Use of Passive Stormwater Samplers in Water Sensitive Urban Design

Ian Brodie[1], Mark Porter[2]
Faculty of Engineering and Surveying, University of Southern Queensland[2]
Toowoomba QLD 4350
AUSTRALIA
E-mail: ibrodie@skm.com.au[1], porter@usq.edu.au[2]

Abstract

The application of WSUD practices requires information about stormwater runoff quality from urban surfaces. Passive samplers are not powered and rely on the physical flow of stormwater to obtain a sample and have been used in past studies to collect samples from small urban catchments. Various types of samplers are available and can be classed in terms of the main hydraulic principle that is applied in their design. These principles are gravity flow, siphon flow, rotational flow, flow splitting and direct sieving.

This paper reviews each class of passive sampler to establish their strengths and weaknesses. Factors to be considered in the use of these devices to sample runoff from urban surfaces are discussed. Desirable attributes of a passive sampler to determine Event Mean Concentrations are also identified, leading to a set of design criteria. The criteria includes recommendations on minimum catchment area to be sampled, the design storm frequency used to determine hydraulic capacity, the sample flow volume ratio (SFVR) and sample storage requirements. As particles are conveyed in stormwater as washload, bedload or floating, it is important to clearly state the type and upper size limit of the particles to be sampled.

It is concluded that samplers that use the principles of rotational flow or flow splitting offer the greatest potential in terms of sampler performance. A concept design of a flow splitter device is provided in this paper. The intended use of the device is to obtain stormwater samples from small urban catchments (approximately 200 m^2 in area) in order to determine unbiased concentrations of organic and inorganic particles smaller than 500 µm in size.

1. INTRODUCTION

As Water Sensitive Urban Design (WSUD) is often practised at a lot scale (100 to 1000 m^2), there is a growing need to obtain more information about the quantity and quality of stormwater runoff from urban surfaces. These surfaces include roofs, paved and unpaved carparking, road pavements, grassed and landscaped areas. Stormwater data from specific types of urban surface is required in order to more effectively design WSUD measures such as grass swales, filter strips and infiltration systems.

Passive samplers offer significant advantages in acquiring this kind of stormwater data. Passive samplers are low-cost, simple devices that are typically installed in the stormwater flowpath to capture and store a water sample. These devices are referred to as being 'passive' as they are reliant on the physical flow of stormwater to obtain a sample. 'Active' samplers, as typified by the automatic pumping sampler, use a powered mechanical device such as a pump to collect samples.

This paper investigates the use of passive samplers in WSUD by exploring the limitations of available devices. Sampling requirements associated with WSUD and factors that affect the design of passive samplers are discussed. A sampler design is provided to meet the WSUD requirements while overcoming some of the technical limitations of currently available passive samplers. Details of further research plans using the proposed sampler design are also discussed.

2. TYPES AND LIMITATIONS OF PASSIVE SAMPLERS

Bent *et al*. (2001) provides a summary of various passive samplers that have been used in previous studies to sample urban runoff. Many of these samplers, and others, can be classed in terms of the main hydraulic principle that is applied in their design: gravity flow, siphon flow, rotational flow, flow splitting and direct sieving.

2.1. Gravity Flow Samplers

Gravity flow samplers are simply designed to collect and store stormwater flow as it submerges or flows over the sampler intake. An example is shown in **Figure 1** which was used by Waschbusch *et al.* (1999) to sample road runoff. The device was installed flush to the road surface so that a portion of the stormwater flow drained into the sample bottle through a small hole shown at the top. The size of the drain hole, which could be adjusted by a setscrew, regulated the flow into the bottle.

Similar products are commercially available with larger storage capacity (typically 5 L) and have the capability to isolate the sample container when full by means of a ball valve. Dudley (1995) had used this approach in installing a sampling device within a grated road gully pit.

Figure 2 shows a gravity flow sampler used by Stein *et al.* (1998) to sample stormwater flows from a road pavement. The design includes a 5L storage container housed within the pavement surface. A number of ports capture stormwater as it flows over the top of the device. A buoyant flap closes off the ports when the container is full.

A limitation of this type of device is that the sample containers may completely fill before stormwater runoff has ceased. It is then difficult to ascertain what portion of the event has been sampled. Their main application is thus generally restricted to the capture of initial or first flush samples. Debris may also fully block the sampler intake or restrict the amount of stormwater entering the storage container.

