The removal of urban solid waste from stormwater drains

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1. Introduction

Urban litter (alternatively called trash, debris, flotsam, jetsam, floatables, gross pollutants, rubbish or solid waste) has become a major problem in modern society. It typically consists of manufactured materials such as bottles, cans, plastic and paper wrappings, newspapers, shopping bags, cigarette packets and hypodermic needles, but it can also include items such as used car parts, rubble from construction sites and even old mattresses! It accumulates in the vicinity of shopping centres, car parks, fast food outlets, railway and bus stations, roads, schools, public parks, garbage bins, landfill sites and recycling depots. There it remains until either someone removes it, or it is transported by the wind and / or stormwater runoff into the drainage system.

Once in the drainage system, the litter is potentially able to travel via the stormwater conduits, streams, rivers, lakes and estuaries until it eventually reaches the open sea. Along the way, however, items frequently become entangled in the vegetation along the banks of the streams, rivers or lakes, or strewn along the beaches. Some of this debris is picked up - often at great expense. Most of it is probably buried in the river, lake or beach sediments.

The existence of such litter in the waterways and on the beaches has a number of impacts:

- Litter is aesthetically unattractive.
- There is a potential health hazard to humans associated with, for example, the putrefying contents of bottles and tins, or pathogenic organisms attached to discarded hypodermic needles.
- Aquatic fauna are at risk of becoming entangled in, or suffocating from, litter ingested in the course of their search for food.
- Pathogenic organisms or toxins, for example heavy metals, may be taken into the food chain poisoning aquatic life and possibly later impacting on humans.
- Local authorities incur significant costs in conducting clean-up operations.

Litter in the waterways and on the beaches is a worldwide problem. In 1991 South Africa produced some 40 million tonnes of solid waste - mostly of domestic origin (President’s Council Report, 1991). 780,000 tonnes of this was believed to enter the drainage system with 195,000 tonnes reaching the sea (CSIR, 1991). Local governments in Texas spend upwards of US$14 million per year to clean their beaches (Baur and Iudicello, 1990). Annually, an estimated 230,000 m$^3$, or 1.8 billion items, of litter (approximately 60,000 tonnes of wet material) enter the waterways of greater Melbourne in Australia (Allison, 1997). This is unacceptable. Something needs to be done to:

- Reduce the quantities of litter being deposited in the catchments.
- Prevent the deposited litter from entering the drainage system wherever possible.
- Remove the balance from the drains where necessary.
2. Litter classification

For the purposes of this discussion, urban litter will be defined as visible solid waste emanating from the urban environment with an average dimension of greater than about 10mm. Various researchers e.g. Allison and Chiew (1995), Island Care New Zealand Trust (1996), Armitage et al. (1998), or Armitage and Rooseboom (2000a) have identified different types of litter. A simplified classification system is proposed below:

- Plastics – e.g. shopping bags, wrapping, containers, bottles, crates, straws, polystyrene blocks, straps, ropes, nets, music cassettes, syringes, and eating utensils.
- Paper – e.g. wrappers, newspapers, advertising flyers, ATM dockettes, bus tickets, food and drink containers, and cardboard.
- Metals – e.g. foil, cans, bottle tops, and vehicle number-plates.
- Glass – e.g. bottles and various broken pieces.
- Vegetation – e.g. branches, leaves, rotten fruit and vegetables.
- Animals – e.g. dead dogs, cats and sundry skeletons.
- Construction material – e.g. shutters, planks, timber props, broken bricks and lumps of concrete.
- Miscellaneous – e.g. old clothing, shoes, rags, sponges, balls, pens and pencils, balloons, oil filters, cigarette butts and old tyres.

3. The composition and quantity of catchment litter

The composition of the litter, and rate at which it finds its way onto the catchment, are highly variable. Some contributing factors are:

- The type of development, e.g. commercial, industrial, residential.
- The density of development.
- The income level of the community. In some regions of the world, poor people do not have access to many consumer products and hence are not in a position to discard them – or their packaging. In other regions, the population can afford consumer products, but the tax base is not large enough to support an adequate refuse removal service.
- The type of industry – some industries tend to produce more pollutants than others do.
- The rainfall patterns, e.g. does the rain only fall in one season, or year-round? Litter will build up in the catchment until it is either picked up by a refuse removal service, or is swept into the drains by a downpour. Long dry spells give greater opportunity to the local authority to pick up the litter, but also tend to result in heavy concentrations of accumulated rubbish being brought down the channels with the first rains of the season – the so-called “first flush”.
- The type of vegetation in the catchment. In Australia, for example, leaves form the major proportion of “litter” collected in traps. Some species of trees cause more problems than others e.g. London Plane trees have relatively large leaves which are slow to decompose and mostly shed over a very short period in autumn.
- The efficiency and effectiveness of the refuse removal service – including both the removal of refuse from private properties and the cleaning of the streets and street bins.
It is also important that sweepers do not, for example, sweep or flush the street litter into the stormwater drains.

- The levels of environmental concern in the community – leading to, for example, the reduction in the use of certain products, and the recycling of others.
- The extent of legislation prohibiting or reducing waste, with which is associated the effectiveness of the policing of the legislation, and the level of the fines.

