# Examination of the existence of first flush characteristics: implications for treatment of road runoff

## Analyse de l'effet de premier flot : conséquences pour l'assainissement routier

T.R. Weber[1], M.E. Barry[1], J.P. Stewart[1]

BMT WBM Pty Ltd, 490 Upper Edward St, Spring Hill, Queensland, Australia
(corresponding author email: Tony.Weber@bmtwbm.com.au)

## RÉSUMÉ

L'importance du traitement des rejets urbains par temps de pluie est bien reconnue. Les normes exigent souvent l'assainissement de tous les événements pluvieux jusqu'à une période de retour donnée, de trois mois, par exemple. Malgré cela, les concepteurs d'ouvrages comme les pièges à polluants ou pièges à sédiments ne prennent souvent en compte que le premier flot en dimensionnant leur système. Une étude a été réalisée afin de caractériser les eaux de ruissellement d'une chaussée (en termes d'hydrologie et de qualité de l'eau), pour aider à la conception de réseaux d'assainissement routier. L'étude a été basée sur la simulation de pluies sur des surfaces routières de 188 à 408 m$^2$ où le débit a été mesuré, ainsi que les concentrations et les flux de polluants. L'effet de premier flot a été bien observé pour la concentration (autrement dit, la concentration maximale a précédé le débit maximal), mais le flux des polluants n'a pas montré cet effet.

Cet article vise donc à déterminer si le concept de premier flot est utile pour dimensionner les ouvrages d'assainissement routier, en termes de conséquence pour la masse captée par de tels ouvrages. De plus, le transfert des polluants de l'échelle d'une parcelle à l'échelle d'un bassin versant a été modélisé afin d'analyser la propagation potentielle d'un premier flot vers la sortie d'un tel bassin versant. Les résultats ont montré qu'un bassin versant simple, comprenant exclusivement des surfaces routières, présenterait un effet premier flot important. Toutefois, un bassin plus complexe avec des surfaces perméables et d'autres surfaces imperméables (comme des toitures) aurait un effet de premier flot beaucoup plus faible. La masse cumulative des polluants a augmenté uniformément au cours d'un événement pluvieux, de telle manière que le premier flot représente moins de 20 % de la masse totale de l'événement. Un traitement limité au premier flot n'est donc pas une stratégie efficace pour l'assainissement routier.

## ABSTRACT

The need to treat urban stormwater runoff has been widely accepted in Australia and overseas (BCC 1998, ARQ 2007), and typical guidelines recommend an approach of addressing smaller storm events such as the 1 in 3 month Average Recurrence Interval event, rather than treating the "first flush" of stormwater. Typically however, proprietary devices for stormwater management are strongly focussed on treating this "first flush". As part of a study on examining road runoff characteristics (both hydrology and water quality), rainfall simulation techniques were applied to road surfaces of between 188 and 408 m$^2$ and the resultant flow rates and runoff constituents were monitored. The results showed a very strong "first flush" in regards to concentration, defined in this paper as where the peak of the constituent concentration precedes the peak of the hydrograph, however the cumulative mass load of constituents showed no such characteristic.

This paper reviews the results of this study, and examines whether the concentration peak is a useful measure for assigning treatment measure sizing and the resultant mass load removal likely to be experienced if used. In addition, the hydrology and constituent behaviour from the plot scale measurements were examined collectively if contributing through a typical road stormwater drainage network to determine if similar "first flush' characteristics were likely to be present over larger stormwater networks. The results showed that if only road runoff contributed to catchment runoff, the strong concentration "first flush" was likely to be present regardless of the catchment size, however it was expected that if combined with roof runoff and pervious area surface flows, then the first flush concentrations were anticipated to reduce. The cumulative mass load was found to increase relatively consistently over the entire period however, and demonstrated that systems designed to treat a concentration "first flush" from road runoff were likely to capture less than 20% of the total mass load.

## KEYWORDS

Stormwater, roads, runoff, pollutants, first flush, mass load, treatment performance, SUDS, WSUD.