These devices are typically installed within the urban surface to sample the shallow overland flow that is generated during storm events. In some circumstances, the catchment area that drains to the sampler is difficult to accurately determine or could be subject to bypass flows from adjacent areas.

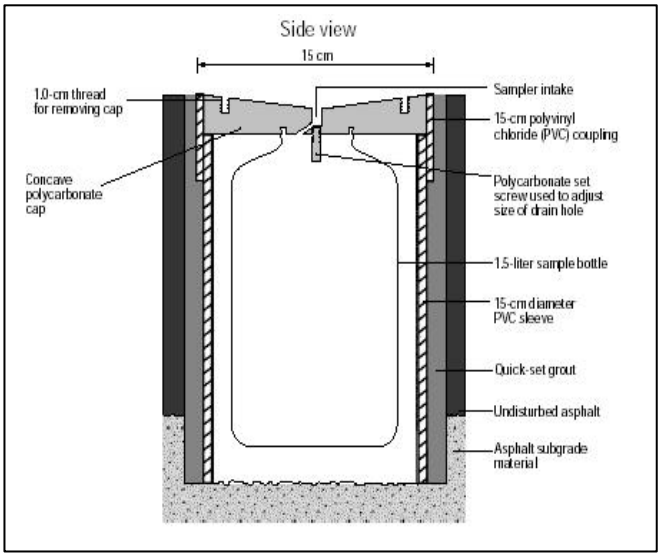

Figure 1 Gravity flow sampler by Waschbusch, Seibig et al (1999)

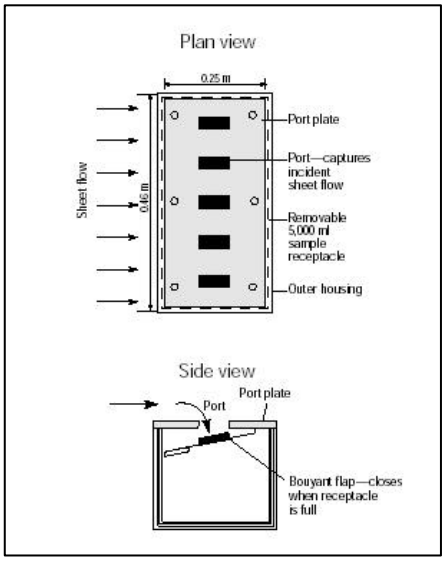

Figure 2 Gravity flow sampler by Stein, Graziano et al (1998)

2.2. Siphon Flow Samplers

An example of a siphon flow sampler is provided in **Figure 3**, adapted from Gray & Fisk (1992). This device, also referred to as a 'single stage sampler', relies on the formation of a siphon action as the water level rises above the sample intake tube. Water is siphoned into the container until it is filled.

A number of siphon samplers can be stacked vertically to collect samples throughout the rising part of the runoff event and this technique has been used in several river studies (Newham et al. 2001; USGS 2000). Once siphonic action is initiated, rapid filling of the sample container generally occurs and thus the technique is suitable for obtaining discrete or 'grab' samples at specific stages of the runoff event.

Siphon samplers provide a reliable basis to sample water, providing that most suspended sediment particles are in the silt to clay size range (less than 62 µm). Larger particles may not be consistently captured, depending on the location of the intake tube relative to the channel bed and the amount of suction that is available.

A major limitation of siphon samplers is that they are unable to operate when water levels are falling and thus do not capture samples during the recession part of a runoff event. These devices are mainly deployed at open channels and waterways where water depth ranges over a few metres. A reliable siphon action is not expected to form under shallow water conditions, as is the case for stormwater flowing over urban surfaces.