Figure 1: Composition of collected gross pollutants by dry mass from different catchments in Coburg (after Allison and Chiew, 1995)

The variability in the nature of the litter associated with different land-uses has been identified by a number of researchers, for example, Allison and Chiew (1995). They showed that for a fully urbanised catchment at Coburg, which is situated about 10 km north of the Melbourne CBD, “garden debris” made up 85% of the litter collected from a residential site, but only 36% from a light industrial site. “Paper” and “plastics” made up 64% of the litter from the light industrial site, but only 13% from the residential site (Figure 1). Similar profiles have been obtained for Auckland (Cornelius et al., 1994; Island Care New Zealand Trust, 1996).
There is an enormous variation in the published data on measured litter loadings. Not only are there large differences between the littering profiles of different catchments, but often the data merely reflects the state of the catchment at the time of measurement. What complicates the matter further is that there is no uniformity in the reporting of catchment litter data. The mass of a sample will vary with its moisture content, and frequently samples taken from drains are not dried before they are weighed. The density of the sample can increase by as much as five times from being loose in the drain to being compacted in the back of the refuse removal vehicle. Sometimes leaves or silt or construction debris are taken as being part of the litter and sometimes not, and the process of removing the leaves, silt and/or construction debris will also change the density of the residual sample. Sometimes litter loadings are expressed in terms of the curb length. At other times they are expressed in terms of the land area.

The quantity of litter finding its way into the drainage system is also extremely sensitive to the efficiency of the refuse removal and street sweeping services in the area, and these are frequently not reported. In many parts of the developing world, formal domestic refuse removal is either non-existent or inadequate. Domestic litter is dumped onto the street or into the nearest open space. A stormwater canal is a particularly favoured candidate as the water washes away the evidence of illegal dumping.

<table>
<thead>
<tr>
<th>Catchment description</th>
<th>Annual load (kg/ha.yr)</th>
<th>Density (kg/m$^3$)</th>
<th>Annual load (m$^3$/ha.yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Melbourne</strong> (winter rainfall with a mean annual precipitation of 730mm) - 150ha of the inner-city suburb of Coburg, 25% commercial, 65% residential, 5% light industrial, 5% park-lands. Daily street sweeping along the major commercial streets, fortnightly sweeping in the residential areas.</td>
<td>30</td>
<td>250</td>
<td>0.4</td>
</tr>
<tr>
<td>Average inclusive of leaf matter (dry)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average inclusive of leaf matter (wet – from the trapping device)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average excluding leaves (dry)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial areas excluding leaves (dry)</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential areas excluding leaves (dry)</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light industrial areas excluding leaves (dry)</td>
<td>7.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>New York City</strong> (year-round rainfall with a mean annual precipitation of 1,092mm). Figures based on a measured quantity of 11g litter per 100ft of curb length per day measured along 90 blockfaces throughout the city. The assumed curb density is 370m/ha. The frequency of street sweeping is unknown.</td>
<td>50</td>
<td>94</td>
<td></td>
</tr>
</tbody>
</table>

Table 1b: Typical litter wash-off rates in the developed world
### Catchment description

**South Africa:**

**Springs** (summer rainfall with a mean average precipitation of 750mm): Central Business District, 85% (254ha) commercial / industrial, 15% (45ha) residential

- Average catchment load before street sweeping
- Average catchment load before street sweeping assuming no contribution from the residential area
- Average load in the stream after daily street sweeping in the commercial and industrial areas with an overall removal efficiency of approximately 83%
- Average load in the stream after street sweeping assuming no contribution from the residential area

Measured dry litter densities:
- On the street: 35
- On the banks of the stream: 95
- In the trapping structure: 95
- In the back of the refuse vehicle: 150

The average litter load of the first major storm of the rainy season is 3.6 times the average of all storms.

**Johannesburg** (summer rainfall with a mean annual precipitation of 713mm): 800ha of the central districts with a mix of residential, commercial, industrial and informal trading areas. Limited street cleaning. The average litter load of the first major storm of the rainy season is 1.5 – 2.0 times the average of all storms.

<table>
<thead>
<tr>
<th>Catchment description</th>
<th>Annual load (kg/ha.yr)</th>
<th>Density (kg/m³)</th>
<th>Annual load (m³/ha.yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springs</td>
<td>470</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>Johannesburg</td>
<td>48</td>
<td>95 (assumed)</td>
<td>0.5 (measured)</td>
</tr>
<tr>
<td>Cape Town</td>
<td>104</td>
<td>58</td>
<td></td>
</tr>
</tbody>
</table>

**Cape Town** (winter rainfall with an overall mean annual precipitation of 518mm - but with large local variation):

- Ocean View sub-economic residential area for poor people including both stand-alone dwellings and “hostels” (3-story, high-density apartment blocks), no street cleaning – excluding vegetation
- Vegetation load for Ocean View
- Summer Greens medium density, medium income residential area, no street cleaning – excluding vegetation
- Vegetation load for Summer Greens
- Welgemoed low density, high income residential area, no street cleaning – excluding vegetation
- Vegetation load for Welgemoed
- Montague Gardens light industrial park, no street cleaning – excluding vegetation
- Vegetation load for Montague Gardens
- Cape Town Central Business District including office blocks, hotels, line shops, informal traders and a bus terminus, extensive street cleaning (up to 3 times daily) with a removal efficiency of approximately 99% - excluding vegetation
- Vegetation load for Cape Town Central Business District

Table 1b: Typical litter wash-off rates in the developing world (South Africa)
Frequent street cleaning can dramatically reduce the quantity of street litter reaching the drainage system – even where there is a generally adequate refuse removal service. If the street sweeping is infrequent, its effectiveness depends strongly on the rainfall patterns. If there are periods of major rainfall between cleaning events, a lot of litter is likely to end up in the drains. If not, the litter will tend to accumulate in the street until such time as it is removed.

