

Balcombe Creek Estuary Sediment Study

Sediment loads and water quality monitoring and analysis

Technical Report No. 77

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Executive Summary

Background:

Balcombe Creek Estuary is an intermittently open estuary of regional significance. Urbanisation and changes to land uses in many of the waterways within this catchment have contributed substantial changes to hydrology over the past 50 years. In particular, accumulation of sediments within the estuary is a key threat with potential impacts including high accretion rates, turbid waters and associated changes to the estuarine ecosystems, such as loss of seagrass, food and habitat for fish and macrofauna.

Scope and Aims:

Mornington Peninsula Shire Council (MPSC) has been working with the local community group, Balcombe Estuary Rehabilitation Group (BERG), to reduce sedimentation to the estuary. This study aimed to increase the understanding of the impact stormwater run-off is having on sedimentation loads to the estuary, and to assist in prioritising further management actions.

Methods:

Fifteen sites were monitored in this study using spot samples to prioritise sites with high sediment loads. Water samples were measured for turbidity by water quality meter and analysed for suspended solids as well as average velocity (flow). This data allowed instantaneous loads to be calculated during storm sampling. A further three sites were sampled continuously to characterise loads over three rainfall events.

Results:

Findings of the spot sampling suggest run-off from three study sub-catchments contributed substantial sediment loads to the estuary during high rain-fall events, namely Ferrero Reserve, Henley Ave and Augusta St catchments (See Figure 3, page 17). A summary of the sedimentation flow rates is shown in the Table below:

	Site	Average Instantaneous Sedimentation Discharge Rate	Catchment Size	Predominant Suspended Sediment Type	Likely origin / comment
1	Ferrero Reserve sub-catchment (Hopetoun Creek)	224 g /sec	204	Poorly sorted fine to coarse silts	Highest suspended sediment load and highest yield of sediment per square metre
2	Henley Ave	35 g/sec	60.4	Poorly sorted silty sand. Coarse sands will quickly fall out of the water column and settle directly in the lower estuary	Second highest suspended sediment load and highest yield of sediment per square metre.
3	Augusta Ave	22 g/sec	30.3	Poorly sorted corase silts to fine sands	Third highest estimated sediment loads and yield of sediment per square metre
4	Mirang Ave	19 g/sec	20	Poorly sorted medium silt	Fourth highest estimated (instantaneous) sediment loads
5	Uralla Drive	0.8 g/sec	22	Poort sorted very coarse silt	Lowest overall discharge from all events

The instantaneous loads estimates showed:

- Ferrero sub-catchment (Hopetoun Creek) had the highest average instantaneous discharge of 684 grams per second, followed by Henley Ave with 35 g/sec
- Loads from Augusta (West) outfall were the third highest, and ranged between 10 and 39 grams per second over three events
- Mirang was generally lower than Ferrero, Henley and Augusta, except for one event with 56 grams per second of suspended sediment, while otherwise ranged from 2 to 19 grams per second
- Uralla measured the lowest average discharge from all events, ranging 0.3 to 2 grams per second over the four events, and is an unlikely source of large volumes of sediment
- Particle sizes varied with sediments consisting of coarse silts and sands and from Henley and mostly fine silts and sands from Ferrero

Three catchments, Fererro Reserve, Henley Ave and Augusta St were selected for continuous monitoring over three rainfall events. A summary of the total estimated loads from the three events is shown in the table below:

Total estimated suspended sediment load (kg) during each event based on linear interpolation. Error reported as cumulative uncertainty (±30%).

Site	Event 1	Event 2	Event 3
Augusta	4.2 ± 1.3 kg	166 ± 50 kg	263 ± 79 kg
Ferrero	178 ± 53 kg	1,528 ± 458 kg	10,114 +/- 3,034 kg
Henley	155 ± 47 kg	ND	1,664 ± 499 kg

Based on the estimated total loads and yields of suspended solids from the three sub-catchments durring 28 Sep – 23 Oct, it was shown that:

- Approximately 14 tonnes of suspended sediments were discharged into Balcombe Creek estuary from the three sub-catchments during the three storm events,
- Hopetoun Creek (sub-catchment Ferrero), with a catchment area of 204 Hectares, representing around 70% of the total monitored area, generated the highest suspended sediment load and had the highest yield of sediment per square metre,
- Rainfalls during continuous monitoring event ranged from 3.2 mm to 21.2 mm,
- Augusta Street has the lowest estimated loads and yield of sediment per square metre.

Recommendations

This study provides crucial information to enable council to improve the decision-making processes around sediment and stormwater management within the Balcombe creek catchment area. There is a need to improve the quality of stormwaters to protect Balcombe Creek, through changes in the catchment, additional treatment, and/or slowing or diverting water flows prior to draining into the estuary. Addressing issues with sediment management for the Balcombe Creek estuary should be prioritised based on the findings from this report of suspended sediment loads and yields, along with recommendations from other sources, and in discussion with relevant waterway stakeholders.

There is a need for adaptive management strategies to allieviate the volume of sediments entering Balcombe Creek estuary from across the catchment. Utilising well designed road drainage and diversion systems to funnel eroded material into buffer systems such as vegetated and unvegetated roadside swales and sediment pits should be used to offset water quality degradation downstream. The order of priority should follow a cost benefit analysis and risk matrix to be developed by MPSC in consultation with Melbourne Water and the community, taking into account the available resources and relevant information. There are several key findings from this study and priority urban sub-catchments which require further treatment, namely,:

1. Henley Ave - Investigate alternative options for treating suspended sediments including disconnection of stormwater flows, vegetated swales, graded pits and increased vegetation in verges. Review the size, capacity and maintenance of the existing CDS GPT. Any upgrade of the existing GPT will require frequent maintenance and are unlikely to deliver major benefits. Construction of a sediment pond would require a much larger area of land and higher in terms of cost of construction and maintenance.
2. Ferrero Reserve - Investigate options to revegetate riparian corridors, install vegetqated swales to slow down inflows to Hopetoun Creek and reduce flow rates, trap suspended sediment and increase natural infiltration in this catchment prior to entering the creek
3. Augusta Street – results indicate this catchment is not a major source of suspended sediments and a lower priority. While sealing dirt roads may help alleviate the volume of road base material entering the creek, this would result in increased flow rates from impervious surface run-off, requiring further infrastructure to treat stormwaters prior to entering the creek. Currently, suspended sediment from this catchment appear to consist primarily of fine silts and clays, with larger particles entering as bed-load material

Suitable treatment technologies should be evaluated by Council in consultation with waterway stakeholders and stormwater designers. Vegetated swales can be used as part of a water sensitive urban design strategy to convey and decrease run-off velocities into road verges and trap suspended sediments. The use of a constructed wetlands is a large undertaking for removal of sediments and should be carefully considered, as it would require a sediment basin, high flow bypass channel, regular maintenance and sediment disposal and would need to be costed and designed according to the Melbourne Water design manual. Recommendation for further assessment are for ongoing sediment and water quality monitoring of Balcombe Creek catchment. Further consideration should also be made for bed-load transport and other pollutants including gross litter and contaminants which are likely to be causing additional stress to the ecosystem.

Introduction

Background

Balcombe Creek drains a catchment area of 87 km^2 and includes tributaries such as Tuerong, Devilbend, Harrap and Hopetoun Creeks, as well as a number of smaller tributaries and stormwater inflows. The estuary is of regional significance as a comparatively intact intermittent estuary on the eastern side of the Bay. With increasing pressure from urbanisation and changes to land uses, many of the waterways within this catchment have undergone substantial changes to hydrology over the past 50 years, with land clearing and development for housing, roads and other infrastructure. The potential for pollution entering the creek and estuary was identified in earlier studies, and concern from the community on how pollution may be impacting the ecology of the estuary has been expressed.

Accumulation of sediments in Balcombe Creek estuary can impact estuarine processes and can lead to losses of seagrass, food and habitat for fish, macrofauna and birds. The ecological impact of suspended sediments will vary depending on the volume, frequency, timing and severity of inputs. The particle size of sediments will also influence the types of impacts on the receiving ecosystem. Fine silts and clay particles can bind chemical contaminants through mineral complexes, with higher concentrations able to adsorb to the larger surface area of small particles. These fine particles are also more easily transported for larger distances in the water column. Greater volumes of coarse sediments can increase channel aggradation and accretion rates, in turn reducing water depths and flows (Nelson and Booth 2002).

Sediment can enter the estuary from numerous sources across the catchment. However, the primarily focus has been on the impact of urban runoff in Mount Martha at the sub-catchment scale within the vicinity of Balcombe Creek estuary. Often following heavy rain, unsealed roads and car-parks are scoured by flows carrying sediments off the catchment into the estuary via stormwater.

Event-based stormwater runoff is the primary mode of transport for particulate pollutants of non-point origin. Sediment wash off during high intensity rainfall events can cause a large degree of displacement of fine and coarse particles from surfaces within the catchment. Typically, the majority of the annual loads of sediments will be transported during storm events, which only occur with the onset of larger rainfall runoff events. Therefore, it is essential that samples for total suspended solids are taken during these periods to determine accurately the total loads entering the estuary from each catchment.

Existing knowledge

Several previous studies have examined some of the issues and threats facing Balcombe Creek estuary and the inflows from tributaries and the main creek.

Previous work to date has estimated the potential runoff and sediment loads from several sub-catchments and provided suggestions for managing stormwater assets to protect the values of Balcombe Creek (Water Technology 2010). This sedimentation study by Water Technologies modelled the sediment and nutrient inflows from several sub-catchments which drain directly into the estuary, including LaTrobe Drive, Henley Ave, Augusta Street and the Kindergarten Carpark. Their modelling using SWMM (USEPA) and MUSIC (eWater) suggested a potential reduction of between 10-25% in annual suspended sediments loads from these catchments using several stormwater treatment technologies, including sediment basin (LaTrobe and Henley), vegetated swales (all), sealing of roads and/or carpark (all), and surface treatment sprays (Water Technology, 2010).

Pollution concentrations in sediments in Balcombe Creek estuary have been monitored by CAPIM since 2010, adjacent the park at the end of Mirang Drive. Sediment particle size in this area consist of sandy silt (median 80 µm), with around 25% coarse to medium sand (250 – 2000 µm) and around half silt (2 – 63 µm) (CAPIM, unpublished data). Metal pollution remains low and relatively stable over the past 7 years, while pesticide residues, primarily synthetic pyrethroid insecticides bifenthrin and permethrin, have been detected intermittently (Sharley and Sharp, 2015, 2017).

The Healthy Waterways Strategy (HWS) developed in partnership with Melbourne Water and the Victorian State Government aims to maximise investment to protect and improve priority community and environmental values and increase liveability (Melbourne Water, 2013). The priority values for Balcombe Creek identified in the HWS are amenity and birds for the Estuary, as well as frogs for the freshwater creek area. This study should help to address the risk from sediment pollution by providing much needed information on sediment loads across the Balcombe Creek estuary catchments, and prioritise further action where most required.

Scope

CAPIM were engaged by Mornington Peninsula Shire Council to provide input on sediment pollution flowing from the surrounding catchment, with the view to provide data that will demonstrate how planned management works may reduce sediment loads to the estuary.

This study aimed to measure turbidity, suspended solids and stormwater flows, quantifying sediments loads draining to Balcombe Creek from the main inputs surrounding the estuary.

The study was divided into two Phases.

The primary aim of Phase 1 was to collect data over storm events to then determine turbidity and suspended sediment concentrations, flow depth and velocity to calculate instantaneous discharge from multiple sub-catchments and stormwater assets and prioritise areas for further investigation.

The purpose of Phase 2 of the study was to capture suspended sediment loads during high rainfall events, including the peak flow period.

This report provides a summary of the two phases of monitoring for key sub-catchments and identified priority catchments for treatment of suspended sediments inflows from stormwater.

Aims

- Determine concentrations of suspended solids entering Balcombe Creek estuary
- Estimate the total volumes and sizes of sediments discharged during high and medium intensity stormwater flows;
- Understand the relative loads from the sub-catchment storm flows to assist in prioritising works

Methods

This project consisted of two approaches, with the first, based on a snapshot sampling method to provide greater spatial coverage for monitoring. This sampling builds on existing community monitoring by BERG supported by MPSC, which involved spot measurements of turbidity and other water quality parameters at 14 sites within the estuarine and lower riverine sections of Balcombe Creek (Figure 1). Initially this work was carried out during base-flow periods, however flow rates at these sites were negligible during periods with no antecedent rainfall. With support from CAPIM, this monitoring was adjusted to include measurements for total suspended solids (TSS), flow and estimate instantaneous sediment discharge over four rainfall events from March to August 2016.

The second phase, involved the deployment of water flow loggers and turbidity meters at the three priority sites from 28 September until 22 October 2016 (Figure 3). Three storm events were recorded during this period.

Sediment loads were estimated through the relationship between turbidity, TSS and flow. To determine the quantity and particulate size of sediments flowing from stormwater, entering the upper and lower Balcombe Creek estuary, particle size measurements were determined using a laser particle analyser.

A summary of the two phases of this study and methods are provided below, while further details can be found in Appendices 1 – 4.

Phase 1 - Spot Sampled Storm Events

This study assessed stormwater flow at 15 sites (with an additional outfall measured at Augusta Street) on the Mornington Peninsula in Mount Martha within the Balcombe Creek estuary catchment (Figure 1). Water samples were measured *in situ* for turbidity by water quality meter. Velocity (m/s) was measured by velocity meter (Global probe FP211). Cross sectional areas was calculated from measured water height (h) and diameter (d) of stormwater outfalls to within the nearest cm by ruler. Total suspended solids were analysed by standard methods (APHA 2005) with a limit of reporting of 1 mg/L.

Total discharge was calculated from total flow (velocity * cross sectional area) * suspended solids and are reported in grams per second (g/s).

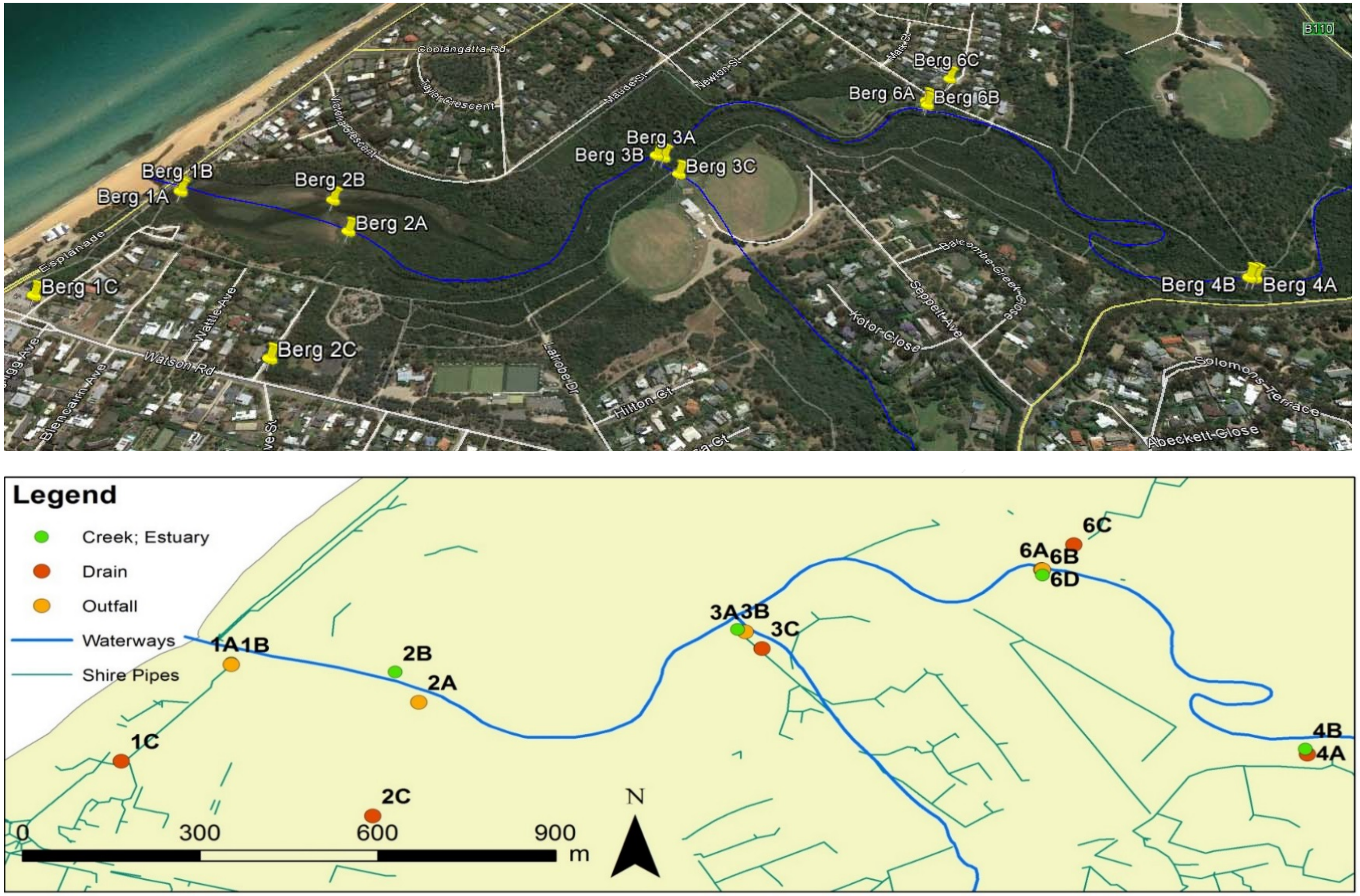

Figure 1 – Maps showing the 15 BERG sampling sites along Balcombe Creek estuary.

