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THE REMOVAL OF LITTER FROM STORMWATER CONDUITS IN THE DEVELOPING WORLD

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ABSTRACT

As the less developed countries (LDC's) become more developed, they have experienced an exponential growth in the production of urban litter. Unfortunately few of these countries have the infrastructure to cope with the removal of this litter, and as a result it tends to end up in the water courses. Grids cannot be placed over stormwater inlets for fear of blockage and consequential flooding. Once the litter has entered the drainage system it is difficult to remove. This paper summarises the results of three years of laboratory investigations sponsored by the Water Research Commission of South Africa into the movement of urban litter through potential trapping structures. The results show substantial agreement with those of an independent investigation carried out in Australia. It concludes that declined self-cleaning screens show the greatest promise for the removal of urban litter from most stormwater conduits and streams in the LDC's. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Water pollution control; screens (sizing); storm sewers; refuse collection; litter removal; litter traps.

INTRODUCTION

The problems associated with the removal of litter from stormwater conduits in the less developed countries (LDC's)are somewhat different to those familiar to most professionals working in the more developed countries. As the LDC's become more developed, traditional ways of life are giving way to urbanisation and the consumerism of the more developed countries with their multiple layers of environmentally unfriendly packaging and a throw away mentality. This has resulted in an exponential growth in the production of litter.

Although the central areas of many cities are provided with the normal civil engineering services, poverty and mismanagement frequently lead to the collapse of such basic services as litter collection and removal. Furthermore, many millions of people live in shacks in informal settlements on the urban fringe where services are rudimentary or non-existent. The high intensity rainfall, common to the tropics and subtropics where most of the LDC's lie, soon carries the litter into the drainage system. To compound the problem, in areas where formal stormwater drainage conduits exist (usually separated from the sewage system but that does not preclude an inflow of sewage if the sewage system is poorly maintained - which is often the case), they are often regarded as a form of refuse removal. Grids cannot be placed over stormwater drainage entrances for fear of blockage and consequential flooding, and when they are provided, they are frequently stolen. For most people in the developing world, the struggle for survival takes precedence over care of the environment.

The end result is that in South Africa, for example, more than 780 000 tonnes of litter is estimated to enter the drainage system each year (CSIR, 1991). The bulk of this litter is comprised of plastic bags and containers, tin cans, bottles, and paper, but it is common to see the bodies of dead animals, discarded tyres, mattresses and even the occasional abandoned car in stormwater conduits and streams. This is unacceptable, but there are a shortage of resources to address the problem. Inexpensive, reliable, effective trapping structures are therefore required which ideally have no moving parts, are robust, are vandal proof, require no external power source, are easy to clean (preferably self-cleaning) and do not increase flood levels in the vicinity of the structure. This clearly excludes the standard screens and de-gritting devices commonly found at waste water treatment works. It also excludes the standard trash-racks comprised of vertical or near vertical bars which are commonly to be found across river off-takes. With no surplus flow to scour them, these racks rapidly block from the bottom upwards. To this end, the Water Research Commission of South Africa funded a three year study into the removal of urban litter from stormwater conduits and streams (Armitage *et al.*, 1998).

Although the flows through stormwater conduits and streams in South Africa are often polluted by heavy metals, nutrients and even pathogenic organisms, the study restricted itself to the removal of litter - here defined as visible solid waste. The study looked at many existing structures world-wide, particularly in Australia where separated drainage systems are also used, the climatic conditions are similar to South Africa, and where a lot of research is currently being undertaken into litter traps. Those structures showing the greatest potential for the South African situation were evaluated in greater detail. This paper summarises the results of the parallel laboratory investigations that were made into alternative trapping structures.

METHODS

Nine undergraduate students and one postgraduate student were tasked with developing and testing concept model litter traps or the operational components thereof. The model structures were constructed and tested in the hydraulic laboratories at the University of Stellenbosch and the University of Cape Town. In each case, water was supplied from a constant head tank to a point upstream of the model structure, excessive vorticity was eliminated by passing the flow through a small reservoir and / or flow straighteners (usually in the form of bundled pipes), litter was added to the flow, the flow was passed through the structure, litter that was not trapped was removed by means of a downstream screen, and the water was re-circulated to the constant head tank. The flow was either measured with the aid of an orifice plate in the supply pipe from the constant head tank, or by the insertion of a weir (usually a V-notch) in the channel.

