Sizing the First Flush and its Effect on the Storage-Reliability-Yield Behavior of Rainwater Harvesting in Rwanda

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Outline

- Project context
- Intro to rainwater harvesting
- Intro to first flush (FF)
  - Definition
  - Design options
- Fieldwork
  - Methods
  - Results
- Storage-Reliability-Yield (SRY) simulation
- Effects of first flush diversion on SRY behavior

Project Details

- Project Location
  - Bisate Village, Northern Province, Rwanda
- Population ~8,500
- Project Partner
  - Dian Fossey Gorilla Fund International

Project Context

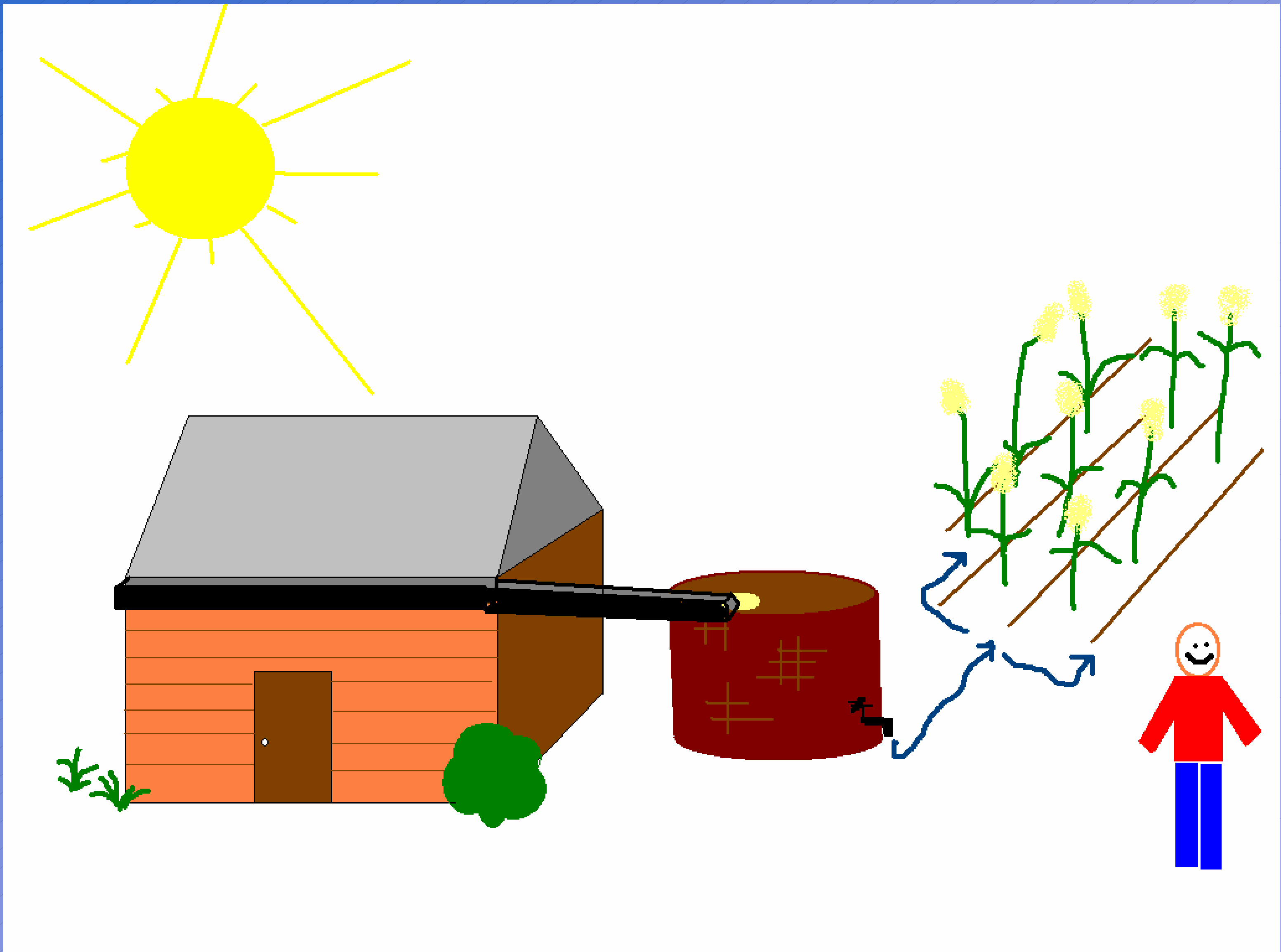
Problem:

- 95-99% of the population infected with worms
- Inadequate water supply (volume)
- Contaminated water supply

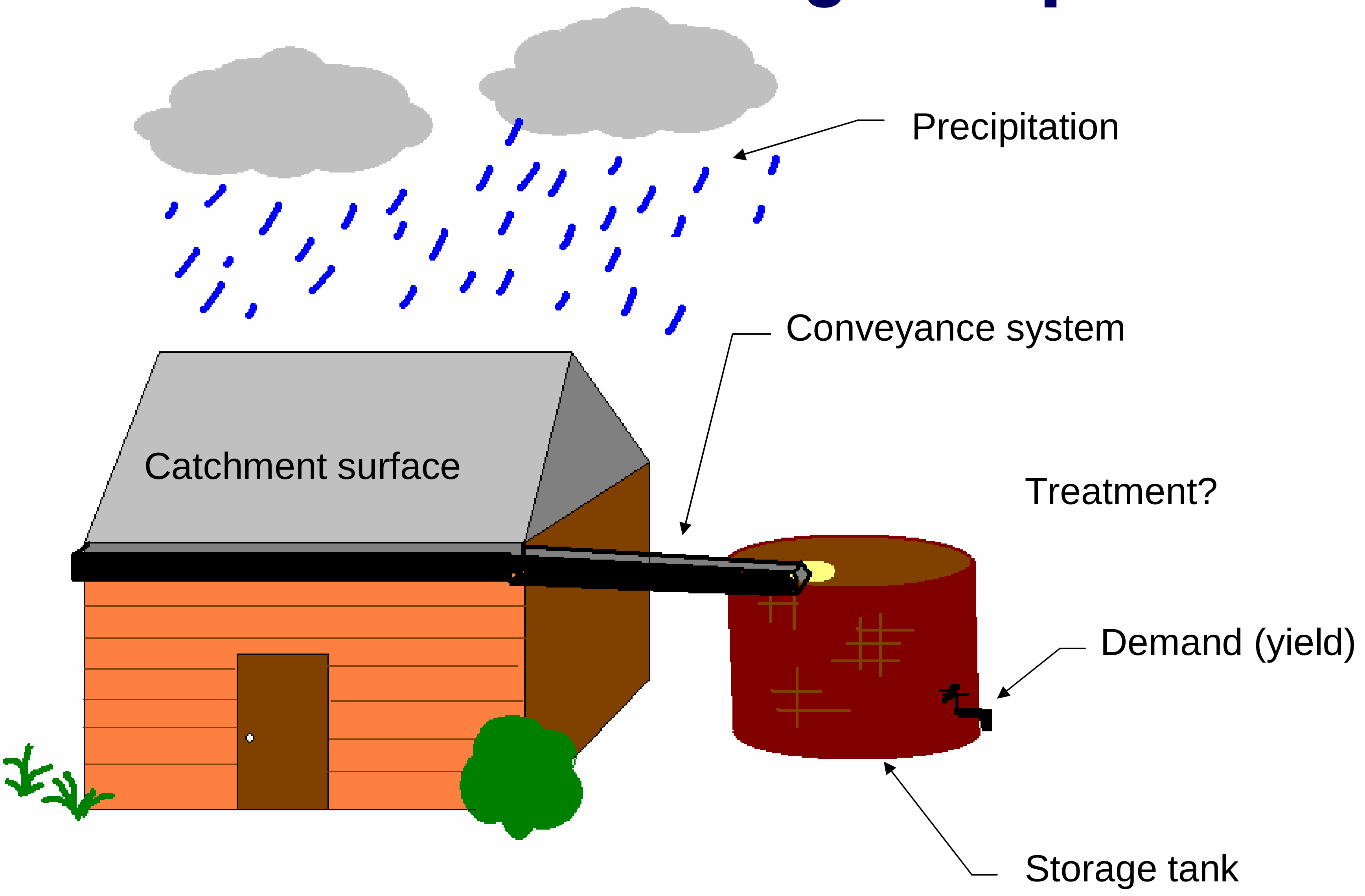
Approach:

- Rainwater harvesting (water supply)
- First flush diversion (treatment)