In consequence of the foregoing, litter data should ideally be collected from the site of interest prior to the design of any litter removal system. Failing that, Table 1 lists data on litter loadings in various different parts of the world. Table 2 offers some suggested design values for South African conditions (Wise & Armitage, 2002).

<table>
<thead>
<tr>
<th>Land-use Type</th>
<th>Litter Load excl. vegetation (kg/ha.year)</th>
<th>Vegetation load (typical) (kg/ha.year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Density Residential</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Medium Density Residential</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>High Density Residential</td>
<td>150</td>
<td>30</td>
</tr>
<tr>
<td>Informal Settlements (no formal refuse removal services or stormwater reticulation, but within 50m of an open drainage channel)</td>
<td>6 000</td>
<td>10</td>
</tr>
<tr>
<td>Manufacture/Industrial</td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>Retail</td>
<td>2 500</td>
<td>30</td>
</tr>
<tr>
<td>Offices</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Halls, Stadiums &amp; Entertainment Facilities</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>Taxi Ranks etc.</td>
<td>6 000</td>
<td>30</td>
</tr>
<tr>
<td>Schools</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Hospitals</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2: Suggested litter wash-off rates in South Africa (assuming no street-sweeping) (After Wise & Armitage, 2002)

4. Reducing the litter load

Much can and should be done to reduce the quantity of litter that finds its way into the stormwater drainage system. The most sensible way of going about this is through the development of an integrated catchment litter management strategy. Two categories of litter reduction methods are available:

- Planning controls (restricting litter-generating activities to areas where their impact can most effectively be controlled and reduced).
- Source controls (reducing litter loads entering the drainage system through *inter alia* education and enforcement programmes).
A comprehensive **integrated catchment litter management strategy** will also include structural controls, i.e. the removal of litter from the drainage system (Figure 2).

![Integrated Catchment Litter Management Strategy Diagram]

**Figure 2: Components of an integrated catchment litter management strategy**  
(Marais & Armitage, 2003)

### 4.1 Planning controls

Planning controls are aimed at adopting land-use policies which:

- Preserve existing valuable elements of the stormwater system, such as natural channels, wetlands and riparian vegetation by restricting the use of such areas.
- Minimise the risk of litter reaching the drainage system by situating litter-producing activities in areas where it is easier to contain and control litter accumulation.
- Require pollution control measures as part of any development application.

### 4.2 Source controls

Source controls are aimed at reducing the litter loads entering the drainage system by dealing with pollution at source. There are numerous **options**:

- Upgrade cleansing operations by, for example; the better placement and design of litter bins, more frequent collections of litter, monitoring street sweeping methods to ensure that litter is not swept into catchpits, and ensuring that communal collection depots are appropriately placed. The latter may also be a way of promoting jobs in recycling.
- Control construction activity by ensuring that site management plans are in place to prevent contaminant spills and rubble from reaching the drainage system.
• Conduct business surveys to determine the nature and extent of activities likely to generate litter that reaches the stormwater system. This could lead to, inter alia, encouraging manufacturers to move to more environmentally friendly packaging, or to charge deposits on containers to encourage their return.

• Run litter education campaigns targeted at businesses and households informing them how the streets, stormwater drainage system, rivers and oceans are interconnected and how daily activities affect stormwater quality (Victoria Stormwater Committee, 1999). Typical activities include organised clean-ups which serve the dual purpose of creating awareness and reducing the amount of litter, “adopt-a-block” programmes, or encouraging the separation of litter into different types so that homeless people can collect the recyclable material.

• Improve the enforcement of anti-litter legislation by, for example, setting up pollution “hot-lines” to encourage the general public to report cases of littering and increasing the number of personnel enforcing anti-litter legislation.

• Tax products (including packaging) that are considered likely to be major contributors to the litter stream.

Owing to their effectiveness, street sweeping and the installation of grids over catchpit entrances are discussed in greater detail below.

4.2.1 Street sweeping

After the implementation of an efficient and effective refuse removal service, the next most effective method of removing large quantities of litter from the catchment is via street sweeping.

There is little published data on the effectiveness of street sweeping in the removal of litter. In view of the relatively large size of most litter, it is safe to assume that it is relatively easy to pick up – whether by machine or by hand. The biggest problem is likely to be the removal of litter from between or underneath parked vehicles. The frequency of sweeping will, however, have a large impact on the efficiency of litter removal. Street sweeping carried out two to three times daily in the commercial business district of Cape Town, South Africa appears to remove as much as 99% of the total litter load from the streets (Marais & Armitage, 2003). On the other hand, sweeping selected streets in Springs, South Africa once a day removes only about 83% (Armitage et al, 1998). Where the cleaning frequency is less than the frequency of the runoff producing storms (with, say, more than 5mm of rainfall), the litter removal efficiency is likely to drop below 50%. In the absence of data, the maximum expected efficiency of litter removal is indicated by Equations 1a and 1b or Figure 3:

\[
\eta_{\text{removal}} = 1 - \frac{F_{sw}}{2F_s} \quad (\text{for } F_{sw} < F_s) \tag{1a}
\]

\[
\eta_{\text{removal}} = \frac{F_s}{2F_{sw}} \quad (\text{for } F_{sw} \geq F_s) \tag{1b}
\]

where

\[
\eta_{\text{removal}} = \text{estimated efficiency of street cleaning (fraction)}
\]

\[
F_{sw} = \text{average number of days between street sweeping (d)}
\]
Where there is a significant difference in the sweeping and/or rainfall frequencies for different seasons, each season must be evaluated separately and an average taken over the full year.