The width of the inflow/outflow channel was different for each model and varied from 280 mm to 900 mm. The nominal scale (which was required for the purpose of relating litter size, litter settling velocity, flow rate, length, depth and slope to prototype structures) was also different for each model, and varied from 1:25 for the smallest models to full scale for the largest.

Plastic chips were generally used to represent litter. Different litter fractions could be modelled by choosing plastic chips of different sizes and settling velocities (related to the shape and density of the chips). In the case of the full scale model, polyethylene shopping bags were used as the representative litter fraction, as previous experience, both in the laboratory and in the field, had shown that these bags are simultaneously the largest single litter fraction (up to 60% of the litter load) and the hardest to trap (Armitage *et al.*, 1998). The trap efficiency of each structure at each flow rate was expressed as the litter fraction trapped divided by the amount of litter released. These quantities were measured by counting the individual items, weighing the litter, or measuring its volume - whichever was most appropriate for the particular test concerned. Particular care had to be taken where litter was weighed or its volume measured, as the results were easily distorted by water and / or air bound up with the particles.

Although the students conducted their experiments as accurately as possible, it soon became apparent that, owing to the highly variable nature of litter to be found in stormwater conduits and steams, and the practical problems associated with modelling this in the laboratory, the results of the tests would be more qualitative than quantitative in nature.

RESULTS AND DISCUSSION

The tests may be conveniently divided into two groups. Initially the investigation was mainly focused on screen-less traps, or traps with a limited penetration into the water column (if the screen blocked, stormwater would still be able to pass the structure with limited upstream flooding). As it became apparent that screen-less or limited screen traps were not efficient in the majority of applications, the focus of the investigation was switched to "self-cleaning" screens. The traps were generally conceived as structures capable of screening the relatively high flows to be expected at some point downstream of a fairly extensive urban catchment.

SCREEN-LESS AND PARTIAL PENETRATION SCREEN TRAPS

Concerns over problems caused by the blocking of screens prompted a series of exploratory investigations into structures that did not use them at all. Attempts were instead made to reduce the transporting capacity of the flow by reducing the average velocity to a point where the suspended material divided into flotsam and bed-load material which could be separated by means of suspended baffle walls and weirs respectively.

Uys (1994). In an attempt to save as much space as possible, Uys split the flow in two around the separation structure, and then turned the two streams inwards through almost 90° to pass under a long baffle wall. A low weir in the downstream channel ensured that the opening under the baffle-wall was always under water. (Fig. 1)

Although the structure seemed to show considerable promise whilst the flow rate was reasonably low, as soon as the flow rate increased above a certain critical value, the increased vorticity re-entrained the scaled litter particles and passed them through the trap and into the downstream canal. Some improvement in retention was achieved by the addition of a second baffle-wall and an intermediate weir on either side, but in general the trap was a failure.

Wilsenach (1994). In the Wilsenach structure, longitudinal slots were located at approximately mid-height along both walls of the inflow channel. This channel ended with a blank wall. The hope was that the bed-load and flotsam would be desegregated as a result of the reducing velocity in the central channel and be trapped there. The slots would then allow the relatively litter-free mid-depth water out of the inflow channel into outflow channels constructed on either side of, and parallel to the inflow section. A downstream weir would keep the water depth in the inflow channel within narrow limits.

Problems were immediately encountered with vorticity in the inflow section as a result of the torturous path the water had to follow through the slots and into the side-channels. The vorticity was particularly severe in the vicinity of the stop-end. The addition of flow deflectors, flow straighteners, and a second weir parallel to the flow direction helped to improve the performance of the trap, but the result was an extremely complicated structure (Fig. 2). Once again the trap was considered a failure.