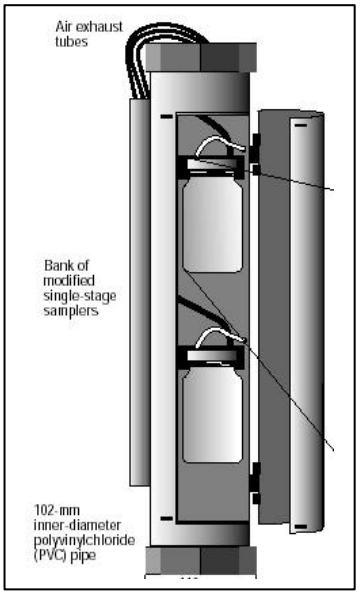

Figure 3 Siphon sampler by Gray and Fisk (1992)

Figure 4 Flume and Coshocton wheel (Reproduced from www.rickly.com, accessed on 1 March 2004)

2.3. Rotational Flow Samplers

An example of a sampler that applies rotational flow is the Coshocton sampler originally developed by the US Department of Agriculture to capture sediment samples from field plots (USDA 1979). A typical installation is shown in **Figure 4** and consists of a flume and a Coshocton wheel.

The flume, usually an H flume, provides a measurement of peak runoff discharge and also jets the flow of water onto the face of the Coshocton wheel. The wheel is inclined slightly from the horizontal and the impact of the water causes the wheel to rotate. An elevated sampling slot mounted on the face of the wheel extracts a water sample when it rotates through the flow jet. The sample is then routed through the base of the wheel to the sample storage tank.

Samples taken by a Coshocton wheel are continuosly composited and flow-weighted, thus providing representative sampling of the entire storm flow. The device is widely used in the US for monitoring of soil erosion and agricultural runoff research. Rabanal & Grizzard (1995) used an H-flume and Coshocton wheel to obtain samples from four small impervious urban catchments in Washington DC.

A limitation of the device is that a vertical drop is required to form a flow jet from the flume onto the Coshocton wheel and thus may not be able to be operable in flat terrain. At high flows when the wheel rotation exceed 35 rpm, the rotation may become irregular and stall the wheel (Bonta 2001).

Researchers from the University of Idaho have developed a hybrid passive-automatic sampler based on a pumping sampler (Idaho Research Foundation 1999). A diaphragm pump that extracts the water sample is self-powered by flowing water driving a set of rotational impellers. The rate of sampling is proportional to flow rate and the impeller speed also provides a measure of flow velocity.

2.4. Flow Splitting Samplers

A flow splitting flow sampler relies on techniques that separates and diverts a small portion of the stormwater flow. An example as used by Clarke *et al.* (1981) to obtain composite samples of highway runoff is presented in **Figure 5**. The device consists of a 3.7m long, steep chute with a series of vertical baffles at the lower end. These baffles act to isolate a constant proportion of the stormwater flow, which is channeled into a storage tank.

The sampler is relatively large in size and this aspect is a constraint where available space is limited. Supercritical flows are required in order for the device to function hydraulically. To achieve this flow regime, the chute needs to be inclined at a steep gradient of up to 9%. This requirement may be a problem in flat terrain or roads that are located in a cutting. The sampler also has a large open surface that may collect debris and atmospheric dust that can be washed into the storage tank.

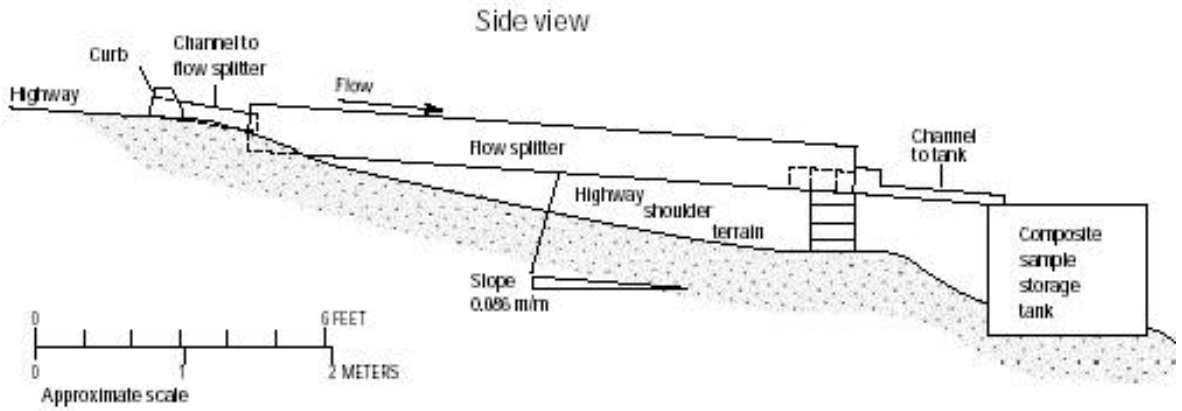

Figure 5 Flow splitting sampler by Clarke et al (1981)

2.5. Direct Sieving Samplers

Direct sieving samplers are used specifically for the determination of sediment concentration in stormwater runoff. An example applied by Pratt & Adams (1981) is shown in **Figure 6** and uses a number of conical-shaped mesh screens that are arranged vertically. Stormwater flows are directed onto the top screen. Mesh openings decrease in size such that coarse material is retained in the top screen and progressively finer particles are collected on the subsequent screens. The process is analogous to laboratory techniques using screens to determine sediment particle size distributions.