How Rainwater Harvesting (RWH) Works



Rainwater Harvesting Components



RWH Design Components

- Catchment surface
  - Roof area
  - Material
- Conveyance system
  - Material
  - Slope
- Treatment system
  - Pre- or post- storage
  - Final water use
  - Acceptable risk
- Storage tank
  - Size
  - Material
  - Management plan

Rainwater Tanks 2007

The New Tanks

The Clinic- 41 m^3

People Served:
- 20,000 people served
- 100 patients per day
- 15 patient beds

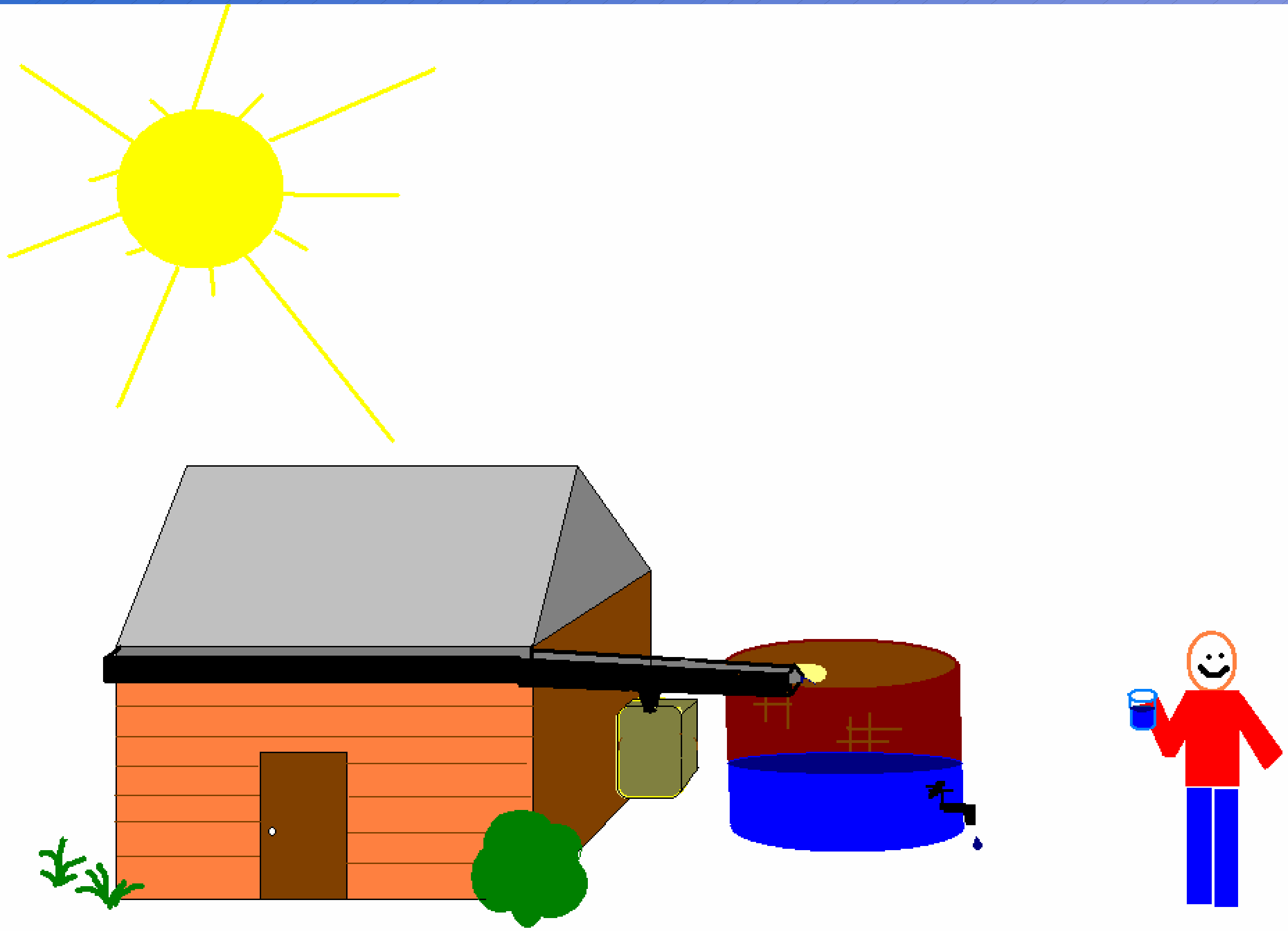
Trackers' House-43 m^3

People Served:
- 50 trackers

People Served:
- 1,700 students

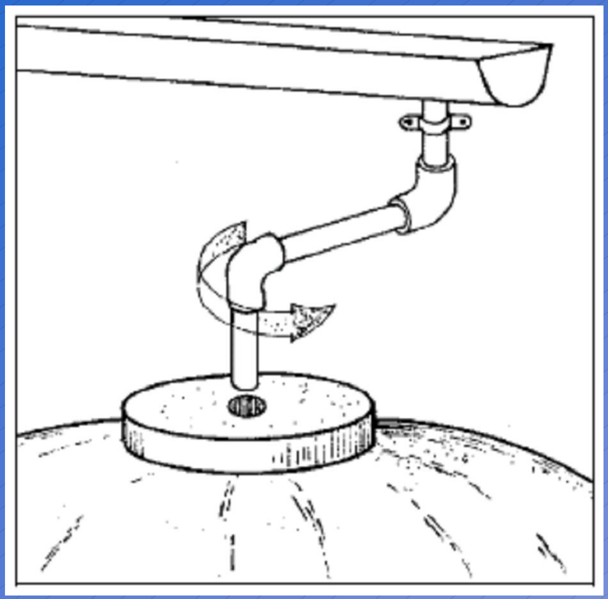
Primary School-40 m^3

How First Flush Diversion Works

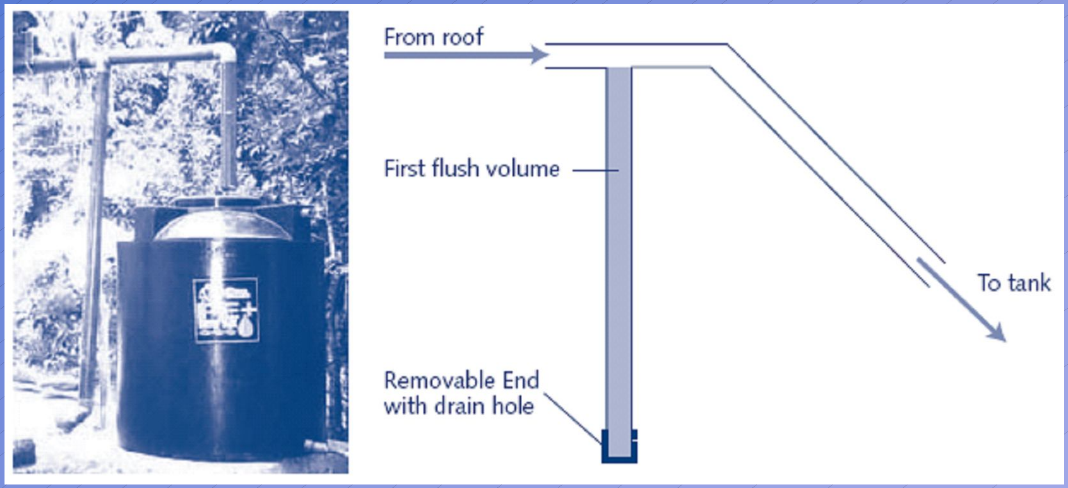


First Flush Design Options

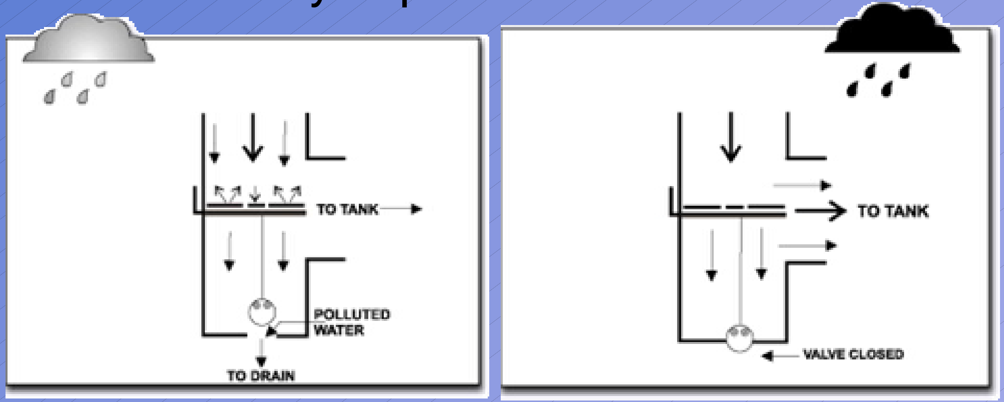
Manual diverters



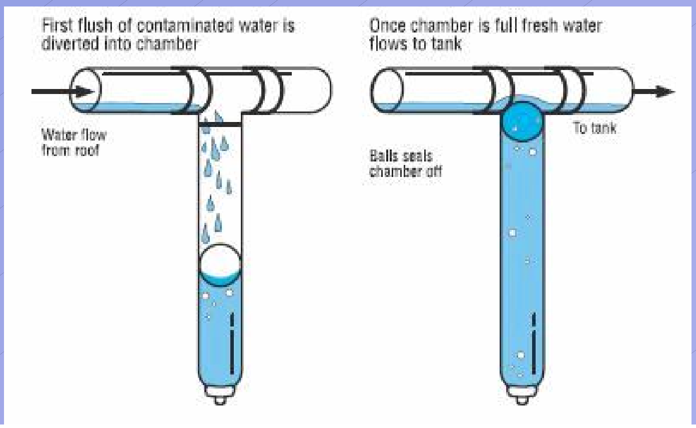
Constant volume diverters



Intensity-dependent diverters



Constant volume diverters
with floating ball



Constant Volume Diverter

Courtesy of Matt Stevenson

Research Questions

- How much water should be diverted to improve water quality in the tank?

- How does first flush diversion affect the reliability of the harvesting system?

The GIZMO

