QUANTIFYING THE FIRST-FLUSH PHENOMENON

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ABSTRACT

Removing the first millimetres before rainwater is diverted to a store is a much-used method for ensuring high water quality in rainwater harvesting systems. Such first-flush systems rely on the initial rain to partly wash the roof before runoff water is allowed in the store. While there is almost universal acceptance that this is beneficial, there is no agreement on just how much water should be diverted or indeed whether the diversion should be based on volume, depth or rainfall intensity.

This paper presents an analysis of first-flush based on theory used for calculating dirt loads in urban drainage. The first flush-phenomenon is found to match that theory, which results in the rule-of-thumb "contamination is halved for each mm of rainfall flushed away".

INTRODUCTION

First-flush diversion (whether to waste or to a separate buffer store) is increasingly recognised as a useful way of reducing contaminate loads in rainwater systems e.g. (Church, 2001; Ntale & Moses, 2003). It is becoming more widely practiced as its benefits are better publicised. Such first-flush systems rely on the initial rainfall in a storm to wash the roof before water is allowed into the main store. While there is almost universal acceptance that this is beneficial, there is no agreement on just how much water should be diverted, or whether such diversion should be based on volume, depth or rainfall intensity.

Over the last few years, the DTU has measured runoff turbidities from a variety of roofing materials in several countries. This paper presents the results of those tests, links them to theory widely used in calculations of sediment loads in municipal stormwater runoff and suggests rules for choosing how much rainfall to divert.

FIRST-FLUSH THEORY

How much to flush

The basic idea behind first flush diverters is that the dirt in a stream of water coming off a roof is also an indication that the roof is becoming cleaner. The continuous removal, by the washing action of rainfall as a storm progresses, of dust and other debris from a roof results in the runoff stream getting progressively cleaner. This means that if one diverts the first part of a storm away from the water storage, the remainder will be much cleaner and the need for its subsequent treatment is reduced or even eliminated. Unlike filtering, this is true for both suspended and dissolved material.

There has been a fair amount of literature dedicated to the first-flush phenomenon. The classic paper is that of Yaziz et.al. (Yaziz et al., 1989) where a number of experiments based on fixed volumes (aliquots) are described. He suggested, as a rule-of-thumb *for the roof he studied,* diverting 5 litres of foul flush. Other publications have recommended “between 1 and 2 gallons / 100 ft^2 of roofing”, i.e. 0.4–0.8 mm of rain. (Texas Water Development Board, 2005) and, “20-25 litres for an average size roof” (enHealth Council, 2004). These rules-of-thumb have a large number of built in assumptions that may or may not be true. Often, particularly in rural areas of low-income countries, they substantially underestimate the amount to flush.

There has been a great deal of interest in the first-flush phenomenon from engineers involved with stormwater runoff in urban areas. A number of formulae have been developed that are routinely included in such software as the US-EPA Stormwater management model (SWMM) (US-EPA, 2003). The physics of deposition and removal of material on urban hardscape is similar to that of roofs, however there are several important differences.

- Roof catchments are more closely-coupled to their destinations so spatial effects (such as delays in sediment arriving at an outlet) will be much reduced
- Roofs have few different materials and the materials used tend to be smooth
- The slope of roofs is generally greater than that of streets

Sartor and Boyd (Sartor & Boyd, 1972) developed an equation to describe the changes in runoff quality from streets as a function of rainfall intensity and time:

$$N = N_0 e^{-krt} \tag{1}$$

where:

N is the sediment remaining, itself determining the turbidity of current runoff
N_0 is the initial sediment load available to wash-off prior to the rain event
k is a constant (of dimensions – mm^{-1})
r is rainfall intensity (mm/hr assumed constant during storm) and t is rain duration (hr)

We can usefully also employ t to mean ‘time since storm started’, in which case the product of r and t is cumulative depth of rain that has fallen. This formula provides a slightly simplistic view of first flush but does point to an exponential reduction as the storm progresses. The value of k was found to vary from 0.01/mm to 0.18/mm and was affected by street texture, but not by rainfall intensity and particle size. The value to be used for k are however the subject of much controversy and most recent authors recommend it be determined locally. In any case, the differences between roof and road catchments mean that their values for k are likely to be substantially different.