Phase 2 - Continuous Storm Event Sampling

Study locations

The second phase of this study assessed stormwater flow at 3 sites (Henley 2A, Ferrero 3A and Augusta 6D) on the Mornington Peninsula in Mount Martha within the Balcombe Creek estuary catchment (Figure 3). While sub-catchments have different land use characteristics, the primarily land uses comprise of urban residential, commercial and open space/parkland (ABS, 2016).

Figure 2 – Photos of the sampling sites A) Henley Ave stormwater outfall, B) Augusta Street stormwater outfall (West), and C) Ferrero Reserve stormwater (Hopetoun Creek) outfall.

Catchments

The three catchments are described below in Table 1 and visualised in Figure 3. Ferrero Reserve stormwater outfall drains includes stream water from Hopetoun Creek

Table 1 – Catchment properties and details of the monitoring sites.

Catchment	Area (Ha.)	Predominant Land use	Pipe Diam. (cm)	Stormwater Infrastructure
Augusta	30.3	Medium density residential, unsealed and sealed roads	110	Piped drainage, surface runoff from Augusta Street
Henley	60.4	Medium density residential, mixed road types	87	Piped drainage, open roadside swales, Rocla CDS
Ferrero	204	Medium density residential and mixed sealed and unsealed roads	75	Piped drainage, open roadside swales into reserve

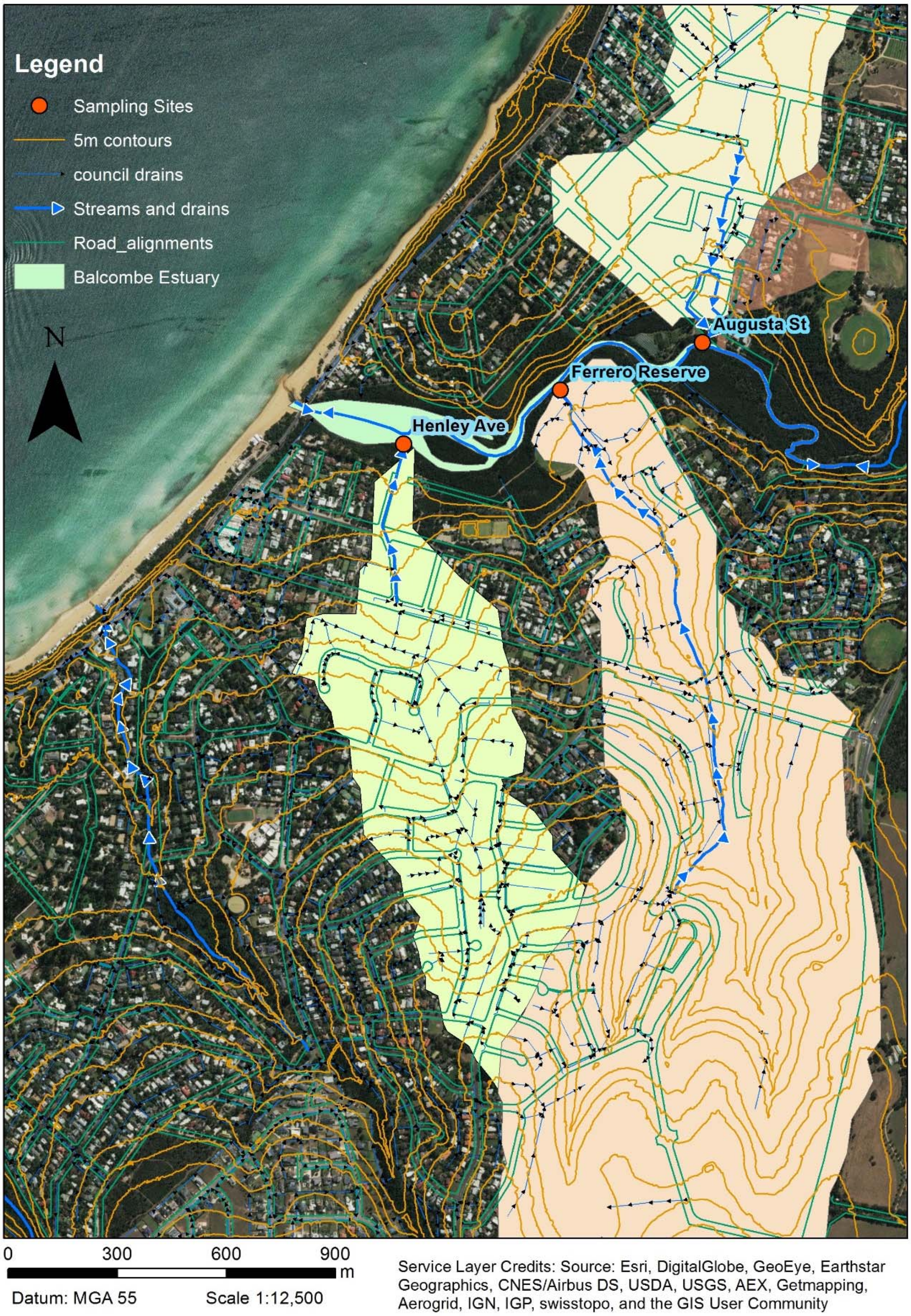

Figure 3 – Catchment map of the three continuously samples sites and their catchments as mapped by 10m DEM showing stormwater pipes and pits, river and main roads.

Rainfall observations

Rainfall measurements were provided by Melbourne Water and derived from the closest rain gauge which was Devil Bend Reservoir [Station ID: 586206; -38.2769, 145.1] (Melbourne Water, 2016), which lies 6.7 km to the east of Mt Martha and records at 6-minute intervals.

Rainfall and Flow Characteristics

The use of Intensity Frequency Duration (IFD), Average Recurrence Interval (ARI) and Average Annual Exceedance Probability (AEP) are notable in rainfall-runoff analysis (Engineers Australia 2006; BOM 2016). The AEP was compared to the rainfall from each of the events to determine the likelihood and frequency of this event occurring each year.

The runoff coefficient (Eq. 1) was used to determine the total volume of flow relative to the amount of rainfall over each event and was calculated as follows:

$$(1) \quad rc = \frac{v}{r \text{ X A}}$$

Where *rc* is the run-off coefficient, *r* is the rainfall (m), A is the catchment area (m^2) and v is the total runoff volume (m^3). A coefficient >1 would indicate more flow than suggested by rainfall.

Flow measurement

ISCO 750 low-profile area velocity flow modules were deployed at the outfalls to measure velocity by ultrasonic Doppler and depth by pressure transducer at the three main stormwater drains. These were programmed to log water depth and water velocity after level measurement and a zero level offset. Flow rate (m^3s^{-1}) was then calculated at one minute intervals using cross sectional area multiplied by average velocity. Data was checked and processed and aggregated to 6 minute averages to coincide with rainfall and turbidity logging intervals (detailed in Appendices 2, 3 and 4).

Measurement of water quality

Sediments were measured using turbidity sensor calibrated to TSS over multiple events and individual catchments. Turbidity was used as a surrogate for TSS to log continuous readings and compare against flow data (Lewis 1996). This provides calibrated catchment models which future sampling can be compared to for each catchment for any future community monitoring and logging using similar equipment.

Estimated Loads

Loads were calculated using linear interpolation as the primary method for estimating total suspended solids, so long as samples were available either side of the rising and falling limb of the hydrograph. Where data was limited, both the Beale Ratio and linear interpolation were used.

Loads were estimated using flow rates (m^3s) and water concentration data (estimated TSS) with a 6-minute time step in Water Quality Analyser (WQA) 2.1.2.4 (eWater CRC 2012). The process involved:

- Estimated TSS from turbidity using linear interpolation from regressions analysis on a 2 minute time-step

- flow data (m^3s^{-1}) were imported into WQA on a minute timestamp
- rainfall data was imported into WQA on a 6-minute time-step
- flow data were aligned to the water quality concentration data if necessary
- all data was checked and processed and aggregated to 6 minute time step
- Data for each catchments and event was selected and loads estimation tool was run

Loads are presented as the estimated value plus or minus the probable error (± %) as an estimate of uncertainty in measured flow and TSS data. Based on published literature and considering sampling complexities (such as estuarine backflows, sand accretion over loggers), the cumulative uncertainty was estimated at 30% from the propagation of errors in measuring depth, velocity, analysis of TSS, and calculation of suspended solids from turbidity models (Appenidx 3; cf.Harmel et al 2006).

Sediment Yields

Yields describe the load of pollutants (e.g. kilograms) from each sub-catchment (e.g. km^2) which is monitored (i.e. kg/km^{-2}). Yields can provide useful measures to directly and quickly compare the rate of sediment delivery between monitored sub-catchment areas. Yields also enable a rapid assessment of the differences in the rate of sediment loads derived from dominant land use types in each sub-catchment area. From the 3 auto-sampler sites data collected between September and October 2016, yields were calculated by dividing the total estimated sediment load from all three events by the total sub-catchment area.

To derive catchment areas, a 10m digital elevation model was created from 5m contours and ingrained flow direction from stream and drain layers. Sub-catchments were delineated using the hydro catchment tool in ArcGIS (version 10.4.1) (see Sharley et al 2017 for full methods).

Quality Assurance and Control

A number of checks and decisions steps were applied for suspended sediment concentraitons, turbdidity measumrents and water flow data. Detailed information on these and the quality assurance and control (QA/QC) protocols are detailed in Appendix 4. In summary, they included data verification and validation, error checking, data adjustment for known errors, aggregation and interpolation of data and computation of derived variables. Manual checks were made to detect errors, inconsistencies and apparent malfunctioning in the instrument data. Start and finish times were compared to field logs, and data were reduced to the periods of observation.

Results

Phase 1 – Spot Sampled Storm Events

Samples over four moderate size rainfall events were collected by CAPIM staff, MPSC staff and/or BERG volunteers. This was an expansion of the existing base-flow sampling conducted by BERG in conjunction with MPSC. Turbidity and total suspended sediment measurements during each rainfall event between March and August 2016 were compiled and are shown in Appendix 4.

Samples taken over the three events showed high concentrations of suspended solids ranging greater than 500 and maximum of 1,246 mg/L. Figure 7 shows instantaneous sediments loads from each event. Ferrero clearly showed much higher loads of TSS than all other catchments, while the lowest discharge was from Uralla.

Rainfall

Mean long-term annual rainfall is around 742 mm (Mornington, 086079, 38.24°S 145.07°E), generally with slightly higher rainfalls from April to October (BOM 2014). Total annual rainfall for 2016 was 753.2mm (Devilbend Reservoir, Melbourne Water). During the sampling period, the largest rainfall event in 24 hours was 26.2mm on 10 May, with May also the wettest month with 122 mm. Rainfalls were relatively similar to long-term averages and mean monthly totals.

- 15.2 mm of rainfall fell over the 24 hours from 9am of the 18 March to 19 March, in addition to 17mm in the previous 24 hours.
- 6 April had only 3.6mm during the day, but 11mm the previous 24 hours.
- On the 5 July, a total of 18.8mm fell over 24 hours.
- 19 August recorded 13.2mm over a 24 hour period.

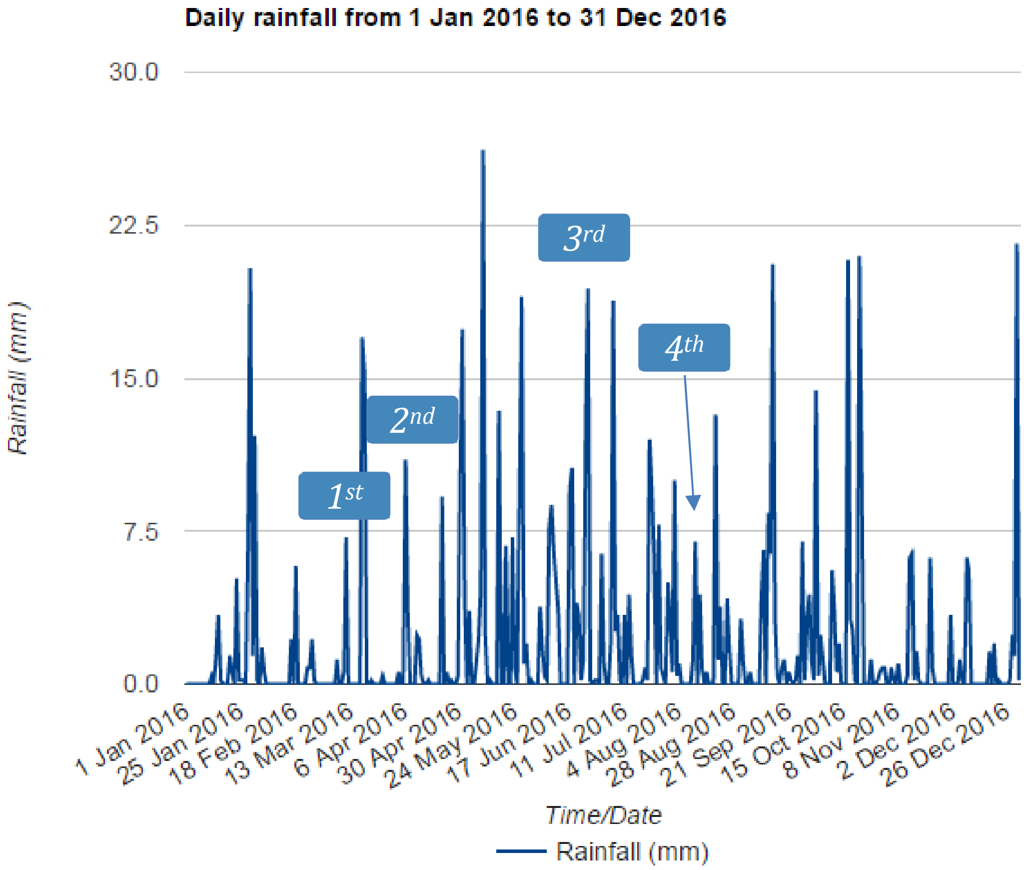

Figure 4 - Daily rainfall data for 2016 from Devil bend Reservoir rainfall gauge (Melbourne Water, 2016).