# 1 INTRODUCTION

The existence of “first flush” has previously been described in other papers (Deletic 1998, Saget et al 1995), however its definition is still not generally agreed to. Though some numerical descriptions have been proposed, for example to compare different sample sets through examination of the load transported during the first 20% of flow (Deletic 1998), the lack of clear definition, in addition to uncertainty regarding the importance in addressing it from a treatment perspective, continues to lead to confusion in the stormwater management industry .

Commonly, the use of the term “first flush” has been widely used by proprietors and still recommended as requiring treatment by government agencies (DECCW 2009, Weidmann 2005). These have usually been in reference to a “concentration first flush” and suggest that effective treatment of stormwater simply requires targeting of this component of the storm runoff. From the literature, it is apparent that the lack of a clear definition of what is meant by “first flush” may have resulted in misunderstandings of the value of characterising this part of an event. The terms “concentration first flush” and “mass first flush” have been proposed previously (Kayhanian and Stenstrom 2008). By comparison of those to the numerical descriptions of first flush proposed in Bertrand-Krajewski (1998), two definitions are proposed below.

Concentration First Flush – The peak in concentration of the constituent occurs within the first 30% of runoff volume

Mass First Flush – At least 80% of the mass load occurs within the first 30% of runoff volume

Using these definitions then provides a suitable method for examining the importance of first flush characteristics during runoff events.

In addition to the lack of suitable definitions, previous studies have attempted to examine the existence of mass first flush using measurements at end of pipes of both segregated and combined stormwater sewers (Bertrand-Krajewski 1998), however studies of runoff from particular surface types are rare and this presents some difficulties in determining the overall contributions of different surface types to the combined stormwater constituent load.

To assist in evaluating the contribution of road surfaces in terms of constituent loads and first flush characteristics, the use of rainfall simulator techniques provides controlled conditions for experimental analysis. This paper outlines a study of three separate rainfall simulator experiments on similar road surfaces and examines the results of both runoff and constituents obtained.

# 2 METHODOLOGY

## 2.1 Rainfall Simulators

As part of a study into the characteristics of road runoff, both in hydrological and water quality contexts, rainfall simulators were used to undertake quantitative measurements of runoff and constituent load contributions from minor suburban roads. The rainfall simulator consisted of a 10,000L header tank supplying diesel water pump flowing to a series of riser pipes and spray nozzles which could be varied to produce consistent droplet sizes closely simulating rainfall droplets (Croke et al 1999) at a specified flow rate.

Antecedent rainfall conditions were broadly similar for each plot, with no rainfall within 72 hours of the simulator experiments at any site. Plot areas ranged from 188 $m^2$ to 408 $m^2$. A 10 minute, 1 in 3 month Average Recurrence Interval (ARI) rain event was simulated and rainfall distribution was analysed through the distribution of rainfall gauges throughout the plot area. The rainfall intensity for this event magnitude was 45 mm/hr. An example of a typical plot is shown in Figure 1, with the plot layout shown in Figure 2.

Areas adjacent to the road were isolated by the installation of metal bunds to prevent cross contamination by other surfaces. Samples were collected from the end of the plot in detergent washed and distilled water rinsed HDPE bottles (for physico-chemical and total nutrient analytes), and acid washed, solvent rinsed amber glass bottles (for metals and hydrocarbons). All samples were preserved (where required and appropriate) and transported for analysis to a quality assured laboratory. Samples were collected at one minute intervals once flows commenced until 10 minutes. After 10 minutes, the rainfall intensities were varied further to examine the potential effects of increasing rainfall intensities on constituent generation, however these results are not reported in this paper.