The affect of rainfall intensity

Since Sartor and Boyd published their results, a number of authors have found correlations between rainfall intensity and particle removal. Sensitivity to rainfall intensity is conventionally described by multiplying N_0 in equation 1 by an empirically derived “availability factor” (A) to get a value N_{0a} relevant to a particular storm (Novotny & Chesters, 1981) This corrects for the relative energy of the particular rainfall – light rains with less energy can only access less sediment. Thus:

$$N_{0a} = A\, N_0 \qquad \text{where} \qquad A = 0.057 + 0.04r^{1.1} \tag{2}$$

The value of factor A should be less than or equal to 1. A reaches this maximum value at intensity r =18 mm/hr. As a large portion of tropical rainfall exceeds this intensity, one might assume A has a value close to 1 in the tropics. Roof catchments are also smoother and more sloped than road catchments so the energy needed to move sediments should be lower and A=1 will be reached at lower rain intensities than for roads.

The speed of contaminant build-up

The speed of contamination build up is a contentious issue. It is generally agreed that the deposition of debris/dust is a linear phenomenon, however there are also present non-linear processes of material removal, mainly through wind action, which confuses any modelling. This confusion is exacerbated by the noisiness of the datasets that characterise all studies of sediment build-up on streets. Most road surfaces also have means of material removal – such as the passage of traffic - not available to roofs. Nevertheless several attempts have been made to model contamination build up on roads and these have some relevance to roofwater harvesting systems.

Possibly the most useful equation is by Pitt (1979):

$$Y = ax - bx^2 + c \tag{3}$$

Where

Y is the contaminant loading on a road at time x
a, b and c are constants
ax represents the process of dirt accumulation
bx^2 represents the various processes of dirt removal (such as traffic and wind)
c represents some initial dirt loading

After a long period of time, this equation will predict a *falling* level of contamination (due to the quadratic term in the equation). However it is assumed that once the maximum value for Y is reached its value will remain stable until the next rain. On streets, this time to reach a maximum can be one week, however on roofs it should be considerably shorter as the materials are smoother and roofs are higher where wind tends to be stronger. It should also be noted that wind is also a primary force for *deposition* of material onto roofs, adding to the uncertainty.

MEASUREMENT OF FIRST FLUSH

To assess the parameters of the first flush phenomenon, the DTU and collaborators have carried out a large number of aliquot-based tests in a number of locations and with several roof types.

Apparatus and Methodology

The apparatus can be divided into two major components

- the catchment
- the sampler

The catchments were mainly specially constructed roofs consisting of several different roofing materials placed next to each other on a single structure (Figure 1a). Each section was about 1m^2 in area and was separately guttered. The slope of the roof was typical of local housing made with that material. Roofs were made from a variety of materials;

- Corrugated galvanised iron sheet (GI),
- Corrugated asbestos sheet

- Clay tiles
- Tar sheet.

The roofs were variously located, namely:

- Near to a dirt road (Kampala – Figure 1b)
- Away from the road in a compound (Kampala, Kandy)
- Near to a busy tarmac highway (Colombo)

The sampler was based on the design used by Yaziz et. al. for their FF experiments. It consisted of bottles connected together in series (Figure 1b) so that the first bottle fills, followed by the second and so on. Each bottle was connected with a long pipe to constrict the zone of mixing and prevent subsequent water from mixing with that in an already full bottle. The apparatus was mounted at an angle to ensure each bottle fills in turn. As an exponential decay was expected, each bottle was generally larger than the one before. Several series of bottles were used as the experiments developed.

- 0.5, 0.5, 1.0, 1.0, 1.5, 1.5, 1.5 (litres)
- 1.0, 1.0, 1.0, 1.5, 1.5, 1.5, (litres)
- 0.5, 0.5, 1.0, 1.5 (litres)

All horizontal pipe lengths were made as short as possible and their capacities recorded. A means of draining the pipes down was installed on the inlet end of the apparatus

Figure 1: Equipment used in one of the experiments

a. Tile and GI roofs c. Location near to a dirt road b. Bottle array

As soon as possible after a rainfall event, water from each bottle was tested for turbidity, a measure which is well correlated with suspended solid contamination. Some samples were also tested for conductivity (to measure dissolved contamination) and for thermo-tolerant coliforms (to test for risk of microbiological contamination). The date, total rainfall in the storm and days since the last storm ended were also recorded.

After each test, the pipes were drained down and the bottles thoroughly rinsed to ensure contamination was not carried through from test-to-test.

Results

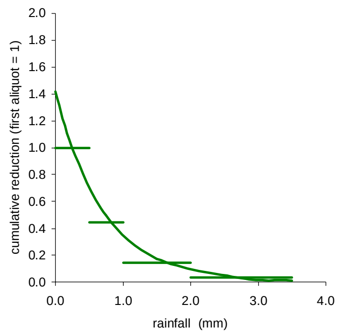
The turbidity results were recorded along with the capacity of the bottle used and the size of the roof. These results were normalised to the turbidity of the first sample, i.e. the turbidity of each aliquot was expressed as a fraction of the turbidity of the first aliquot. These fractions were averaged over the total samples for that roof type and location.

