Effect of first flush on storage-reliability-yield of rainwater harvesting
Kelly C. Doyle and Peter Shanahan

ABSTRACT
Rainwater harvesting (RWH) entails capture of rainwater falling on a roof and conveyance to a storage tank for later use as domestic water supply. During dry weather, dust and pollutants accumulate on the roof surface and are subsequently washed off with the ‘first flush’ at the beginning of the next rain. Diverting the first flush can improve the quality of stored water but at the cost of reducing the reliability with which the system can supply water. A storage-reliability-yield (SRY) analysis of RWH was completed for Bisate, Rwanda for a period of 20 years with a range of normalized storage volumes and yields. Reliability expressed as days per year on which demand was met was determined for alternative first-flush strategies and compared to the reliability of an otherwise equivalent system without first-flush diversion. Diversion of the first flush was found to reduce reliability by at most 8%. Analysis of three existing RWH systems in Bisate indicates that a recommended 1 mm first-flush diversion would reduce the number of days the system meets demand by no more than 7 days per year.

Key words | first flush, rainwater harvesting, storage-reliability-yield, water supply

INTRODUCTION
Rooftop rainwater harvesting (RWH) is a simple method of collecting rainwater for domestic supply. This paper considers the design of RWH systems for the village of Bisate in the Northern Province of Rwanda. Bisate is densely populated with approximately 8,500 people in an area of 28 km²; the primary economic activity is subsistence agriculture. The main water supply is a catchment system in which a surface stream is captured and conveyed without treatment by a galvanized steel pipe to a single tap stand at the village center from where villagers fetch water using jerry-cans. Rain falls in Rwanda in four distinct seasons: the long rainy season from March to May, the long dry season from June to September, the short wet season during October and November, and the short dry season from December through February. Total annual rainfall averages 1,240 mm/year. The supply to the village tap diminishes and sometimes ceases during the two dry seasons. Unfortunately, alternative supplies are few: the geology is unfavorable for groundwater supply and any new surface-water development would illegally encroach on a national park. But, while the existing supplies and these potential alternatives are problematic, the available rainfall is adequate and falls in a pattern of twice-annual wet-dry seasons that is favorable for RWH.

An important consideration for RWH system design is management of the ‘first flush.’ The first flush is the water that first flows from the roof after the start of a rain storm and is presumed to be of lower quality because it carries the dust, leaves, animal excrement, dead insects, and other contaminants that have accumulated on the roof since the last storm. Preventing the first flush from entering the storage tank is a simple and effective way to improve the quality of the water provided. A number of different types of devices have been proposed to divert the first flush (Gould & Nissen-Petersen 1999; Thomas & Martinson 2007; Doyle 2008). The most commonly used design is a dead-end pipe connected to the drain pipe from the roof to the storage tank. When rainwater first starts to flow
from the roof, a fixed volume fills the diversion pipe. After this pipe is filled, the rest of the flow goes on to the storage tank. After the storm, the diversion pipe is emptied to be ready for the next storm. Design of a first-flush diversion system requires determining the depth of run-off needed to be diverted so as to achieve adequate water quality without excessively compromising supply reliability.

Rooftop RWH systems are rarely 100% reliable in meeting demand. Such systems are usually limited by available rainfall, roof size, or tank size, and can be over-taxed by high demand. Additionally, evaporation, leaking roofs, and first-flush diversion reduce the volume of water flowing into the tank, also affecting the reliability of the system. Originating from studies of reservoir operation (McMahon & Adeloye 2005), storage-reliability-yield (SRY) analysis determines the reliability of a water storage and delivery system subject to varying supply and demand. This paper considers the effects of first-flush diversion on the SRY behavior of a RWH system.