In theory the sweeping frequency can be reduced during long dry periods without a significant increase in the litter reaching the stormwater systems. In reality though, other mechanisms, such as wind action, tend to move a certain amount of litter into the drains. The first major runoff producing rainfall then washes the accumulated litter away as a highly concentrated litter “plug”.

It is important that the street sweeping is carried out in an acceptable manner. A survey carried out by the Board of Works, Melbourne in 1990 revealed that, at that time, 67% of 54 councils in the metropolitan area used street flushing to some extent. Of these about half regularly and extensively used flushing equipment or street hydrants to clean shopping centres and similar litter accumulation areas (Senior, 1992). Under these circumstances, street sweeping could increase the quantities of litter reaching the drainage system.

Data collected from South African catchments
(Armitage et al., 1998) suggests that the first flush can contain up to four times the normal quantity of litter. This must be allowed for in sizing the storage capacity of any litter traps.

### 4.2.2 The installation of grids over catchpit entrances

The most obvious method of preventing litter from getting into the drainage system is to ensure that some form of grid covers as many entrances as possible. Clearly, this can only be implemented together with a regular street sweeping service. This approach is the norm in many of the more developed countries – for example in Europe or North America. In less developed countries, however, it is not always a satisfactory solution. High litter loads together with high rainfall intensities and unreliable maintenance programmes frequently lead to blockages and the associated risk of flooding. The question of who is liable for damages in the event of flooding associated with such an eventuality is unclear, but the local authority is likely to be a focus of attention. For this reason, many local authorities allow some form of unrestricted overflow even when grids are provided. Where unrestricted overflows exist, litter will certainly be found in the drainage system.

Paradoxically, the installation of grids over the catchpit entrances may be a potential solution in the very high-density, low-income informal urban settlements surrounding many major cities. This is for the simple reason that if the residents can see the grids blocking, and if there is a risk that their own homes will be affected by the consequent flooding, they are likely to take the appropriate action to keep them clear. If the litter trap is hidden away, or if local drainage is unaffected by moderate litter loads, it is unlikely that the residents will help keep the drains clear of litter, leaving it to the local authority to take full responsibility for maintenance. This has been observed in Khayelitsha near Cape Town, South Africa (Compion, 1998). There is of course a risk of serious flooding if a major storm occurs at night.

### 5. Structural controls – litter traps

Since it is difficult to prevent all the litter from reaching the drainage system, the balance will probably have to be removed some other way. In areas that have combined sewer systems (typically in Europe and parts of North America), this can be readily achieved at the wastewater treatment works. The main focus of attention is then on the overflows (at the “Combined Sewer Overflows – CSOs”) that occur in very wet weather. In many parts of the world, however, the stormwater drainage is always (theoretically at any rate!) kept separate from the foul sewage system, and thus the litter must be trapped and removed along the watercourse.

The **ideal trap would have**, inter alia, **the following features** (Armitage et al., 1998):

- Reliable.
- Economic to construct and operate.
- No moving parts.
- No external power source.
• Minimal water head requirement (i.e. it can be used in association with flat gradients).
• Does not increase flood levels in the vicinity of the structure.
• High removal efficiency.

Unfortunately, the ideal trap does not exist. All designs represent some sort of compromise. It is the engineer’s task to choose the most appropriate structure to fit the circumstances. Ideally this should form just one part of a total litter removal strategy that also takes into account planning and source controls. One of the biggest problems facing the designer of a litter trap is that litter can be just about anything - any size, any shape, any density, and any hardness. Furthermore, the physical characteristics of individual items sometimes change as they move through the drainage system. Plastic bags deform and tear, bottles break, and aluminium cans fill with water and/or sediment. The high degree of variability in litter characteristics makes it extremely difficult for the designer to design a structure that will cater for every eventuality. Many litter trapping structures work extremely well in low, but not in high flows – or vice versa – or work well with certain types of litter, but not with others. Many litter traps pose major cleaning problems.

Research carried out into some 50 different types of trapping devices for the Water Research Commission of South Africa (Armitage et al., 1998, Armitage & Rooseboom, 1999, Armitage & Rooseboom, 2000b) showed that litter is difficult to trap without the assistance of a screen. The options considered included in-line screens, self-cleaning screens, booms, baffles, detention/retention ponds, and vortex devices. They were evaluated in terms of the following criteria:
• The size of the catchment that could be serviced by the device (which is related to the runoff and the litter loads).
• The typical cleaning frequency.
• The hydraulic head requirement for operation.
• The efficiency (expressed as a percentage of litter removed from the flow).
• The capital and operating costs.
• Any other features that might make the structure attractive or unattractive to the potential user.

Ultimately, two or three patented devices stood out as showing the most promise for use in typical urban drainage situations in developing countries such as South Africa. There were, however, others that might be more appropriate for use in certain specialised circumstances. Two of the most effective traps are described in greater detail below. Descriptions of some of the others are to be found in the previously-mentioned references.