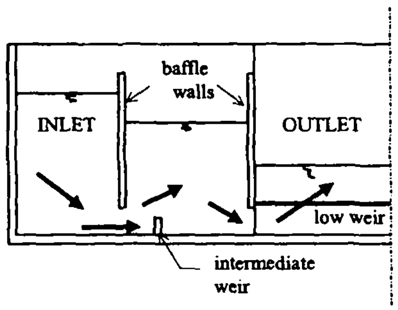

Figure 1. Half-section through the Uys trap.

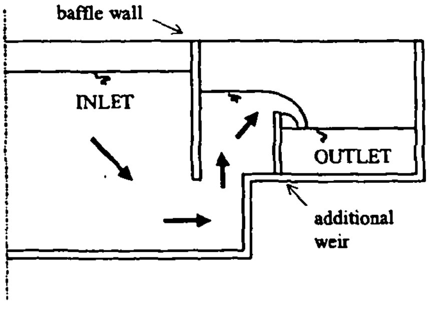

Figure 2. Half-section through the Wilsenach trap (straighteners not shown).

Furlong (1995). The failure of the Uys and Wilsenach investigations now prompted some fundamental research into the limitations of suspended baffle walls as a method of stripping flotsam.

A single suspended baffle wall was shown to be almost completely ineffective at trapping flotsam (Fig. 3(a)). Except at extremely low flow rates, almost all the litter followed the streamlines (indicated by the addition of vegetable dye) and was pulled under the baffle wall. Frequently, more litter was trapped in the vortex downstream of the baffle wall than was trapped upstream of the sluice!

Double baffle walls either acted as though they were one (if they were close together), or like two separate baffle walls (if they were further apart). There did not appear to be any benefit in using double baffle walls.

When a single suspended baffle wall was used in conjunction with a horizontal shelf suspended above the bottom of the channel in the upstream direction (Fig. 3(b)), the combined structure behaved almost exactly as though the shelf was not there and the litter passed beneath the baffle.

If however the solid shelf was replaced with a screen, provided the litter was floating above the line of the screen immediately upstream of the trap, it was generally caught. Very good packing was achieved in the area above the screen, the capacity of which appeared to be only limited by its length. It appeared that there was almost always sufficient draught through the previously deposited litter to ensure that later deposits were overlaid in an efficient manner. The biggest shortcoming with this structure appeared to be the fact that if there was intensive vorticity upstream of the trap, the litter particles tended to move closer to the bottom of the flume and consequently pass underneath. Inclining the screen improved velocity head recovery (Fig 3(c)).

Louw (1995). The purpose of this investigation was to explore the possibility of using an inclined suspended screen in association with a long length of weir to trap the flotsam and bed-load respectively.

The average flow velocity was reduced, partly by expanding the canal section, and partly through the damming effect of the weir. This, it was hoped, would induce the necessary desegregation. To reduce the size of the structure, the weir was constructed in the form of a 'V', with the apex pointing upstream. At the same time, the expanded section was brought uniformly back to that of the original canal over the length of the weir. The uniformly reducing section coupled with the relatively uniform overflow rate over the weir guaranteed that the "forward" velocity was also more or less constant. The long overflow length guaranteed that the normal velocity was fairly small and also more or less constant. No attempt was made, with the small scale model that was used, to study the effect of the addition of the screen. See Fig. 4.

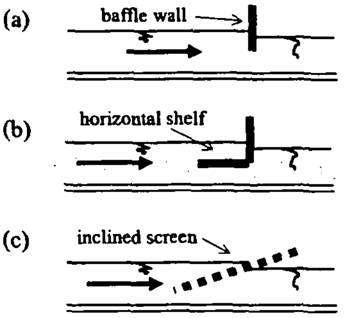

Figure 3. The Furlong experiments.