Graduated Inflow-collector for Zero Mixing with Overflow

New Clinic Roof (CL)

First try: 0.66 mm rain

Second try: 1.34 mm rain

Roof material: new iron sheets

Location: close proximity to road

Rusty Roof House (HS)

Captures first 1.45 mm of rain

Roof material: old, rusty iron sheets

Location: far from vehicle road

Potato House (PT)

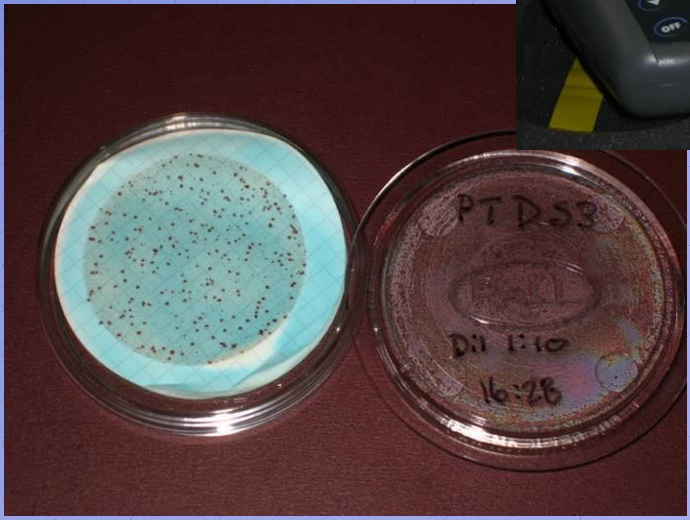
Captures first 1.61 mm of rain

Roof material: old clay tiles

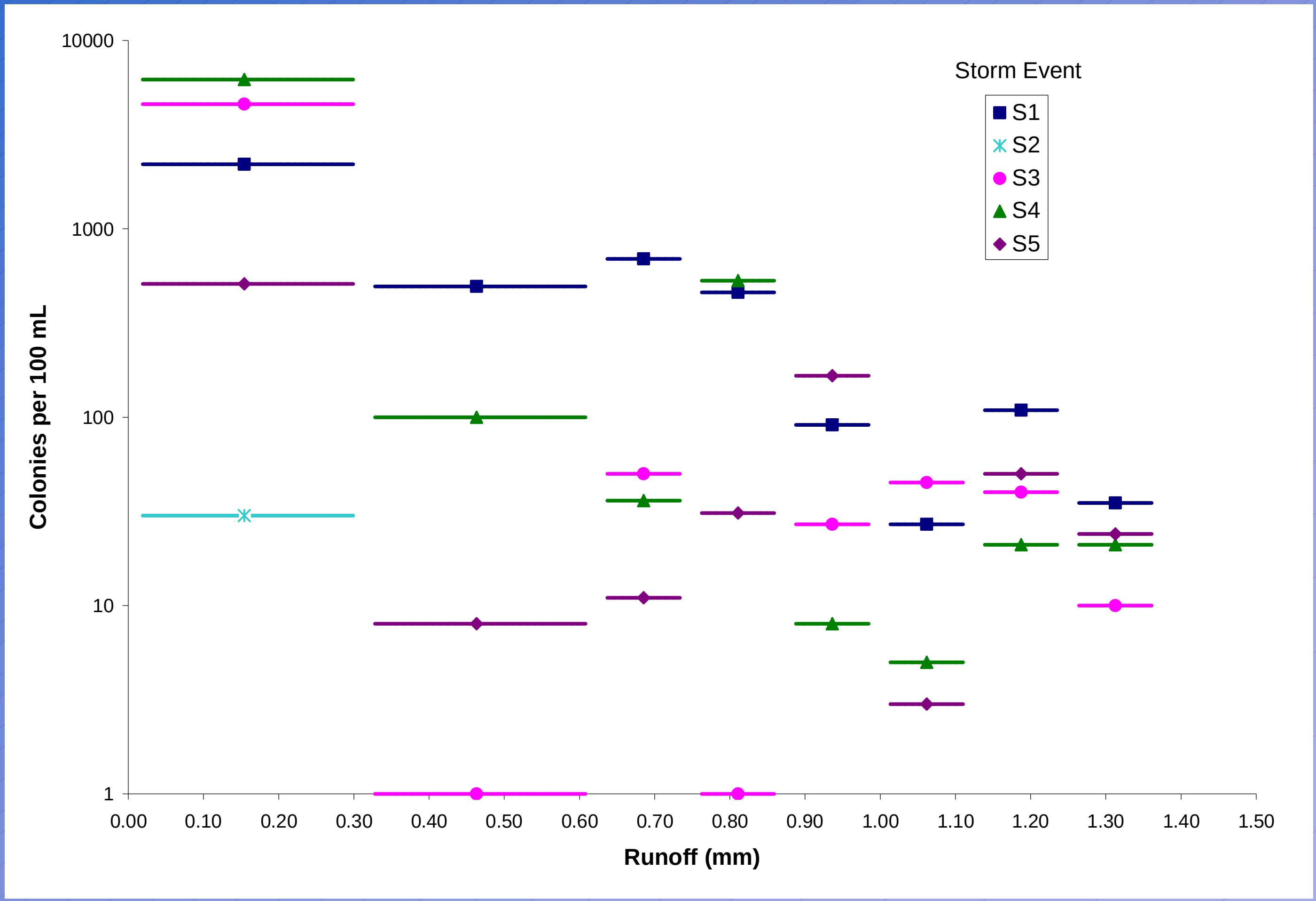
Location: moderate distance from vehicle road

Water Quality

- Membrane filtration
  - Total Coliform
  - E. coli
- Turbidity
- pH
- Conductivity



Total Coliform Sample Results
HS location



E. coli Results

Level of fecal pollution (*E. coli* colonies per 100 mL sample)	Inference
1 – 10	Reasonable Quality
10 – 100	Polluted
100 – 1,000	Dangerous
> 1,000	Very Dangerous

WHO Standard: 0 colonies per 100 mL

CL- E. coli colonies per 100 mL

Runoff Depth	S1	S2	Runoff Depth	S3	S4	S5	S6
0.03 – 0.18 mm	<100	<10	**0.03 – 0.46 mm**	<10	**10**	**5**	NS
0.22 – 0.37 mm	<100	<10	**0.50 – 0.93 mm**	<10	<1	<1	NS
0.41 – 0.56 mm	<100	NS	**0.98 – 1.12 mm**	<10	<1	**1**	NS
0.61 – 0.75 mm	<10	NS	**1.17 – 1.32 mm**	<1	<1	<1	NS

