Quantifying the First-Flush Phenomenon: Effects of First-Flush on Water Yield and Quality

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ABSTRACT
First-flush diversion is increasingly recognised as a useful intervention to reduce both suspended and dissolved contaminate loads in rainwater systems. Such first flush systems rely on the early rain to wash the roof before 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 is to be diverted and the reset of the device rarely considered. In a paper delivered at the 12th IRCSA conference the authors presented a number of field measurements and derived an exponential decay constant for the first-flush phenomenon based on rainfall depth. This paper builds on these results by applying this decay constant, and a time constant for debris accumulation derived from the same data, to a water-balance model. The results show that most current first-flush devices used in the field have a poor performance; however it is possible to remove up to 85% of incoming material while retaining 85% of the water if the device is designed carefully. Better material removal performance is possible but only at the expense of lower water yield; similarly water yield can be improved by reducing overall material removal. The key to good performance is found to be to use a slow device reset combined with a large water diversion, though not as large as had been initially feared. A design procedure is discussed along with practical technical constraints, possibilities and currently available techniques.

KEYWORDS
Accumulation; mass balance; first-flush; wash-off; water quality; water yield.

INTRODUCTION

First-flush diversion is increasingly recognised as a useful intervention to reduce contamination in rainwater systems. Such first-flush systems rely on the initial rainfall in a storm to wash the roof before water is allowed into the main store. First flush systems have a number of advantages over filtration:

- They are not sensitive to particle size, which is particularly important when the small size of roof dust is considered
- They will remove dissolved contaminants as well as suspended ones, which is important if trace minerals such as lead and zinc are problematic

While there is almost universal acceptance that this is beneficial and impressive results have been shown for the effectiveness of first flush devices on water quality in rainwater tanks (Abbott et al., 2007; Ntale and Moses, 2003) , there is no agreement on just how much water should be diverted, or whether such diversion should be based on volume, rainfall depth , rainfall duration or rainfall intensity.

In a paper presented at the 12th conference in New Delhi (Martinson and Thomas, 2005), the authors presented a relation for wash-off based on the exponential decay function derived by Sartor and Boyd (1972) and determined the appropriate constants for roof runoff based on a series of measurements of roof runoff. The measurements presented showed a wide variation but allowed the generation of a simple rule-of-thumb for first-flush behaviour:

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

This rule remains a useful simplification, but the interactions between the underlying physical processes and equipment performance are complex, and a more detailed approach is required to properly design first-flush devices.

This paper describes the results of a series of water balance models used to simulate the effect of first-flush devices on the water quality and water yield of a roofwater harvesting system and presents an empirical formula and procedure to calculate the necessary design parameters for first-flush diverters. As space is limited the specific derivation of the equation is not detailed in this paper, however the behaviour discovered is described and the rationale behind the derivation is presented. The underlying detail is the subject of a journal paper currently in preparation and is also described in Martinson (2008). The nature of the work is necessarily mathematical, however it is hoped that practitioners interested mainly in sizing systems will find the results useful.

METHODOLOGY

The flow of contaminants and water through the system

The performance of a first-flush system depends on the physical processes involved in the accumulation of material on the roof and on the flow of water and contaminating material off the roof and through the system. These flows interact with first-flush device and the storage tank and are summarised in Figure 1 and described below.

