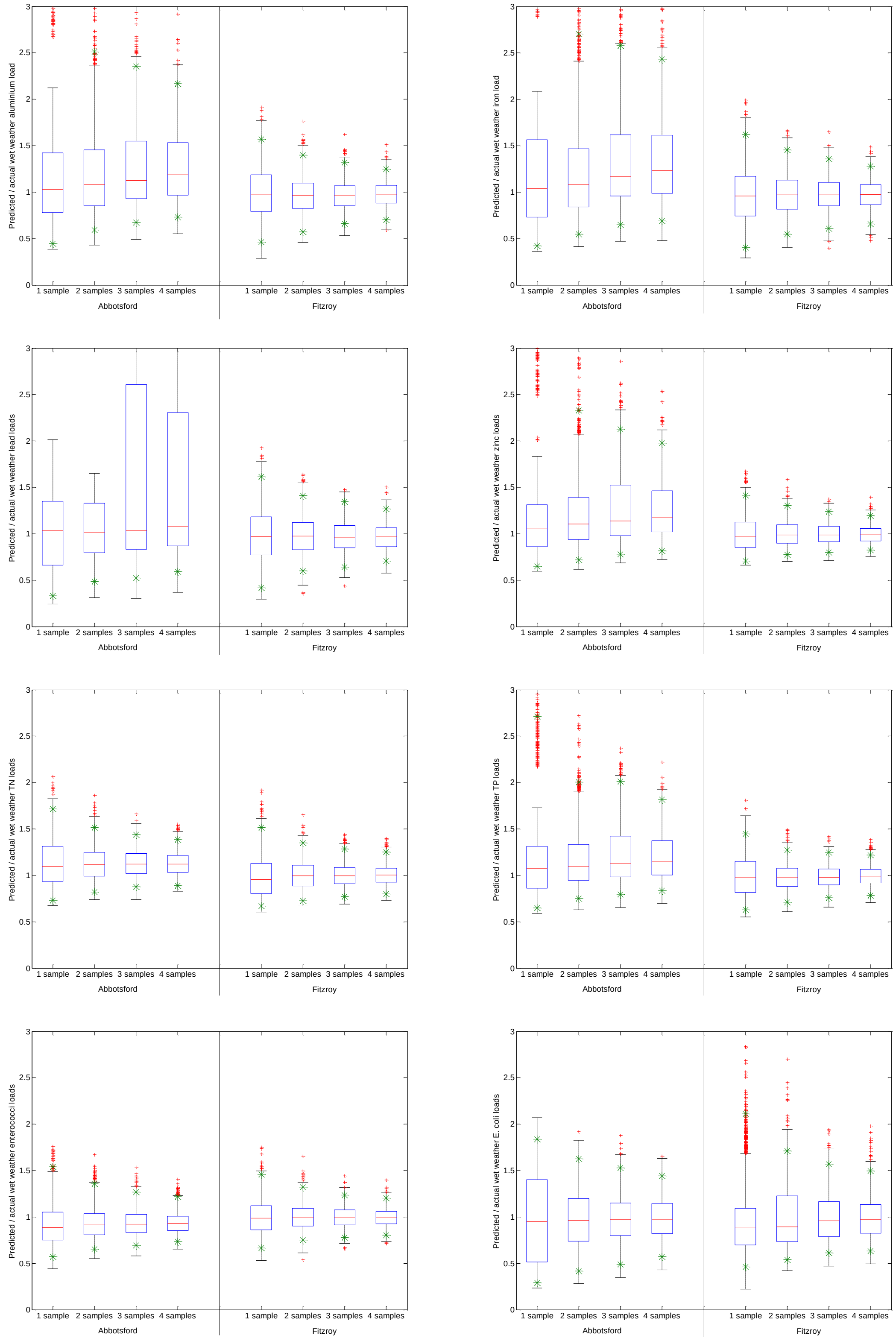

Figure 12. Boxplots showing the accuracy of using one, two, three and four samples randomly selected from each wet weather event to estimate total wet weather loads at each catchment. Green stars indicate 95% confidence interval.

The differences seen in Figure 12 between the two catchments is sometimes large, with Abbotsford having higher errors in total wet weather loads for most pollutants when compared with Fitzroy. However, for a few pollutants (such as enterococci, TN and TP) the boxplots and 95% confidence intervals (presented using stars) are similar for both catchments.