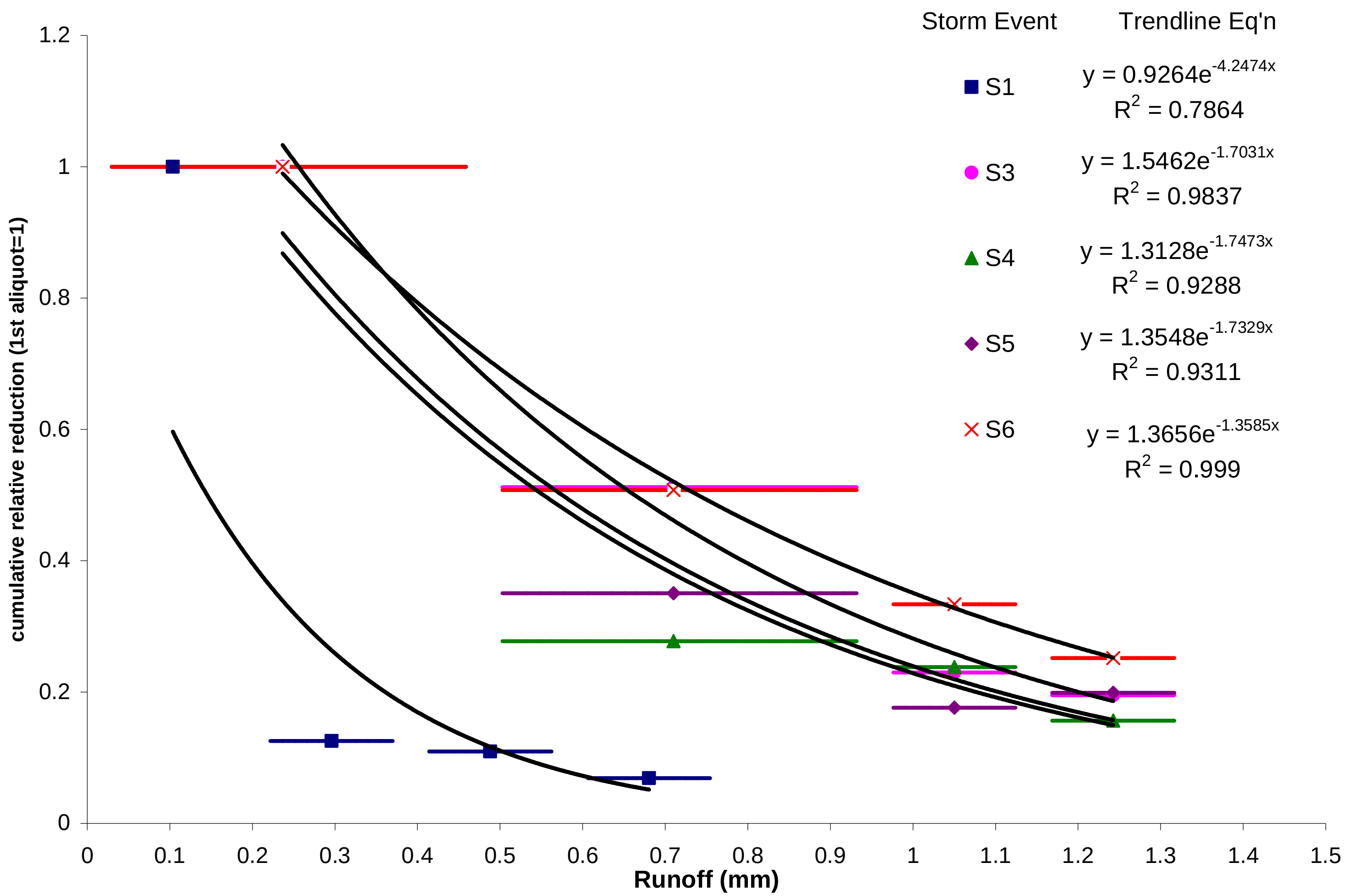
HS- E. coli colonies per 100 mL

Runoff Depth	S1	S2	S3	S4	S5	S6
0.02 – 0.30 mm	<100	**10**	<100	**200**	**3**	NS
0.33 – 0.61 mm	<100	NS	<100	**10**	<1	NS
0.64 – 0.73 mm	<100	NS	<10	**70**	<1	NS
0.76 – 0.86 mm	<10	NS	<100	**20**	<1	NS
0.89 – 0.98 mm	<10	NS	<10	<1	**1**	NS
1.01 – 1.11 mm	<10	NS	<10	**1**	<1	NS
1.14 – 1.24 mm	<10	NS	<10	<1	**1**	NS
1.26 – 1.36 mm	<1	NS	<1	<1	<1	NS

PT- E. coli colonies per 100 mL

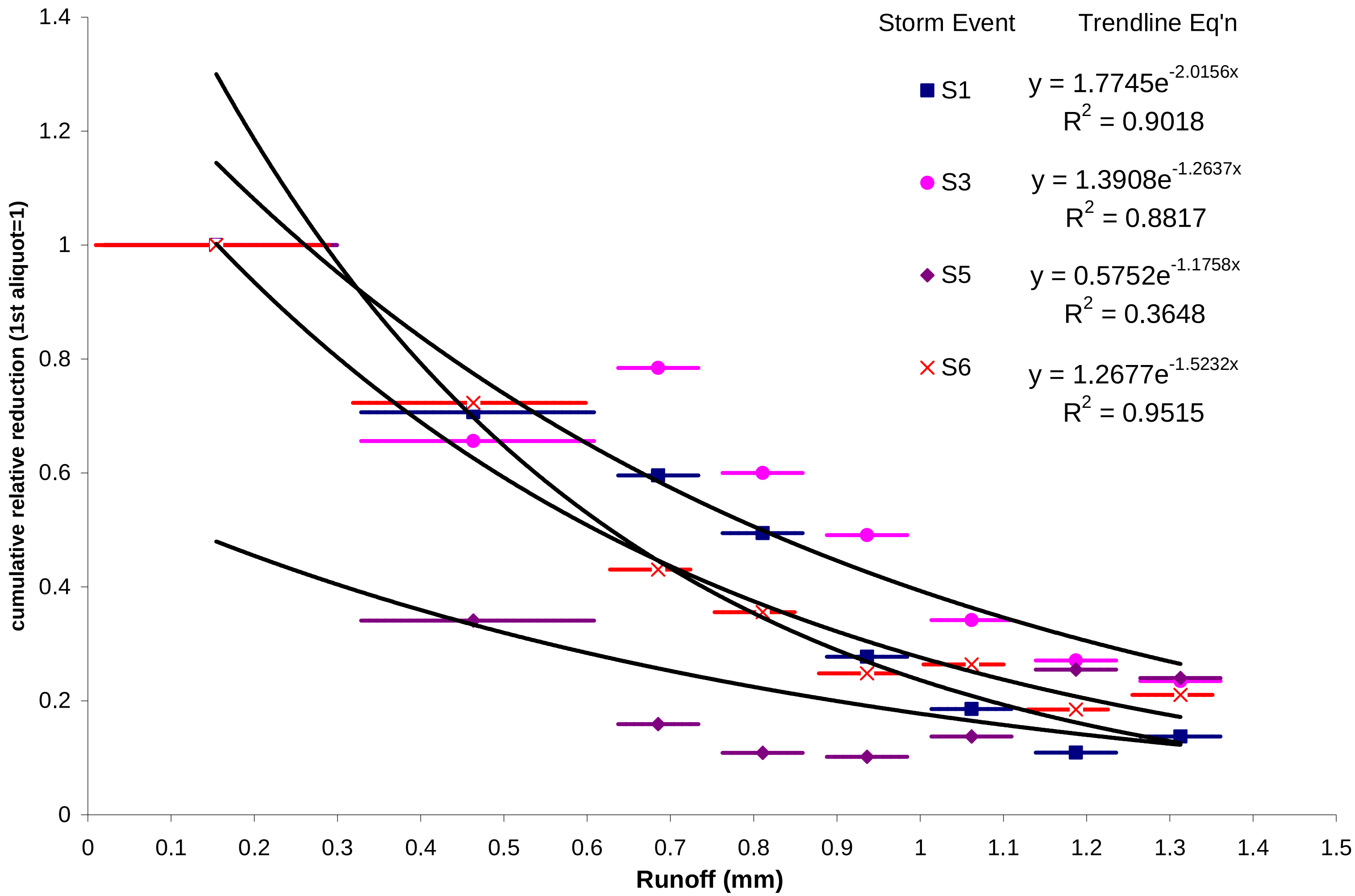
Runoff Depth	S1	S2	S3	S4	S5	S6
0.06 – 0.38 mm	NS	NS	<10	<100	<1	NS
0.47 – 0.79 mm	NS	NS	<10	**100**	NS	NS
0.89 – 1.20 mm	NS	NS	<10	<10	NS	NS
1.30 – 1.61 mm	NS	NS	<10	<10	NS	NS