The device relies on capturing sediment particles as distinct from other types of passive sampler that aim to capture a representative sample of the stormwater flow. Determination of sediment concentrations requires an estimate or measurement of the total flow volume passing through the screens.

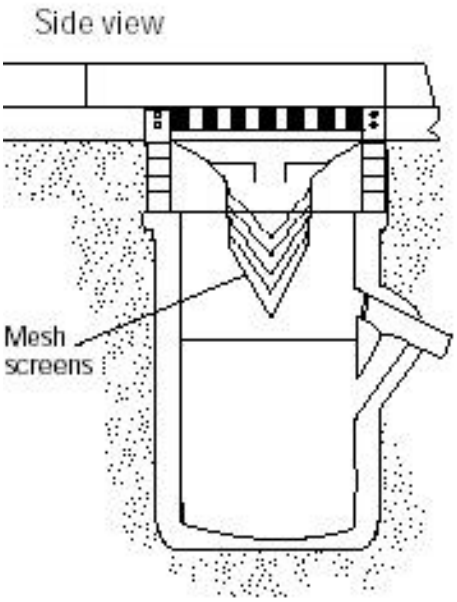

Figure 6 Direct sieving sampler by Pratt & Adams (1981)

3. FACTORS TO CONSIDER IN PASSIVE SAMPLER DESIGN

WSUD at a lot scale requires information on the quantity and quality of stormwater washed from urban surfaces. The Event Mean Concentration (EMC) provides a practical basis to characterize the stormwater loads generated from an urban surface. EMC is defined as the total pollutant mass discharged during a runoff event divided by the total runoff volume. In practice the product of EMC and runoff volume V gives the mass load M for a specific storm event, i.e.

$$M = 0.001 \times EMC \times V \qquad (1)$$

Where M = mass load in kg
EMC = event mean concentration in mg/L; and
V = total runoff volume in m^3

Passive samplers have a major role in obtaining EMC data providing several factors in their design are met. Desirable attributes of a passive sampler are listed in **Table 1** divided into two groups; the physical features of the sampler and its ability to obtain representative sampling.

Table 1. Desirable attributes of a passive EMC sampler

Physical Features	Representative sampling
✍ Compact and easy to install ✍ Not highly visible to reduce incidence of vandalism ✍ Able to easily retrieve sample container ✍ Clogging by debris is prevented or reduced	✍ Able to obtain a flow-proportional sample over full duration of runoff event ✍ Able to capture, store and isolate a sample for subsequent retrieval and laboratory analysis

✍ Adequate hydraulic capacity to handle the design flow ✍ Limited exposed surfaces that may accumulate pollutants ✍ Able to be installed in a defined flowpath	✍ Able to service a catchment area that is representative of the selected urban surface ✍ Able to obtain a sample that is representative of the particle size distribution of the runoff flow

Some of these attributes are discussed in more detail below.

3.1. Flow Proportional Sampling

EMC and runoff volume are measurement outcomes of a sampling program used to estimate the pollutant mass generated for an individual storm. Laboratory analysis of a flow-weighted composited sample provides a representative EMC value. This can be achieved by obtaining sample aliquots that are proportional to the instantaneous stormwater discharge throughout the full duration of the storm runoff event. Sampling could be continuous or at regular time intervals during the event.

If continuous sampling is conducted and the ratio of sample discharge to stormwater flow discharge remains constant throughout the event, then the sample volume represents a direct measure of the total runoff volume. This provides a simple basis to determine runoff volume (V in Equation 1). Estimates of runoff volume based on recorded rainfall data would also provide a useful check of the equipment's accuracy.