Figure 1 Rainfall Simulator Plot and V-notch weir

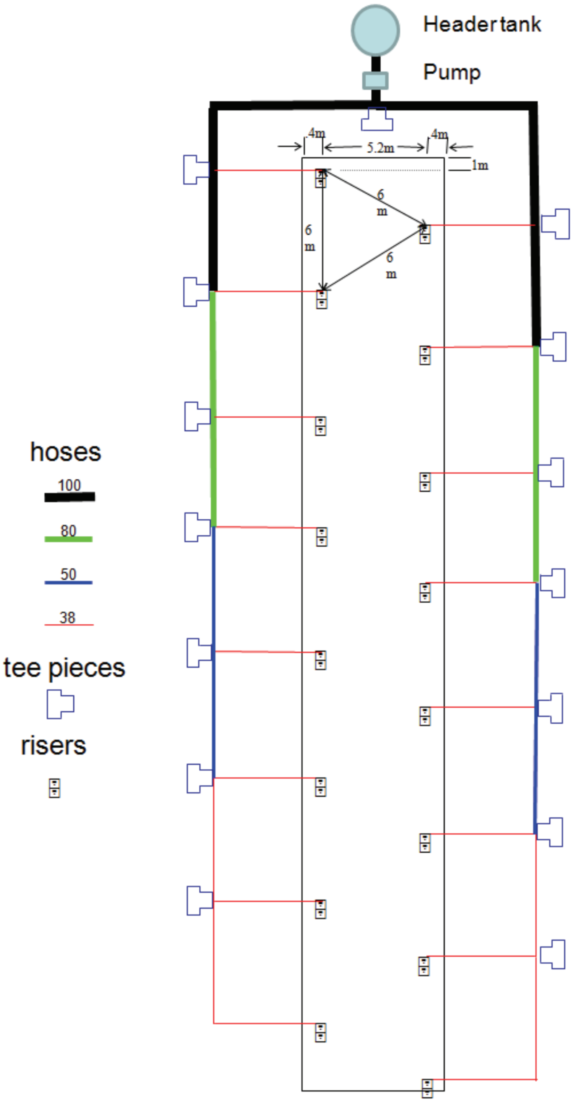

Figure 2 Schematic of Rainfall Simulator Plot

Flow rates were determined from analysis of water consumption from the header tank, rainfall gauges in the plot area, and direct measurements from a v-notch weir placed in a gully pit at the end of the plot as shown in Figure 1 above.

## 2.2 Catchment Analyses

All analytical results were compiled using spreadsheet tools and examined individually for outliers.

The resultant data sets were then combined using areal weighting to derive flow rates and mass loads per hectare of road surface over the 10 minute duration events.

To examine the contributions of road surfaces over a typical urban catchment, an existing urban catchment of 2.25 ha was used to derive travel times from gully pits to the catchment outlet using pipe drainage networks and deriving flow velocities from the relevant pipe sizes. The drainage network was obtained from local government GIS staff and overlayed on aerial and cadastral information to determine local road subcatchment areas. All pipes were assumed to be free draining with no temporary storage.

A series of 39 subcatchments were identified, with a uniform area 600 $m^2$ used based on the spacing of gully pits and the areas of road draining to them. These drained to a single piped outlet, with pipe travel lengths from gully pit to outlet ranging from 100 to 568 m, with resulting travel times (at 1 m/s velocities) of between 1 and 10 minutes. No routing of constituents or flows within the pipes were assumed for simplicity, however it was reasoned that this was not likely to significantly impact upon concentrations or flows at the outlet with such small travel times and short event durations.

A 1 in 3 month ARI 10 minute critical duration event was then simulated through the model using the combined results of all rainfall simulator experiments and scaling these according to each subcatchment size.

By examining a catchment in this way, it allowed the derivation of a longer term hydrograph and associated constituent concentrations and loads to examine the likely removals for treatment measures at this size of catchment. The actual catchment selected was being considered for installation of either a proprietary stormwater treatment device or a vegetated treatment system and hence treatment performance sizing was a requirement of any design.

# 3 RESULTS

## 3.1 Rainfall Simulator Experiments

### *3.1.1 Hydrology*

The results from the 1 minute v-notch weir heights were calculated as flow rates (in L/s) and plotted against time as shown in Figure 3.