Table 7 shows the 95% confidence intervals for estimating total wet weather event load for each catchment and each pollutant using one, two, three and four samples from each of the available events. There is a degree of variability in these 95% confidence intervals. As described above, these intervals were generally larger for Abbotsford than for Fitzroy, indicating that more grab samples are required to be collected from Abbotsford in order to achieve the same accuracy in wet weather load predictions as that for Fitzroy. For example, to achieve a +/-50% accuracy in total wet weather heavy metal load prediction when using grab samples (i.e. a 95% confidence interval of <1), the Abbotsford catchment would generally require at least 4 randomly collected grab samples per event, whilst just two samples per event from the Fitzroy catchment is usually sufficient. This requirement changes for *E. coli*, where around three samples per event for both catchments are required to achieve the same accuracy. The number of samples per event decreases to just one for nitrogen and ammonia at both catchments, and phosphorus at the Fitzroy catchment.

Table 7. 95% confidence intervals for estimating a pollutant's wet weather load using just one, two, three or four samples randomly selected from each event. Only select pollutants are included in this analysis.

	Abbotsford				Fitzroy			
	1 sample	2 samples	3 samples	4 samples	1 sample	2 samples	3 samples	4 samples
Al	3.06	1.92	1.68	1.44	1.11	0.83	0.66	0.54
Ba	2.06	1.38	1.19	1.02	0.83	0.61	0.49	0.43
Cu	1.78	1.17	1.01	0.88	0.81	0.56	0.47	0.42
Fe	3.40	2.16	1.93	1.74	1.22	0.91	0.75	0.62
Pb	6.66	3.71	3.97	3.29	1.20	0.81	0.70	0.56
Mn	2.84	1.87	1.61	1.43	1.08	0.80	0.67	0.54
Sr	1.06	0.78	0.63	0.56	0.54	0.43	0.34	0.28
Ti	1.82	1.27	1.01	0.92	1.00	0.74	0.61	0.54
Zn	2.40	1.61	1.35	1.16	0.71	0.53	0.44	0.37
E. coli	1.55	1.21	1.04	0.87	1.65	1.17	0.96	0.87
Enterococci	0.97	0.70	0.57	0.49	0.79	0.57	0.46	0.40
TN	0.98	0.70	0.56	0.49	0.85	0.62	0.51	0.45
Ammonia	0.84	0.57	0.51	0.41	0.73	0.50	0.38	0.34
TP	2.06	1.25	1.22	0.98	0.82	0.56	0.49	0.44

After further investigation, a general trend became apparent that for the pollutants in Table 4 which have high variability (i.e. their RSD value is high), the 95% confidence interval presented in Table 7 (representing the accuracy of using just one sample per week) becomes broader. This means that as the variability of a pollutant in the wet weather samples increases, the accuracy in using one sample per week to estimate that pollutant's wet weather load decreases. This finding is logical, since the wet weather load for a pollutant which has stable concentrations (i.e. its RSD is close to zero) will be estimated well using any combination of pollutant concentrations. Conversely, a pollutant which varies significantly throughout each event, and between events, will require more samples to achieve a similar level of accuracy. These results are simply a product of the central limit theorem.

From the above findings, further analysis was conducted to determine whether there would be any quantifiable relationship between a pollutant's variability and the accuracy of the weekly load estimation using one sample per week. As such, the RSDs of pollutants (from Table 4) were plotted against the 95% confidence intervals (from Table 7) and this plot is shown in Figure 13. There is a direct positive relationship between the variability of the pollutant and the accuracy of using a number of grab samples to estimate the wet weather event load.