**The first-flush phenomenon**

The concept of the first flush has been applied to urban run-off (Bertrand-Krajewski et al. 1998), highway run-off (Sansalone & Buchberger 1997), industrial site run-off (Line et al. 1997), and combined sewers (Geiger 1987), as well as to roof run-off. The presence or absence of a first flush depends on the contaminant; for example, for run-off from the land surface, Deletic (1998) found that suspended sediments exhibited a first flush, but pH, conductivity, and temperature did not. While the urban stormwater literature provides useful generic concepts, Martinson & Thomas (2005) point out the inherent differences between rooftops used for RWH and urban landscapes producing stormwater run-off. Roof systems are smaller than urban drainage areas and lag times for water and pollutants to reach the outlet are shortened; roofing materials are typically smoother than urban pavement such that particulate matter is more likely to wash off and sediment less likely to accumulate in voids; and roof slopes are usually steeper than street slopes magnifying the first-flush effect. The net result is a strong first-flush effect for rooftops. Yaziz et al. (1989) report distinct first flushes for total, suspended, and dissolved solids, turbidity, conductivity, zinc, and lead from tiled and galvanized iron roofs and apparent but less distinct trends for fecal and total bacteria. Martinson & Thomas (2005) observed generally exponential decreases in turbidity during storms from corrugated galvanized iron, corrugated asbestos, clay tile, and tar-sheet roofs. Schriewer et al. (2008), Athanasiadis et al. (2010), and He et al. (2001) reported first flushes for copper and/or zinc. Kus et al. (2010) reported first-flush behavior for suspended solids, turbidity, iron, aluminum, lead, and ammonia from weathered concrete roof tiles and Mendez et al. (2011) for conductivity, total coliforms, fecal coliforms, turbidity, total suspended solids, dissolved organic carbon, aluminum, arsenic, iron, lead, and zinc for a variety of roof types. Doyle (2008) found consistent exponential decreases in turbidity on clay-tile and sheet-metal roofs but only on clay tile for total coliforms. In summary, there is clear evidence of a first flush for solids and metals on a wide variety of roof types but more equivocal evidence for coliform bacteria.

Designers of rooftop RWH systems typically seek to exclude the first flush from the water to be harvested but the volume of the first flush depends upon such site-specific factors as the proximity to roadways, distance from trees, quality of the roofing material, and abundance of wildlife. Table 1 compares some of the diversion recommendations from the literature. The Texas Water Development Board (TWDB 2005) also recommends that a rainfall intensity of at least 2.5 mm/h is necessary to wash contaminants from the roof surface. While intensity is a legitimate consideration, it is not considered in this paper because minute-by-minute

<table>
<thead>
<tr>
<th>Reference</th>
<th>Specifications</th>
<th>Amount to be flushed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacey &amp; Cullis (1986)</td>
<td>Based on measurements in Thailand</td>
<td>First 10–20 min of storm</td>
</tr>
<tr>
<td>Michaelides (1987)</td>
<td></td>
<td>0.28 mm</td>
</tr>
<tr>
<td>Yaziz et al. (1989)</td>
<td>To prevent microbial contamination</td>
<td>0.33 mm</td>
</tr>
<tr>
<td>Ntule &amp; Moses (2003)</td>
<td>Should be decreased in rainy season</td>
<td>0.85 mm or first 10 min</td>
</tr>
<tr>
<td>TWDB (2005)</td>
<td>Depending on dry days, debris, trees, and season</td>
<td>0.41–0.82 mm</td>
</tr>
<tr>
<td>Rain Harvesting Pty. Ltd (2010)</td>
<td>Minimum Low pollution High pollution</td>
<td>0.20 mm 0.50 mm 2.0 mm</td>
</tr>
<tr>
<td>Kus et al. (2010)</td>
<td>Recommended for Australia</td>
<td>2.0 mm</td>
</tr>
</tbody>
</table>
rainfall measurements were not available for the study site. The antecedent dry weather period (ADWP) also affects the amount of particulate matter that deposits on the roof and thus the first flush (Yaziz et al. 1989; Furumai et al. 2001; Schriewer et al. 2008). The length of the ADWP is generally not considered in operating a RWH system other than with the following simple but practical binary algorithm: if it has recently rained and the ADWP is short, the first flush need not be diverted.