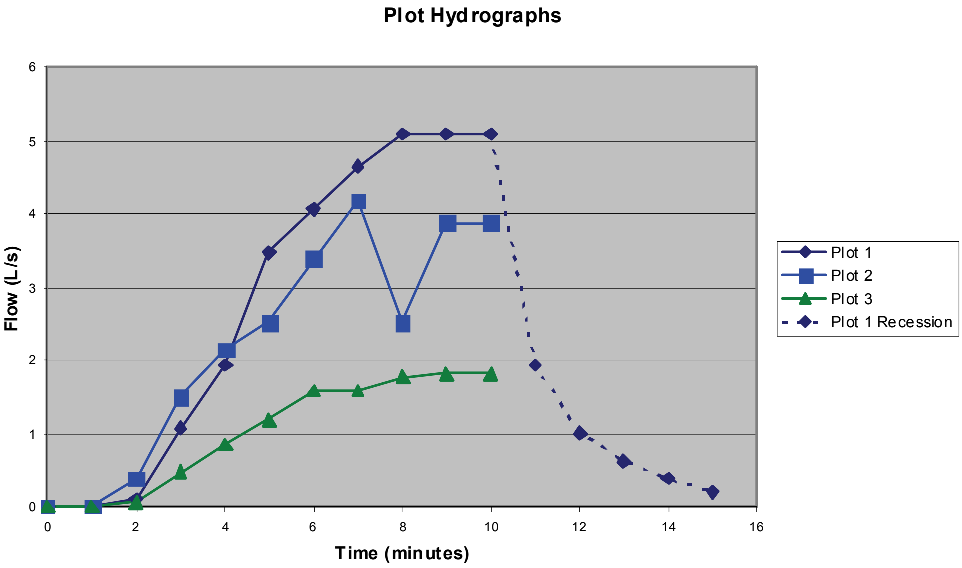

Figure 3 Rainfall Simulator Plot Hydrographs

As can be seen from the above figure, all road plots exhibited similar behaviour, with initial losses approximately equivalent to 1.1mm of rainfall, then flow rates steadily increased over a period from 2 to 8 minutes before reaching steady flow. Plot 2 showed one anomalous result at 8 minutes which may have been an outlier due to incorrect reading of the v-notch height. While not shown, all hydrographs exhibited recession after cessation of flow of approximately 4 to 5 minutes depending on final flow rates used for the subsequent 30 minutes of the experiment. This is exemplified by the recession for Plot 1 shown in Figure 3, as the flow rate for this area was maintained at the same value over the subsequent 30 minute period as for the initial 1 in 3 month 10 minute critical duration event.

### *3.1.2 Constituents*

The temporal evolution of constituents were analysed by the development of pollutographs which showed constituent concentrations at each 1 minute sampling interval. As the source of "rainwater" was in fact from the reticulated potable water supply, concentrations of all constituents were corrected for the concentrations present in the "rainwater" supply. Each major constituent (Total Suspended Solids, Total Nitrogen and Total Phosphorus) are shown in Figures 4 to 6, however all constituents showed very similar behaviour.