Turbidity Reduction Trends-CL



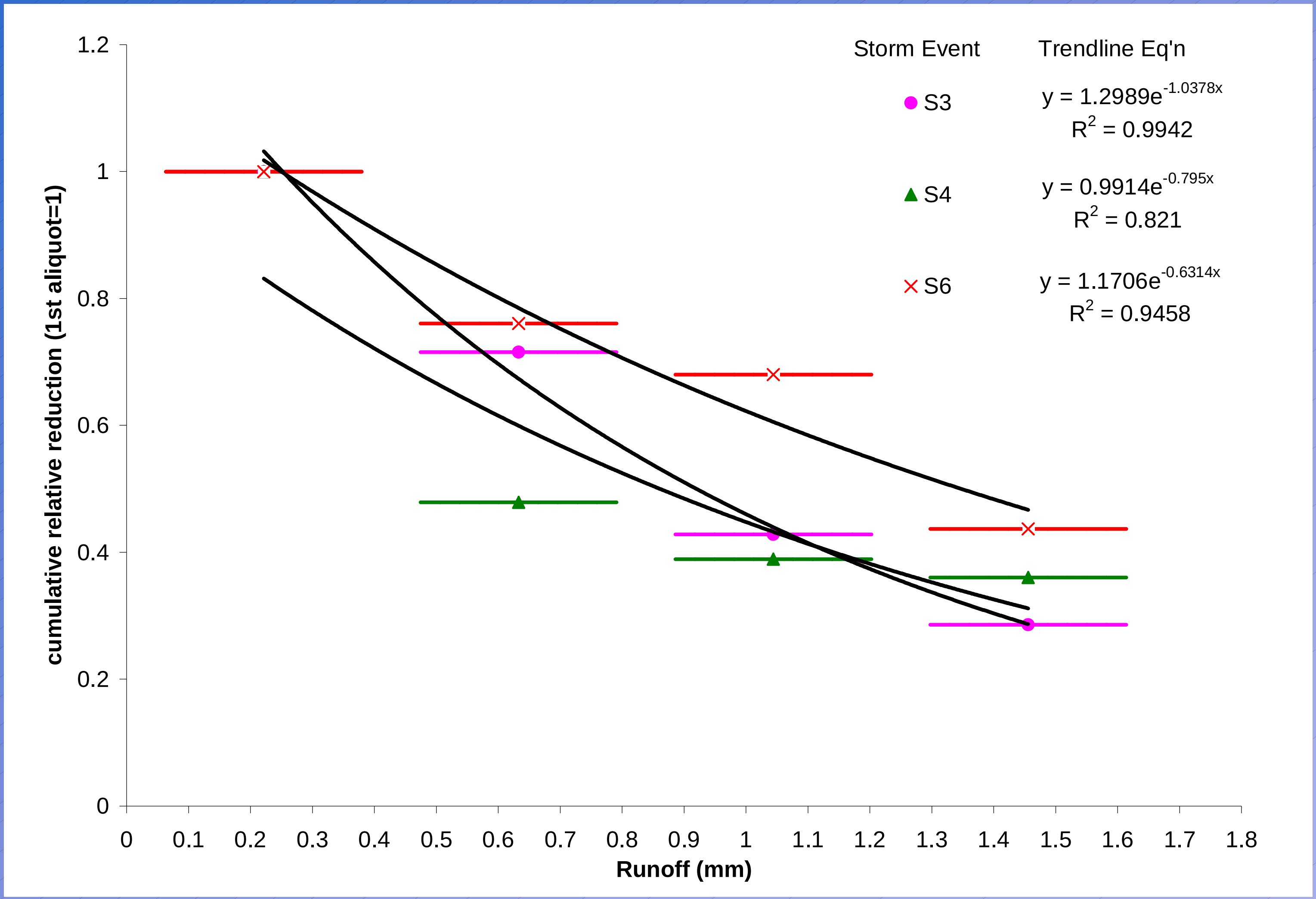
** Note: Storm S1 had a different array setup than subsequent storms