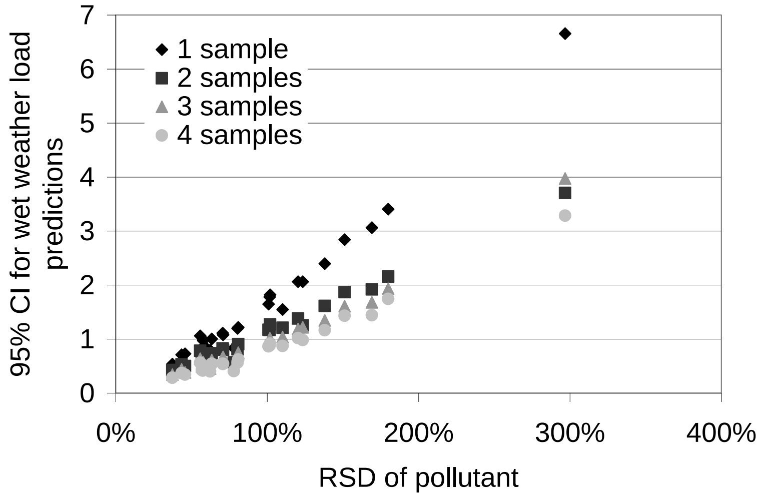

Figure 13. Relationship between the overall variability of a pollutant during wet weather (represented by Relative Standard Deviations given in Table 4) and the accuracy of using one, two, three and four random samples per event to estimate total wet weather loads (represented by the 95% Confidence Interval of the pollutant, obtained from Table 7).

This section has presented information which can be used to help identify the number of samples required to be collected during events to accurately estimate wet weather loads. It demonstrates that it is possible to accurately estimate total wet weather loads from taking just one random sample from each event (e.g. ammonia at Fitzroy). However, it also illustrates that there are definitely different wet weather sampling regime requirements for different pollutants at different catchments. From the results presented here, it is not possible to assume that the sampling requirements of a pollutant at one catchment are identical to those of the same pollutant at a different catchment. In any case, further collection and subsequent analysis of the data will help us understand the true underlying distributions (i.e. true population variability) for different pollutants. This could then be used to obtain 'minimum' sampling requirements to meet the likely maximum variability of a pollutant.

3.4 Comparison of pollutant loads

Wet weather loads

Table 8 shows the estimated annual wet weather event loads from both catchments. The Abbotsford catchment produces a higher annual load for all pollutants than that produced from the Fitzroy catchment. This is a combination of two factors: 1) the higher concentrations found at the Abbotsford catchment (see Table 4) and 2) the higher volumes leaving the Abbotsford catchment during rain events (see Table 3).

The loads leaving these catchments are significant, with more than 40kg of phosphorus and 250kg of nitrogen being exported each year from the Abbotsford catchment. These high nutrient loads can deteriorate downstream systems and lead to significant impacts on the Yarra River and ultimately Port Phillip Bay. From the perspective of human health, these export rates are quite concerning with a total wet weather load of lead (for example) of over 5kg per year discharging from the Abbotsford catchment. Furthermore, over 2.7×10^{13} *E. coli* come from this catchment each year, which is equivalent to that found in around 750kg of human faeces (calculated using a human faecal concentration of 3.6×10^{7}/g; Leeming *et al.*, 1998). It is noted that these *E. coli* are not necessarily all sourced from human origins.

Table 8. Comparison of estimated annual wet weather event loads for both catchments. Pollutant concentrations used for this analysis which were below detection were assumed to equal the detection limit.

		Abbotsford	Fitzroy
Heavy metals [kg]	Aluminium	148	18.1
	Arsenic	0.21	0.03
	Barium	3.80	0.59
	Cadmium	0.05	<0.01
	Chromium	0.53	0.07
	Copper	3.57	0.61
	Iron	240	29.1
	Lead	5.25	0.69
	Manganese	5.59	0.86
	Nickel	0.52	0.08
	Strontium	2.83	0.64
	Titanium	5.01	0.56
	Vanadium	0.36	0.05
	Zinc	69.7	25.5
Microbes [No.]	*E. coli*	2.71×10^{13}	2.93×10^{12}
	Enterococci	1.39×10^{13}	2.25×10^{12}
Nutrients [kg]	TN	256	79.2
	NH3	23.9	10.7
	TP	43.2	9.69

Dry weather flows

The data was also analysed for dry weather flows, however, as explained in Section 1.1, water quality sampling was not conducted. The Abbotsford catchment had detectable dry weather flows on 15 days during the monitoring program (120days), meaning that dry weather flows occurred once every 8 days on average. The total dry weather volume leaving this catchment during the monitoring period was approximately 30kL (although this is likely to be higher since some dry weather flows were not detectable). Although this is a significant amount of water, it is much smaller than the total volume from wet weather flows, which was over 15ML (i.e. just 0.2% of the total flow leaving this catchment was derived during dry weather periods). The Fitzroy site had detectable dry weather flows on just three days during the monitoring program (i.e. dry weather flows occurred once every 25 days), with a total dry weather volume of 1400L. Again, this is very small in comparison to wet weather volumes (2ML), meaning that less than 0.07% of total water leaving this catchment is from dry weather periods.