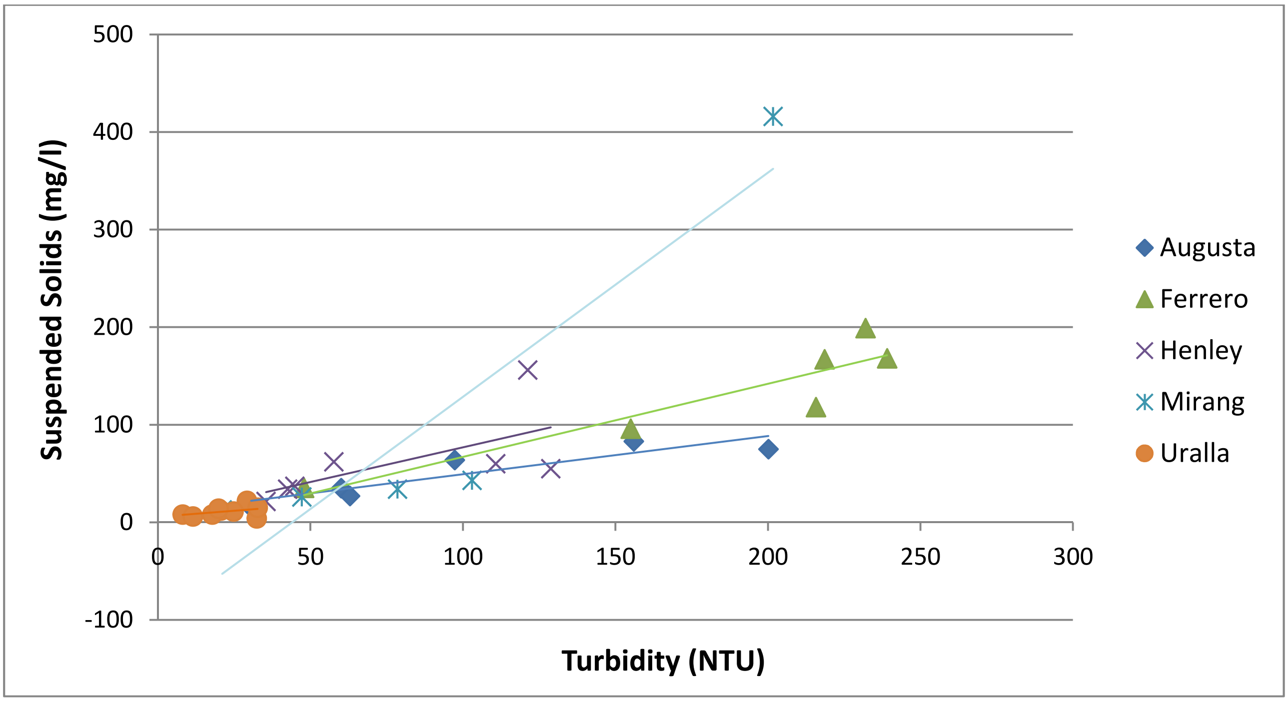

Figure 5 – Scatterplot matrix and estimated linear fits for the correlation between suspended solids and turbidity from initial data.

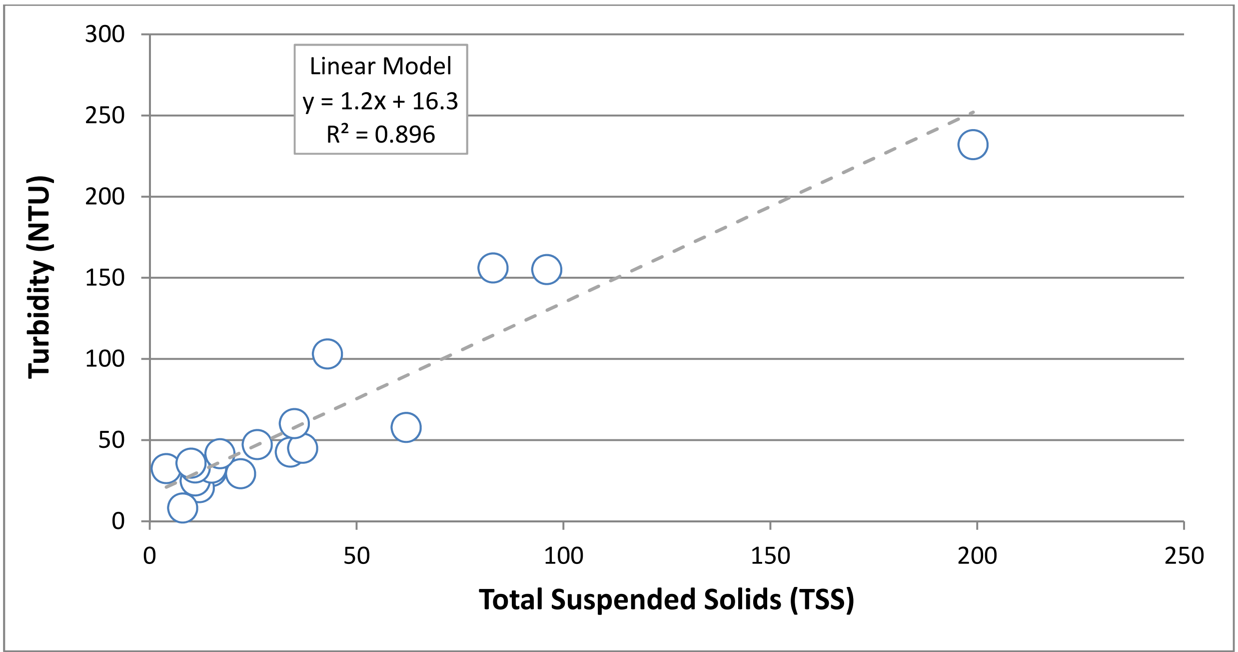

Figure 6 –Scatter plot and estimated linear model of the relationship between total suspended solids (TSS) and turbidity (NTU) from initital samples.

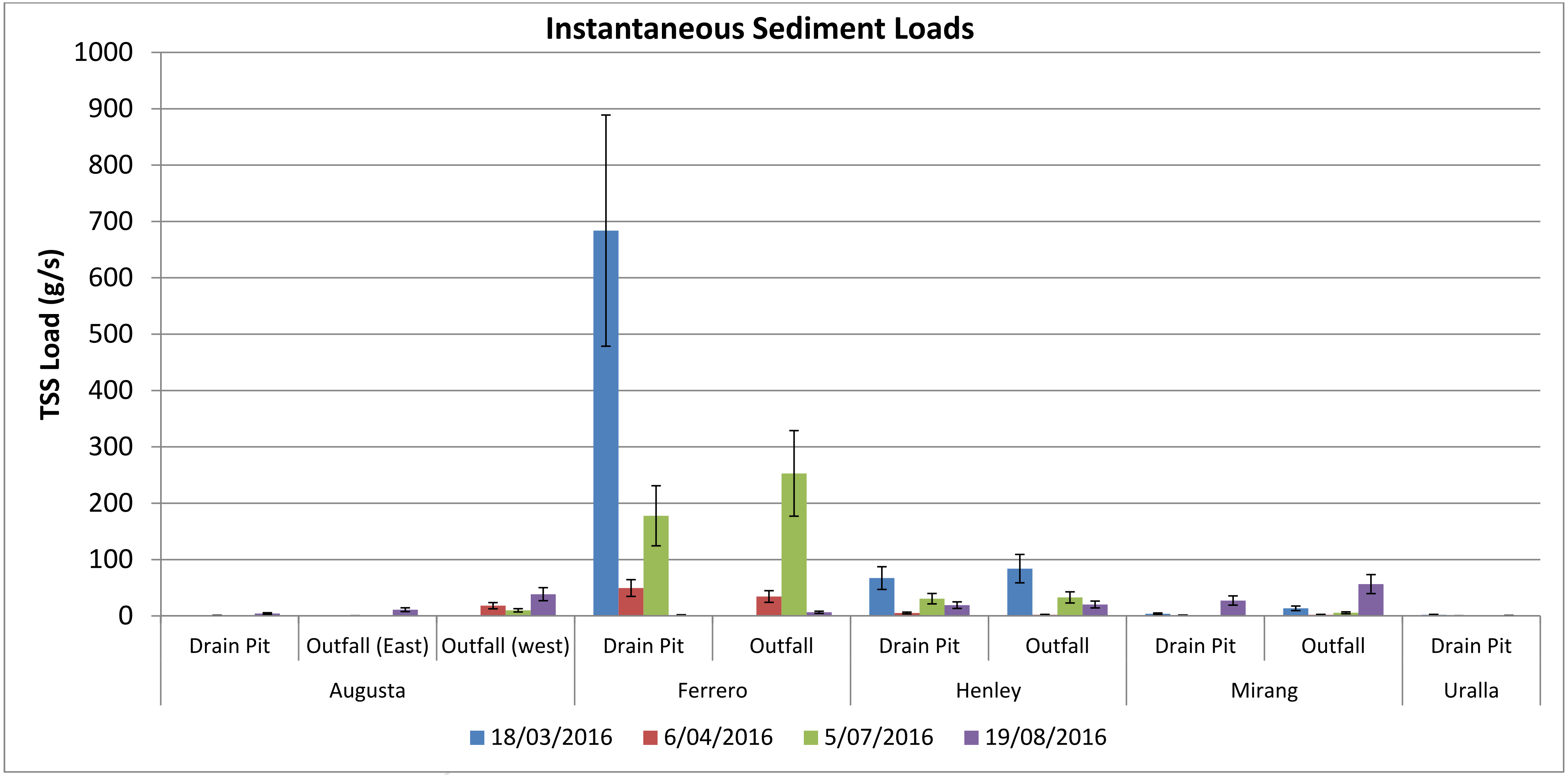

Figure 7 - Instantaneous loads from stormwater drains and outfalls calculated from suspended solids and water flow rates. Error bars represent (±30%) probable error from cumulative uncertainity analysis.

Instantaneous Loads

Total instantaneous sediment discharge was highest from Ferrero, followed by Henley, Augusta and Mirang (Table 2). Henley had similar volumes of sediment from both the drain pit, upstream of the GPT, and from the outfall. Measured flows and concentrations of suspended solids over the four rainfall events provide a clear assessment of the priority areas for sediment incursion into the upper (Ferrero and Augusta) and lower estuary (Henley).

Table 2 – Summary of average instantaneous suspended sediment loads, sediment type and evaluation from four rainfall events in 2016.

	Site	Average Instantaneous Sedimentation Discharge Rate	Catchment Size (Ha.)	Predominant Suspended Sediment Type	Likely origin / comment
1	Hopetoun Creek (Ferrero Reserve sub-catchment)	224 g /sec	204	Fine and coarse silts	Highest suspended sediment load and highest yield of sediment per square metre
2	Henley Ave	35 g/sec	60	Silty sand. Coarse sands will quickly fall out of the water column and settle directly in the lower estuary	Second highest suspended sediment load and highest yield of sediment per square metre.
3	Augusta Ave	22 g/sec	30	Fine silts and clays	Third highest estimated sediment loads and yield of sediment per square metre
4	Mirang Ave	19 g/sec	20	Poorly sorted medium silt	Fourth highest estimated (instantaneous) sediment loads
5	Uralla Drive	0.8 g/sec	22	Poort sorted very coarse silt	Lowest overall discharge from all events

Particle Size

The differences in particle size between the sites and within storm flow events were assessed for selected samples over the four stormwater events.

Particle size ranges from all sites including Augusta, Ferrero, Mirang and Uralla were variable. However, Henley Ave generally showed a high volume of sand in both samples taken on the 19 August upstream (2C) and downstream (2A) of the Rocla Continuous Deflection Separation (CDS) Gross Pollutant Trap (GPT) unit (Figure 8).

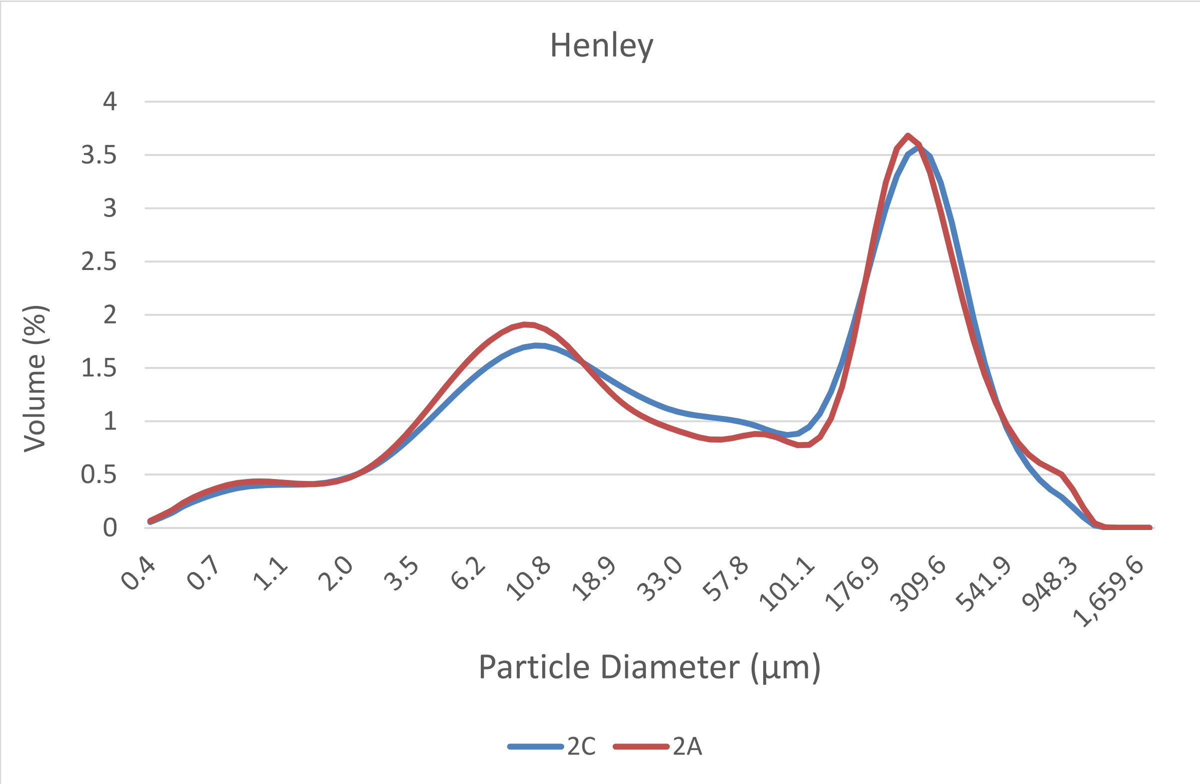

Figure 8 – Particle size distribution for Henley Ave stormwater samples from (2C – Drain pit) upstream and (2A – Outfall) downstream of the GPT during a high-flow event, 19 Augusta 2016.

Phase 2 – Continuous Storm Event Sampling

Rainfall Patterns

Rainfalls over the month of September (72.8 mm) was similar to the long term average, while in October rainfall was around 33% higher than the long-term average with a total of 92.2 mm. Figure 9 shows the daily rainfall for September and October 2016 and the three rainfall events over which continuous sampling was conducted is shown in Table 3.

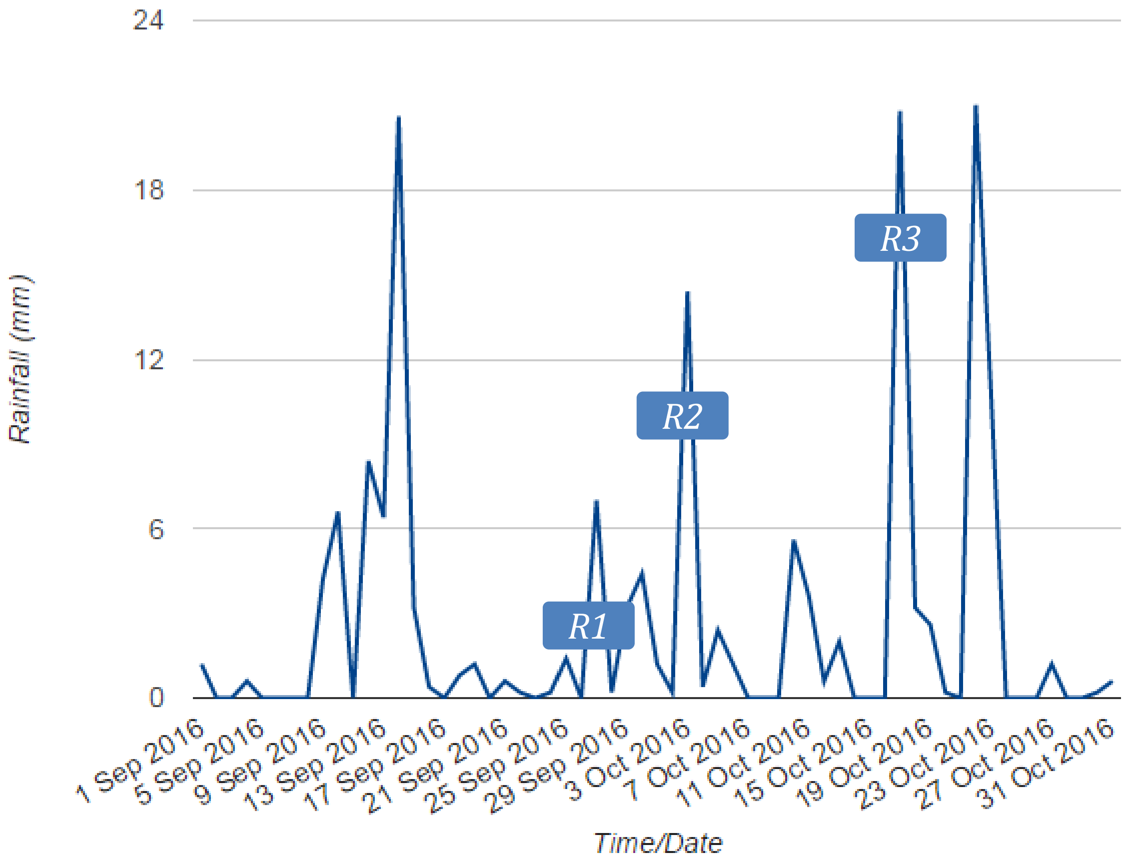

Figure 9 – Daily rainfall observations (mm) from Devilbend Reservoir rain gauge for September-October 2016 and sample events (Melbourne Water, 2017).