Turbidity Reduction Trends-HS



** Note: Storm S4 was not included for clarity. See discussion regarding outliers below.

Turbidity Reduction Trends-PT

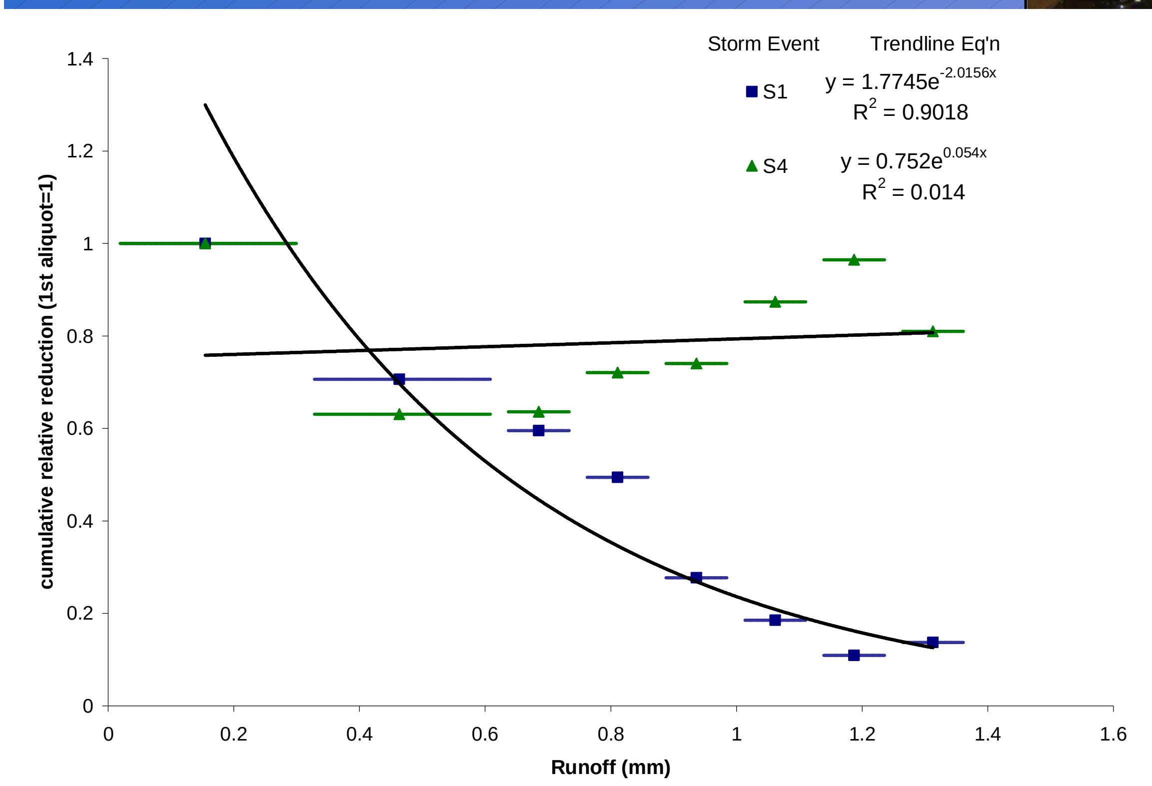


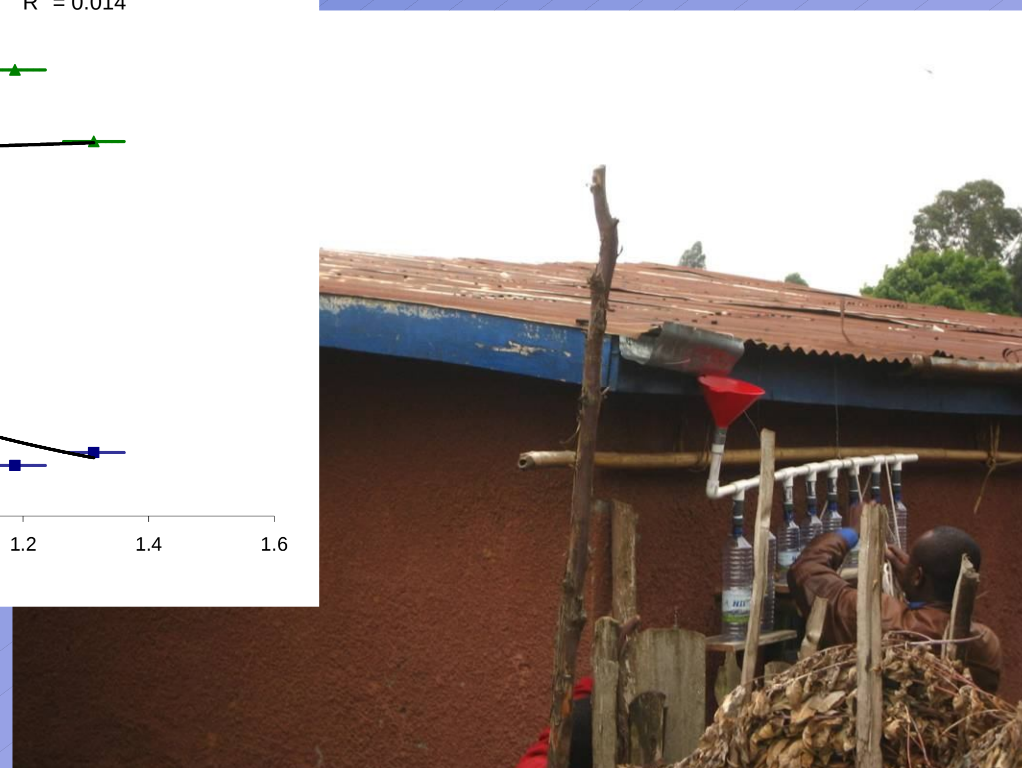
Previous Work

- Martinson and Thomas 2005
  - Uganda
  - $N = N_0 e^{-krt}$
  - k range 0.65 – 2.2

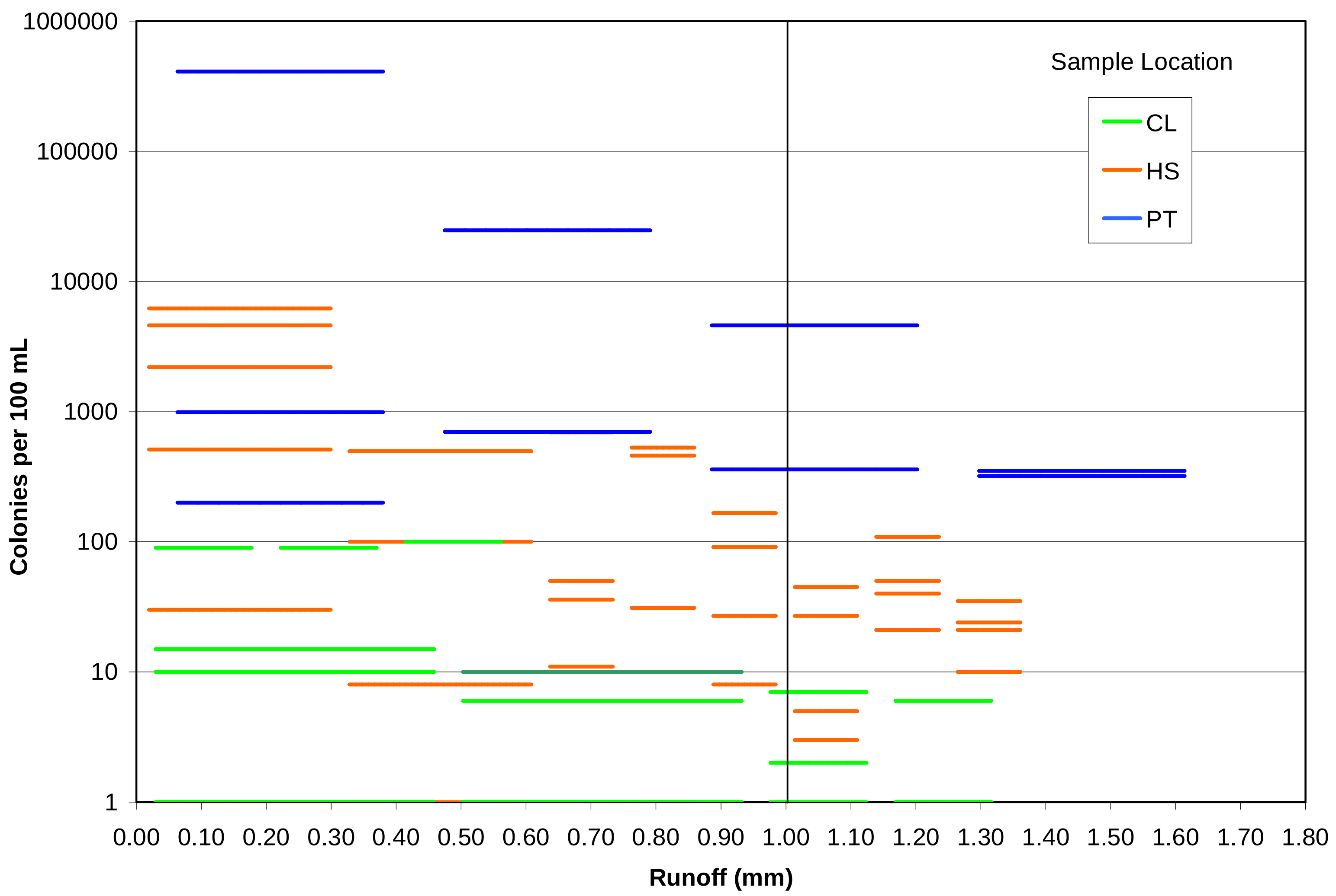
- Doyle 2008
  - Rwanda
  - k range 0.63 – 2.0
    (without outliers)

Outliers


Storm Event
Trendline Eq'n
S1
y = 1.7745e^-2.0156x
R^2 = 0.9018
S4
y = 0.752e^0.054x
R^2 = 0.014
cumulative relative reduction (1st aliquot=1)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Runoff (mm)



Recommendation to divert 1st mm of runoff: Coliform reduction



Recommendation to divert 1st mm of runoff: *E. coli* reduction

Level of fecal pollution (*E. coli* colonies per 100 mL sample)	Inference
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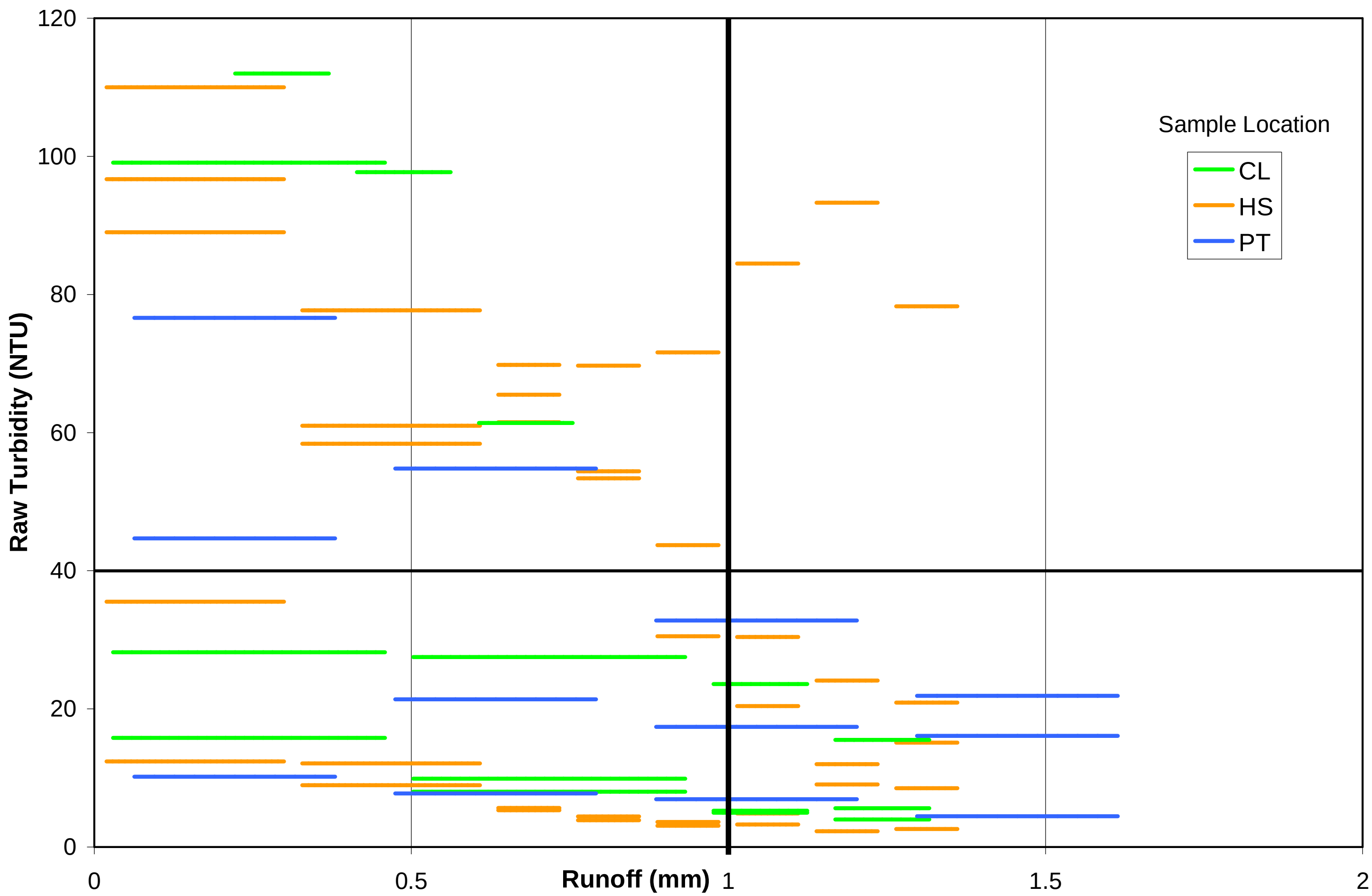
0.89 – 1.20 mm	NS	NS	<10	<10	NS	NS
1.30 – 1.61 mm	NS	NS	<10	<10	NS	NS