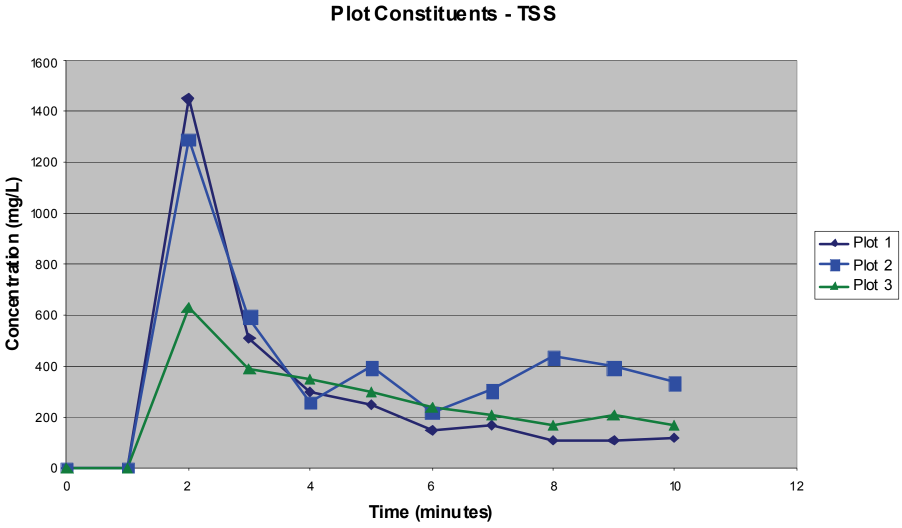

Figure 4 TSS Pollutograph

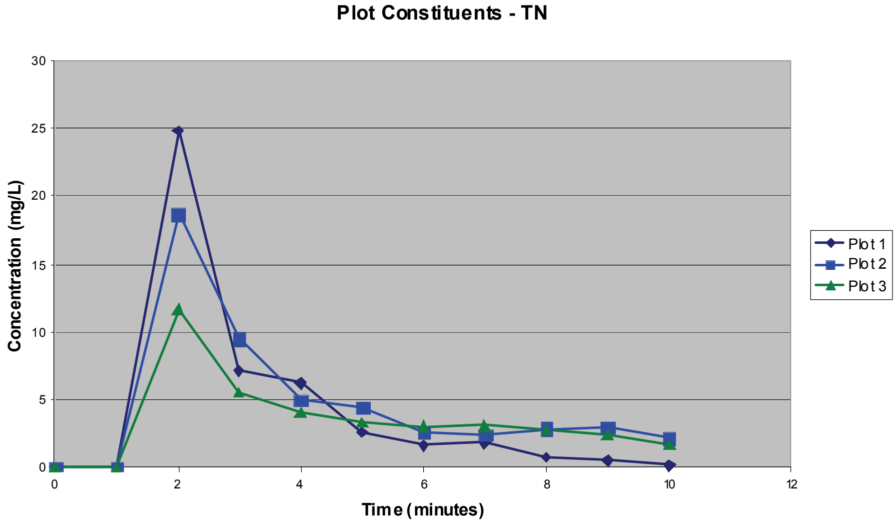

Figure 5 TN Pollutograph

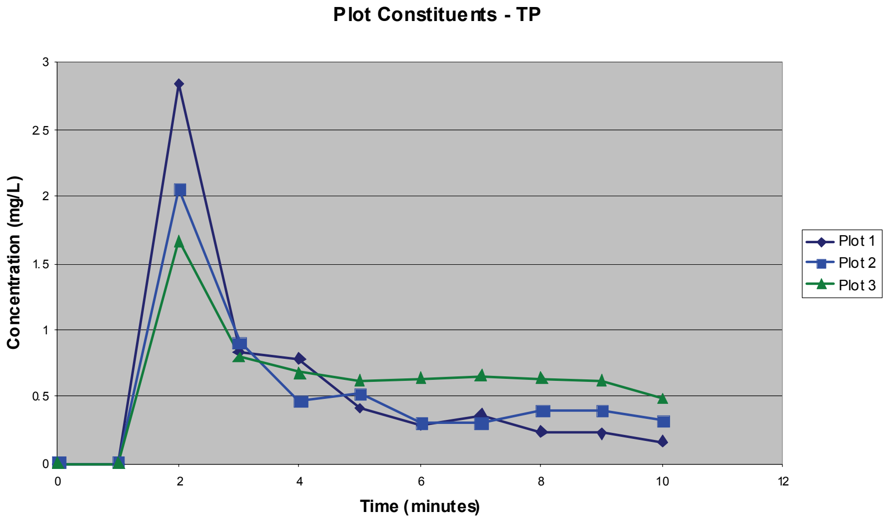

Figure 6 TP Pollutograph

# 4 DISCUSSION AND ANALYSIS

## 4.1 Rainfall Simulation Experiments

As can be seen from each of the previous charts, all road plots exhibited extremely strong concentration first flush characteristics and the behaviour was consistent amongst all constituents analysed, including heavy metals and petroleum hydrocarbons. Of interest is that post the initial peak, the constituent concentrations decay to a relatively stable concentration, suggesting that the mobilisation of constituents is not source limited, but constrained by the rainfall and transport energy available. This process may be an important one in understanding constituent generation processes from impervious surfaces, and based on observations from the field experiments, further research on the importance of the liberation and transport of particulates from impervious surfaces and the importance of both the energy available and the effect of depression storages and voids may be warranted. An example of the surface storage available is shown in Figure 7.