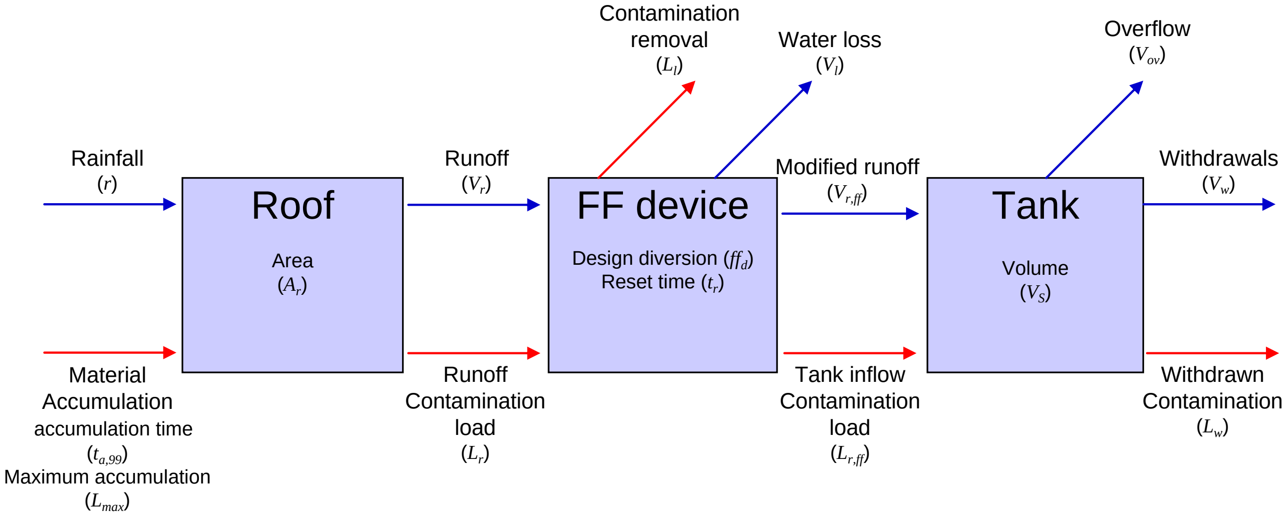


Figure 1: Contaminant and water flow through a RWH system with first-flush

1. Material accumulates on the roof over time.

2. During a rainfall event, rain falls on the roof, collects some of the accumulated material, which mixes with the water. Both the runoff water (V_r) and runoff contaminant (L_r) flow into the first-flush device, the contaminant concentration reducing with rainfall.

3. The first-flush device diverts a certain amount of the rainfall depending on its volume and allows the remainder to enter the tank. The design diversion (ff_d) of the first-flush device represents the maximum that can be flushed, however once the rain has stopped, a well designed diverter will slowly reset over time and so when it next rains the device may not be completely

reset. As a result, the actual first-flush diversion (*ff*) will increase with antecedent dry period until the full design diversion is reached after the complete reset time (t_r).

4. Once the first-flush device has diverted the appropriate amount, the runoff water is then allowed to enter the tank. Thus there will be reduced water flow ($V_{r,ff}$) and a reduced contaminant flow ($L_{r,ff}$) delivered to the tank.

Steps 3 and 4 form the first interaction between physical processes and equipment performance. The most obvious is the first-flush diversion interacts with the change in contaminant level to produce the reduction in contaminants entering the tank over the course of a rain event. A lesser understood interaction is the accumulation of contaminants on the roof and the resetting of the diverter which results in changes in the level of contaminants entering the tank from one rainfall event to the next. Generally, it is assumed that the reset is fast enough that the diverter will completely reset before the next rainfall event. This is not necessarily the case, nor is it desirable.

5. Finally, Water is and contaminant is withdrawn from the tank or allowed to overflow.

This second interaction is important, primarily as the reduced water flow ($V_{r,ff}$) interacts with the tank volume, user demand behaviour, overflow, and volumetric diseconomies of scale to substantially change the volumetric efficiency of the total system – generally for the better.

Physical processes

Material wash-off. The wash-off of contaminants is well described by the exponential decay function derived by Sartor and Boyd (1972). The function is based on the assumption that the rate of removal of material washed off a surface is proportional to the amount of material present on the surface and the rainfall intensity. As discussed in Martinson and Thomas (2005), the Sartor-Boyd function can be simplified and stated in terms of accumulated rainfall:

$$L = L_0 e^{-k_w r} \qquad \text{Equation 1}$$

Where; L is the contaminant load remaining; L_0 is the initial contaminant load; k_w is the wash-off constant (mm^{-1}); r is the accumulated rainfall (mm).