Table 3 - Summary of rainfall over three events for continuous flow sampling.

Parameter	Event 1 29/09/16			Event 2 2-3/10/16			Event 3 22-23/10/16		
Catchment	Henley	Ferrero	Augusta	Henley	Ferrero	Augusta	Henley	Ferrero	Augusta
Runoff coefficient	0.25	0.1	0.41	ND	0.1	0.79	0.8	0.27	0.26
Total event rainfall (mm)	3.2	3.2	3.2	14.4	14.4	14.4	19.6	19.6	19.6
Total event runoff (m^3)	514	640	393	ND	2,857	2,526	6,421	9,731	2,469

Rainfall Intensity Frequency Duration

Rainfall totals for event 2 and 3 were relatively large compared with event 1 (Table 3). The sample events measured were typical compared with rainfall figures from the Average Recurrence Interval (ARI) and Average Annual Exceedance Probability (AEP). The Average Recurrence Interval (ARI) and the Annual Exceedance Probability (AEP) are both a measure of the rarity of a rainfall event (BOM, 2017). Figure 10 shows the various durations and the AEP statistics of how probable this event type is on an annual basis. The rainfalls totals during the continuously monitored period were not greater than the probability thresholds of being equalled or exceeded in any one year (AEP, Figure 10). In terms of likely frequency of rainfall total (i.e. probably number of exceedances per year (EY)), rainfall during event 2 exceeded the totals for <12EY over 3 hours and <6EY over both 6 and 12 hours, while rainfall during event 3 exceeded <12EY over both 24 and 48 hours.

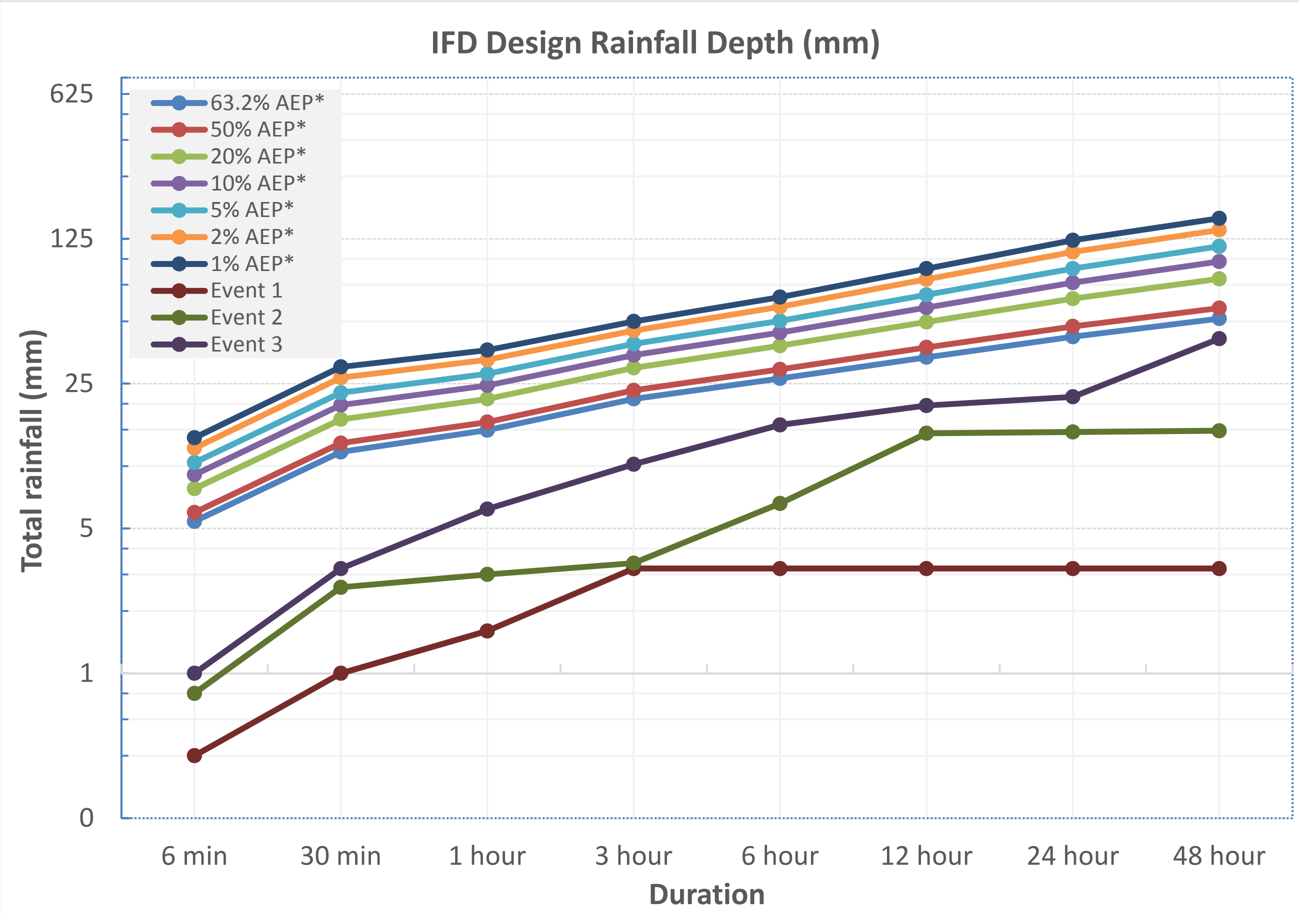

Figure 10 - Rainfall totals for different time intervals over the continuous sampling compared against Intensity Frequency Duration (% probability) and Annual Exceedance Probabilities (AEP).

Suspended Sediment Concentrations

Total Suspended Solids (TSS) concentrations over the sampling events ranged from 3 to 416 mg/L, with a median value of 32.5 mg/L (*n* = 82). Estimated TSS concentrations were derived using spot samples collected from each sub-catchment over a range of flow rates and turbidity and TSS concentrations (Appendices 2 and 3). Results from each catchment are presented below.

Augusta

Stormwater from Augusta Street outfall (West) drain during Event 1 had high concentrations of suspended solids between 5am and 1pm on 29/09/2016, with TSS ranging between 4.7 and 376 mg/L. Rainfall total was 3.2mm at 5:30 am during the run-off event. The second and third events were much larger in terms of rainfall by comparison, with around 14 and 20mm, respectively (Table 3), with resulting flows substantially greater (Figure 11).

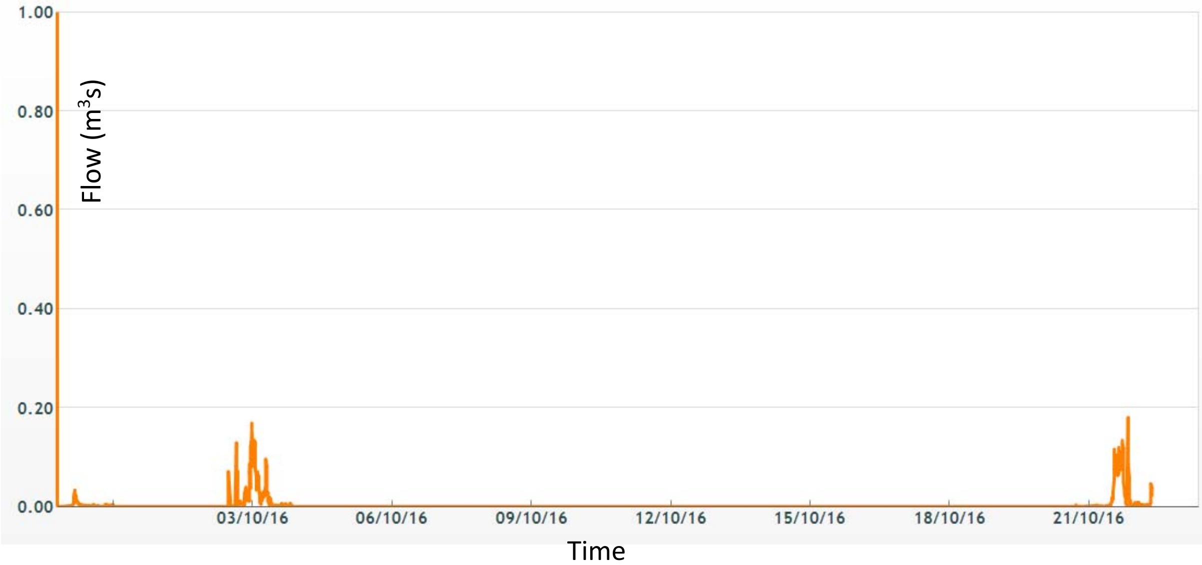

Figure 11 – Augusta Street stormwater drain total flow volumes (m^3s) during three events, 29 Sep, 3 October and 21-22nd October 2016.

Henley

Stormwater from Henley outfall drain had very high concentrations of suspended solids between 5am and 1pm on 29/09/2016, with TSS ranging between 361 and 1,246 mg/L. Corresponding rainfall peaked at 3.2mm during the first run-off event, 14mm for the second and 20mm for the third event resulting in substantially increasing flow rates for each successive event (Figure 12).

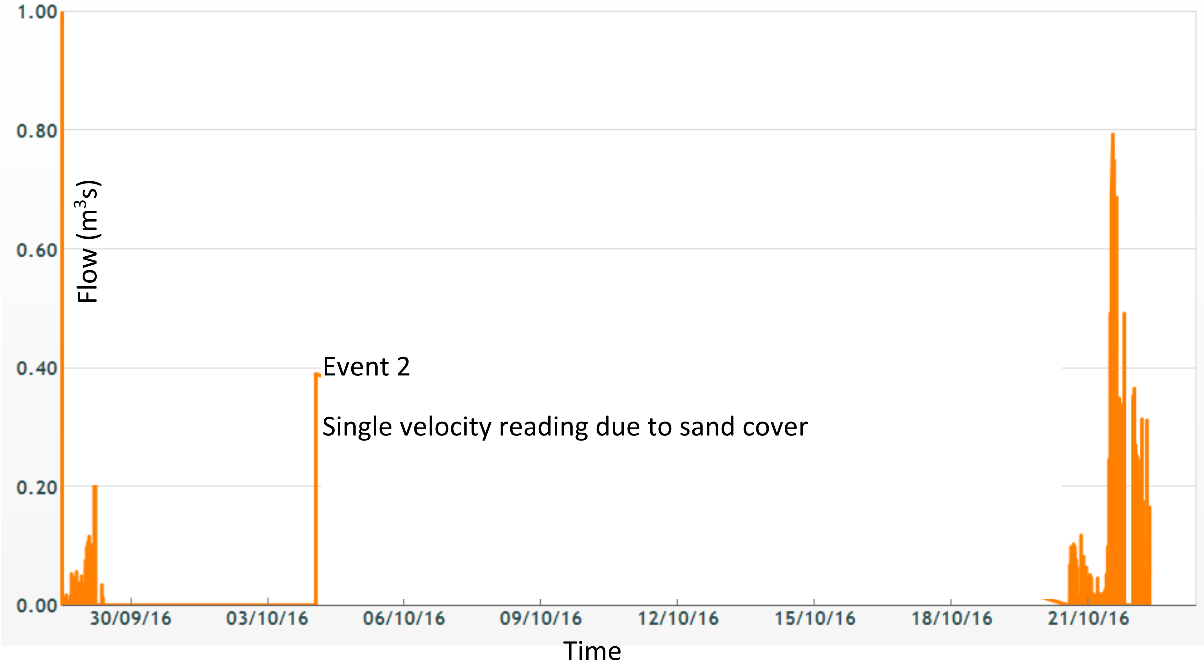

Figure 12 – Plot of flow (m^3s) at Henley over one month.

Ferrero

Storm flows from Ferrero (Hopetoun Creek) outfall drain during Event 1 had high concentrations of suspended solids between 3am and 1pm on 29/09/2016, with TSS ranging between 4.7 and 376 g/L. Corresponding rainfall peaked at 3.2mm during the run-off event. The volume of flow was much greater during the third event than the previous two events (Figure 13).

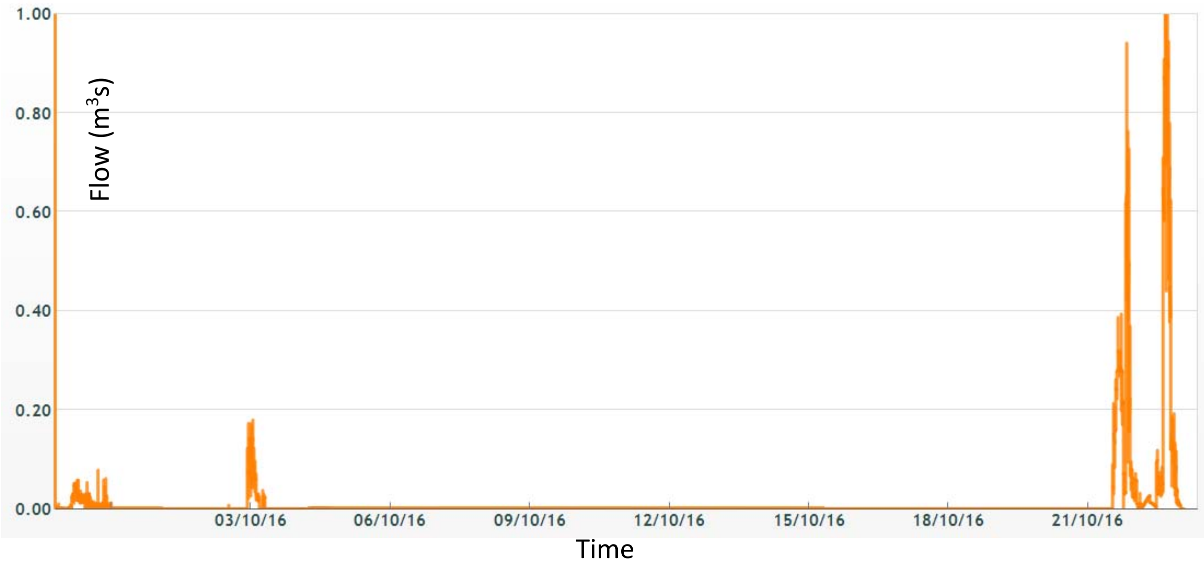

Figure 13 – Line plot of total flow (m^3s) over the month at Ferrero Reserve outfall (Hopetoun Creek).

Total suspended sediment loads

The total suspended solid loads over the three sampling events discharged approximately 14 tonnes of sediment into Balcombe Creek estuary (Table 4). The principal source of these loads was Ferrero, following by Henley, while Augusta had much lower concentrations of suspended sediments.

In terms of percentage, Augusta showed a discharge of between 2 and 11% of the suspended load compared with Ferrero over the three events. Henley had a similar suspended loads compared with Ferrero with around 87% during event 1, while the third event was only around 16%. The flow and turbidity loggers at Henley outfall become covered in sand between the first and second rainfall event, resulting in missing data for discharge volume and estimated TSS, and hence loads could not be estimated.

Table 4 – Total estimated suspended sediment load (kg) during each event based on linear interpolation. Error reported as cumulative uncertainty (±30%).