3.2. Catchment Area

In order to measure the stormwater characteristics from a specific type of surface, the catchment area to be sampled should be homogeneous with well-defined boundaries. Ideally, the site should have a single discharge outlet and not be subject to bypass flows from adjacent areas.

The size of the catchment is limited by the capacity of the passive sampler to capture and store the stormwater sample. The catchment should be as large as practical to ensure that small-scale variations in the urban surface do not unduly influence the sampling outcomes. It is considered that the minimum catchment area should be approximately 200m^2 in order to obtain representative measurements. This size is consistent with the typical scale of specific surface types (eg roof, paving, grassed areas) found in urban residential lots.

3.3. Sample Capture and Isolation

Water samples should be physically captured and stored within a container that can be easily retrieved after a storm event has ceased. This allows laboratory analysis of water quality determinants to be conducted that are specific to the needs of the study.

In should be noted that direct sieving samplers and other techniques (such as use of turbidimeters) provide a basis for suspended sediment measurement. However, these approaches do not physically obtain a water sample and are thus restricted in their scope. In particular, they do not provide any information on the nature of the pollutants in the water.

An important aspect of the passive sampler design is to ensure that the sample container is isolated from further stormwater entry when it is full. This issue has been resolved in previous designs by the use of ball valves, floating flaps and other simple devices to seal off or close the sampler intake.

3.4. Sample Volume

The volume of the collected sample should be as large as practical to provide maximum integration of pollutant variations throughout the runoff event. Sample storage volume is dependent on the proportion of total runoff volume that is captured and the storm event that is targeted.

In practice, the sample flow volume ratio (abbreviated in this paper as SFVR and defined as the ratio of the sample volume to the event runoff volume) can cover a wide range depending on the mode of sampling. For example, if the bulk of the runoff is collected in a 2000L tank as done by Sansalone *et al.* (1998) in their investigation of road runoff then the SFVR may be close to 1:1. At the opposite end of the range, US EPA (1999) suggests that sampling by automatic pumping samplers using 500mL bottles may have a SFVR as low as 1:70 000. A more typical SFVR range for continuous flow samplers (e.g. Coshocton wheel and flow splitting devices) is expected to be of the order of 1:100 to 1:1000.

For ease of installation and sample container retrieval, handling and transport it is recommended that the maximum volume of a sample container should not exceed 50L. The minimum sample volume could be dictated by laboratory analysis requirements. For example, the precision of Total Suspended Solids (TSS) analysis is limited by the amount of residue retained after filtration. Based on a minimum residue mass of 100 mg (from Davies-Colley & Smith, 2001), the corresponding minimum sample volume is of the order of 10L if the stormwater runoff has low TSS (less than 10 mg/L). Smaller storage volumes are also expected to have a low SFVR or have a higher potential to be filled prior to the end of the runoff event.

Analysis of Australian urban catchments indicate that the sum of all stormwater flows up to the 1 year Average Recurrence Interval (ARI) can represent greater than 95 percent of the mean annual runoff volume (Engineers Australia 2003). On this basis, the sample container should be sized to store at least the captured runoff from the 1-year ARI design storm. Selection of an appropriate storm duration should be based on site access and other factors that may affect the timing and ability to retrieve samples, but is anticipated to fall in the range of 12 to 24 hours.

3.5. Representative Particle Size and Type

The definition of the maximum particle size to be collected by the sampler device is a critical, but often neglected, aspect of stormwater sampling. It is critical for several reasons:

- Particles are conveyed in stormwater in suspension (as washload) or along the flow surface (as bedload). There is no single threshold in particle size that delineates washload from bedload. If the intended particle size limit is relatively coarse (greater than 500 µm), then the majority of these particles would be near the bed and the sampler intake would need to be designed to take this into account.

- The physical dimensions of the maximum particle size governs key aspects of the sampler design such as the intake opening to the sample storage container.

- Laboratory techniques for TSS and similar measures of suspended matter concentration such as Suspended Sediment Concentration (SSC) do not prescribe an upper limit for particle size. As these are weight-based measures, the presence of a relatively small number of large particles may bias the TSS concentration. It is difficult to make comparisons between TSS data collected from different areas if the maximum particle size is not known. This is especially the case in relating Australian data for road runoff to European or US data as Australian sediments tend to be finely graded in comparison (Lloyd & Wong 1999).