Martinson & Thomas (2005) assess first-flush diversion volumes for RWH based on Sartor et al.'s (1974) proposal that contaminant concentrations in run-off decay exponentially:

\[ N = N_0 e^{-kt} \]  

(1)

where \( N \) is the turbidity of the run-off at time \( t \); \( N_0 \) is the initial turbidity; \( k \) is a constant that depends on catchment surface texture; \( r \) is the rainfall intensity in mm/hr; and \( t \) is time in hours from the beginning of the storm. Martinson & Thomas (2005) found \( k \) to vary between 0.65 and 2.2 mm\(^{-1}\) for rooftops of various types in Uganda and recommended \( k = 0.7 \) mm\(^{-1}\) as a conservative value for design. This value is equivalent to each millimeter of run-off halving the contaminant load.

The ideal first-flush device is large enough to avoid the majority of pollutants washed off but not so large as to waste a lot of clean water. The sources listed in Table 1 recommend diverting anywhere from 0.2 to 2 mm of run-off, but many sensibly recommend considering site-specific factors. For our application to Bisate, Rwanda, we conducted a field sampling program to evaluate roof run-off quality over time (Doyle 2008; Doyle & Shanahan 2010) and found that turbidity and conductivity followed the same exponential decrease with a similar range of \( k \) values as found by Martinson & Thomas (2005). We determined that diversion of the first 1 mm of run-off lowered *Escherichia coli* concentrations to 10 colony-forming units/100 ml, a concentration recommended as a practical alternative for developing countries by Gould (1999) and Gadgil (1998), and reduced turbidity from the order of 100 NTU to less than 40 NTU. While we selected this diversion quantity to address both turbidity and bacterial concentrations, this should be recognized as a site-specific measure based on our field observations. As discussed above, the first-flush phenomenon for coliform bacteria is equivocal and coherent behavior of turbidity and bacteria cannot be presumed at all sites.

**METHODS**

**Determining tank size for RWH systems**

A particular RWH system design challenge is to optimize the tank size so as to ensure a reliable supply within the limits posed by economic and environmental constraints. Methods to determine storage volume range from very simple ‘back-of-the-envelope’ calculations (DTU 2008) to simulation models of varying complexity (Thomas 2002; DTU 2008; Hanson et al. 2009). For this study, a simulation model was used in order to understand the effect of losses and first-flush diversion on system performance. Hanson (2007) developed a SRY analysis method and applied it to 232 first-order weather stations in the contiguous USA. Losses and first-flush diversion were not considered however. For this study, we coded a simulation program in Visual Basic for Applications based on Hanson’s method modified to include losses and first-flush diversion.

The SRY method accounts for the roof collection area, volumetric tank capacity, daily demand (yield), and rooftop run-off coefficient for a specific site. We ran simulations to develop curves of constant reliability based on dimensionless daily yield and tank storage capacity. We define the yield of the system using a dimensionless yield fraction (\( \alpha \)), defined by Hanson (2007) as:

\[ \alpha = \frac{y}{\mu dp A_c} \]  

(2)

where \( y \) is the daily yield (demand) (m\(^3\)/day), assumed constant; \( \mu dp \) is the mean daily precipitation (m/day); and \( A_c \) is the collection area (m\(^2\)). Also following Hanson (2007), the storage ratio (\( S_t \)) is used to quantify the capacity of the storage tank normalized by the collection area:

\[ S_t = \frac{s}{A_c} \]  

(3)
where $s$ is the storage capacity of the tank (m$^3$) and $S_r$ is measured in meters. Using guidelines from Thomas (2002) for a generic roof type, we assume that losses amount to 15%, meaning that 85% of the rain hitting the roof runs off. We also recommend for Bisate that the first 1 mm of run-off be diverted from the main supply into a first-flush device if three or more days have passed without adequate precipitation (more than 1 mm/day of run-off) to clean the roof. If the daily run-off amounts to less than 1 mm, then all should be diverted if three or more days have passed since the last rainstorm with more than 1 mm of run-off. However, if there has been an adequate rainfall within the last 3 days, none of the day’s rainfall need be diverted. Variations on the recommended diversion amount and number of days between storms were also assessed as discussed below.