Figure 7 Road Surface Depression Storage

The quantity of sediment trapped in this zone was not able to be quantified, however it shows that there is still sufficient sediment available to be liberated, providing that the energy to remove it from the depression storage and transport it to the catchment outlet was available.

The generation of a concentration first flush appeared to be related to the amount of material available on the road surface, but possibly just as importantly, within the gutter. Prior to rainfall commencing, visual observations of the amount of material available on the road surface were noted as shown in Figure 8.

Figure 8 Material in gutter prior to experiment

On commencement of the rainfall, and once the initial loss was overcome, the concentration first flush appeared to result from the material within the gutter that was easily mobilised by the small initial flows. From the observations made during the collection of this first part of runoff, there appeared to be significant quantities of both floatable particles (leaves etc), but also fine dusts, some which appeared hydrophobic. It may therefore be supposed that the concentration first flush was dependent upon the amount of material present in this gutter (and also if this type of material was present on the road surface) and that the presence and/or magnitude may be dependent upon the number of antecedent dry days prior to rainfall if the amount of material at that location is important and if it is easily mobilised.

That the pollutographs showed a decay to a relatively constant concentration during the event also suggests that once this easily mobilised material has been exhausted, the remaining material is not source limited. Once again, observations of the road surface during the rainfall showed that particles were being moved off the road not specifically by flow, but by raindrop energy combined with the energy of surface sheet flow, and this tended to move particles from the crown of the road towards the gutter. This process was relatively slow, however once particles became entrained in the concentrated flow in the gutter, they were readily transported to the catchment outlet. It therefore may be possible that if the duration of rainfall was significantly longer than the 10 minutes simulated, some exhaustion may be possible.

## 4.2 Catchment Processes

To understand whether catchment and drainage processes may have some impact upon the generation of concentration first flush, and to investigate mass load changes that may be present at a larger scale, a spreadsheet model was developed to simulate a 2.25 ha catchment using a GIS analysis of an existing urban area as the basis for determining road surface catchment areas and drainage complexity. The results from this model, using TSS as the constituent, were then plotted to examine the synthetic hydrograph and pollutograph and are shown in Figure 9.