Site	Event 1	Event 2	Event 3
Augusta	4.2 ± 1.3 kg	166 ± 50 kg	263 ± 79 kg
Ferrero	178 ± 53 kg	1,528 ± 458 kg	10,114 +/- 3,034 kg
Henley	155 ± 47 kg	ND	1,664 ± 499 kg

Yields

The yield of suspended solids from each catchment and each event are presented in Table 5. The highest total yield across each of the three continuously sampled events were from Ferrero (Hopetoun Creek) catchment, followed closely by Henley Ave drain.

Table 5 – Suspended sediment yields calculated for Sep/Oct 2016 with sub-catchment areas.

Sub-Catchment	Cat. Area	Event 1	Event 2	Event 3
Augusta (DEM)	30.3	0.1	5.5	8.7
Ferrero (DEM)	204	0.9	7.5	49.6
Henley (DEM)	60.4	2.6	ND	27.6

Particle Size

Analysis of particle size showed slight differences in particle size between sites and catchments (Figure 14). Overall, Henley had slightly higher sand content that the other sites, while Ferrero had more consistent volumes of fine particles. Augusta was variable, likely dependent on incident rainfall intensity and flow rates prior to sampling. Stormwater carried coarser particles earlier in each of the flow event, likely corresponding to higher rainfall (Figure 14).

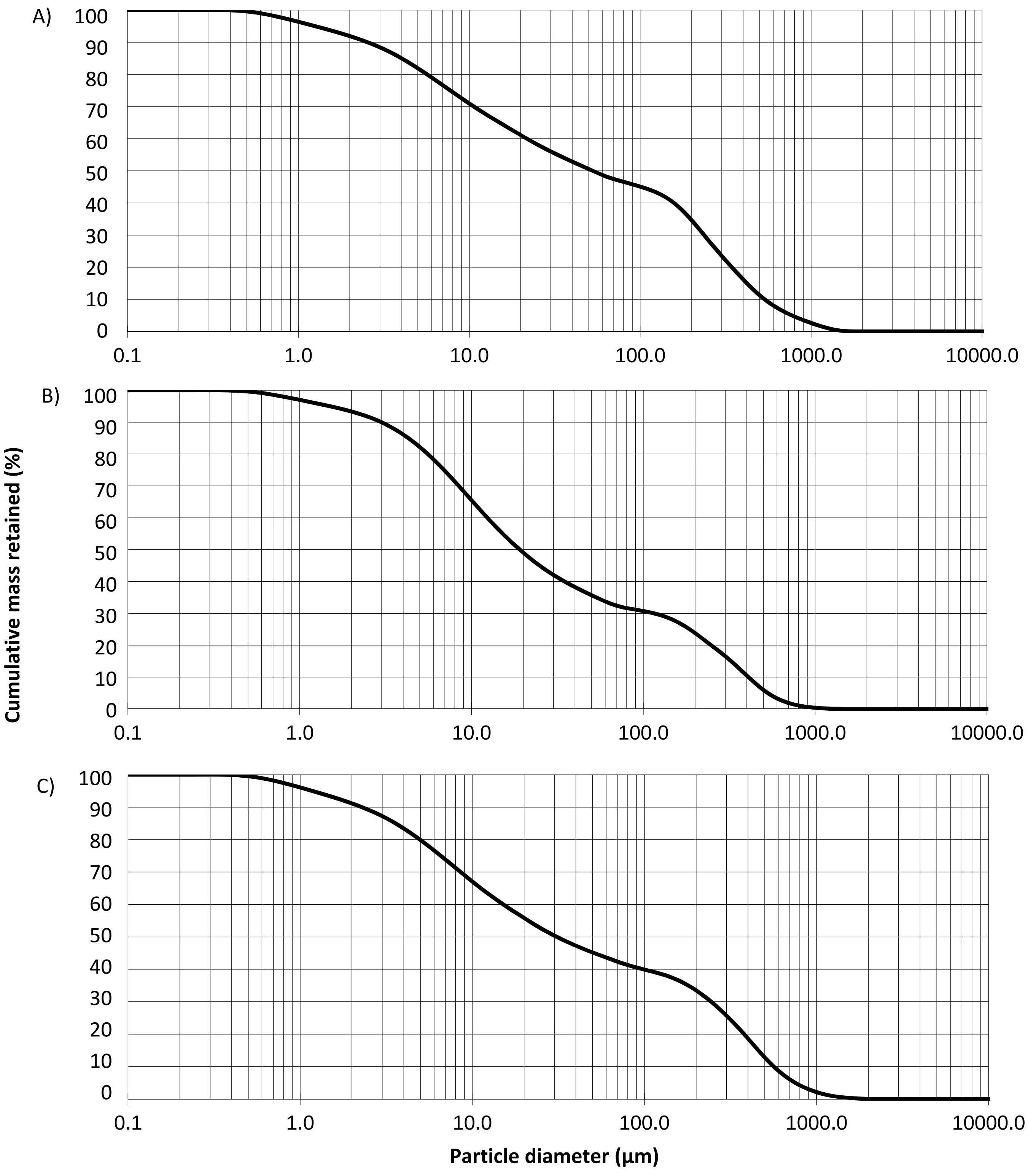

Figure 14 –Mean particle size distribution associated with suspended sediments transported during storm event samples within each sub-catchment, A) Augusta, B) Ferrero and C) Henley.

Suspended sediment samples were primarily characterised as silty sands, sandy silt and silts (Figure 15). Particles from Henley consisted of very poorly sorted very coarse silts (fine silt to coarse sand), with a geometric mean particle size of 38 µm and an average of 190 µm (n = 13). Ferrero sediment samples consisted of very poorly sorted coarse silt (corase silts to medium sands), with a geometric mean particle size of 28 µm and an average of 122 µm (*n* = 9*).* Augusta Street consisted of very poorly sorted very coarse silt (fine silts to medium sands), with a geometric mean particle size of 45 µm and an average of 193 µm (*n* = 7).

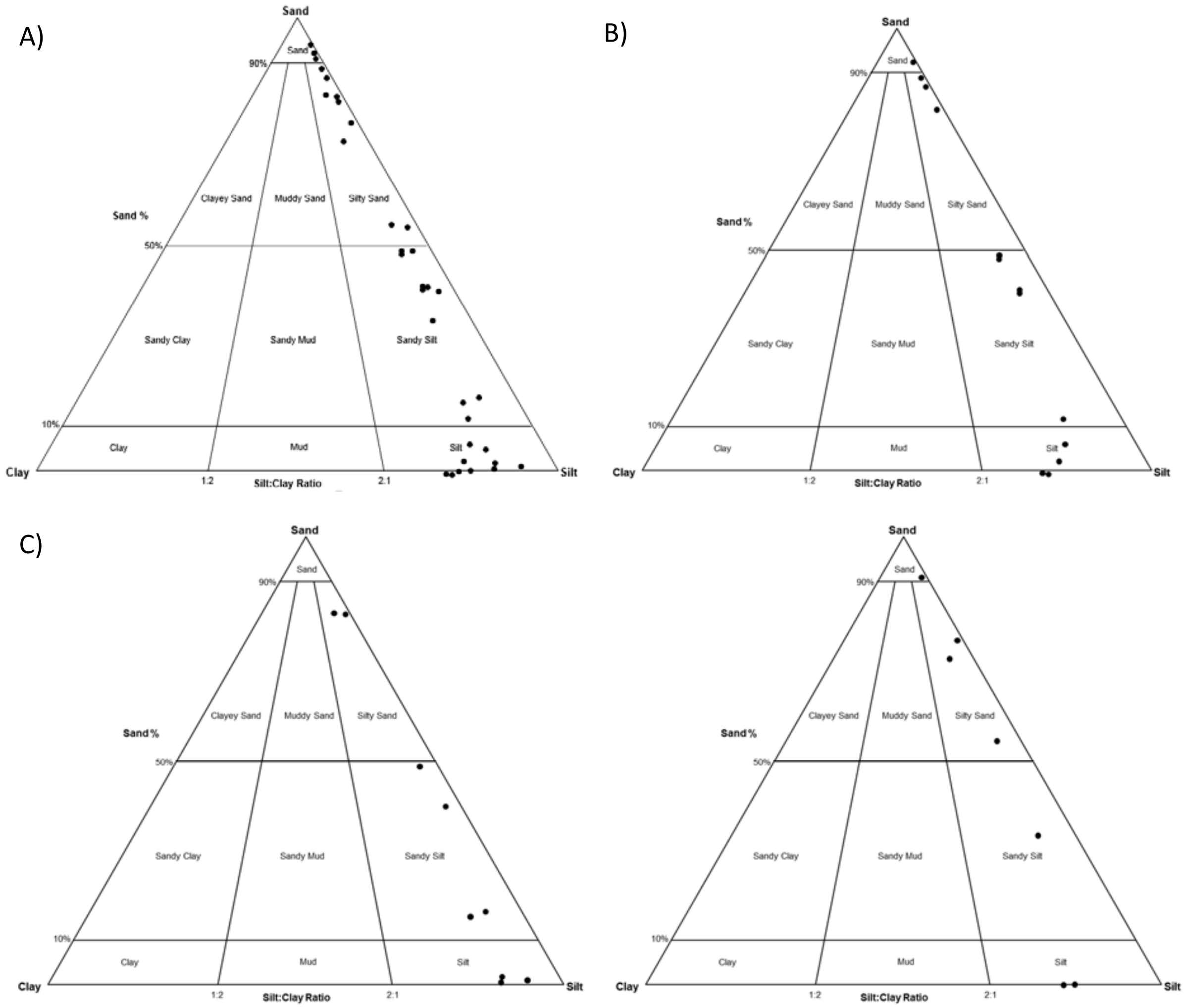

Figure 15 – Textural classification of particle size of suspended sediment samples from A) all samples from three sites, B) Henley Ave, C) Ferrero Reserve and D) Augusta St from samples collected during spot samples and from continuous sampling events (29 Sep – 22 Oct 2016).

Discussion

Suspended sediment inflows

The spot sampling approach used initially in conjunction with MPSC and BERG provided data collection over several rainfall events and allowed for quick estimates of sediment discharge to be made from each of the outfalls. Spot sample event data from monitoring with BERG was able to isolate three key catchments where inputs were consistently higher. These sites were selected for continuous sampling. The involvement of the community and council was a key factor for this initial approach. Randomised instantaneous sampling across multiple catchments assisted with prioritising further suspended loads estimates at a smaller number of sites. This involvement also provided a monitoring regime suitable for ongoing sampling, which could inform changes into the future.

The continuous sampling results showed that there were three catchments with elevated levels of suspended sediment being discharged. Continuous sampling also showed that there was substantial variation between events, with the third event containing much higher loads of sediments at both Ferrero and Augusta than in previous sampling. Comparisons between the continuous data and the instantaneous load estimates showed similar patterns, with Ferrero providing the highest loads of suspended sediments, followed closely by Henley.

Runoff and Rainfall patterns

Overall rainfall during the last event was substantial and resulting in large volumes of suspended sediment being discharges to the estuary. Both the second and third rainfall events had high rainfall volumes during certain periods which were likely to occur between 6 to 12 times each year. Therefore, annual suspended sediment loads are likely to be at least 10 times the total discharges measured over these three events. The relationship exists between suspended sediment concentration and water discharge during flood events can be highly variable, with patterns of first flush in urbanised catchments and a lag behind the peak flows in more rural and forested catchments often observed (e.g. Walling and Web, 1987, Slattery and Burt 1997). Many studies have shown that much of the sediment transported in streams and stormwater is carried during single flood events (Lenzi and Marchi 2000).

The runoff coefficients indicated around one tenth to eight tenths of the rainfall during each period which fell in the catchments flowed directly out into Balcombe Creek. There was more flow runoff from Augusta Street stormwater catchment in the second event, possibly due to antecedent rainfall and saturation of the ground leading up to this event or the overflow of wetted areas. There was substantially less flows from the Ferrero outfall compared with total rainfalls recorded in the catchment during all events, likely due to surface infiltration of vegetated and impervious areas, attenuation of flows through natural and vegetated embankments present along the creek.

Research conducted by CSIRO and BOM (2014) showed that by 2030, modelled mean annual rainfall volume was estimated to decrease up to 8%, while intensity of extreme rainfall events could increase up to 1.6%, resulting in substantially greater flooding events. Simultaneously, average annual temperatures are likely to rise by 1.3˚C and an overall decrease in rainfall levels, which are likely to increase result in higher erosion, greater potential for fires, higher evaporation rates, reduced base-flow and lower standing water levels, exposing sediments. Thus, consideration of future management of sediments takes these changes into account.

Stormwater Sub-Catchment Areas

Stormwater drainage varied within each catchment. Henley has a large stormwater drain which receives inflows from various council drains, with a Rocla CDS unit towards the bottom of the catchment, prior to being discharged directly into the lower estuary. Augusta catchment is interspersed with unsealed roads and has a mix of piped and overland runoff, prior to discharging at one of three large stormwater drains in the mid-estuary reach. The Ferrero outfall catchment largely consists of Hopetoun Creek, with interspersed catchment of bushland, residential and roads, with the last 300 m piped under Ferrero reserve, with a GPT treating water before being discharge into the upper estuary. Urban residential and roads is the predominant land use in these catchments, with drainage pipes bypassing much of the natural surface water flows, and collecting storm runoff from road culverts. Thereby, the resulting stormwater waters are directly discharged to Balcombe Creek estuary and have very limited by way of retardation prior to entering the creek.

A number of important observations were also made of these catchments during the course of this study. The most noteworthy observation was that during high-flow events in the Augusta Street catchment, a large pool of water accumulates on the south-side of the road at the base of the catchment and appears to act as a sediment basin and wetland. This acts to slow the flow of water and limit the volume, rate and timing of discharge out from the Augusta Street drain, and helps to explain the lower volumes of sediment yield being discharged from this catchment. The second important observation was following the first large flow event between the 28 September and 6 October, Henley Ave outfall and estuary channel between the existing silt jetties became clogged with silty sand, and prevented the measurement of turbidity and flow, as the sand was so dense it covered both sensors, and an increase in depth of approximately 5cm. This is despite this catchment having a GPT upstream of the outfall. Furthermore, analysis showed no apparent difference by way of any reduction in sediment volume or particle size between upstream and downstream of the GPT. By comparison, there was limited visual sediment deposition at Ferrero Reserve outfall, suggesting that the existing GPT is removing the majority of coarse particles from Hopetoun Creek catchment.

Several limitations were encountered with accurately characterising storm event flows. The outfall at Augusta Street measured during this study was the western most drain, and is one of three drains at the bottom of Augusta Street. Based on stormwater infrastructure maps, two of the stormwater drains (west and middle) appear to capture similar sized catchments, while the other (east) captures a much smaller catchment area (approximately 9.7 Ha.). As only one of the drains was monitored at any one time, a conservative approach would be to double the total sediment load estimates for this catchment, or to half the catchment area in the calculation of yields, which would result in twice the yield. However, the runoff coefficient values from the three rainfall events suggests that the volume of water discharged from the Western most drain is proportionate to the total volume of rainfall while accounting for some infiltration. Therefore, it is likely that the western most drain provides the majority of flow from this site. This data is in line with observations during rainfall events showing more turbid water and higher flows from the western drain (Appendix 3).

Relationship between suspended solids and turbidity

Due to the high-frequency of sampling required for measuring suspended sediment loads, an easier and more cost effective approach is to monitor concentrations continuously using in situ device for turbidity (Lewis 1996). Data collected from the three main stormwater monitoring sites within Balcombe Creek show a good correlation ($R^2 > 0.77$) between turbidity levels and TSS over a concentration of ranging 3 – 1,246 mg/L. The measurement of turbidity as a surrogate for TSS is much quicker and more cost effective than collection of individual water samples. Calculating loads using continuous turbidity loggers enables the reduction of uncertainty in computing load estimates compared with infrequent grab sampling. Uncertainty from spot sample estimates of sediment loads can be greater than 100% (Harmel et al 2006). Continuous turbidity logging is more cost effective than automated methods, such as discrete or composite water samples at specified intervals (time, stage or flow weighted), which also require knowledge of the expected rainfalls and resulting flows.