5.1 The Stormwater Cleaning Systems (SCS) structure

This is similar to the Baramy® Gross Pollutant Trap, which has been patented in Australia. Flow from the conduit is directed over a screen declined at an angle of between 20° and 45° below the horizontal. There are two alternative layouts; with the screen installed in the path of flow for small flows emanating from, say, a pipe, and with the screen installed at right-angles...
Figure 4: Plan of, and long-section through, a typical SCS litter trap

Figure 5: View of an SCS litter trap (near Springs, South Africa) being cleaned and repaired (screen parallel to the dominant flow direction). The flow would normally be from right to centre and down. A portion of the screen has been removed for repair. The collection bin is on the left.
to the dominant flow direction for the larger flows in canals (See Figures 4 and 5). The water flows through the screen and either goes under the waste collection bin, or past it. The litter is separated from the water by the screen and is deposited in the bin ready for removal by a skid-steer loader (Bobcat or similar) that gains access down a concrete ramp. A settling basin can be provided upstream of the weir to trap the bed-load separately if required (Armitage et al., 1998).

5.2 The Urban Water Environmental Management (UWEM) concept

A hydraulically controlled sluice gate is used to create the necessary head required to force the stormwater through a series of screens, under a suspended baffle wall and over a weir. In the event of a major flood coming down the channel, the sluice gate automatically lifts to pass the peak and prevent upstream flood levels from being raised higher than they would have been had there been no structure at all (Armitage et al, 1998). See Figures 6 and 7.

Figure 6: View of the Robinson Canal screens after cleaning. The hydraulically operated sluice gate is visible on the right-hand side of the picture beyond the weir-wall.
Figure 7: Plan of, and section through part of, the UWEM Pollution Control Works on the Robinson Canal, Johannesburg, South Africa
The device is readily adapted to the removal of pollutants other than litter e.g. silt or sewage. It can be designed to handle very large flows. Its chief advantage, however, is that it can be applied in areas with flat gradients such as along the coast, as the head that is required to operate the trap (in the order of 1 - 2m) is generated by the hydraulically operated sluice gate.

5.3 Selecting a litter trapping system

Since the selection of an appropriate litter trapping system is quite a complex process, it will be described in some detail here. Refer to Armitage et al (1998) or Armitage & Rooseboom (2000c) for more information.

5.3.1 The importance of trap location

The choice of trapping system is site-specific and therefore the location of the traps is an important decision. Clearly, the closer a trap is located to the head of the drainage system, the smaller the flow and therefore the smaller the structure required. On the other hand, many more of these structures will be required to cover the entire catchment. The construction and maintenance of large numbers of smaller traps will almost certainly be greater than the construction and maintenance of one or two larger traps situated at the mouth of the main canal or stream draining the entire catchment.

No trap is 100% effective. It is often more cost effective to aim for a trap efficiency of, say, 70% and to look to trap the balance at another point in the system. Many traps are designed to handle peak flow rates in the region of only 1:1 month recurrence interval (RI) (i.e. the structure is bypassed twelve times a year on average). The surplus flow – with its associated litter – bypasses the trap. A design flow of 1:2 years (which is the capacity of many conduits) is probably the largest flow rate that would ever be considered for a litter trap. Consideration should therefore be given to providing at least two traps in series.

Another important issue is access for cleaning and maintenance – particularly for larger structures. Ease of cleaning is crucial. Trapping efficiency will rapidly fall to zero if the traps are not properly cleaned and maintained. In some instances, the cost of providing adequate access may be more than the cost of the structure itself.

5.3.2 The recommended selection procedure

Once the designer has some idea of the potential trapping points and associated structures, the recommended selection procedure is as follows:

1. Identify the catchment associated with a potential trapping point together with its drainage system / waterways. It may be necessary to divide the catchments into sub-catchments depending on the number, type and location of structures envisaged.
2. Identify and measure the area of each land use \((A_i)\) within each catchment (the main land-use categories being commercial, industrial and residential).

3. Estimate the total litter load \((T)\) in each catchment area. In the unlikely event that there are existing litter traps of known efficiency already operating in the catchment/s, information gleaned from these traps would be used to estimate the total litter load/s. Otherwise Table 1 could be used to give a first estimate of likely litter loads. A typical litter density of 95kg/m\(^3\) (Armitage, et al., 1998) can be used to convert masses to volumes if necessary. Then estimate the street cleaning service factor \((f_{sci})\), the vegetation load \((V_i)\) and the basic litter load \((B_i)\) for each land use in each catchment or sub-catchment, and apply Equation 2:

\[
T = \sum f_{sci}(V_i + B_i)A_i
\]  

(2)

where:

\[
T = \text{total litter load in the waterways (m}^3/\text{year)}
\]

\[
f_{sci} = \text{street cleaning factor for each land use (dimensionless)}
\]

This factor relates the anticipated efficiency of street cleaning – including private refuse collection if applicable – to the efficiencies that pertained during data collection. If there is no difference, \(f_{sci} = 1\). Otherwise:

\[
f_{sci} = \frac{(1 - \eta_{design})}{(1 - \eta_{data})}
\]  

(2a)

where:

\[
\eta_{design} = \text{anticipated efficiency of street cleaning (fraction)}
\]

\[
\eta_{data} = \text{efficiency of street cleaning during data collection (fraction)}
\]

\[
V_i = \text{vegetation load for each land use (m}^3/\text{ha.yr)}
\]

(varies from 0.0m\(^3\)/ha.yr for poorly vegetated areas to, say 0.6m\(^3\)/ha.yr = 58kg/ha.yr, for densely vegetated areas)

\[
B_i = \text{basic litter load for each land use (from local data or Table 1) (m}^3/\text{ha.yr)}
\]

\[
A_i = \text{area of each land use (ha)}
\]

4. For each potential trap site, carry out a hydrological assessment to estimate the relationship between the flood peaks and their frequency, and the relationship between the treated flow volume and the design capacity of the structure.