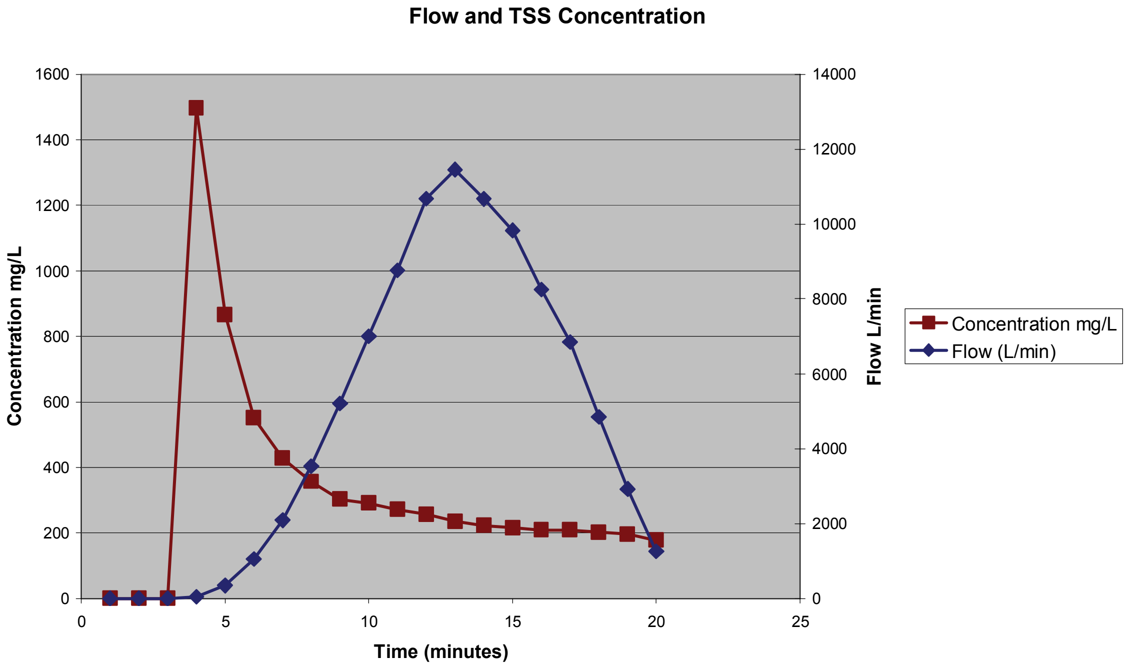

Figure 9 Flow and Concentrations over Modelled Catchment

This shows that the increase in catchment size and complexity has no effect on the concentration first flush, and this is expected, as the first subcatchment to respond in the catchment is that which has the shortest travel time, and the concentrations from this subcatchment will not be mixed with any other flows. As subsequent subcatchments respond, their flows combine and the lower concentrations mix with the higher concentrations to mask any further concentration first flush signals. It is therefore proposed that if sufficient antecedent dry days have occurred, and the rainfall and transport energy are sufficient, a concentration first flush signal should be present from any combination of road surfaces. Obviously, this is not likely to be the case in an urban catchment, as roof runoff and runoff from other pervious and impervious surfaces would combine with the road runoff and influence the concentrations present.

The above does show that the presence or absence of concentration first flush may be due to the presence of other diluting flows in addition to road runoff. If a roof area was also to contribute at a much lower TSS concentrations which are typically present in roof runoff (Fletcher et al 2004), and respond in a similar timeframe, the concentrations of TSS in the stormwater runoff from the combined roof and road runoff would significantly reduce, and where roof areas respond more rapidly than surrounding roads due to drainage configuration (e.g. inter-allotment roof drainage), the concentration first flush signal may be completely obscured.

The mass load present from the modelled catchment was also examined. This was derived by integrating the mass load over each minute as a result of the flows and concentrations present. These were again plotted against time and using a cumulative frequency graph as shown in Figure 9. From the rainfall simulator experiments, while there was a higher variation in mass load per plot over time due to variance in the flows and concentrations, when combined in the modelled loads as shown in Figure 10, the variance impacts reduce.

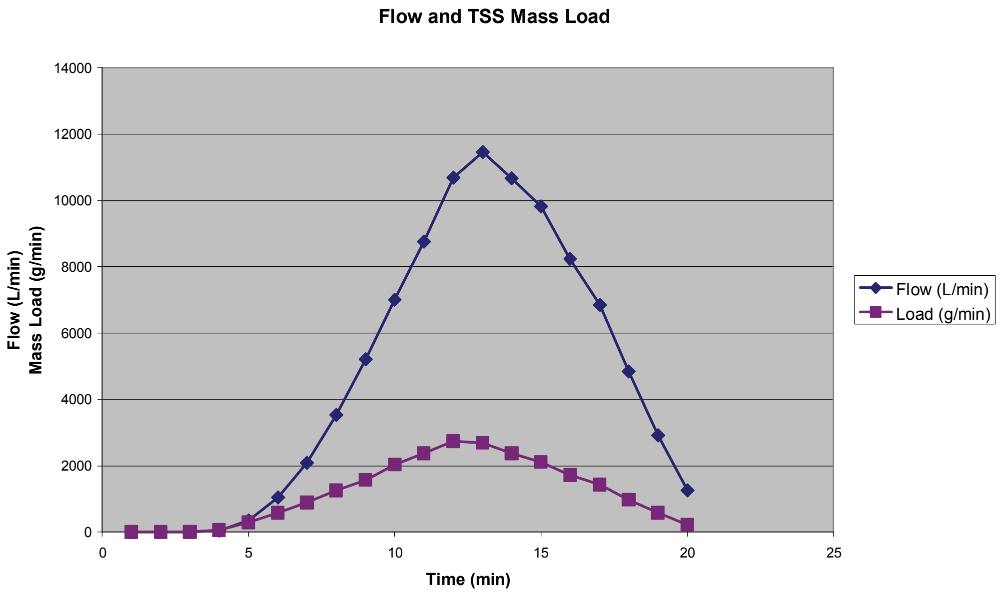

Figure 10 Flow and Loads over Modelled Catchment

The chart above shows that no mass first flush (as per the definition proposed) for TSS would result if all road subcatchments responded as per the rainfall simulator road plots. The reason is simply that when the concentration first flush occurs, flow rates are very low, hence the overall mass load at that time is also low. As flows increase, the concentrations reduce, however they are still of sufficient magnitude to result in a significant load being transported.