- Organic particles generally have low densities and remain suspended or are floatable, even at macroscopic scale (>1mm). In an urban stormwater context, these larger particles fall into the category of ‘gross pollutants’. There is no commonly accepted definition in Australia for minimum gross pollutant size, however Engineers Australia (2003) defines gross pollutants as ”trash, litter and vegetation larger than 5mm”. It should be clearly stated if it is intended to sample organic particles and, if so, the upper particle size limit should also be defined.

Particles in urban runoff can be either conveyed as bedload, suspended within the water flow or float on the water surface. It is expected that the available types of passive samplers would have varying strengths and weaknesses in capturing particles within each of these forms of flow conveyance. Consequently, the definition of which particles to be sampled is a crucial aspect that influences sampler design and operation.

4. TOWARDS A NEW PASSIVE SAMPLER DESIGN

4.1. Adopted design criteria

In addition to the desirable attributes listed in **Table 1**, specific criteria were established for the design of a passive EMC sampler for use in the monitoring of urban surfaces. The design criteria are provided in **Table 2**.

Table 2. Adopted design criteria for a passive EMC sampler

Design Criteria
✍ Able to service a minimum impervious catchment area = 200 m^2 ✍ Hydraulic capacity to handle 1 year ARI 12 hour duration storm runoff ✍ SFVR in the range of 1:100 to 1:1000 ✍ Sample storage volume in the range of 10L to 50L ✍ Able to provide continuously composited and flow-weighted samples ✍ Able to take representative samples of organic and inorganic particles less than 500 µm in size

The adopted 500 µm upper limit corresponds to threshold between medium sand to coarse sand sizes, using the USGS sediment classification system (Bent *et al.* 2001). Inorganic matter of this size is anticipated to readily settle out and be efficiently captured by stormwater measures such as sediment traps and swales. Smaller particles are difficult to remove by a stormwater treatment process and thus represent a more significant management focus. An upper limit of 500 µm for TSS has also been suggested by Lloyd & Wong (1999) on the basis that larger particles are expected to be generally conveyed as bedload.

4.2. Description of proposed passive sampler

The hydraulic principles of rotational flow or flow splitting are considered to offer the best outcomes in terms of sampler performance. Direct sieving is excluded on the basis that it is restricted to sediment capture and no water sample is obtained. Siphon flow samplers are expected to have limited application in shallow flow conditions and may not be reliable in obtaining unbiased samples of particles larger than silt size. Gravity flow samplers are useful for first flush sampling but need to be substantially modified to ensure consistent flow-weighted sampling over the full duration of a runoff event.

Flow splitting that uses vertical baffles extracts samples over the full depth of water flow and thus provides a method to collect particles that are conveyed as bedload, washload or floating. It was decided to focus on designing a flow splitting device that overcomes some of the limitations of previously used samplers of this type. These limitations include the relatively large size of the device, exposure of a large surface to the open air and requirement to be installed at a steep incline (refer Section 2.4).

Figure 7 shows the design of a proposed flow splitting sampling device for use in the monitoring of

small urban areas. For clarity, elements including the sample storage container, inlet and outlet transitions to train water into and out of the device, a rack or screen to intercept debris etc are not shown.

The basis of the device is the sequential operation of two flow splitters. Stormwater flow is directed into a rectangular channel, nominally 150mm wide. The channel is set at a grade such that a subcritical flow regime is maintained with a velocity that provides mobilization of particles less than 500 µm (greater than 0.5 m/s). It was considered that faster, supercritical flows might introduce hydraulic effects including oblique standing waves that would impair the sampler performance. It is intended that, when installed, the bed of the channel would match the existing ground surface.

A horizontal slot parallel to the flow direction is provided midway in the channel base. Vertical walls either side of the slot split the flow and direct a portion of the discharge through the slot. The spacing between the walls control the amount of water that is delivered through the slot to a secondary channel that is fitted to the underside of the channel bed. It is intended that the SVFR associated with this first flow splitter be of the order of 1:20.

The split flow is conveyed in the secondary channel and passes another slot arrangement, similar in design to the flow splitter located in the main channel. The SVFR of this second flow splitter is planned to be of the order of 1:10, which when combined with the first flow split gives an overall SVFR of approximately 1:200. Sampled flows are drained to a storage container located under the device. Excess flows continue through the rectangular channel and exit the passive sampler.