The results are graphed below in Figure 2. The width of each horizontal line represents the rainfall contained in each aliquot sample and the height of the line is the fraction of the turbidity of the initial sample. Curves representing the Sartor and Boyd formula have been fitted by eye to the results and the value for k noted.

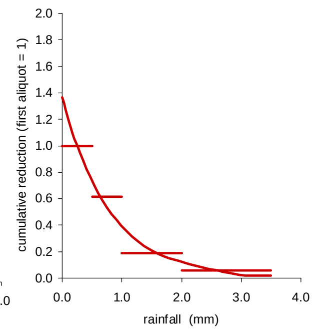
Figure 2: Results of aliquot-based field readings with fitted Sartor/Boyd curves

Vertical axis equals turbidity of particular aliquot / turbidity of first aliquot
Horizontal axis is cumulative rainfall (mm) since rain event began
Exponential decay constant k has units mm^{-1}

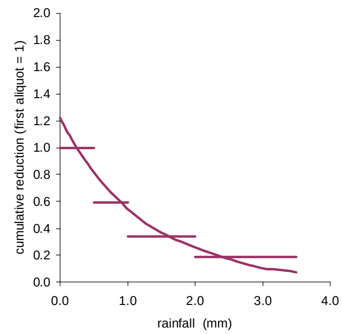
(a) Kampala; Tiled roof away from road. k = 1.4



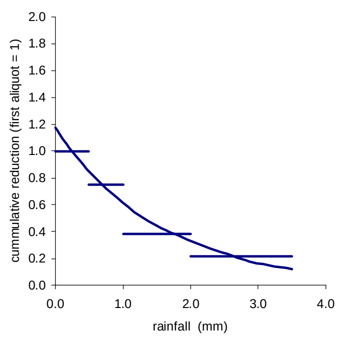
(b) Kampala; GI roof away from road. k = 1.25



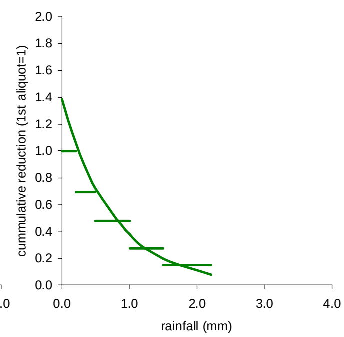
(c) Kampala; Tile roof near road. k = 0.8



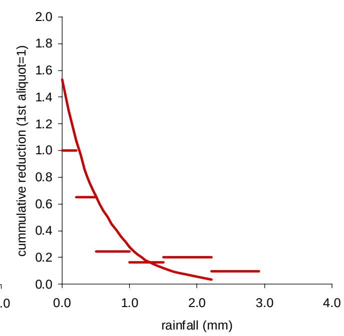
(d) Kampala; GI roof near road. k = 0.65



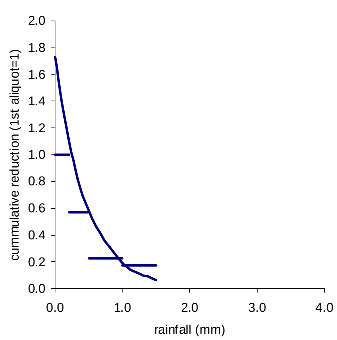
(e) Kandy; GI roof away from road. k = 1.4



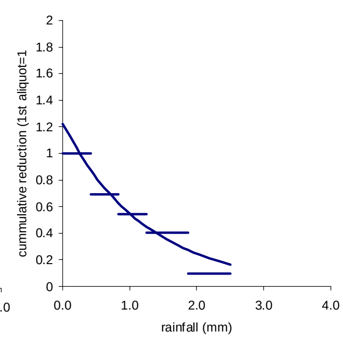
(f) Kandy; Asbestos roof away from road. k = 1.7



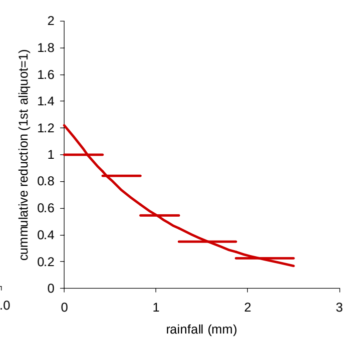
(g) Kandy; Tar Sheet roof away from road. k = 2.2