Material accumulation. The accumulation of material on a roof between rain events has two components:

- Deposition of material
- Removal of deposited material by wind etc.

An assortment of accumulation functions are used and the most commonly applied was developed by Shaheen (1975). It considers material deposition to be linear and removal to follow the same rules as first flush:

$$L = L_{\max}\left(1 - e^{-k_a t}\right) \qquad \text{Equation 2}$$

Where L is the contaminate load; L_{max} is the maximum contaminate load that can be sustained by the surface, or more specifically the equilibrium load where the deposition and removal processes balance; and k_a is the "accumulation constant" (hr^{-1}). For simplicity, this can be expressed as an accumulation time (t_a) which is the time required to achieve a certain fraction of L_{max} e.g. $t_{a,90}$ is the time needed to achieve a 90% of L_{max}.

Diverter parameters

First-flush design diversion. The design diversion (ff_d) is the maximum rainfall a first-flush diverter is capable of removing. In most cases, this will be when the diverter has fully emptied.

First-flush device reset time. The device reset time (t_r) is the time it takes for the first-flush diverter to reset itself – usually by emptying. The device reset may be linear, e.g using a slow release valve or by user behaviour such as regularly removing a set volume of water; based on turbulent emptying, e.g from a weep hole in the bottom of the diverter; or by laminar emptying, e.g by seepage through a porous substance. In the case of laminar emptying, the device will never completely reset so the reset time must be considered in the same way as accumulation time. i.e $t_{r,90}$ is the time needed to achieve a 90% of complete reset.

First-flush diversion. The diversion (*ff*) is the actual rainfall that a diverter removes for a particular rainfall event. If the antecedent dry period is longer than the reset time this will be the entire design diversion, if it is shorter, the diversion will be less than the design diversion.

Performance measures

First-flush diverters change the inlet stream; reducing the contaminant load, but usually also reducing the water delivered to the tank. The more water that is diverted by the first first-flush device, the cleaner the water delivered to the tank will be, however greater diversion will also mean less water will be delivered to the tank. Balancing these factors is key to rational first-flush device design.

Removal efficiency. The removal efficiency (η_r) of a first-flush system is a measure of how well it removes contaminants from the incoming water stream. It can simply be defined as the ratio of contaminant removed by the first-flush system (L_l) to the total contaminant load washed off the roof (L_r):

$$\eta_r = \frac{\sum L_l}{\sum L_r} \qquad \text{Equation 3}$$

The measure can either be applied over an individual storm or over a number of storms. In this paper, the removal efficiency is applied to the entire time series to give the overall performance of a particular system.

Volumetric efficiency. The volumetric efficiency (η_v) is a measure of how little water is "wasted" by the first-flush system. It can be measured in two places; the tank inlet ($\eta_{v,i}$) and the tank outlet ($\eta_{v,o}$). The most intuitive loss to consider is that at the inlet; however in reality it is the loss at the tank *outlet* reflecting the reduction in available *withdrawals* that is the real loss to the user. The efficiency when measured at the tank outlet differs significantly from the inlet and is usually higher.

Volumetric efficiency at the tank inlet ($\eta_{v,i}$) can be calculated by simply dividing the sum of runoff after first-flush diversion ($V_{r,ff}$) by the sum of the runoff without diversion (V_r), as the roof area is the same for both, the $\eta_{v,i}$ can simply be calculated using the rainfall (r) and first-flush diversion (ff):

$$\eta_r = \frac{\sum V_{r,ff}}{\sum V_r} = \frac{\sum (r - ff)}{\sum r} \qquad \text{Equation 4}$$

Volumetric efficiency at the tank outlet is calculated by using $V_{r,ff}$ in place of V_r in a mass balance and dividing the total withdrawals from the system with the first-flush diverter ($V_{w,ff}$) by the total withdrawals from a separate mass balance without first-flush diversion (V_w)