It is extremely important to have an accurate collection between turbidity and measured TSS in order to use turbidity as a surrogate for calculating suspended sediment loads (cf. Lewis 1996). Differences in particle size can affect the turbidity–concentration relationship. Initially, all data were combined to provide a correlation of TSS versus turbidity for estimating loads. However, on further review of the data, catchment specific differences in particle size characteristics and flow evidently were unaccounted and caused substantial inter-catchment variation. It has been shown than turbidity meters respond linearly to sediments from a particular grain size distribution, as well as particle shape and composition, and are more sensitive to fine clay and silt particles than they are to sand (Lewis 1996, Gippel 1995). Therefore, improvements were made by correlating turbidity and TSS for each specific sub-sets of the data (i.e. sub-catchment) to determine the site specific nature of inflows and flow conditions. Logging turbidity during stormwater events should utilise a turbidity meter capable of logging up to 2000 NTU or above to capture exceedingly high turbidity levels.

Best practice and optimisation of monitoring suspended sediments using turbidity requires that data is collected over varying conditions such as variances with rainfall intensity, total and duration, soil moisture levels and antecedent period without rainfall (Gippel 1995, Grayson, Finlayson et al. 1996, Daphne, Utomo et al. 2011). Calibration of turbidity versus TSS was extensively sampled over multiple events and on a site-specific basis to reduce errors and uncertainty in the measurements. Given the importance and focus of accurate estimates of sediment loads, and increased uncertainty from less frequent grab sampling estimates, using turbidity loggers for future sampling is a simple approach for future monitoring of Balcombe Creek. Lewis (1996) found that around 75% of the sediment load was delivered after the turbidity peak, such that the importance of logging intervals both before and after the peak flow should be captured for accurate estimation of loads.

Sediment Particle Transport

Significant variation in loads and particle size of suspended sediment was shown from the data. Sediment particle size is influenced by catchment properties such as soils, roads and land use activities, as well as hydrological variables including water discharge, variation in rainfall intensity, volume and flow patterns and will vary between each rainfall event (Sansalone et al 1998). Particle size from Augusta tended to be slightly coarser than the higher volumes of finer particles from Henley Ave and Ferrero Reserve. Studies have shown that suspended sediment particles from urban stormwater run-off tends to be relatively fine from urban roads (e.g. Walker et al, 1999) and unsealed roads (Lane and Sheridan, 2002). Similarly, while there are many unsealend roads in Mt Martha, the suspended sediments measured in this study contain primarily fine silts to medium sands, while large proportions of coarser sands and gravels are likely transported as bed-load.

The types of particles entering the estuary can have a strong indication of the likely deposition and associated impacts. Coarse sands and gravels from road-base will quickly fall out of the water column once flows dissipate with mixing into slower parts of the upper or lower estuary. While there can be some first flush with higher loads of sediments from within urban areas, the unsealed roads which are present in the sub-catchments surrounding Balcombe Creek estuary are likely to deliver higher loads and coarser particles with increased rainfall intensity and volumes and subsequently higher water discharge rates and greater mobilisation (cf. Lenzi and Marchi 2000). Some of the suspended sediment particles in samples were primarily fine grained silts and clays, which will continue to remain in suspension even in very low flows and can be transported long distances until flow velocities reduce, such as in the estuary.

Difference in the impacts of sediments are liely for aquatic biota. Fine silts and clay particles are able to bind higher concentrations of chemicals due to their higher specific surface areas relative to size. Finer grained particles are also transported more easily longer distances and are likely to accumulate only once flows recede, such as in the estuary. Meanwhile, coarse sediments are likely to increase channel aggradation and accretion rates, settling adjacent to their inputs and reducing water depths and flows (Nelson and Booth 2002).

The majority of particles flowing from the three drains consist of fine silts to medium sands. These particles are unlikely to be removed by standard GPTs. Henley Ave has an existing GPTs which appears to be inaffective, likely due to clogging from high loads of coarse sediments, which would require frequent and costly maintenance after each storm event to ensure it is functioning. Hopetoun Creek catchment is three to six times larger than Henley or Augusta. Suspended sediments from Ferrero Reserve are generally finer than Henley Ave, which tends to have a higher proportion of sand content. Options for reducing the loads of these include swales, disconnecting urban runoff through integrated infiltration systems. Construction of a sediment pond is likely to require a much greater area of land and higher costs. The suitability of the area for these treatment options and their respective maintenance requirements should be considered as part of a cost benefit approach.

While Hopetoun Creek contributes the highest sediment load to the upper estuary, in terms of yield, this catchment contributes similar volumes of sediment per square meter to Henley Ave catchment. Furthermore, sediments from Ferrero are predominately fine particles, and are likely to flow in suspension to the lower estuary and discharge during high flows when the estuary mouth is open. Meanwhile, Henley Ave continues to input medium to coarse silts and sands directly into the lower estuary. Both catchments will remain as key sources until further treatment within the catchments, such as revegetation, removing direct stormwater flows by vegetated swales or additional stormwater infrastructure such as sediment ponds.

Average settling rates for fine silts (3 to 20 µm) can be 0.1 m per hour, while for medium to coarse sand particles (>250 µm) it can be greater than 1m per minute (Lawrence and Breen 1998). In flowing water, these fine sediments will likely have been transported to the estuary zone, and deposit once flows recede. Particles larger than gravels, as well as aggregates and coarse sands will flow down the catchment and deposit into the creek and estuary in bed-load transport, as their weight it too heavy to keep them in suspension. Samples collected from stormwaters using grab samples, autosampler or turbditiy logger are unlikely to provide a measure of bed-loads. However, there can be large variation in size distributions and fall velocities between sites and storm events, such as those from urban studies across Melbourne (Lloyd et al, 1998; Lloyd and Wong, 1999). It is likely that medium to coarse sands will deposit directly downstream of outfalls, and will be transported in the bed-load during high flows following storms. Suspended particle residence times are likely to be very short, given that the velocity estuarine waters was typically less than <0.1 m/s when measured during spot sampling surveys.

Sediment transport beyond the mouths of these stormwater outlets is beyond the scope of this study and would involve more complex data collection and modelling processes to understand the flow and velocity of Balcombe Creek and estuary during peak flows and examine the fate and behaviour of sediment discharge downstream. The flows and sediment loads from this catchment has not been compared with total discharge volumes of fine sediments entering the estuary. The catchment loads of fine suspended particles may be relatively high. The proportion of suspended sediment to total sediment load can be highly variable, and has been reported to range from 20% to 90% for upland rivers and from 70 to 95% for lowland rivers based on a number of published studies (Lenzi and Marchi 2000, Billi et al 1998, Walling and Webb 1987). The relationship between suspended versus bed-load sediment delivery is of great importance, and would indicate the total volume of sediment load. The grain size of sediments in the estuary trapped downstream of each inlet can indicate the dominant particles and respective loads being deposited from the catchment, and also help identify properties of sediments contributing the greatest total volume, as well as associated contaminants bound to sediment particles. Additional spatial assessment of surface sediments, their particle size and associated bound contaminant residues would help to further discriminate catchment inputs.

Stormwater management infrastructure

Melbourne Water is generally responsible for the installation and maintenance of stormwater drainage systems for catchments greater than 60 hectares, while Council is responsible for assets with smaller catchments. Information collected by Council and Melbourne Water on sediment management is important to assess the performance of systems such as GPTs, street sweeping, in addition to the influence of regrading unsealed roads and new developments. Both council and Melbourne Water have invested in a number of existing stormwater treatment systems to reduce the volumes of litter, sediments and other pollutants which would otherwise impact on the quality of receiving water and sediments.

The types of infrastructure that could be considered for future management include constructions of vegetated swales, integrated infiltration systems, stormwater treatment and harvesting, street tree irrigation, permeable paving, road surface sprays, road sealing, sediment ponds and upgraded GPTs. Mornington Peninsula Shire Council have completed an evaluation and priority process to address the capacity building opportunities. This is supported by earlier work from Water Technologies (2010) who proposed various Water Sensitive Urban Design (WSUD) treatment options across the catchment for stormwater infrastructure using modelling to estimate sediment and nutrient loads from three catchments (Henley, Latrobe and Augusta), providing an evalution of the costs and treatment potential.

While urbanisation may reduce erosion rates from some surfaces, through sealing of roads and parking areas, it can also increase channel erosion further downstream and increase the severity and frequency of high flows (Nelson and Booth 2002). Roads can contribute up to 70% of the total impervious area in an urban catchment, leading to increased volumes of stormwater to manage and/or treat (VicRoads, 2013). The majority of the roads in the Henley Ave catchment are already sealed, and are likely contributing smaller volumes of sediment from the catchment, while increasing flow rates downstream. The Augusta Street catchment relatively steep, and sealing roads would also require substantial flow reduction systems, as high flow volumes would otherwise be likely to cause scouring and impacts further downstream or changes at the outfall. A natural accumulation of water, acting as a sediment wetland, was observed in the Augusta Street catchment. This served to reduce the volume and timing of stormwater run-off and sediment delivery to the creek (see photo, Apppendix 1).

Existing stormwater treatment infrastructure is limited to a Rocla CDS GPT at the bottom of the Henley catchment. The quoted performance of these units suggest they can retain up to 95% of particles >215 um (Rocla CDS, 2017). However, capacity for sediment retention relies on the treatment chamber being clean. Otherwise, they are susceptible to re-suspension and loss (Rocla CDS, 2017). Working limitations of these devices can include site hydraulics, velocity impact, tidal or backward levels and overdue maintenance (Rocla 2017). The particle size information and suspended concentration data from this site would suggest this unit was clogged and not working during the period of the instantaneous spot sampling, likely due to the chamber being full and high-flows bypassing treatment. The size, maintenance and condition of this asset and its capacity for removing sediment loads from this catchment should be reviewed in line with the benefits and associated costs and time involved to make changes. Data from Council and Melbourne Water managed stormwater assets can provide a useful measure of the sediment loads, timing and frequency required to properly maintaining these devices.

Further opportunities for installing stormwater treatment measures should be identified and optimised by combining estimates of flow with measurement of pollutant concentrations. In particularly, the volume, timing and velocity of stormwater entering waterways should be managed to minimise adverse impacts on receiving waters (e.g. Balcombe Creek estuary, Port Philip Bay Phillip Bay), and reduced loss of bank stability, changes to flow regimes and loss of in-stream aquatic flora and fauna. Essentially, these devices should attempt to mimic the riparian vegetation, stream channel meanders, dissipating flow and increasing the transit time to allow a reduction in the velocity and timing of sediment and flows directly draining to the estuary. Options for reducing suspended sediment include decentralised water sensitive urban design, vegetated swales, sediment pond and wetlands and surfacing of roads. While sealing roads would reduce the available volume of direct sediment run-off, higher flow rates would also result, requiring additional treatment to limit erosion and discharge of pollutants further downstream.

Urban pollution

In addition to sediments, gross litter and contaminants bound to the surface of particles are washed from catchments and can impact the estuarine ecosystem. Objectives from the Urban Stormwater Best Practice Environmental Management Guidelines contain environmental stormwater standards, focusing on reducing mean annual loads of stormwater pollutants (Victorian Stormwater Committee, 1999). Decreasing the volume of sediment is important to protect receiving waterways in Balcombe Creek, however, the impact from other stressors should be considered.

Urbanisation has a major impact on run-off, resulting in significant increase in both the volume and peak discharges of stormwater events, which are primarily due to the land use, slope and relative density of impervious surfaces within catchments (Engineers Australia 2006). While the loads of sediment were the focus of this study, the types of pollutants bound to sediments from urban stormwater include gross pollutants, metals, hydrocarbons, pesticides and micro-organisms from surfaces, roads, household products and pets (NRMMC-EPHC 2006).

Correlations between imperviousness, drainage connection and other catchment can be highly correlated with the total loads (e.g. Hatt et al 2004), however they may not clearly indicate the resulting concentrations of suspended sediments. For concentrations of pollution in sediments, however, it has been shown that the types of land use within catchments (e.g. industrial, rural residential) can highly influence the resulting sediment quality in receiving waterways (Marshal et al 2016, Sharley et al 2017).

Sediment quality monitoring for Melbourne Water at Balcombe estuary and creek has shown concentration of metals have remained relatively stable over the past seven years (Sharp and Sharley 2015, Sharley and Sharp 2017). Trace residues of pesticides have been detected on occasion, likely resulting from spraying to control termites using synthetic pyrethroid insecticides. These contaminants may further impact on the ecosystem health by sub-lethal or direct toxicity to invertebrates. Earlier studies conducted by CAPIM were unable to determine any major source within sub-catchments, where higher concentrations of insecticides occurred (CAPIM, unpublished data). Concentrations of heavy metals measured in surface sediments in 2017 were below the trigger values of sediment quality guidelines, suggesting metal contamination is unlikely to cause toxicity to benthic organisms. However, certain contaminants in sediments such as zinc and petroleum hydrocarbons may exceed clean-fill guidelines for disposal and this should be considered in future decisions for sediment management if sediment ponds are considered.

Furthermore, a large amount of gross litter was observed in the estuary during this study, particularly with prevailing westerly winds and high water levels washing debris up to the silt jetties enclosing Henley Ave stormwater outfall (Appendix F.10). The amount of debris suggests there are urban stormwaters entering the estuary without preventative controls such as gross pollutant traps (e.g. Mirang Ave, Appendix F.8), or substantial litter from other soruces. Some of the litter entering the estuary is likely to be trapped in sediments, while the remainder could be washed to the bay, presenting a potential for ingestion, entrapment of wildlife and accumulation of waste. Reducing sources of gross pollutants should be targeted to improve the condition of Balcombe Creek estuary.

Limitations and Uncertainties

Uncertainties due to data collection in pollutant and flow data have been previously reported in the literature, with possible cumulative uncertainty in the range of 18 to 53% when applied to the prediction of loads using similar methods (De Silva 2003; Harmel et al 2006). The cumulative uncertainty from this study was limited by the use of a strong correlation between turbidity and TSS, which reduced the time-step for collecting data (2 min), and hence the variability over the total flow event is captured at a higher resolution. With reference to the observed flow, the noise in the velocity data and backflows from estuarine inflows may have limited the accuracy of some of the measurements. The difficulty with logging flow at one site was highlighted at Henley outfall where the logger become covered in sand between the first and second logged rainfall events. Furthermore, the infilling of the estuary between events 1 and 2 at all sites may have also contributed to a reduced level of precision, with velocity readings close to the limit of measurement, caused by some backflow, flow retardation and the potential for some stratification. Therefore, the overall estimated uncertainty for sediment loads was approximated to be 30% in light of these observations.

Conclusions

This study found high concentrations of sediments were discharged from three sub-catchments to Balcombe Creek estuary during high rainfall events.

The instantaneous loads estimates showed:

- Suspended sediment discharged ranged between 0.2 to 684 grams per second
- Hopetoun Creek (sub-catchment Ferrero) recorded the highest discharge with 684 grams per second
- Uralla measured the lowest overall discharge from all events, ranging 0.3 to 2 grams per second over the four events, and is an unlikely source of large volumes of sediment
- Mirang was generally lower than Ferrero, Henley and Augusta, except for one event with 56 grams per second of suspended sediment, while otherwise ranged from 2 to 19 grams per second
- Loads from Augusta (West) outfall were the third highest, and ranged between 10 and 39 grams per second over three events

Based on the estimated total loads and yields of suspended solids from the three sub-catchments during 28 Sep – 23 Oct, with rainfalls ranging from 3.2mm to 21.2mm, it was shown that:

- Around 14 tonnes of suspended sediments were discharged into Balcombe Creek estuary
- Hopetoun Creek (sub-catchment Ferrero), with a catchment area of 204 Hectares, representing around 70% of the total monitored area, generated the highest suspended sediment load and had the highest yield of sediment per square metre
- The lowest estimated loads and yield of sediment per square metre were from Augusta

Following this investigation of flow monitoring and event data over a three week period, there are several key recommendations:

- Sediment management for Balcombe Creek estuary should be prioritised based on the findings of suspended sediment loads and yields
    - Henley Ave should be investigated as a priority site and sub-catchment:
        - Large volumes of sands and silts flow directly into the estuary at this site;
        - The existing GPT should be reviewed;
        - Bed-load transport should be estimated,
        - Further treatment options should be reviewed and prioritised.
    - Hopetoun Creek (Ferrero Reserve) should be investigated for stormwater treatment such as revegetation and construction of vegetation swales
    - Augusta Street catchment is considered a lower priority, however estimating bed-load transport may indicate a need for improvements in stormwater treatment
- Water and sediment quality montiroing should continue and transport of sediments in bed-load and other pollutants including gross litter and heavy metals should be considered as part of future monitoring to improve the environment and amenity for the estuary.
- It is important to address stormwater improvements, either through changes in the catchment, additional treatment, and/or slowing water flows before entering the estuary to protect Balcombe Creek, with the key catchments of concern being Henley and Ferrero.