The flood peak / frequency curve (Figure 8) is a plot of the flood peak in m\(^3\)/s versus the recurrence interval (RI), whilst the treated flow volume / capacity curve (Figure 9) expresses the percentage of the total flow volume intercepted by a structure versus its design capacity.
The calculation of the flow volume is shown schematically in Figure 10. Its significance lies in the fact that trapping structures are seldom designed to handle the maximum expected flood peak. Usually they are designed to handle a much lower flow – typically with a RI in the order of one or two months. Under these circumstances, the total volume bypassing the structure will generally be a relatively small percentage of the total. If the assumption (usually conservative) is made that the concentration of litter is...
constant, then the overall trapping efficiency of the structure at any design capacity can be calculated from a knowledge of the proportion of flow passing through the structure. Considerable cost savings can often be made at the expense of a minimal drop in efficiency by selecting a smaller structure with a slightly higher bypass ratio.

The assumption of a constant litter concentration is made in the interests of simplicity. In reality, there is initially insufficient flow to mobilise the litter and any runoff is essentially clear of large particles. Once, however, there is sufficient flow to move the litter, its concentration in the runoff increases sharply to a maximum that is related to the type and quantity of litter available and the carrying capacity of the flow. This maximum cannot be sustained. Even if the runoff rate remains constant, the majority of the litter is soon flushed out of the system and the concentration starts to drop back towards zero. Whilst this pattern is repeated for nearly every storm, the concentration values depend on the condition of the catchment at the time.

The hydrological assessment would typically be carried out with the assistance of one of the numerous urban hydrology computer packages. Care must be taken to ensure that the capacities of any conduits are taken into account.

5. Consideration is now given to the candidate trapping structures. Once a preliminary selection has been made, the patent holders / suppliers should be contacted for more up-to-date information on design and cost.

6. To calculate trap storage volumes and cleaning frequencies, it is suggested that the total litter load is assumed to be split between the significant downpours (with more than, say, 5mm of rainfall) with the greater weighting given to those storms following long, dry periods. Storm litter loads may then be estimated from Equation 3:

\[ S = f_s T / \sum f_{si} \]  

where:

- \( S \) = storm load in the waterways (m³/storm)
- \( f_s \) = storm factor
  - (Suggested factors are:
    1.0 for storms occurring less than a week after a previous downpour
    2.0 for storms occurring after a dry period of about a month
    3.0 for storms occurring after a dry period of about two months
    4.0 for storms occurring after a dry period of more than about three months)
- \( T \) = total litter load in the waterways (m³/yr)
- \( \sum f_{si} \) = the sum of all the storm factors for all of the storms in the year (since this information is generally not available, a suggested alternative is to count the average number of significant storms in a year and multiply by 1.1)
7. The cost-effectiveness of the candidate structures may now be determined by means of an economic analysis. There are many ways of carrying out this economic analysis, but the simplest is described below:

a) For each particular structure, consider several design capacities with RIs varying between, say, 1:1 month (the structure is bypassed twelve times a year) to 1:2 years (which is the capacity of many pipe conduits). For each design capacity, obtain an estimate of the overall efficiency of the trap by multiplying the published trap efficiency by the percentage of flow volume treated by the structure, as previously determined in step 4 above, using Equation 4:

\[ \eta_o = \eta_s \eta_f \]  

(4)

where:
- \( \eta_o \) = overall efficiency of the installation (fraction)
- \( \eta_s \) = published efficiency of the structure (fraction)
- \( \eta_f \) = treated flow volume expressed as a fraction of the total flow

b) The required storage capacity can be calculated as follows. First multiply the proposed average cleaning frequency in days by the average estimated storm load, \( S_{av} \), (determined with the aid of Equation 3 above utilising a typical storm factor \( f_s \) for the area) and by the overall efficiency of the installation. Then divide the result by the average storm frequency (in days) during the wet season determined from municipal records. The calculation is shown in Equation 5:

\[ V_t = F_c \eta_o S_{av} / F_s \]  

(5)

where:
- \( V_t \) = required trap storage (m³)
- \( F_c \) = average number of days between trap clearouts (d)
- \( \eta_o \) = overall efficiency of the installation (fraction)
- \( S_{av} \) = average estimated storm load (m³)
- \( F_s \) = average number of days between significant storms (d)

The storage capacity should ideally also be more than the maximum expected storm load, \( S_{max} \), which is determined from Equation 3 utilising the maximum expected value of \( f_s \). This, of course, assumes that the trap is 100% effective in trapping the litter during this event – a desirable although unlikely circumstance.

c) For each particular type and size of structure, decide on the repayment period, and estimate the capital cost and the real interest rate (a reasonable approximation is to subtract the historic average inflation rate from the historic average nominal interest rate). The capital recovery amount may then be determined from Equation 6:

\[ A = P.i(1+i)^n / ((1+i)^n-1) \]  

(6)

where:
If the payments are subject to inflation, the initial payments will be higher than the later payments in real terms, but this does not change the overall picture.

d) The total volume of litter that the trap is likely to intercept each year at each particular design capacity is obtained by multiplying the total litter load estimated in Step 3 by the overall efficiency of the installation using Equation 7:

\[
L = T \cdot \eta_o
\]  