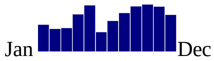
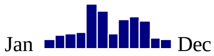
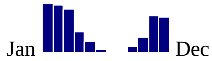
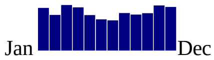
$$\eta_{v,w} = \frac{\sum V_{w,ff}}{\sum V_w} \qquad \text{Equation 5}$$

The mass balance model

The processes described above were used in a mass balance that modelled the material accumulation and washoff, roof runoff, first-flush diversion, tank storage and user behaviour. More specific detail regarding the technicalities of the model and equations used can be found in Martinson (2008)

The model used fifteen minutely data which was obtained from the US National Climatic Data Center (NCDC product DS3260) representing a number of climate types and rainfall patterns as shown below in Table 1. The data was chosen to reflect single wet season and bimodal rainfall distributions in both high and low rainfall areas. A typical temperate climate with medium rainfall without marked seasonality was also included for comparison.

Table 1: Data sources

State	Town	Köttek climate type	Mean annual rainfall (mm)	Rainfall Pattern
Puerto Rico	Corozal	Am	1 900	
Texas	Big Lake	BSh	480	
California	Blue Canyon	Dsb	1 700	
Hawaii	Kekaha	As	550	
Rhode Island	Newport	Cfa	1 200	

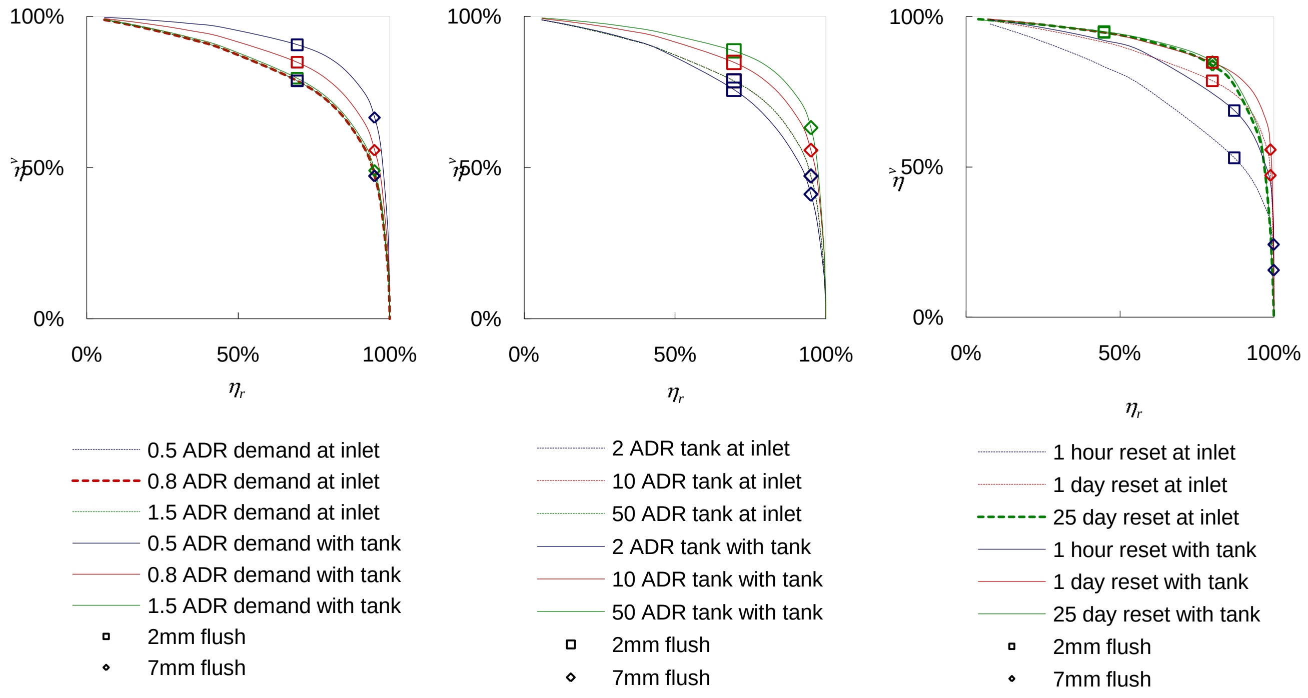
The results of each simulation were a removal efficiency and volumetric efficiency for the design diversion and reset time selected. A series of simulations were carried out for each location varying diverter parameters and other system parameters such as user demand, demand pattern and storage volume. All volumes were non-dimensionalised by dividing by the average daily runoff (ADR) from the roof and so the results are scalable. Each parameter was varied separately from a "standard" system where the tank volume was 10 x ADR and nominal demand was 0.8 $\times$ADR. Based on the sampling reported in New Delhi and some further analysis of this data, accumulation time was taken as 99% of maximum in 25 days and wash-off as halving for each millimetre.