Unless concentrations of pollutants during dry weather flows are much higher than that found in wet weather flows, these results imply that dry weather loads are insignificant when calculating total pollutant export. For example, dry weather flows from Abbotsford will contribute the same load as wet weather flows only if dry weather concentrations are greater than 500 times that found during wet weather. This increased to 1500 for the Fitzroy catchment. While this is unlikely to be the case, water quality testing of the dry weather flows should be conducted to confirm this statement.

4 Conclusions and recommendations from the results

The report has shown the high level of pollutants which are washed from the surfaces of two catchments in Melbourne, Australia, during rainfall events. Estimated annual loads for each catchment were presented and showed the significant amount of pollutants being exported to downstream systems during rainfall events. It is important that stormwater is treated before leaving the catchment in order to protect the Yarra River and Port Phillip Bay. The dry weather flows for both catchments were barely detectable and as such it was hypothesised that the loads contributed to downstream systems during dry weather flows are dwarfed by wet weather periods. However, this report did not quantify any pollutant levels during dry weather flows.

Notable differences were observed between the catchments for both average pollutant levels and the variability of these levels. The differences were present even though the predominant land-use of each catchment was the same (commercial), and both were within 4km of one another. An explanation for these differences might be the fact that the Fitzroy catchment was known to have a slightly higher proportion of residential land-use when compared with the Abbotsford catchment. Furthermore, the Abbotsford catchment is known to have a small percentage of industrial land-use and a slightly different social behaviour (i.e. habits and practices which may influence stormwater runoff – e.g. street cleaning, dumping of waste, etc) to that found in the Fitzroy catchment. These characteristics could mean that the sources of stormwater from these systems are different enough to cause these varying pollutant levels. Even though there are differences in the pollutant levels originating from each catchment, these levels are comparable with that found in the literature for commercial catchments (Makepeace *et al*., 1995; Duncan, 1999), although Fitzroy was generally at or just below these levels.

The high variability in pollutant concentrations found for both catchments for some pollutants poses a large problem when estimating total wet weather loads using grab sampling methodologies. This is because pollutants which vary so dramatically during events require many more grab samples than those which only vary slightly during events (e.g. a pollutant which has a rather constant concentration during events can have its load accurately estimated using just one sample per event, since this concentration will not change significantly). This report demonstrated this point by showing that the accuracy of using any random grab sampling methodology to predict total wet weather event loads was highly dependent on the variability of the pollutant within these events.

In general, the nutrient loads from both catchments could be accurately estimated using the results from taking just one random sample during each event. Estimating microorganism loads required taking around three samples per event for accurate *E. coli* load prediction, yet just one sample per event for accurate enterococci load prediction. Using grab samples to estimate heavy metal loads at Fitzroy meant taking one to two random samples per event whilst for the Abbotsford catchment this increased to three to four samples per event. Again, these requirements were directly related to the variability of each pollutant during the wet weather events.

While grab sampling methodologies are theoretically the best for accurately estimating annual wet weather loads (because it is possible over a year to take many samples from different events and different positions within each hydrograph), it is more common that semi-systematic grab sampling methods are adopted. This is because sampling teams might arrive at the site at roughly the same time after each wet weather event begins, because, for example, they have a constant travel time to the site after they are notified that it is raining. This was found to be the case for grab sampling programs conducted by Monash University. Whilst this suggests that for large events they are present at the start of the event, and for smaller events they arrive at the middle of the event, it generally means sampling teams always take samples either in the rising limb or the peak of the hydrograph. This type of methodology is not a problem for pollutants considered stochastic within an event, or which follow no apparent pattern, because the systematic method is likely to capture the pollutant's true variability. However, for pollutants which exhibit a first flush effect (or an end-flush effect, such as that seen for *E. coli*), then this semi-systematic method of sampling can cause an over estimate (for pollutants with a first flush) or an under estimate (for pollutants with an end flush) of the actual wet weather pollutant load. In fact, it was found that for many of the pollutants, there was a significant first flush present, with just one pollutant (*E. coli*) showing an end flush. If sampled using a systematic method, the estimated loads for these pollutants would contain a significant amount of bias. Further work using this dataset could determine how systematic grab sampling approaches are impacted by pollutants which experience a first flush effect.