We measured system reliability in terms of the amount of time the system fails to meet demand:

$$q = 1 - \frac{d_i}{n}$$

(4)

where $q$ is dimensionless time-based reliability; $d_i$ is the total number of days demand is not met; and $n$ is the total number of days in the rainfall record (and thus the simulation). Reliability is reported as a number between 0 and 1, where systems with reliability 0 never meet demand and with reliability 1 always meet demand.

The simulation of the system considers the rain that falls on the roof each day, the water removed by losses and first-flush diversion, the remainder that flows to the storage tank, spillage of water in excess of tank capacity, and finally removal for daily demand. Actual tank use during the course of a day will intersperse occasional withdrawals with rainfall recharge, a subtlety that is ignored when using a daily simulation time step. Also, withdrawal need not be constant and users often adopt the strategy of decreasing use as supply dwindles. Since our goal here is an evaluation of the generic effects of first-flush diversion, we did not consider variable demand scenarios but such analyses would be useful for actual system design. There are two options for simulating the daily inflow and outflow from the tank: a yield-after-storage (YAS) algorithm or a yield-before-storage (YBS) algorithm. YAS, also called spill-before-yield, assumes that when the tank is at capacity any additional water added to the tank will spill out and be wasted. Only at the end of the day does the user extract the full daily yield. In contrast, the YBS algorithm assumes that the user will extract the daily yield before the day’s rain. Considered to be more conservative, the YAS approach is used in our simulation program, which marches through the record of rainfall on a daily time step, tracks the inflows and outflows to the tank, and tallies the number of days the tank fails to completely satisfy demand. The simulation was repeated for multiple combinations of specified yield and storage, determining reliability for each combination. The goal of the SRY analysis is to understand the relationship between storage, reliability, and yield, which we represent here with contour plots of reliability as a function of the dimensionless storage ratio, $S_r$, and the dimensionless yield, $a$.

## RESULTS

### Application to Bisate, Rwanda

The methods described above were employed to determine the SRY behavior of proposed RWH systems to be constructed in Bisate, Rwanda. System performance over 20 years was simulated. As is typical in developing-country settings, meteorological records were sporadic. Only a 2 year record of daily rainfall was available for Bisate; however, a longer but discontinuous monthly record was available for Musanze about 18 km away. Several short gaps in the Musanze record were filled by substituting average rainfall for that month of the year and a long gap during the Rwandan civil war was passed over. The final record included the years 1977–1992 and 2002–2005, an imperfect but nonetheless representative 20 year record of monthly rainfall. In order to complete a daily simulation, Doyle (2008) created a pseudo-daily record for Bisate from the available daily and monthly records using an approach developed by Thomas (2002) for RWH systems. He gives an empirical formula to determine the probability of rain on any given day of each month and then assigns a rainfall depth to each rainy day, finally scaling daily values so as to achieve the correct monthly total. An empirical parameter
determines the frequency of wet days and corresponding average rainfall intensity; Doyle (2008) adjusted its value by trial and error to match the 2 year daily record for Bisate.

The 20 year synthetic rainfall record was used in the SRY simulation model to compute reliability for a range of \( \alpha \) and \( S_r \) values for alternative RWH strategies (Table 2). Figure 1 shows computed contours of reliability versus non-dimensional storage (\( S_r \)) and non-dimensional yield (\( \alpha \)) for these strategies. The contour lines in Figure 1 are displayed at constant reliabilities of 99, 90, 80, 70, 60, and 50%.

Strategy 1 (Figure 1a) does not consider losses or first-flush diversion of any kind, but rather treats the entire rainfall as available for storage and use. It is not a realistic ‘strategy’ in that zero loss is a physical impossibility; however, it is included for comparison with the prior work by Hanson (2007) and Hanson et al. (2009) in which losses were not considered. For Strategies 2 through 6, 15% of the rainfall was assumed to be lost but with different diversion options in place for each. Strategy 2 assumes no diversion for first flush – all run-off is allowed to enter the storage tank. Strategy 3 diverts the first flush every time it rains, regardless of whether or not there was rain on the days before, while Strategies 4, 5, and 6 account for rain on the three prior days.