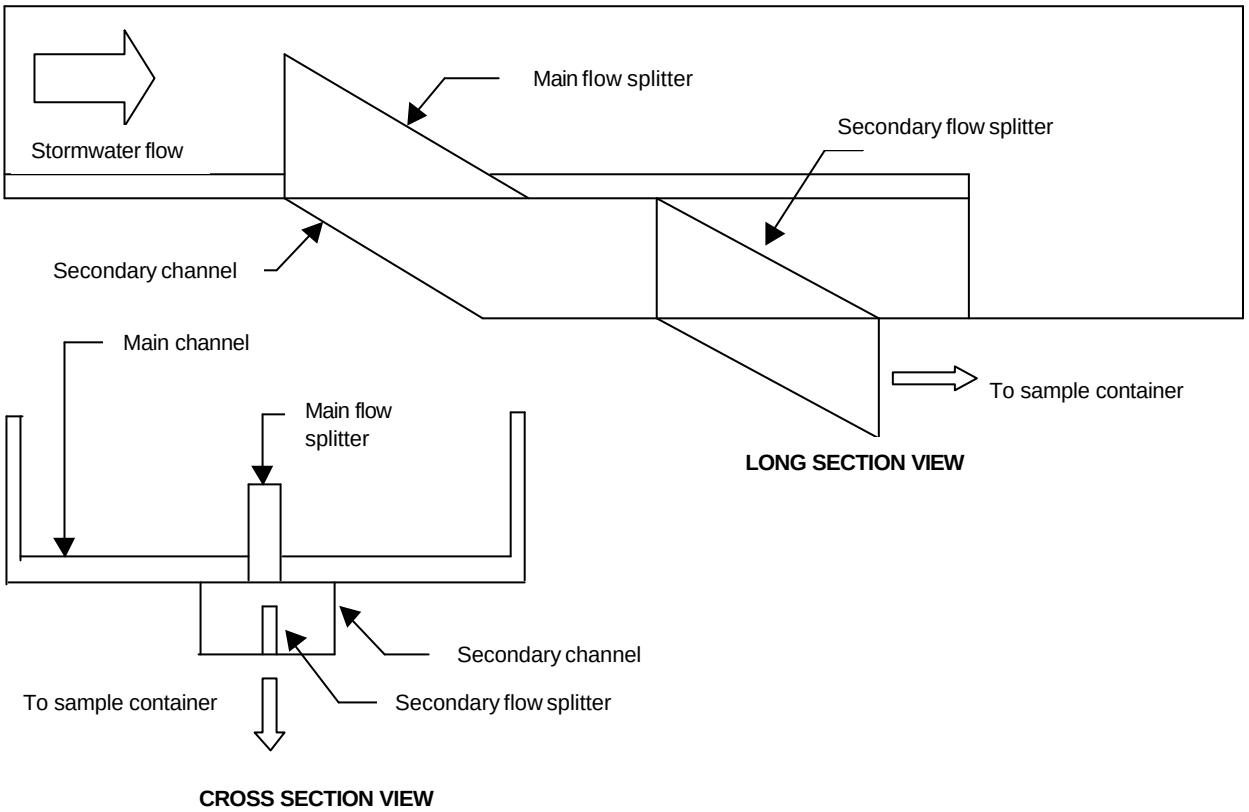

Figure 7 Concept design of flow splitting sampler

5. FURTHER WORK

As part of further research work, it is planned to construct a prototype of the proposed flow splitter and test the device in a laboratory flume. The flume test will investigate the efficacy of the device to extract a consistent SFVR for a range of stormwater flowrates. The performance of the device to obtain representative samples of the concentration of particles less than 500 µm will also be evaluated. Once proven and calibrated in laboratory studies, it is planned that a number of these devices will be constructed and installed to obtain runoff samples from a range of urban surfaces. This work is part of PhD research project by the first author.

6. CONCLUSIONS

Passive samplers have significant potential in obtaining stormwater samples from small-scale urban catchments. These catchments include the surfaces that comprise urban development such as roofs, carparks, road pavements, grassed and landscaped areas. Data on the quantity and quality of stormwater runoff generated from these surfaces is needed to design WSUD measures.