RESULTS AND DISCUSSION

Efficiency trade-offs and the effect of system parameters

To gauge the trade-offs between removal efficiency and volumetric efficiency, the reset was set to match the accumulation and the design diversion was varied. The removal efficiency and the volumetric efficiency at the tank inlet and outlet were noted and plotted. Typical results are shown in Figure 2. The figures show the results from only one location (Corozal), however very similar patterns of results were obtained from all locations.

The results consistently show that first-flush diversion is more volumetrically efficient with larger tanks and with smaller demand while demand pattern was found to have a negligible effect. The volumetric efficiency is also consistently greater at the tank outlet than for the incoming stream. A particularly interesting result is shown in Figure 2c which shows that matching reset to accumulation is not the optimal solution and that a faster reset time can yield better performance.



a. Varying demand **b.** Varying tank size **c.** Varying reset time

Figure 2: Removal vs volumetric efficiency graphs

Iterative optimisation and empirical rules

Figure 3 plots the effect on volumetric efficiency resulting from a number of mass balance simulations where reset time is varied until a target removal efficiency is achieved for a certain FF diversion.

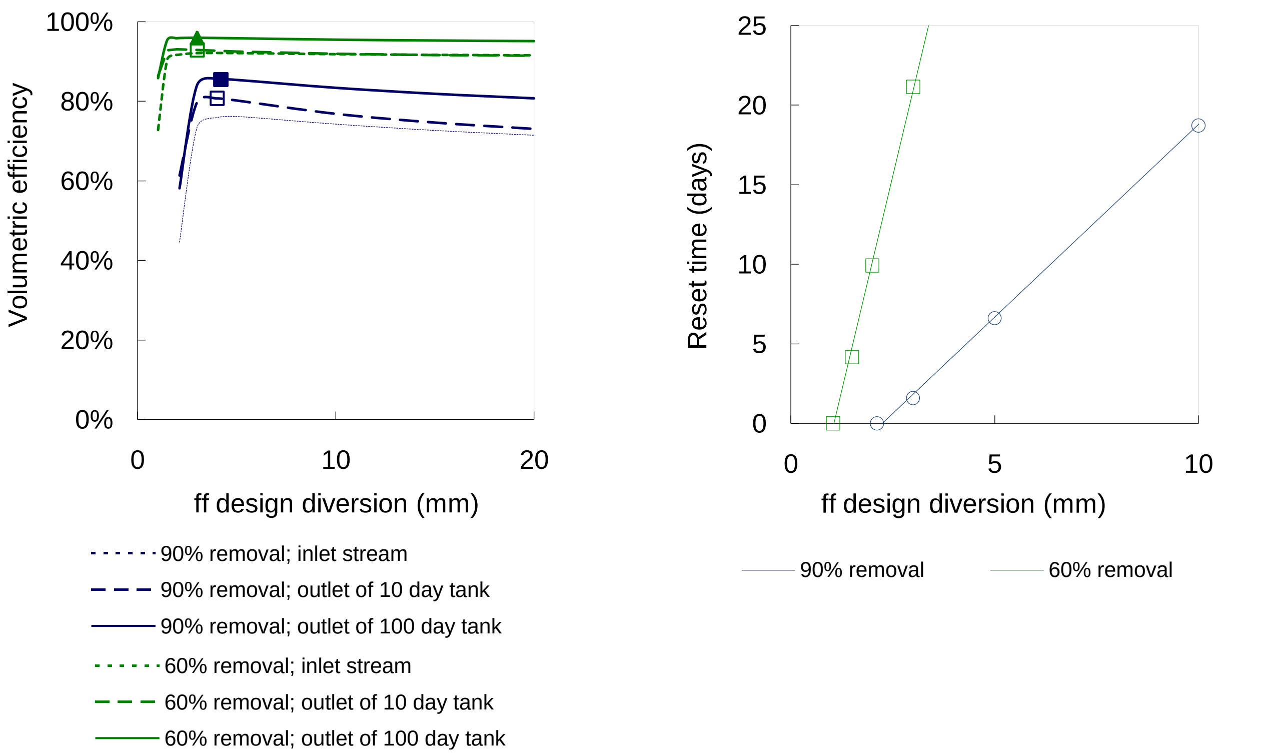


Figure 3: Optimal design diversions and reset times