**DISCUSSION**

Figure 1 shows how reliability is affected by first-flush diversion. The effects can be seen by considering the asymptotic behavior of system yield, \( \alpha \). As the storage ratio, \( S_r \), increases, the yield fraction, \( \alpha \), eventually reaches an asymptotic value, \( \alpha_{\text{max}} \), which varies with the value of reliability. This asymptotic condition is shown in Figure 1 by the plotted contour lines becoming vertical (which happens in some cases above the range of the plotted \( S_r \) values). Above the value of \( S_r \) at which a reliability contour line becomes vertical, the daily yield of the system will not increase even if the tank volume is increased – system performance at this point is limited by the availability of rainwater, not the amount of storage. To attain a higher reliability, \( \alpha \) can only be improved by either increasing the size of the collection area or reducing demand.

Surprisingly, the graphs in Figure 1 do not vary much from one strategy to the next. Compare, for example, the value of \( \alpha \) at which the 99%-reliability contour reaches its asymptote, which we designate as \( \alpha_{\text{max,99}} \) and tabulate in Table 2. Higher values of \( \alpha_{\text{max,99}} \) imply greater yield and thus more reliable system performance. The scenario with the most available run-off for RWH is Strategy 1 (Figure 1a) which achieves a value of \( \alpha_{\text{max,99}} \) of approximately 1.0, a yield fraction that indicates the daily yield per unit area is equal to the mean daily rainfall (an unrealistic result that is only possible because this strategy does not consider losses). Strategy 2 (Figure 1b), with a realistic loss of 15%, achieves a maximum \( \alpha_{\text{max,99}} \) value of 0.85 which is equivalent to a daily yield of all rainfall except the lost 15%. Strategy 3, which diverts the first flush regardless of ADWP (Figure 1c), has the least amount of run-off available for capture and has a \( \alpha_{\text{max,99}} \) value of 0.77. Strategies 4, 5, and 6, all with losses of 15% and accounting for ADWP, but with increasing diversion volumes, show \( \alpha_{\text{max,99}} \) yields of 0.83, 0.81, and 0.78 respectively – somewhat lower yields than 0.85 due to the effects of first-flush diversion. The effect of first-flush diversion can be seen in Figure 1 and Table 2 by contrasting Strategy 2 with no diversion and Strategies 3 through 6 with diversion. Considering these scenarios, first-flush diversion creates a reduction in

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Assumed loss</th>
<th>Diversion</th>
<th>( \alpha_{\text{max,99}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1</td>
<td>Zero loss</td>
<td>No diversion</td>
<td>1.0</td>
</tr>
<tr>
<td>Strategy 2</td>
<td>15% loss</td>
<td>No diversion</td>
<td>0.85</td>
</tr>
<tr>
<td>Strategy 3</td>
<td>15% loss</td>
<td>1 mm diversion on each day with rainfall</td>
<td>0.77</td>
</tr>
<tr>
<td>Strategy 4</td>
<td>15% loss</td>
<td>0.5 mm diversion after three consecutive days each with &lt;0.5 mm run-off</td>
<td>0.83</td>
</tr>
<tr>
<td>Strategy 5 (recommended)</td>
<td>15% loss</td>
<td>1 mm diversion after three consecutive days each with &lt;1 mm run-off</td>
<td>0.81</td>
</tr>
<tr>
<td>Strategy 6</td>
<td>15% loss</td>
<td>2 mm diversion after three consecutive days each with &lt;2 mm run-off</td>
<td>0.78</td>
</tr>
</tbody>
</table>
the yield fraction $\alpha$ from about 0.85 to 0.77 at worst. In other words, first-flush diversion reduces the system yield by at most about 8% of the total rainfall, a relatively small premium to ensure higher quality water.

While the $\alpha_{\text{max,99}}$ parameter reports the yield with theoretically infinite storage, reliability is surprisingly insensitive to diversion even with realistic storage volumes. As can be seen in Figure 1, once the value of the storage ratio is greater than about 0.15, the value of $\alpha$ changes little and the ultimate value, $\alpha_{\text{max,99}}$, is a good indicator of performance. At lower values of the storage ratio, reliability is more sensitive to both the storage ratio and, one might presume, to diversion of the first flush. Reliability is shown for selected values of the storage ratio, including values less than 0.15,
in Table 3. If one compares, for example, Strategy 5 (1 mm diversion after 3 days) with Strategy 2 (no diversion), there is very little reliability penalty for first-flush diversion. Even doubling the diversion to 2 mm (Strategy 6) exacts only a modest penalty.