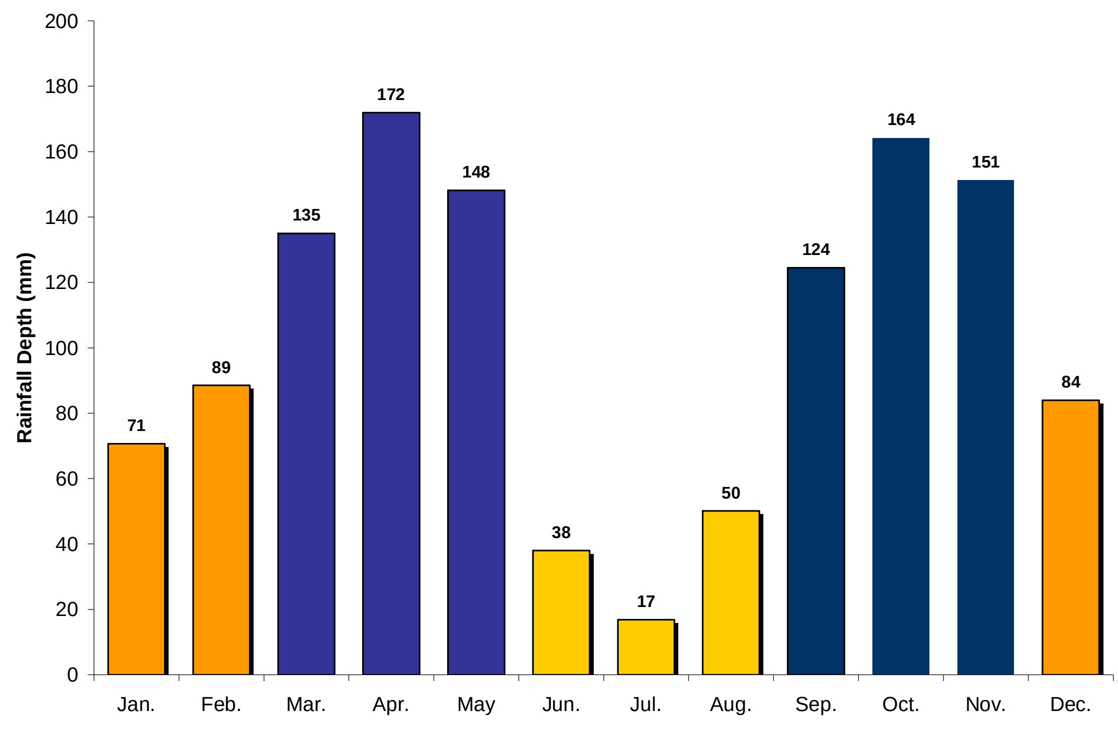
Recommendation to divert 1st mm of runoff: Turbidity reduction



** Note: The turbidity value at CL-S1 was removed to make the graph more readable; the value was 893 NTU

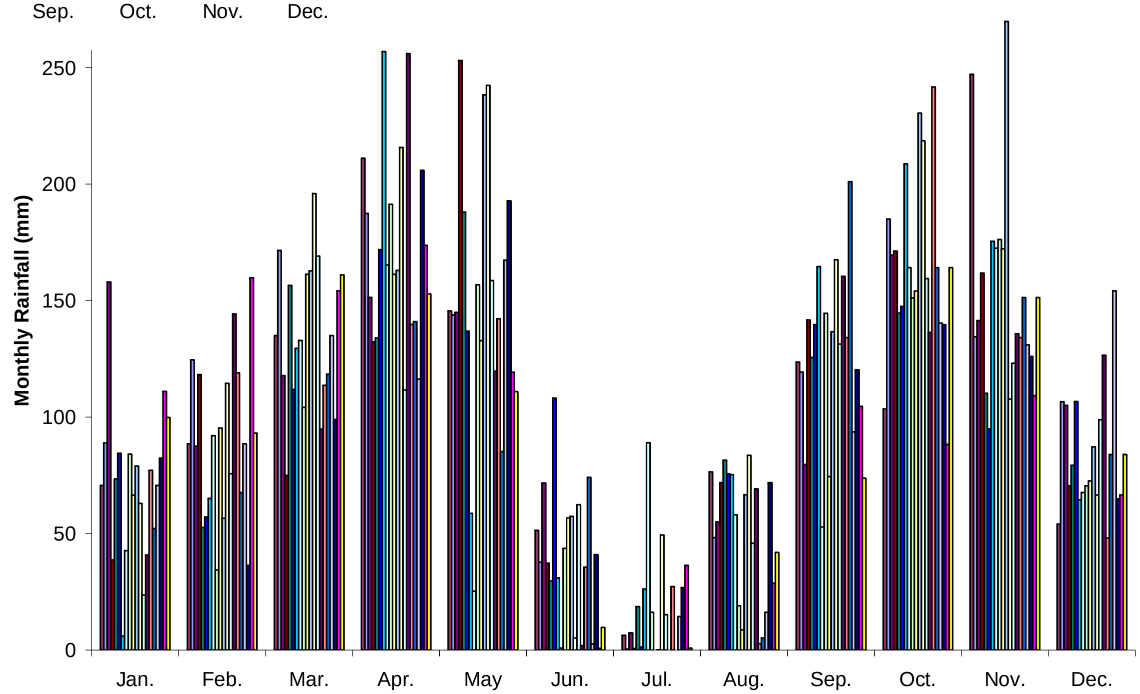
Storage-Reliability-Yield Simple Calculations

- Demand Side Analysis
  - Demand [m^3/day] * Dry Season length [days]
- Supply Side Analysis
  - Q=ciA
    - Q = tank size [m^3]
    - c = runoff coefficient ~0.85
    - i = annual rainfall [m/year]
    - A = roof area [m^2]



Seasonal Variation

Yearly Variation



Storage-Reliability-Yield (SRY) Simulation Model

- Simulate daily water balance within tank
  - YAS: yield after storage
  - Constant demand
  - Daily rainfall

Storage Term

$$S_r = \frac{s}{A_c}$$

S_r = physical storage ratio [m]

s = tank storage capacity [m^3]

A_c = roof area [1 m^3]

Yield Term

$$\alpha = \frac{y}{\mu_{dp} A_c}$$

α = yield fraction [unitless]

y = yield [m^3/day]

μ_{dp} = avg. daily precip [m/day]

A_c = roof area [1 m^3]

Reliability

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

q = time-based reliability

d_f = # days demand is not met

n = total days in study

Pseudo-daily rainfall generation

- Goal: simulate *daily* operation of RWH system over an extended time period
  - Need *daily* rainfall record
  - Only have 20-year *monthly* record and 2-year daily record

Generate one!