The diversion graphs quickly rise to a peak and slowly fall with the design diversion corresponding to the peak value changing slightly with the presence or absence of a tank and only very slightly with tank size. Therefore, for a given location, optimising for any particular removal efficiency results in a very similar design diversion regardless of other system parameters. There is only a small penalty for going above the optimum diversion providing an appropriate reset time is used but making the device too small has a large penalty. Very poor efficiencies have been reported for small devices with quick resets for example Gardner et.al (2004) reported volumetric efficiencies as low as 62% with a 0.5mm diverter and a reset of about 20 minutes. The reset times show a remarkably linear relationship with design diversion.

The similarities between optimal design diversion and the linear relation between reset time and design diversion make it possible to generate an empirical formula that approximates optimal conditions.

A series of curve fitting exercises was performed on the optimal design diversion (in mm) over the 5 data sets simulated and the resulting formula is found to be:

$$ff_{d,opt} = 1 - 1.2\ln(1-\eta_r) \qquad \text{Equation 6}$$

And the reset time (in days) can be found by:

$$t_r = \frac{19000(1-\eta_r)}{r_a}\left(ff_d - 0.24e^{2.4\eta_r}\right) \qquad \text{Equation 7}$$

Unfortunately, this optimum still requires reset times in the order of several days. Devices are available that use slow release valves (Rain Harvesting, n.d.) and seepage through porous media is also a possibility (Knight, 2005), however faster reset are desirable as they are far less technically challenging.

Further iterative simulation limiting the reset time to particular values produces the results shown in Figure 4 which shows that lower reset times may be used, though with some penalty in volumetric efficiency.