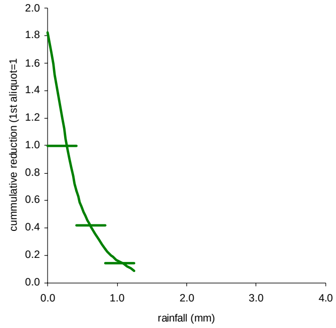
(h) Colombo Asbestos roof close to highway. k = 0.8



(i) Colombo; GI roof close to highway. k = 0.8

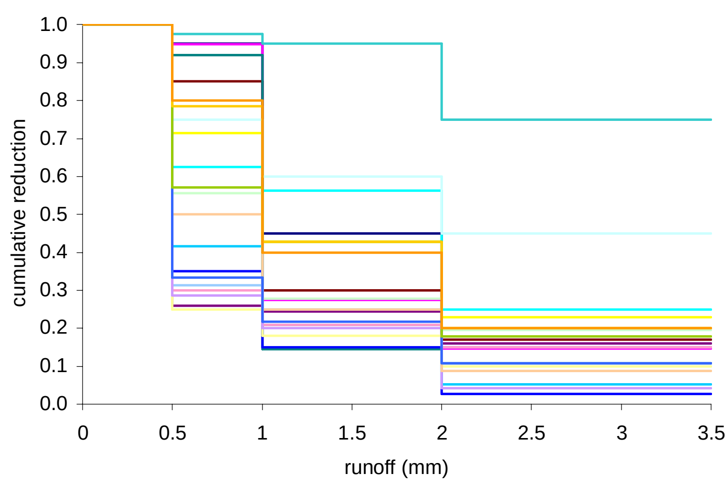


(j) Colombo; Tar-sheet roof close to highway. k = 2.2



The fit is sometimes very good, but the poor resolution of the samples and the uncertainties in measuring turbidity in the field mean that an exact fit is not possible. The data is also noisy with differences in data sets of an order of magnitude (see Figure 3), so the results should be treated as an approximate only. They do, however show a fairly narrow range for k and allow a sensible calculation of first flush amount based on initial turbidity.

Figure 3: Typical set of relative turbidities (first 3.5 mm of runoff for a single roof)



RULES OF THUMB

The good fit of the aliquot data to the Sartor & Boyd equation and the (relatively) narrow range of values for k, allows the development of a simple rule of thumb for sizing first flush systems. If we take a low value found for k (0.7 mm^{-1}) to produce a fairly conservative model we obtain the following rule:

"For each mm of first flush the contaminate load will halve"

This means that to reduce very dirty (say 2000 NTU) water to the high WHO standard of 5 NTU (WHO, 1997), the first 8.5 mm of rain will have to be diverted. This is an extreme case and was only encountered at sites close to a dirt road and after a long dry period. The average initial turbidity near a dirt road was closer to 900 NTU (needing 7.5 mm of first flush to reach that standard), away from roads this average dropped dramatically to 150 NTU (needing 5 mm of first flush).

The large amounts of first-flush water indicated by this model look alarming, however placing them in an annual mass balance model is reassuring. If we assume that in a typical

household system we flush off the recommended number of mm if rainfall follows 3 dry days (but none if the previous rainfall was within 3 days), the amount diverted will only comprise 2%-4% of annual roof runoff with a 3mm first flush or 4%-7% with a 7mm FF.
These examples also assume that the water *entering* the tank must be of WHO quality – Actually the standards refer only to water *exiting* the tank. Further processes such as sedimentation take place in the tank that substantially reduce the water's turbidity. In addition, the turbidity should be averaged over the total water entering the tank after the first-flush diversion. This average will be lower than that measured immediately following first-flushing.

To design a first-flush diversion system we therefore suggest you:

1. measure mean runoff turbidity on wet days following at least 3 dry days,
2. select a target maximum turbidity at which we will allow water to enter the main tank – 20 NTU is usually sufficient,
3. employ the table below to decide how many millimetres to divert
4. divert that amount of water whenever rainfall follows at least 3 dry days.

Table 1 : Recommended first-flush amounts (in mm rainfall)

	Target turbidity (NTU)			
	50	***20***	**10**	**5**
Mean runoff turbidity (NTU)				
50	0	*1.5*	2.5	3.5
100	1	*2.5*	3.5	4.5
200	2	*3.5*	4.5	5.5
500	3.5	*4.5*	5.5	6.5
1000	4.5	*5.5*	6.5	7.5
2000	5.5	*6.5*	7.5	8.5

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