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Appendix A – Collected data

Please note that several Excel spreadsheets have been included as an electronic appendix for the raw data collected during the project. This is because it is neither possible nor practical to display this information in a report format. This appendix includes the following information:

1. Measured flow rates for each study catchment
2. Measured physical water quality parameters (i.e. data from Greenspan and Hydrolab water quality probes): temperature, dissolved oxygen, pH, turbidity, electric conductivity
3. Wet weather sampling times, comments and concentrations of water quality pollutants (heavy metals, *E. coli*, enterococci, TPHs and nutrients)

Appendix B – Bootstrap method testing

Aim: To test the influence of the number of samples used to conduct the bootstrapping methodology. Also to determine whether we have over or under estimated the mean and variance of pollutants, and hence sampling requirements, by taking samples more frequently at the Fitzroy catchment when compared to the Abbotsford catchment.

Methods: Using the data collected from the Fitzroy catchment, remove every second sample and conduct the same analysis which was explained in Sections 2.4.1 and 2.4.3 to determine:

1. the average pollutant concentration for select pollutants;
2. the variance of these pollutant concentrations within each catchment;
3. the accuracy of using four samples per event when estimating total wet weather event loads

These results (i.e. using half the dataset) are then compared with the same results when using the entire dataset to determine whether there is any influence on dataset size on the conclusions.

Results and discussions: Table 9 and Figure 14 show the results of the method explained above. It is clear that there are practically no differences in the mean concentration of any of the pollutants listed. Furthermore, with the exception of just *E. coli*, the relative standard deviations of each pollutant did not differ by more than 10%, indicating that the influence of using a large dataset, as compared with a smaller dataset, is small on both the magnitude and variance of most pollutants during wet weather events. However, it also indicates that for some pollutants, it is possible to see a considerable influence of dataset size, with *E. coli*'s RSD varying by 25%. This will, in turn, influence the sampling requirements for accurate load prediction.

Table 9. Mean and Relative Standard Deviations (RSD = standard deviation divided by mean, expressed as a percentage) of detected constituents in the wet weather events monitored at Fitzroy. Also presented are the 95% confidence intervals for estimating a pollutant's wet weather load using four samples randomly selected from each event. Only selected pollutants are included in this analysis for both the entire dataset (Full) and half the dataset (Half).

	Fitzroy (half)		Fitzroy (full)	
	Mean (RSD)	Wet weather prediction (4 samples - 95% confidence interval)	Mean (RSD)	Wet weather prediction (4 samples - 95% confidence interval)
Aluminium	0.68 (77%)	0.54	0.66 (71%)	0.54
Lead	0.03 (85%)	0.57	0.02 (80%)	0.56
Zinc	0.97 (42%)	0.37	0.96 (43%)	0.37
E. coli	10600 (74%)	0.60	11100 (101%)	0.87
Enterococci	8100 (68%)	0.34	8300 (62%)	0.40
TN	2.98 (67%)	0.49	2.88 (59%)	0.45
TP	0.34 (61%)	0.40	0.35 (58%)	0.44

The fact that most of the variances did not change by more than 10% when using half of the available dataset at the Fitzroy catchment meant that there was not a big change in the accuracy of predicting wet weather event loads using randomly taken samples during each event (see Figure 14 and Table 9). However, for *E. coli* the 25% decrease in variability when using half of the dataset meant that using four samples to estimate wet weather event loads actually became more accurate than when doing the same analysis using the entire dataset.

The results of this analysis suggest that either there is no difference when using a smaller dataset, or that the analysis presented in the main body of the report is, at least, conservative (i.e. using the entire dataset required more samples to be taken than when using just half the dataset).