Past studies have used various kinds of passive sampler to investigate runoff from urban areas. These samplers can be classed according to the hydraulic principle that is applied in their design and operation. The basic principles are gravity flow, siphon flow, rotational flow, flow splitting and direct sieving.

The flow splitting and rotational flow devices are considered to have the most potential in obtaining reliable EMC data. A concept design of a flow splitting sampler is provided in this paper that aims to obtain continuously composited and flow weighted samples. It is designed to take unbiased samples of organic and inorganic particles smaller than 500 µm. A prototype of the sampler will be constructed and subjected to performance testing in a laboratory flume.

7. ACKNOWLEDGEMENTS

Figures 1, 2, 3, 5 and 6 of this paper have been reproduced from Bent *et al* (2001).

8. REFERENCES

Bent, G. C., Gray, J. R., Smith, K. P., and Glysson, G. D. (2001). *A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff. USGS OFR 00-497*, U.S. Geological Survey.

Bonta, J. V. (2001). *Modification and Performance of the Coshocton Wheel With the Modified Drop-box Weir,* Journal of Soil and Water Conservation, 57(6).

Clarke, D. L., Asplund, R., Ferguson, J., and Mar, B. W. (1981). *Composite Sampling of Highway Runoff,* Journal Environmental Engineering, 107, pp. 1067-1081.

Davies-Colley, R. J., and Smith, D. G. (2001). *Dialogue on Water Issues - Turbidity, Suspended Sediment and Water Clarity: A Review.* Journal of the American Water Resources Association, 37(5), pp. 1085-1101.

Dudley, L. A. (1995). *Low Cost Automatic Stormwater Sampler* in H. C. Torno "Stormwater NPDES Related Monitoring Needs", ASCE, Crested Butte, Colorado, pp. 599-608.

Engineers Australia. (2003). *Australian Runoff Quality.* Draft

Gray, J. R., and Fisk, G. G. (1992) *Monitoring radionuclide and suspended-sediment transport in the Little Colorado River Basin, Arizona and New Mexico, USA*, in *Erosion and Sediment*

Transport Monitoring Programs in River Basins. Proceedings of the International Symposium, Oslo, Norway, 1992, pp. 505-516.

Idaho Research Foundation. (1999). *Passive Flow Proportional Sampler.*

Lloyd, S. D., and Wong, T. H. F. (1999), *Particulates, Associated Pollutants and Urban Stormwater Treatment,* in *8th International Urban Storm Drainage Proceedings*, Sydney, Australia, pp. 1833-1840.

Newham, L. T. H., Croke, B. F. W., and Jakeman, A. J.(2001), *Design of Water Quality Monitoring Programs and Automatic Sampling Techniques,* in *Third Australian Streams Management Conference*, Brisbane, pp. 455-460.

Pratt, C. J., and Adams, J. R. W. (1981), *Sediment Washoff Into Roadside Gullys*, in *Urban Stormwater Quality, Management and Planning. Proceedings of the Second International Conference on Urban Stormwater Drainage*, Urbana, Ill., pp.174-183.

Rabanal, F. I., and Grizzard, T. J. (1995), *Concentrations of Selected Constituents in Runoff from Impervious Surfaces in Four Urban Catchments of Different Landuse*."in *Fourth Biennial Stormwater Research Conference*, Florida.

Sansalone, J. J., Koran, J. M., Smithson, J. A., and Buchberger, S. G. (1998). *Physical Characteristics of Urban Roadway Solids Transported During Rain Events*, Journal Environmental Engineering, 124(5), 427-440.

Stein, S. M., Graziano, F. R., and Young, G. K. (1998), *Sheetflow Water Quality Monitoring Device* in *The 25th Annual Conference on Water Resources Planning and Management*, Chicago, Ill., pp. 562-567.

US EPA. (1999). *Measurement of TSS in Runoff*

USDA. (1979). *Field Manual for Research in Agricultural Hydrology*, Office of Research and Development, Washington DC.

USGS. (2000), *Comparison of Water-Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin.* US Geological Survey.

Waschbusch, R. J., Seibig, W. R., and Bannerman, R. T. (1999). *Sources of Phosphorus in Stormwater and Street Dirt From Two Urban Residential Basins in Madison, Wisconsin, 1994-95* in *Water Resources Investigations Report 99-4021*, US Geological Survey.