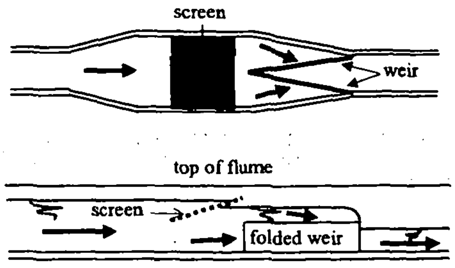

Figure 4. The Louw trap: plan and long-section

Burger and Beeslaar (1996). A key to the success of the Louw structure was the efficiency of the suspended inclined screen in trapping the majority of the flotsam and suspended material. This was now assessed by carrying out measurements with a screen inclined at an angle of 1:5 (vertical:horizontal) to the upstream flow direction (Fig. 5). The tests indicated show that an effective screen opening, a/w = 0,5 resulted in a relatively high trap efficiency, but this was associated with a relatively high head loss. If a/w ≥ 0,6 the head loss across the structure decreased, but so did the trap efficiency. An effective screen opening of 0,5 at the design flow appeared to be the practical lower limit for a partial screening structure if the risk of upstream flooding was to be minimised.

Compion (1997), Part 1. The relative success of the Louw structure prompted an in-depth investigation at a larger scale. Tests were carried out for a variety of flow rates and weir heights for a uniform channel without expansion, and a channel expanded to twice its normal width. Tests were also carried out with the apex of the folded weir pointing both upstream and downstream, and finally, in the case of the expanded channel, with weirs having both single and double folds.

With a single folded weir pointing upstream in a uniform channel without a screen in position using particles with a settling velocity of 27 mm/s (to represent litter with a positive settling velocity), the performance of the trap was almost independent of the channel breadth to weir height ratio. Complete trapping was only achieved when the Froude No (Fr) dropped below about 0,05. If Fr exceeded 0,3, no particles were trapped. Turning the weir around resulted in a decline in trapping performance.

Expanding the channel to twice its initial width was expected to improve the trapping performance since the average velocity would be approximately halved. However the large vortices generated at the diverging section ensured that large numbers of particles were kept suspended by the flow and washed over the weir.

When the screen was installed, there was a major deterioration in the performance of all the layouts. It had now become obvious that the vorticity associated with any obstruction such as an expansion, sluice or screen tends to result in the suspension and carry-over of particles. If partially penetrating screens were to be used in conjunction with weirs, they would have to be kept a substantial distance upstream of the weir.

"Self-cleaning" screens

As it became increasingly clear that screen-less and partial penetration screen traps were not practicable in the majority of stormwater applications, attention was increasingly focused onto "self-cleaning" screens.

Visagie (1994). This layout was investigated as a consequence of problems that Cape Town City Council had had with a litter trap that they built on the Vygekraal Canal in Athlone Park. A screen, comprised of a series of overlapping horizontal rods cantilevered from vertical posts, had been positioned in the canal at an angle of 11° to the flow direction. A 10 m diameter circular "sump" was constructed next to the canal with an opening into the canal in-line with the end-point of the screen (Fig. 6). The hope was that litter would be deflected by the screen into the sump from which it could be later removed. The reality was that litter tended to stick onto the screen - particularly at low flows. The grating only deflected litter at high flows if there was no initial accumulation on the screens. Once deposition on the screens began, the flow direction was affected and the deposits rapidly increased.

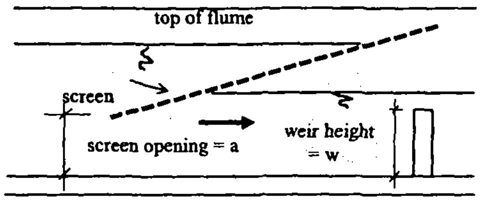

Figure 5. The suspended inclined screen experiments.

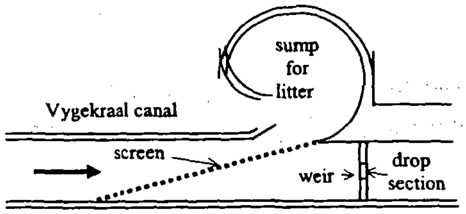

Figure 6. Plan of the Vygekraal Canal trap.