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Appendix 1 – Sampling locations

Sub-Catchment Photos

Appendix F.2 - Henley Ave stormwater outfall at the start of logging and during inundation of the estuary (5 Oct 16) following high rainfall events.

Appendix F.3 - Ferrero Reserve (Hopetoun Ck) outfall (left) and draining to Balcombe estuary (right).

Appendix F.4 - Augusta Street stormwater outfalls during heavy rain event (5 July 2016).

Appendix F.5 – Natural wetland downstream on southern side of Augusta Street and water from inflowing channel during high rainfall event (19 Aug 16).

Appendix F.6 - Mirang Ave stormwater outfall during heavy rain event (5 July 2016).

Appendix F.7 - Balcombe Creek estuary facing east (upstream), and west towards Port Phillip Bay, standing from sediment quality sampling site.

Appendix F.8 – Uralla Drive outfall (left), and overflow channel draining to Balcombe Creek (right).

Appendix F.9 – Henley Ave outfall channel blocked up with sand between the silt jetties

Appendix F.10 – Gross pollution accumulated on Henley Ave silt jetty, Balcombe Estuary west-facing

Appendix 2 – Detailed Methodology

Rainfall

Rainfall measurements were provided by Melbourne Water and derived from the closest pluviograph (tipping electronic rain gauges), which is located at Devil Bend Reservoir [Station ID: 586206; -38.2769, 145.1] (Melbourne Water, 2016), which lies 6.7 km to the east of Mt Martha. The rain gauge readings were in 6-minute intervals with recordings in 0.2mm tips.

Ideally, local rainfall should be sourced within 2 km from the sampling sites to provide high accurate estimates of rainfall totals, intensity and timing (Maheepala et al. 2001). However, only one rain gauge was available within close proximity to the catchment.

Small spatio-temporal variations in the volume and timing of rainfall across the area were considered by calculating rainfall totals from other sites within proximity to the sampling location using the inverse distanced weighted squared method (Ladson 2008; Li & Heap 2008)

The inverse distance weighted (IDW) method estimates values of an attribute (i.e. rainfall) at an un-sampled point using values at sampled points weighted by an inverse function of the distance from the point of interest to the sampled points. This method assumes that measurements closer to the un-sampled site are more similar than those farther away. The unknown rainfall at point R_0 can be found using the following equations:

Equation (1) $$R_0 = \sum_{i=1}^{N} \lambda i \, Ri$$

Equation (2) $$\lambda i = \frac{1/di^P}{\sum_{i=1}^{N} 1/di^P}$$

where:

di = the distance between the site and each rainfall station,

P = a power parameter (see below), and,

n = number of rainfall stations used in the estimation.

Power is general assumed as 2 and the resulting method is often called inverse square distance or inverse distance squared (IDS) (Zhu & Jia 2004; Li & Heap 2008; Lin & Yu 2008).

Correlation was conducted to compare the strength of associations between a local rainfall gauge with a limited data set from 2015 at hourly and daily time-steps (Ferrero Reserve, Mornington Peninsula Shire Council). Adjustments were made for the power (between 0.1 and 5). Results indicated a poor correlation ($R^2 < 0.5$) between the derived IDW rainfall estimates (using all suitable power variables) and daily data from Ferrero, while a better relationship ($R^2 > 0.6$) was shown between Devil Bend rainfall gauge and Ferrero Reserve. Therefore, Devil Bend was used as the primary rainfall gauge.

Flow measurement

Three ISCO low-profile Acoustic Doppler Current Profilers (ADCPs) were deployed at the outfalls from each of the main stormwater drains to be investigated. These were programmed to log water depth, water velocity and calculated water flow rates at one minute intervals. Data was downloaded at the conclusion of the sampling.

The flow meters can measure water depth down to 1 - 2 cm, however they can be inaccurate at very low levels. Velocity measurements of less than 0.01m/s are not recorded, and at low water depths the Doppler shift may not be submerged and therefore no reading was taken in some instances at lower flows. The device is able to measure velocity over the range of 0.01 – 6.1 m/s, with a reported accuracy of ±2% of reading, while published research indicates typcailly uncertainity ranging between 2- 20% for discharge calculated from flow by area (e.g. harmel et al 2006). The minimum reported depth at which the pressure sensors can operate is 2 cm, however, operationally it is likely to be closer to 3 – 3.5 cm for accuarate results.

The logging interval chosen was 1 minute for detection of pulse events and then data was aggregated to 6 minute averages to coincide with rainfall and turbidity logging intervals. The pressure sensor was zeroed or calibrated against the current water depth to the nearest millimetre using a steel ruler prior to installation and logging at each site. Sensor adjustment was made by checking the water height and entering this using the proprietary software. Several additional measurements of water level were made during the course of the investigation.

At Ferrero (Hopetoun Creek) the minimum depth to be able to measure velocity was between 0.037 and 0.044 m, which was prior to or after flow events. At these levels, several outliers were detected and removed from the data prior to analysis. For total discharge at Ferrero and Henley outfall drains, flow rating curves were derived from accurate discharge data as in both instances errors were observed in the logging data later during events due to disturbance of the ADCP and/or sedimentation. The accurate flow rating curves were used for error checking of the data.

Rainfall Run-off Coefficient

To examine that volume of rainfall to total flow for each event, and exclude events relating to other sources of discharge or equipment malfunction, the rainfall-runoff coefficient was calculated using:

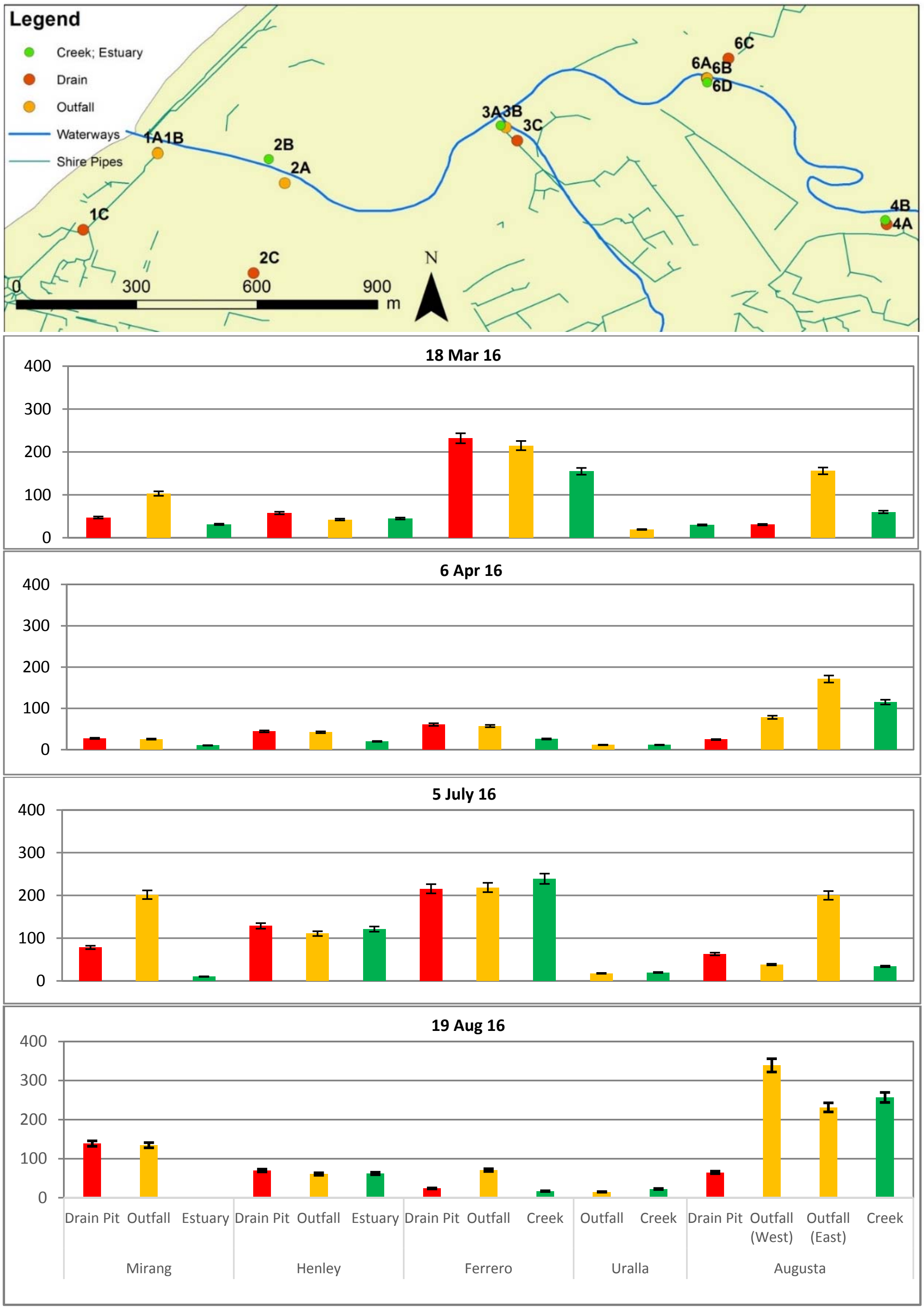
Equation 1

$$rc = \frac{v}{r \, \mathrm{X} \, \mathrm{A}}$$

Where rc is the run-off coefficient, r is the rainfall (m), A is the catchment area (m2) and v is the total runoff volume (m^3). A coefficient >1 would indicate more flow than suggested by rainfall, however, it could also indicate that the observed rainfall data inadequately describes local rainfall patterns (Devil Bend ~5km) (Mahepala 2001). Possible causes of higher *rc* include rainfall events with high spatial variability, such as thunderstorms which affect different areas of the catchment, while lower *rc* values could result from infiltration, stormwater retardation or lower rainfalls at areas of the catchment.

Measurement of water quality

Instantaneous Turbidity Measurements

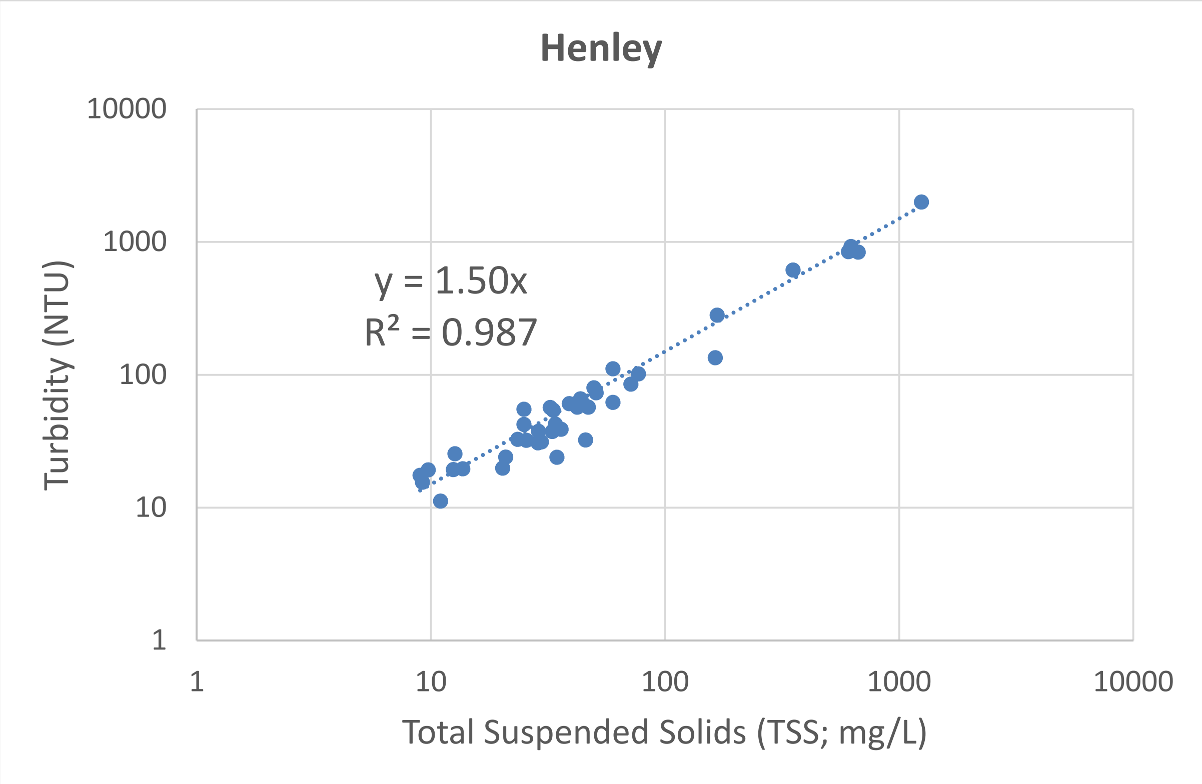


A.1 – F.1 – Map and plots of spot turbidity (NTU) measurements from four events. Mean ± S.E.

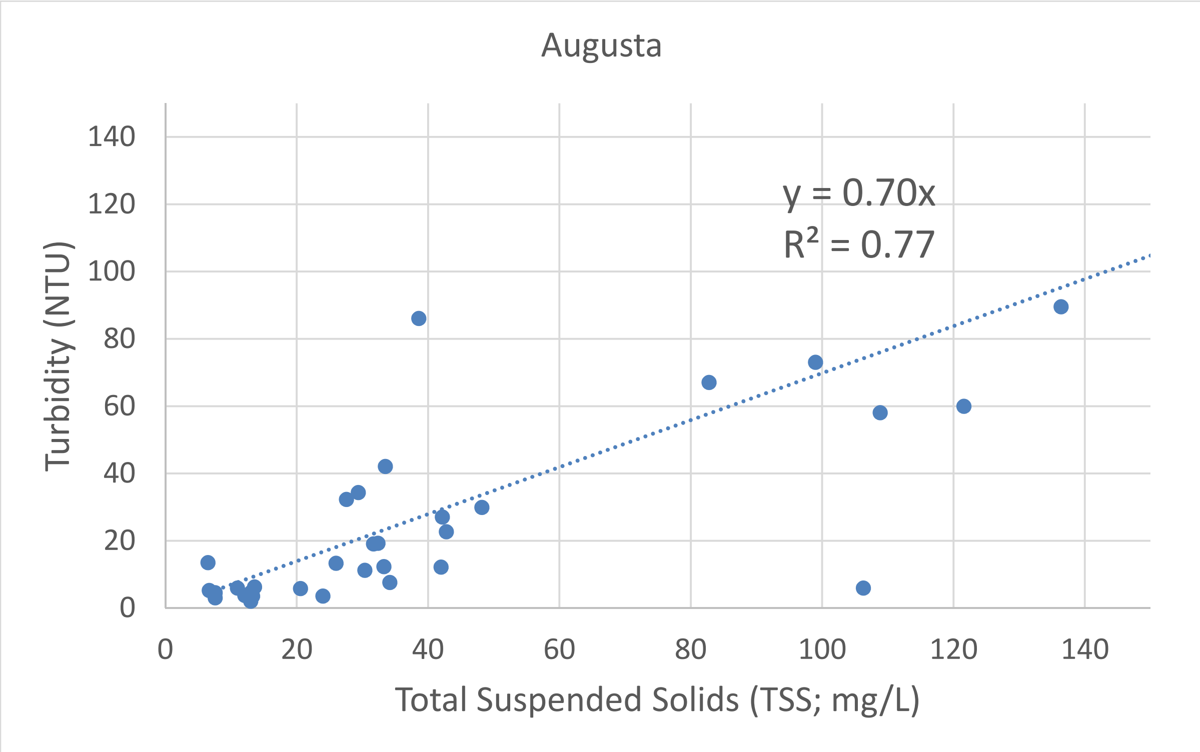
Correlation of Turbidity with Suspended Sediments

Parameters monitored as part of the program were total suspended solids (TSS) (discrete or composite time-based sampling). Turbidity, conductivity, temperature and pH were also recorded at two-minute intervals using a HANNA HI9829 multi-parameter logger. Samples for TSS were analysed using standard laboratory techniques for total suspended solids (APHA 2564-D) by gravimetry. The detection level was <1 mg/L. Precision was assessed by measurement of duplicates, accuracy was assessed by spike recovery, and reporting limits were determined by measurement of blanks, with 1 quality sample analysed in every batch of 10 samples.