Cumulative flows and mass loads were also evaluated to examine the likely mass to be captured by treatment measures sized for the concentration first flush or mass load. A cumulative frequency chart was developed from the modelled data and is shown in Figure 11.

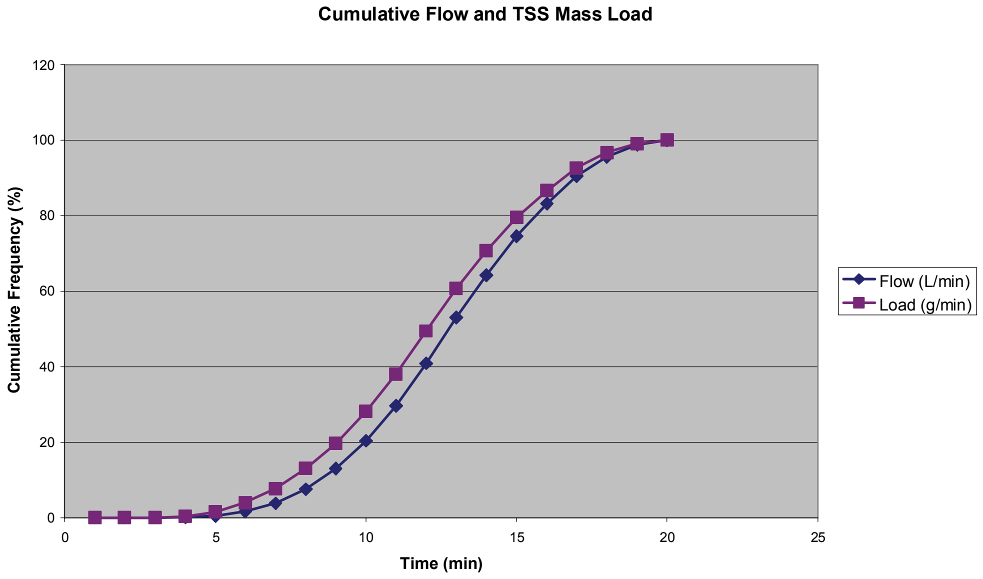

Figure 11 Cumulative Frequency Analysis

What the cumulative frequency chart clearly shows is that the percentage of mass load from these road surfaces closely followed that of the flows. When compared to the pollutograph, it also shows that during the period of highest concentrations 3 minutes to 8 minutes, only 13% of the total event load has actually reached the catchment outlet. The implications of this for treatment measure sizing are quite obvious, that if sized to treat the concentration first flush, the measure will not treat 87% of the total event mass. It also shows that mass first flush may not be a suitable parameter for treatment sizing, as in this case, no mass first flush was found to be present. This does not mean that concentration first flush events should be left untreated, as the results from the rainfall simulation experiments show very high concentrations of all parameters evaluated, such that some may result in acute toxicity effects to organisms in receiving waters, however sizing for these alone is not likely to lead to effective stormwater treatment.

# 5 CONCLUSIONS

The rainfall simulator experiments conducted on road surfaces showed that concentration first flush was strongly evident on the three plot areas examined. When examined as a mass load however, no mass first flush was found to be present. The use of the rainfall simulators also provided interesting insights into the likely processes for generation of constituents from road surfaces and further examination of these would be beneficial, especially with regards to the effects of surface depression storage and the impacts of antecedent dry days on the presence and magnitude of first flush.

A relatively simple analysis of the data to examine the likely implications of treatment sizing using either concentration or mass first flush showed that concentration first flush is not a useful sizing parameter and may result in up to 87% of the mass of a 1 in 3 month ARI 10 minute critical duration event being untreated.

# 6 ACKNOWLEDGEMENTS

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