The study clearly showed that the performance of the structure could be improved by the construction of a low weir a short distance downstream of the screen. The effect of this weir was to reduce the average flow velocity through the screen - particularly at low flows. This reduced the head loss across the screen, which in turn reduced the tendency for litter to be pinned against it - giving more opportunity for it to drift into the sump. The higher the weir, the better as this reduced the average flow velocity still further, but of course this also increased the danger of upstream flooding. The shape of the weir was also shown to be important. Better results were obtained when the flow was concentrated down the centre of the canal by means of a central drop-section.

The structure was shown to be particularly vulnerable to large concentrations of litter coming down the canal. In this instance the litter tended to clump together against the screen, or between the downstream end of the screen and the canal wall.

Compion (1997), Part 2. Compion also attempted the development of an in-line, horizontal, self-cleaning screen capable of removing all the litter from the flow with minimum loss of head.

Flow in a 600 mm channel was forced through critical depth over a 100 mm high broad-crested weir. Once over the weir, the flow was directed down a spillway section consisting of a ramp at a uniform 1:10 slope. A horizontal screen, comprising 5 mm wide bars with 10 mm openings orientated in the downstream direction, was placed at the same level as the top of the weir, and connected to it. The hope was that litter would be separated from the flow by the screen whilst the momentum of the water flow would continually push the litter along the bars and out of the way. The ramp was intended to fulfil two purposes - to maintain a large momentum component in the plane of the horizontal screen (approximately 99,5% of the total at the angle chosen), and help minimise local head losses. At the toe of the ramp, the section was abruptly expanded to twice its original width, whilst the horizontal bar screen gave way to a grid sloped at an angle of 25° above the horizontal over the full expanded width of the channel. The expanded section forced the occurrence of an hydraulic jump which at high flows encompassed the lower portion of the sloped grid. Part of the vorticity generated by the hydraulic jump was thus available to redistribute incoming litter over the full face of the sloped grid. Downstream of the sloped grid, the walls of the channel were tapered at 1:4 so as to redirect the flow back into the original channel section with minimum head loss (Fig. 7).

The structure was extremely effective in high flows, in rapidly fluctuating flows, or in situations where, for whatever reason, the downstream water levels increased (reducing the velocities through both screens). Problems however arose after long periods of low flows. Particles would be deposited on the upstream side of the horizontal section to form a temporary weir. If sufficient particles were deposited in this way, they would not readily be moved and would eventually cause blockage of the section.

The tests on a uniform section were not nearly as successful as the test on the expanded section. Without the expansion, control of the hydraulic jump was lost. Without the vorticity generated by the hydraulic jump to redistribute particles on the sloped screen, both screens soon blocked.

The capacity of the structure was of course still limited by the area of the sloped screen, although the tumbling action of the hydraulic jump generally helped to increase the depth of deposit before blockage.

Watson (1996). Watson improved the performance of the self-cleaning screen designed by Compion by installing an inclined suspended baffle wall upstream of the horizontal screen

The baffle wall was designed in such a way that it remained clear of the water surface except at very high flows or until such time as the horizontal screen began to block (Fig. 7). Once blockage commenced, water levels upstream were raised, forcing an increasing percentage of the flow over the blockage on the horizontal screen, under the baffle wall, and through the relatively large open area of the inclined screen (provided of course that this screen wasn't already blocked by the prior deposition of large quantities of material). The acceleration of the water through the gap between the sluice and the screen increased the shear on the deposited material to a point which was usually sufficient to induce it to move. The baffle wall also appeared to help with the packing of material on the inclined screen by increasing downstream vorticity.

Lawson (1997). The review of existing structures that was carried out in parallel to the laboratory investigations had shown the self-cleaning potential of declined screens (the channel flows over a screen that falls in the direction of flow). They had been used successfully on the River Pradin in France (Bouvard, 1992), and more recently in South Africa (Armitage *et al*, 1998) and Australia (Baramy, 1997). There was no agreement however on the optimum bar shape or declination angle. Lawson therefore carried out a series of full scale tests on screens assembled from round bars (R12), rectangular bars (10 mm wide by 30 mm deep) and a tee section (fabricated by welding together two 5 x 15 mm plates) (Fig. 8). The clearance between each bar was kept constant at 15 mm, whilst the angle of declination was varied between 0° and 45°.