(7)

where:
\( L \) = load trapped by the structure (m\(^3\)/yr)
\( T \) = total litter load (m\(^3\)/yr)
\( \eta_o \) = overall efficiency of the installation (fraction)

e) The total annual cost of the structure is obtained by adding the annual capital recovery amount to the annual cost of clearing and maintaining the structure using Equation 8:

\[
C_t = A + C_c
\]  

(8)

where:
\( C_t \) = total annual cost of the structure ($/yr)
\( A \) = capital recovery amount ($/yr)
\( C_c \) = annual cost of clearing and maintaining the structure ($/yr)

f) The unit cost of litter removal for any particular structure and design capacity is obtained by dividing the total annual cost of the structure by the estimated annual load that will be trapped by the structure as expressed in Equation 9:

\[
C = \frac{C_t}{L}
\]  

(9)

where:
\( C \) = unit cost of litter removal ($/m^3$)
\( C_t \) = total annual cost of the structure ($/yr$)
\( L \) = load trapped by the structure (m\(^3\)/yr)

Unit costs in terms of $/kg or $/ha.yr may be obtained by dividing the unit cost of litter removal by the litter density (typically 95 kg/m\(^3\)), or by dividing the total annual cost of the structure by the catchment area respectively.

8. In theory, the trapping system may now be optimised to give the lowest overall unit cost of removal. In reality, a balance must be struck between the desire to achieve the lowest
overall unit cost of removal, and the overall objective of removing as much litter from the aquatic system as is reasonably possible – in other words, achieving the maximum efficiency. This is a political decision that requires input from all the role players concerned with the removal of litter from the environment, including engineers, hydrologists, aquatic scientists, environmental interest groups, ratepayers and local government. It may also turn out that costs can be reduced and / or efficiencies raised by putting more money into catchment litter reduction measures such as street sweeping. One further caution; data on trapping structures is site-specific and highly variable, and costs and efficiencies may vary considerably from site to site.

The litter removal process is summarised in Figure 11. The trap selection procedure is summarised in Figure 12.

Figure 11: The litter removal process
Figure 12: Summary of the trap selection procedure

Step 1:
Identify each catchment with its associated drainage system

Step 2:
Identify and measure the area of each land use

Step 3:
Estimate the total litter load from Eq. 2:
\[ T = \sum f_{sci} (V_i + B_i) A_i \]

Step 4:
Carry out an hydrological assessment of:
- flood peak / frequency
- treated flow volume / design capacity

Step 5:
Consider candidate trapping structures

Step 6:
Determine the expected storm loads from Eq. 3:
\[ S = f_s T / \sum f_{si} \]

Step 7:
For each particular structure at each location, consider a range of design capacities and calculate for each:
- the overall efficiency (Eq. 4): \( \eta_o = \eta_s \eta_f \)
- the storage capacity (Eq. 5): \( V_t = F_s \eta_o S_{av} / F_s \) and \( V_t \geq S_{max} \)
- the capital recovery amount (Eq. 6): \( A = P (1+i)^n / ((1+i)^n-1) \)
- the total volume of litter trapped (Eq. 7): \( L = T \eta_o \)
- the annual cost of the structure (Eq. 8): \( C_s = A + C_c \)
- the unit cost of litter removal (Eq. 9): \( C = C_s / L \)

Step 8:
Choose the most acceptable solution balancing:
- cost,
- efficiency,
- sediment removal,
- aesthetics, etc.

Main categories:
- commercial
- industrial
- residential

For each land use, estimate:
- the street cleaning factor, \( f_{sci} \)
- the vegetation load, \( V_i \)
- the basic litter load, \( B_i \)

Main criteria:
- the location
- the flow rate
- the allowable head loss
- the trap size
- the trap efficiency
- the trap reliability
- the ease of maintenance
- cost effectiveness

Estimate:
- the storm factors, \( f_{si} \)
- the sum of all the storm factors, \( \sum f_{si} \)

Input from all role players incl.:
- engineers
- environmental interest groups
- ratepayers
- local government

For each land use,
- the location
- the flow rate
- the allowable head loss
- the trap size
- the trap efficiency
- the trap reliability
- the ease of maintenance
- cost effectiveness

For each land use, estimate:
- the street cleaning factor, \( f_{sci} \)
- the vegetation load, \( V_i \)
- the basic litter load, \( B_i \)
5.3.3 The use of GIS – a case study

The best way of carrying out the trap selection procedure is with the aid of a Geographical Information System (GIS). This is readily illustrated by way of a study that was carried out by Jeffares & Green Incorporated in consortium with Neil Armitage Consulting cc for the City of Cape Town, South Africa (Wise & Armitage, 2002; Marais & Armitage, 2003).

The objective of the study was to develop a litter removal strategy for the Salt and Lotus River catchments within the boundaries of the Cape Town Administration, i.e. it did not cover all of the Salt and Lotus River catchments. These catchments are located roughly in the centre of the Cape Metropolitan Area and have a total gross area of approximately 147km$^2$.