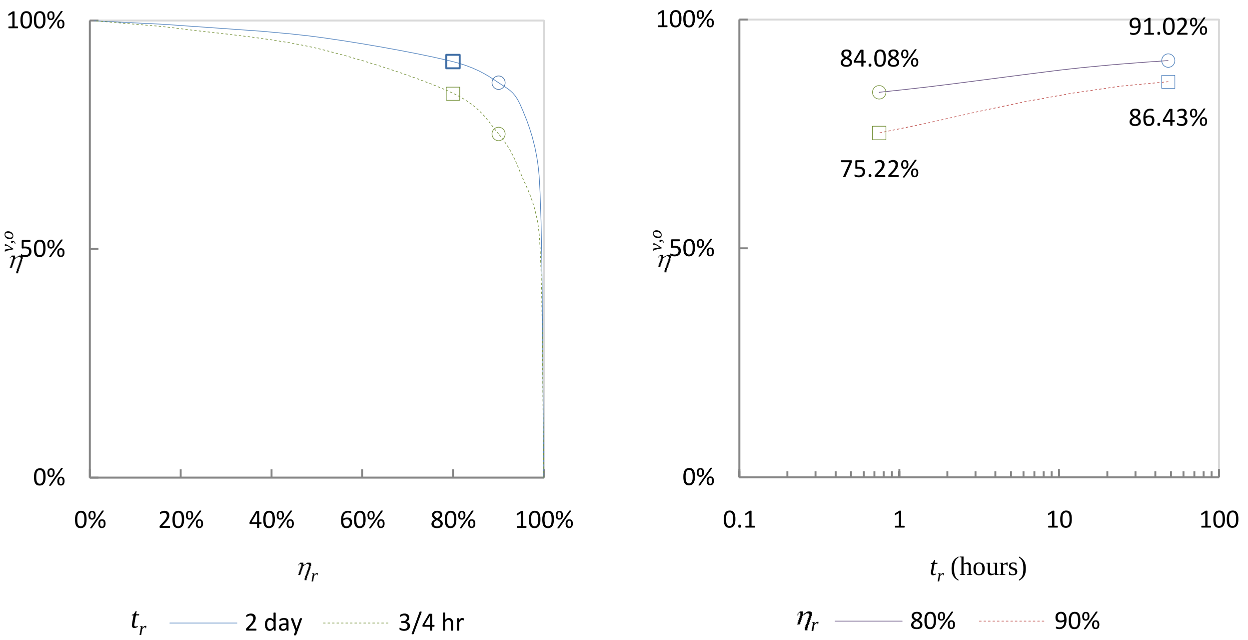


Figure 4: Difference in performance between a slow and fast reseting optimised first-flush device

The penalty can be reasonably significant; however the simplicity afforded by the faster reset may make the trade-off in performance desirable. This suggests a more practical method of optimising a first-flush diverter whereby the longest reset technically practical is used and the design diversion calculated from Equation 7 which can be rewritten in terms of design diversion and with the reset time, more conveniently expressed in hours:

$$ff_d = \frac{r_a}{450\,000}\frac{t_r}{(1-\eta_r)} + 0.24e^{2.4\eta_r} \qquad \text{Equation 8}$$

Applying $ff_d = \frac{r_a}{450\,000}\frac{t_r}{(1-\eta_r)} + 0.24e^{2.4\eta_r}$ Equation 8 to small reset times of an hour does show that typical design diversions of 0.5mm are too small to be effective which is confirmed by simulations of such small diversions which show they have a removal efficiency of less than 35%. A more sensible diversion is over 2mm which both calculation and simulation yield a removal efficiency of about 90%, however the quick reset means that volumetric efficiency is only about 75% which in some situations may be problematic. In these cases, a smaller removal efficiency will need to be accepted or a slower reset specified.

CONCLUSION

The mass balance models used in this study have shown that diverting the first part of the rainstorm can reduce the incoming contamination by 90% while delivering 85% of the water as measured after the storage tank. Greater material removal is possible but with significant loss of water. The rainfall that needs to be diverted is generally larger than the capacity of most devices currently being used, however it is not as large as had been initially feared in Martinson and Thomas (2005). Ideal reset times are significantly lower than the technically unachievable matching of reset and accumulation and furthermore, reset times that are relatively straightforward can be used with a relatively small performance penalty.

Design procedure

1. Establish the desired removal efficiency
2. Establish the maximum reset time technically possible
3. Use figure 4 to confirm the removal efficiency has a volumetric efficiency in an acceptable range. Note: Figure 4a is based on the assumption of a tank that provides about 80% of the building’s water and total water demand that is about 80% of available runoff. Smaller tanks and greater demand will make the diverter less efficient in water delivery, larger tanks and smaller demand will improve the diverter’s water delivery.
4. Use $t_r = \frac{19000(1-\eta_r)}{r_a}\left(ff_d - 0.24e^{2.4\eta_r}\right)$ Equation 7 to determine the optimised first-flush design diversion for building.
5. Multiply this diversion by the roof area to obtain the volume of water that needs to be diverted.

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