A very small declination angle resulted in the accumulation of litter on the screen and eventual blockage. If the angle of declination was increased to a certain critical minimum (different for each bar section), litter would accumulate on the screen until a combination of hydrostatic and hydrodynamic forces would induce it to slide a little. This would open a flow path through the screen upstream of the blockage. Additional material deposition and / or a change in flow rate would cause a commensurate movement of the litter along the screen until an equilibrium position was reached where litter would drop off the end of the screen at much the same rate as it was being deposited. Increasing the angle of declination further eventually resulted in the litter tumbling off the end of the screen without requiring additional deposition.

Within the experimental limits of the apparatus (screen 900 mm wide x 650 mm long, a maximum flow of 60 litres per second, and the litter selected - mainly full-sized polyethylene shopping bags), the critical angle of declination to ensure self-cleaning was 18° for the tee section, 20° for the round section and 22° for the rectangular section. On the other hand, the hydraulic performance - the discharge per unit length of screen - at the critical angle was significantly better for the round and rectangular sections than for the tee section at the flow rates measured. Overall, the optimum screen design (maximum flow capacity for minimum screen size and head loss) appeared to be a round bar section at about a 20° declination angle, but prototype design should be based on experimental data gathered from higher unit flow rates and a more realistic spread of litter type.

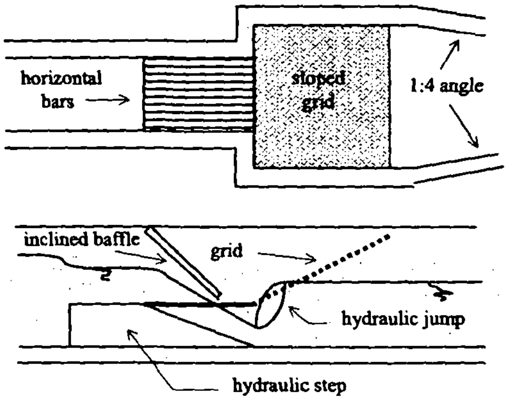

Figure 7. The Compion trap:plan and long-section.

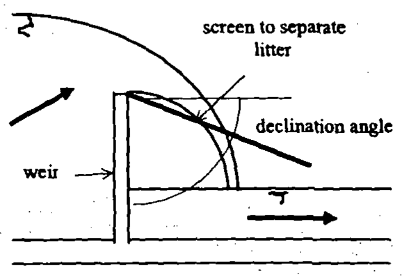

Figure 8. The declined screen experiment.

CONCLUSIONS

The only forces acting on a suspended litter particle are gravity (vertical), pressure (normal to the particle surface), shear (tangential to the particle surface), and inertia (in the direction of movement). These forces combine to cause drag (in the direction of flow), lift (normal to the direction of flow), and rotation.

If a particle touches a screen (or any other solid boundary), then two other forces may come into operation: the reaction of the boundary (normal to the contact surface), and the friction (static or kinetic) resulting from the contact (tangential to the contact surface).

If trapping and consequent blockage are to be prevented, the forces acting to free the particle must be capable of overcoming the forces acting to trap it. Pressure and shear are both directly related to the velocity and velocity gradient of the flow. The reaction of the boundary and the friction resulting from contact are related to the gravity and velocity components normal to the boundary. From this it is clear that the design of litter traps comes down to the advantageous use of flow velocity, velocity gradient and gravity.

The investigations clearly showed that screen-less or partial penetration screen traps are not viable unless there is a substantial increase in flow cross-section resulting in associated decrease in flow velocity (for example through a pond).

Screens can be made to be effectively self-cleaning if they are declined in the direction of flow and continuously subjected to a thin sheet of high velocity flow to maximise the velocity gradient and hence the shear over the screen surface. The bar design is also important. Bars should offer as little resistance as possible to litter sliding along their surfaces, and litter that does penetrate the openings must fall free of the bars. These results show substantial agreement with those of an independent investigation carried out by Beecham and Sablatnig (1994) in Australia.

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