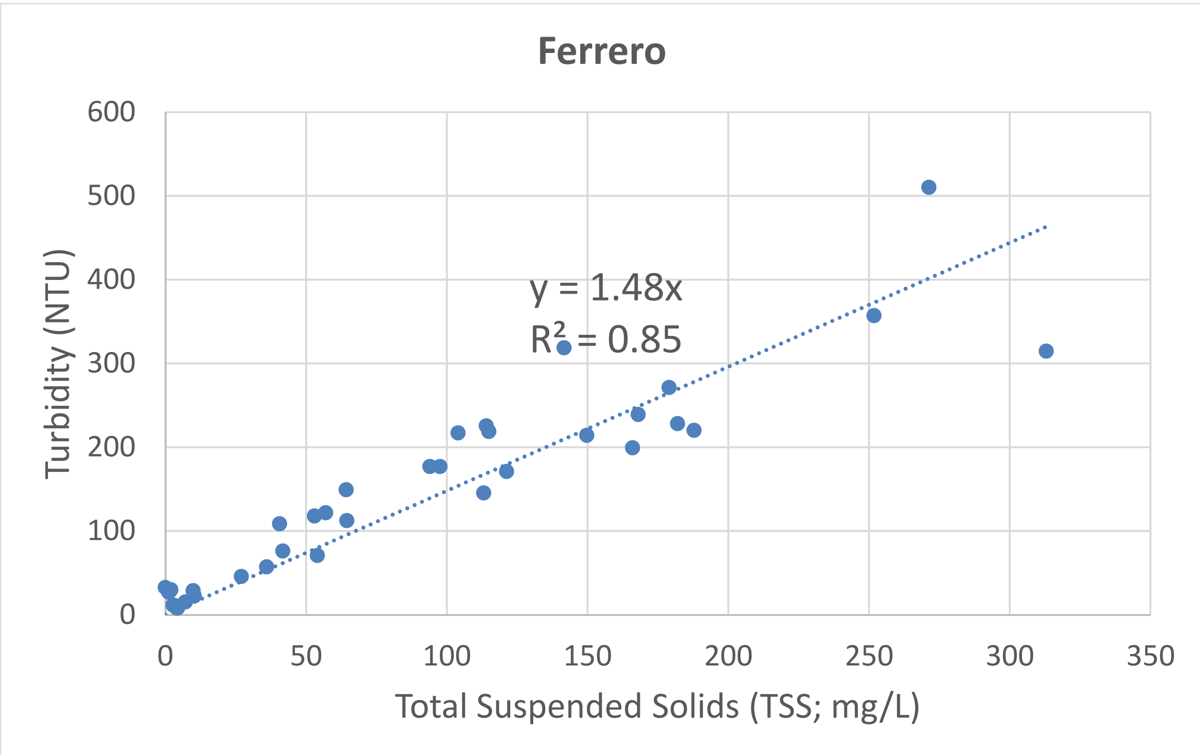
The turbidity readings were calibrated against TSS concentrations for each site and exhibited high correlations. Regressions were determined using SPSS (version 24) and outliers were retained. Uncertainity in the models was deteremined from the standard errors of the slope.



A.2 – Figure 1 – Regression of suspended sediment and turbidity for Henley Ave (*P* < 0.001, df = 1,39, SE_b = 0.03, *u=3.6%*).



A.2 – Figure 2 – Regression of suspended sediment and turbidity for Augusta Street ($P < 0.001$, df = 1,37, $SE_b = 0.1$, u=18%).



A.2 – Figure 2 – Regression of suspended sediment and turbidity for Ferrero Reserve ($P < 0.001$, df = 1,37, $SE_b = 0.09$, *u=13%*).

Appendix 3 – Loads estimation summary data

Spot Samples

A.3 – Table 1 – Instantaneous flow and total suspended sediment (TSS) loads for all sub-catchments measured on four separate random grab sample events. Probable Error (±30%). See below.

Catchment	Asset	Date	Depth (cm)	Velocity (ft/s)	Diameter (cm)	Flow (m^3s)	TSS (mg/L)	Discharge (g/s)
Mirang	Outfall	18/03/2016	22	1	62	0.315	43	14 ± 4
Mirang	Outfall	6/04/2016	15	0.6	62	0.111	19	2.1 ± 0.6
Mirang	Outfall	5/07/2016	20	0.6	62	0.166	*34*	5.6 ± 1.7
Mirang	Outfall	19/08/2016	35	0.9	62	0.518	109	57± 17
Henley	Outfall	18/03/2016	20	7.3	87	0.247	34	84 ± 25
Henley	Outfall	6/04/2016	11	0.6	87	0.086	25	2.2 ± 0.7
Henley	Outfall	5/07/2016	10	4.4	87	0.547	60	33 ± 10
Henley	Outfall	19/08/2016	32	0.8	87	0.520	39	20 ± 6
Ferrero	Outfall	18/03/2016	22	9.7	75	3.436	199	684 ± 205
Ferrero	Outfall	6/04/2016	13	5.7	75	0.957	36	35 ± 11
Ferrero	Outfall	5/07/2016	15	7.3	75	1.505	168	253 ± 76
Ferrero	Outfall	19/08/2016	4.5	3.4	75	0.121	54	6.5 ± 2
Uralla	Drain Pit	18/03/2016	41	0.1	*90*	0.093	22	2.0 ± 0.6
Uralla	Drain Pit	6/04/2016	37	0.05	*90*	0.040	8	0.3 ± 0.1
Uralla	Drain Pit	5/07/2016	27	0.05	*90*	0.026	8	0.2 ± 0.1
Uralla	Drain Pit	19/08/2016	32	0.3	*90*	0.199	4	0.8 ± 0.2
Augusta	Outfall (East)	18/03/2016	5	0.05	110	0.003	83	0.2 ± 0.1
Augusta	Outfall (East)	6/04/2016	5	0.1	110	0.005	62	0.3 ± 0.1
Augusta	Outfall (East)	5/07/2016	4	0.05	110	0.002	*27*	0.05 ± 0.0
Augusta	Outfall (East)	19/08/2016	46	*0.05*	110	0.062	179	11 ± 3
Augusta	Outfall (west)	18/03/2016	ND	ND	110	ND	ND	ND
Augusta	Outfall (west)	6/04/2016	15	0.8	110	0.204	89	18 ± 5
Augusta	Outfall (west)	5/07/2016	18	0.4	110	0.133	75	10 ± 3
Augusta	Outfall (west)	19/08/2016	6	2.3	110	0.152	253	39 ± 12

Continuous Sampling

Loads estimates were based on the software in the Water Quality Analyser (version 2.1.2.4) (eWater, 2011). The choice to use linear regression as the method for estimating loads was based on a decision tree to assess the optimal techniques based on the available data in the program. Notwithstanding this, the Beale Ratio method was also suggested, and provided similar results, but is preferred where data are only collected on one side of the hydrograph.

A.3 – Table 2 - Total estimated loads over the three events using several methods. Error is reported as cumulative measurement of uncertainty (±30%). See below.

	Units kilograms			
	Parameter	**Event 1**	**Event 2**	**Event 3**
Augusta	Total flow	393.23 m^3	2525.982 m^3	2469.414 m^3
	Start date	28/09/2016 7:09	2/10/2016 11:27	20/10/2016 4:51
	End date	30/09/2016 12:55	3/10/2016 9:15	22/10/2016 9:03
	Time span	1d, 5h, 46min	1d, 9h, 48min	1d, 16h, 12min
	Loads Beale Ratio	14.5 +/- 4.3 kg	166 +/- 50 kg	263 +/- 79 kg
	Loads Linear Interpolation	**4.2 ±1.3 kg**	**165.9 ±49.8 kg**	**263 ±79 kg**
	EMC Beale Ratio	36.851 mg/L	65.884 mg/L	106.6 mg/L
	*EMC Flow * Concentration*	*6.343 mg/L*	*22.255 mg/L*	*45.2 mg/L*
	EMC Linear Interpolation	10.7 mg/L	65.7 mg/L	106.4 mg/L
Ferrero	Total flow	640 m^3	2857 m^3	9731 m^3
	Start date	29/09/2016 1:15	2/10/2016 19:27	21/10/2016 13:22
	End date	30/09/2016 9:21	4/10/2016 5:45	22/10/2016 9:01
	Time span	20h, 6min	1d, 10 h, 18 min	1d, 18 h, 30min
	Loads Beale Ratio	178 ±53 kg	3,568 +/- 1070 kg	11,256 ± 3,377
	Loads Linear Interpolation	**178 ±53 kg**	**1,528 +/- 458 kg**	**10,114 ± 3,034 kg**
	EMC Beale Ratio	263 mg/L	1,249 mg/L	NaN mg/L
	EMC Linear Interpolation	**263 mg/L**	535 mg/L	**1,003 mg/L**
Henley	Total flow	513.9 m^3	ND	6420.78 m^3
	Start date	28/09/2016 11:59	ND	21/10/2016 9:00
	End date	29/09/2016 10:54	ND	22/10/2016 8:27
	Time span	22h, 55min	ND	1d, 1h, 48min
	Loads Beale Ratio	221 ±66 kg	ND	**1,658 ±497 kg**
	Loads Linear Interpolation	**155 ±47 kg**	ND	**1,665 ±500 kg**
	EMC Beale Ratio	39.1 mg/L	ND	NaN
	EMC Linear Interpolation	**27.5 mg/L**	ND	**102.8 mg/L**

Estimates of Uncertainty in Measurements

Cumulative probable uncertainty, represented by the probable error, for streamflow and nutrient and sediment storm loads for worst case, best case, and typical scenarios are reported in the literature. Typical scenarios for cumulative uncertainty range from best case of 7%, average of 18% and maximum error of 53%, while grab sampling (single point, random time) uncertainty measurements for TSS were estimated at >100% (Harmel et al 2006) and >50% (Slade 2004). Errors from discrete sampling with 30 minute intervals and up to six composite samples was estimated to range from −32% to 25%, more so with an interval of 120 min, ranging −65% to 51% with the same number of samples (King and Harmel 2003).

To determine cumulative uncertainty, previous authors have compared time or flow-interval sampling using discrete and/or composite samples and linear interpolation to determine 'true' loads and compare against alternate sampling strategies (Harmel et al 2006l; Harmel and King 2005) and turbdidity estimates (Lewis 1996). Lewis (1996) reported probable errors in loads estimates using linear fit of turbidity versus TSS (R^2> 0.98) at 10 min intervals between 1.9 and 7.7%. Higher errors observed in regression models for this study were accouanted for in the uncertainty estimate below.

Sampling using a time-interval sampling strategy with short collection intervals (5 minutes) and discrete sampling can provide uncertainties as low as 0 – 11%, while uncertainty involved with analysis of suspended solids can range between -5 and 6% (Harmel et al 2006). Other variance can occur from single sampling points (single sample intake) during automated sampling, with median uncertainty for TSS ranging from 14% to 33%, with an overall median of 20% (Martin et al. 1992).

The cumulative probable uncertainty results from streamflow measurements has previously been estimated to range from 3% at best, typically 6 – 19%, and higher 42% for worst case scenarios (e.g. Manning's equation, unstable stage-discharge relationship, shifting channel). The velocity-area (direct discharge) method in this study was likely to have an uncertainty between 3 - 20%, with typical (average) conditions around 6%.

Total cumulative uncertainty was calcaulated using published values to estimate the potential sources of error (±%) by propagation of errors by the equation (Taylor theorem, Harmel et al 2006):

$$E_P = \sqrt{\sum_{i=1}^{n} (E_1^2 + E_2^2 + \ldots + E_n^2)} \qquad (1)$$

where, E_P = probable range in error (±%), *n* = total number of sources of potential error. The probable error (E_P) for this study was estimated as ±30% and used as the error term in this report. Average error values in the Table below were used to calculate cumulative uncertainty (E_P).

Source of Error	Uncertianty	Method	Mean Error	Reference/s
Velocity-area	2 – 20%	Doppler	8%	Harmel et al 2006*
Single sampling point	14 – 33%	Logger	20%	Harmel et al 2006*
Minimum Flow Threshold	1 – 5%	Judgment	3%	Harmel et al 2006*
Time-interval	0 – 11%	6-minute	5%	Harmel et al 2006*
Sample analysis	0 – 10%	Gravimetric	5%	Harmel et al 2006*
Loads by turbidity	2 – 8%	Regression	8%	Lewis 1996
Slope Turbidity vs TSS	4 – 18%	Regression	12%	This study, residuals

*cited in Harmel et al 2006, compiled information from several authors to report these values.

Appendix 4 – Quality Assurance and Quality Control

Quality Assurance / Quality Control (QA/QC)

Quality control and assurance methods were derived from published sources. The following documents were consulted in developing a program and internal quality assurance and control procedures for flow monitoring. In accordance with:

- World Meteorological Organization (WMO) (2008) Guide to Hydrological Practices, Volume I. Hydrology – From Measurement to Hydrological Information,
- Standards for the Analysis and Processing of Surface-Water Data and Information Using Electronic Methods,
- Ladson (2008) Australian hydrology: an introduction
- BOM (2013) National Industry Guidelines for hydrometric monitoring,

A range of quality assurance and control procedures were used to check, process and perform data calculations. These include the following methods:

- Data verification and validation,
- Error checking,
- Data adjustment for known errors,
- Aggregation and interpolation of data, and,
- Computation of derived variables.

Data verification and validation

a) Check manual readings against logger data at the beginning and end (and intermediate) measurements;

b) Plots of stage with plot of any other stage values for the period, such as from flow gauging or water quality data sets;

c) Qualitative check of hydrograph shapes and events, looking for suspicious features such as straight lines, steps, spikes or freshets, floods and recessions in conditions where they would not be expected

Error screening

Pressure transducers and Doppler profilers might record erroneous readings during deployment for a variety of reasons, including:

- they can become dewatered during low flow conditions
- high flow events can bury them in sediment
- high flow events could move them
- they might become fouled from debris, aquatic vegetation, or algae
- humans might cause interference
- if moisture enters the cable of a vented transducer, it could result in erratic readings or readings of zero water depth
- if the cable of a vented transducer becomes kinked or plugged, it could result in the data not being corrected for barometric pressure

d) Physio-statistical errors were checked by comparing plots of rainfall total with predicted variables (i.e. water height and velocity)

e) Data were plotted to look for issues such as extended periods of zero flow, velocity or no change

Data adjustments for known errors

f) Errors reported by field staff for manual quality control of data sets, commonly associated with sensor drift, clock adjustments or discrete events (e.g. standardised measurements to time excluding daylight savings)

g) Infill data gaps using a mathematical function (linear interpolation)

h) Correct for drift if any shifts were detected (using a statistical fit)

i) Correct negative height values using a geometric mean from the two adjacent data points.

Aggregation and interpolation of data

j) Reduce the dataset to a longer time period (e.g. 6 minutes) or take the median, geometric mean and/or percentiles and plot trend-lines

k) Flow and TSS (estimated) were aggregated to a cumulative average or sum at 6-minute intervals (matching rainfall 6-minute totals)

Computation of derived variables

l) Recheck and calculate flow from height and velocity Q=V x A to compute total discharge

m) Check if annual discharges are logical and meaningful [compared with local flow data]

Absolute checks were used to ensure all data were within range (i.e. positive, less than height of drain). Where data were negative, an investigation of the possible cause and either a minimum value (typically zeroing for estuary backflow) or re-interpolation was chosen depending on the type and extent of negative data.

Relative checks were used to assess if data were within expected ranges. Outliers were checked using the Walsh test and removed if exceeding the probability level of alpha = 0.05.

Shorter logging periods were used to allow for data smoothing, i.e. a 1 - 2 minute logging interval recommended based on results from other studies (Maheepala et al. 2001), with subsequent aggregation of data. Logging using a shorter time interval, such as every 2 minutes, allows for averaging of height (and velocity for ADCP), better smoothing and greater potential detection of pulses, as thresholds could be set at lower limits (Maheepala et al. 2001). This allows data to be compared against rainfall and pressure data available from the Bureau of Meteorology (BOM) or Melbourne Water, which is typically provided in 6-minute time intervals.

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