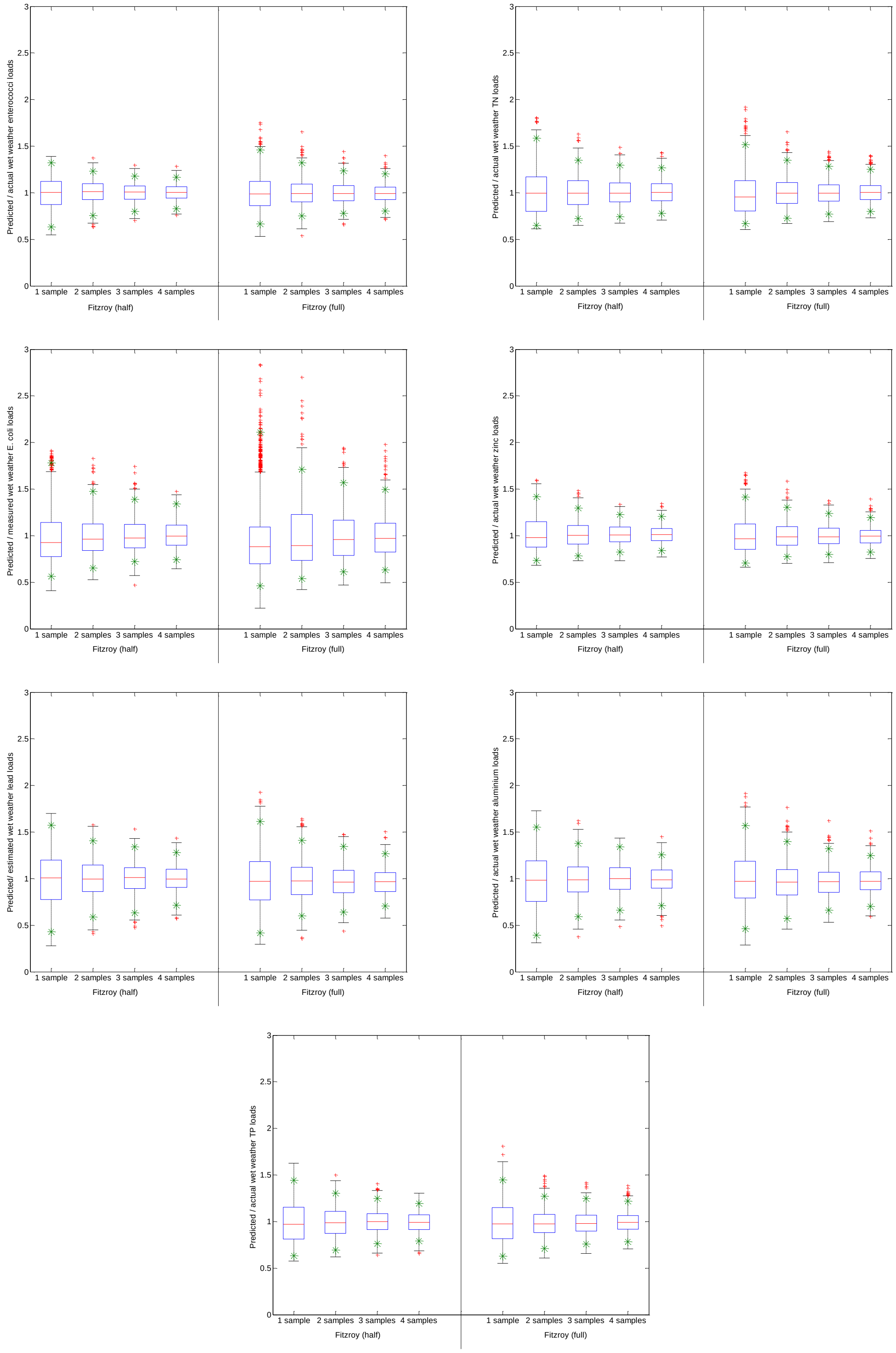

Figure 14. Boxplots showing the accuracy of using one, two, three and four samples randomly selected from each wet weather event to estimate total wet weather loads at the Fitzroy catchment when applying the bootstrapping method to half the collected dataset (Half) and to the entire dataset (Full). Green stars indicate 95% confidence interval.