At the time of this study in 2007, a total of 13 rainwater tanks were planned to be installed in three locations in Bisate: five tanks at the local health clinic (collecting from five separate roof surfaces totaling 378 m²), two new tanks in addition to two existing tanks at the primary school (with the four tanks collecting from four roof surfaces with total area of 535 m²), and five tanks at the Park Rangers’ house (collecting from three roof surfaces amounting to 506 m²). All buildings are covered by corrugated metal roofs. The total area of the collection surface, the total volume of the tanks, and the daily water demand for each of the three locations result in the α and Sr values shown in the upper rows of Table 4. These systems were simulated using the specific α and Sr values for each site in order to calculate the reliability of each, as shown in the lower rows of Table 4. Because enrollment, and thus water demand, is high at the primary school, the α value is outside the range of Figure 1 and reliabilities are very low. Only an increase in rainwater catchment size (i.e., a larger school building) could appreciably increase reliability at the school. Consistent with Figure 1, diversion of a first-flush volume reduces the reliability of these constructed systems by single-digit percentages according to the simulation model. The right side of Table 4 translates the reductions in reliability due to first-flush diversion into the number of additional days per year when the systems will not meet demand. It contrasts Strategies 3 through 6, in which there are diversions, with Strategy 2, with no diversion.

Our recommended strategy for Bisate is Strategy 5, diversion of the first 1 mm of run-off after three or more days with roof run-off of 1 mm or less. For the Health Clinic, such a diversion would require 0.38 m³ of storage volume and a small storage tank dedicated to first-flush diversion was planned. (Unfortunately, due to cost, diversion devices were not installed when the systems were finally constructed.) Table 4 illustrates that first-flush diversion of 1 mm reduces the reliability by only a few days. While Strategy 6, with a greater diversion volume, would presumably create a greater

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Reliability (%)</th>
<th>Additional days per year demand not met compared to Strategy 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1</td>
<td>94</td>
<td>10 days 11 days 12 days</td>
</tr>
<tr>
<td>Strategy 2</td>
<td>92</td>
<td>3 days 2 days 3 days</td>
</tr>
<tr>
<td>Strategy 3</td>
<td>90</td>
<td>6 days 4 days 7 days</td>
</tr>
<tr>
<td>Strategy 4</td>
<td>92</td>
<td>8 days 5 days 6 days</td>
</tr>
<tr>
<td>Strategy 5</td>
<td>91</td>
<td>11 days 9 days 14 days</td>
</tr>
<tr>
<td>Strategy 6</td>
<td>90</td>
<td>12 days 10 days 13 days</td>
</tr>
</tbody>
</table>
margin of safety with respect to water quality, it does so at the
cost of roughly doubling the number of days demand would
not be met (Table 4). Neglecting the washing effects of
recent rain (Strategy 3) also reduces reliability substantially.
Using Strategy 5 with 1 mm diversion after inadequate rain
for 3 days adds only 4–7 days per year when the specified
demand is not met. While Strategy 4 has greater reliability
than Strategy 5, our field studies indicate that 0.5 mm of diver-
sion does not reduce the contaminant load sufficiently and is
thus not recommended.

CONCLUSIONS

The SRY simulations show that the diversion of the first flush
does not substantially reduce the reliability of a RWH system.
Our field study showed that diversion of the first millimeter of
run-off results in roughly a 50% reduction in turbidity and a
reduction in E. coli concentrations to levels recommended
for consumption. Based on the results of the SRY simulation,
the adoption of a ‘1 mm diversion after 3 days’ rule will lead to a
decrease in reliability of 4% or less, which translates into an
additional 4–7 days per year when demand would not be met
by the three RWH systems recently installed in Bisate (Table 4).
Further, the first flush need not be wasted: while not suitable for drinking, the diverted water can still be used
for other purposes such as irrigation.

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