The GIS data sets that were relevant to this study (for example topography, drainage, and land use) were obtained from the Cape Metropolitan Council Administration: Catchment Management Department. These data sets were used to develop a map of the two catchments. The land use across the study area varies and includes agriculture, residential, commercial and industrial activities. A breakdown of the various land uses is given in Table 3.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Area (ha)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>9,937</td>
<td>67.5%</td>
</tr>
<tr>
<td>Manufacture</td>
<td>638</td>
<td>4.3%</td>
</tr>
<tr>
<td>Retail</td>
<td>474</td>
<td>3.2%</td>
</tr>
<tr>
<td>Offices</td>
<td>169</td>
<td>1.1%</td>
</tr>
<tr>
<td>Halls, Stadiums &amp; Entertainment Facilities</td>
<td>109</td>
<td>0.7%</td>
</tr>
<tr>
<td>Taxi Ranks etc.</td>
<td>59</td>
<td>0.4%</td>
</tr>
<tr>
<td>P.O.S., green belts and open land *</td>
<td>540</td>
<td>3.7%</td>
</tr>
<tr>
<td>Farms *</td>
<td>2,046</td>
<td>13.9%</td>
</tr>
<tr>
<td>Other *</td>
<td>757</td>
<td>5.1%</td>
</tr>
<tr>
<td>Total</td>
<td>14,729</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Land-use distribution in study area (* indicates land uses that were not considered to contribute a significant amount of litter)

The land uses marked with an asterisk are those that do not generate significant volumes of litter and were thus not included in the calculations. Of these asterisked land uses, approximately 20km$^2$ (13.9% of the total area) comprises agricultural land.

Discussions were held with the river cleaning teams from the Stormwater Branch of the Cape Town Administration who were able to help in assessing the major sources of litter entering the rivers in the study area as well as the distribution of the litter across the catchment. Interviews were also held with the Cleansing Department District Managers to determine the street sweeping and refuse collection regimes. Particular litter generation hotspots were identified.
The ideal locations for litter traps are those where a step exists in the canal or river floor which will provide hydraulic head for a trap. Locations in the study area where such conditions exist were identified with the help of the Stormwater Branch. Each location was investigated to determine its technical suitability based on the following criteria:

- Canalised? Yes/No
- Width of Channel
- Approximate change in head
- Vehicular access
- Space for structure.

The potential sites were then ranked from poor to very good from a technical perspective.

The study area was then sub-divided into the hydrological sub-catchments applicable to each potential trap location. Each sub-catchment was split into its main land uses using land-use data from the city. The area of each land use was then multiplied by the applicable loading rate (e.g. from Table 1 or 2) to obtain the expected litter generation for each sub-catchment per year (Figure 13). The rest of the trap selection procedure was carried out in accordance with Section 5.3.2.

Figure 13: Litter generation distribution model for the lower-Salt and upper-Lotus Rivers (the potential trap locations are situated at the downstream end of the subcatchments)
Early on during the study it became evident that there are a number of important variables that will significantly affect the litter load generation figures. These included public education campaigns, new regulations regarding plastic bags, the street cleaning frequency and efficiency, and the changing urban environments. It was thus recommended that the litter traps be implemented in a phased approach where one or two traps are installed per phase and the data collected from these traps used to refine the model. The design and sizing of the remaining traps will then be checked using the updated litter collection data and “as-built” efficiency of the existing traps. The first few traps should also be placed as far upstream as possible because, in this way, the downstream traps can be designed with the knowledge gained from the upstream traps. Furthermore, the downstream traps will act as a second line of defence to improve the overall efficiency of the litter removal from the catchments.

6. Costs

A most important component of a catchment litter management strategy is its cost. Costs are however site-specific, and there is always a shortage of reliable data. Table 4 indicates the typical range of costs (2003) in South Africa for various catchment litter management options. Note that some of the options might not be available in specific situations, and the costs are based on optimal, or near optimal conditions. Also, some of the options are not very efficient in the reduction / removal of litter.

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (US$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic refuse collection</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>Street sweeping</td>
<td>1 – 2</td>
</tr>
<tr>
<td>Grids over catchpit entrances (coupled with street sweeping)</td>
<td>1.5 – 2.5</td>
</tr>
<tr>
<td>Clean-outs of the formal stormwater drainage system</td>
<td>0.5 – 1</td>
</tr>
<tr>
<td>Community education programmes</td>
<td>0.3 – 30 (?)</td>
</tr>
<tr>
<td>SCS or UWEM type litter traps</td>
<td>0.2 – 0.6</td>
</tr>
<tr>
<td>Most other litter trap designs</td>
<td>2 – 5</td>
</tr>
<tr>
<td>Removal of litter by hand from the banks of streams</td>
<td>2 – 3</td>
</tr>
</tbody>
</table>

Table 4: Typical South African costs (2003) for various catchment litter management options

7. Conclusions and recommendations

It should be clear from the foregoing that the reduction and removal of urban litter is a complex and difficult problem. Ultimately, each local authority will have to develop a catchment litter management strategy that is appropriate to their conditions.

Obviously, this presentation has had to be brief of necessity. Those wishing to develop a catchment litter management strategy are directed to the following key publications:

The Water Research Commission (WRC) no longer has stocks of this report, but pdf files can be made available to anyone who is particularly interested. Email armitage@eng.uct.ac.za. Alternatively, it has been summarised in Armitage & Rooseboom (2000a, b & c) which may be found on the WRC Website at the following URLs:

- [http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#quantities](http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#quantities)
- [http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#studies](http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#studies)
- [http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#selecting](http://www.wrc.org.za/wrcpublications/wrcwatersa/wsa-apr00.htm#selecting)

2. Mark Marais & Neil Armitage (2003): *The measurement and reduction of urban litter entering stormwater drainage systems*. Water Research Commission (South Africa) Report No. TT 211/03, Pretoria. This may be ordered from orders@wrc.org.za for SUS47 including postage (free if you live in South Africa). Alternatively, it has been summarised in Marais, Armitage & Wise (2004) and Marais & Armitage (2004) which may be found on the WRC Website at the following URLs:


8. Acknowledgements

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References