  - 20-year pseudo-daily record
  - Same monthly totals
  - Same seasonal trends
  - Similar average wet-day rainfall

Rainfall vs. Runoff

- Runoff = Rainfall - Losses
- Losses
  - Evaporation
  - Leaks
  - Splashing
- Related to roofing materials

- Assumed to be 15% of rainfall depth

Antecedent Dry Weather Period (ADWP)

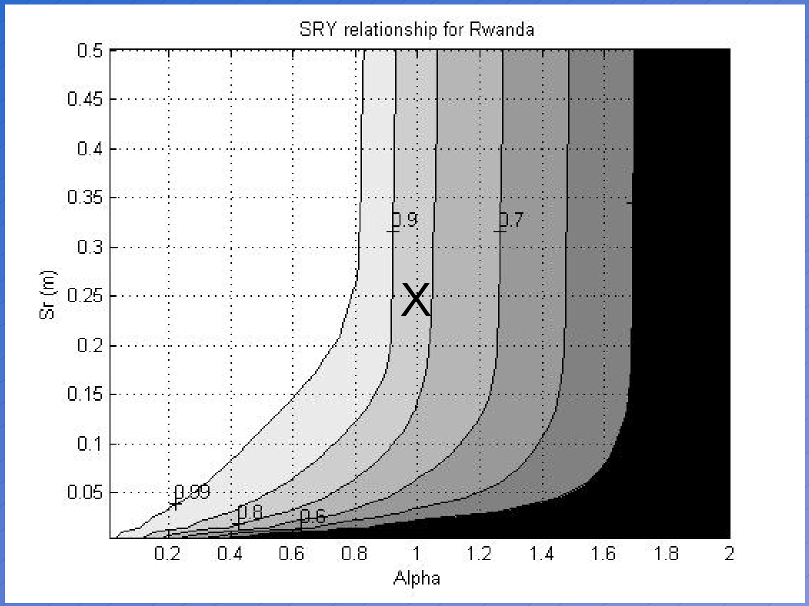
- During dry weather, dust accumulates on roof
- During rainy season, no need to divert everyday

Storm #	Antecedent Dry Weather Period (days)	Turbidity of first 0.3 mm of runoff at HS location (NTU)
S1	4.5	110
S4	3.0	96
S3	1.5	89
S2	0.5	75
S5	0.5	35
S6	0.5	12

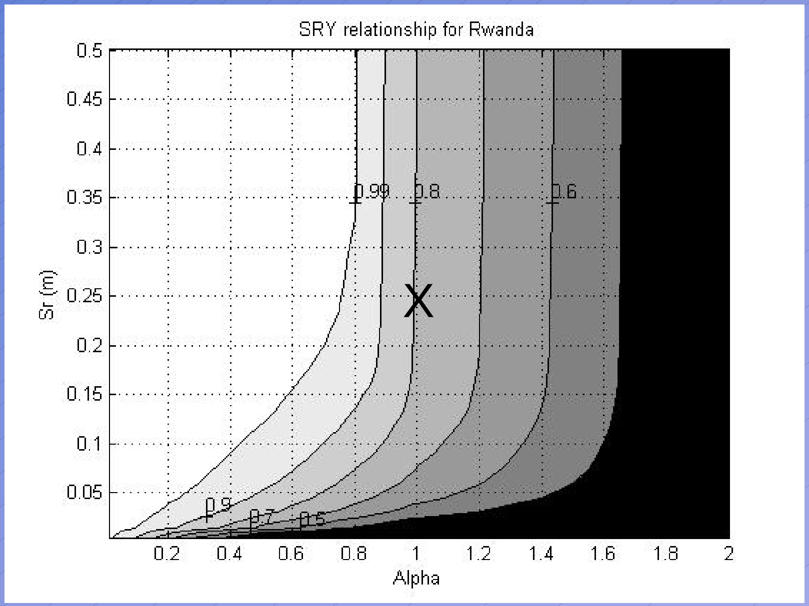
SRY Simulation Scenarios

Scenario	Assumed loss	Diversion
Scenario 1	Zero loss	No diversion
Scenario 2	**15% loss**	**No diversion**
Scenario 3	15% loss	0.5-mm diversion after three consecutive days each with <0.5 mm total rainfall
Scenario 4	**15% loss**	**1-mm diversion after three consecutive days each with <1 mm total rainfall**
Scenario 5	15% loss	1-mm diversion on each day with rainfall
Scenario 6	15% loss	2-mm diversion after three consecutive days each with <2 mm total rainfall

SRY Simulation Results



15% losses, no diversion



15% losses, 1 mm diversion after 3 consecutive days each with < 1mm rain

Reliability Results

		Reliability (%)		
Scenario	**Scenario**	**Health Clinic**	**Primary School**	**Trackers' House**
1	Base case, no losses, no diversion	94.4 %	36.8 %	91.0 %
2	**15% losses, no diversion**	**92.4 %**	**30.6 %**	**88.8 %**
3	15% losses, 0.5 mm diversion after 3 consecutive days each with <0.5 mm rain	91.7 %	30.1 %	88.0 %
4	**15% losses, 1 mm diversion after 3 consecutive days each with <1 mm rain**	**90.9 %**	**29.6 %**	**87.1 %**
5	15% losses, 1 mm diversion on each day of rain	89.7 %	27.8 %	85.7 %
6	15% losses, 2 mm diversion after 3 consecutive days each with <2 mm rain	89.5 %	28.4 %	85.1 %

Effect of First Flush Diversion on Reliability in Bisate

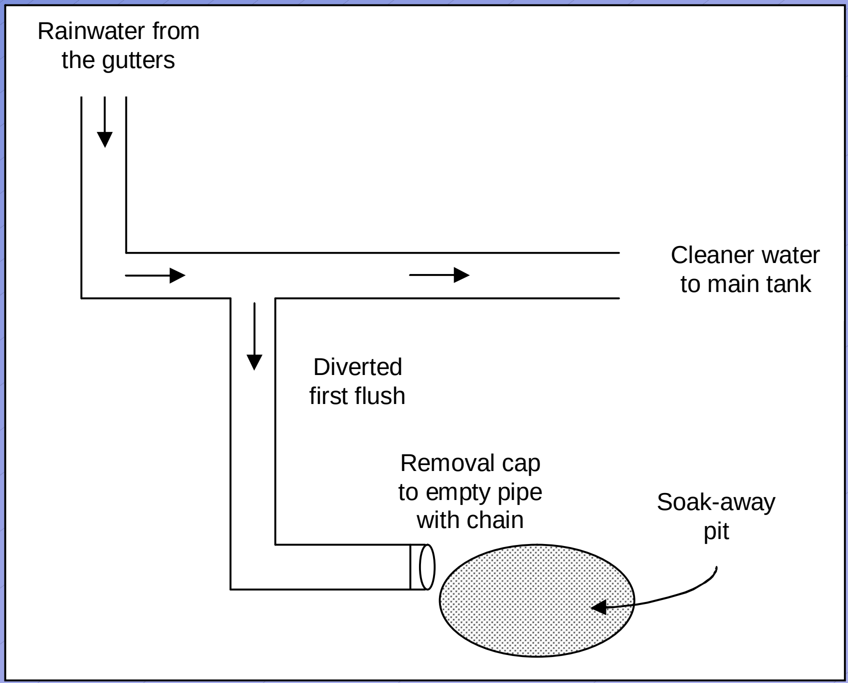
	Health Clinic	Primary School	Trackers' House
Reduction in reliability from 1mm-3 day diversion scheme	1.5%	1.0%	1.7%
Additional days not meeting demand with first flush diversion	6 days	4 days	7 days

- Variability of rainfall
- Non-constant demand
- Need for alternate source of water

Conclusions

- A small reduction in reliability (<2%), diversion of the first millimeter of runoff can lead to 50% reduction in turbidity, drastically lower coliform counts, and reasonably safe levels of *E. coli* (<10 colonies/100 mL)

- Unnecessary to remove first mm after each rain, only after significant build-up of pollutants



Research Needs

- Study of the antecedent dry weather period on runoff water quality
- Importance of intensity on washoff process
- Quantification of loss fraction based on roof type
- Effect of distance to roadway and tree proximity
- Disinfection/filtration options for RWH

Murakoze Cyane!

- Pete Shanahan
- Bernie Isaacson
- John Peter Nshimyimana
- DFGFI
- Charlie Agoos and Kelly Huang
- MIT PSC

Questions?

Pseudo-daily Rainfall Generation

- P_m: probability of a day being wet
- R_m: actual monthly rainfall value
- A: 800 mm (empirical)
- n_{wm}: number of wet days in a month
- R_{wm}: mean wet day rainfall
- Z: scaling factor
- Wet day if random number < P_m

$$P_m = \sqrt{\frac{R_m}{A}}$$

$$n_{wm} = 30P_m$$

$$R_{wm} = \frac{R_m}{n_{wm}}$$

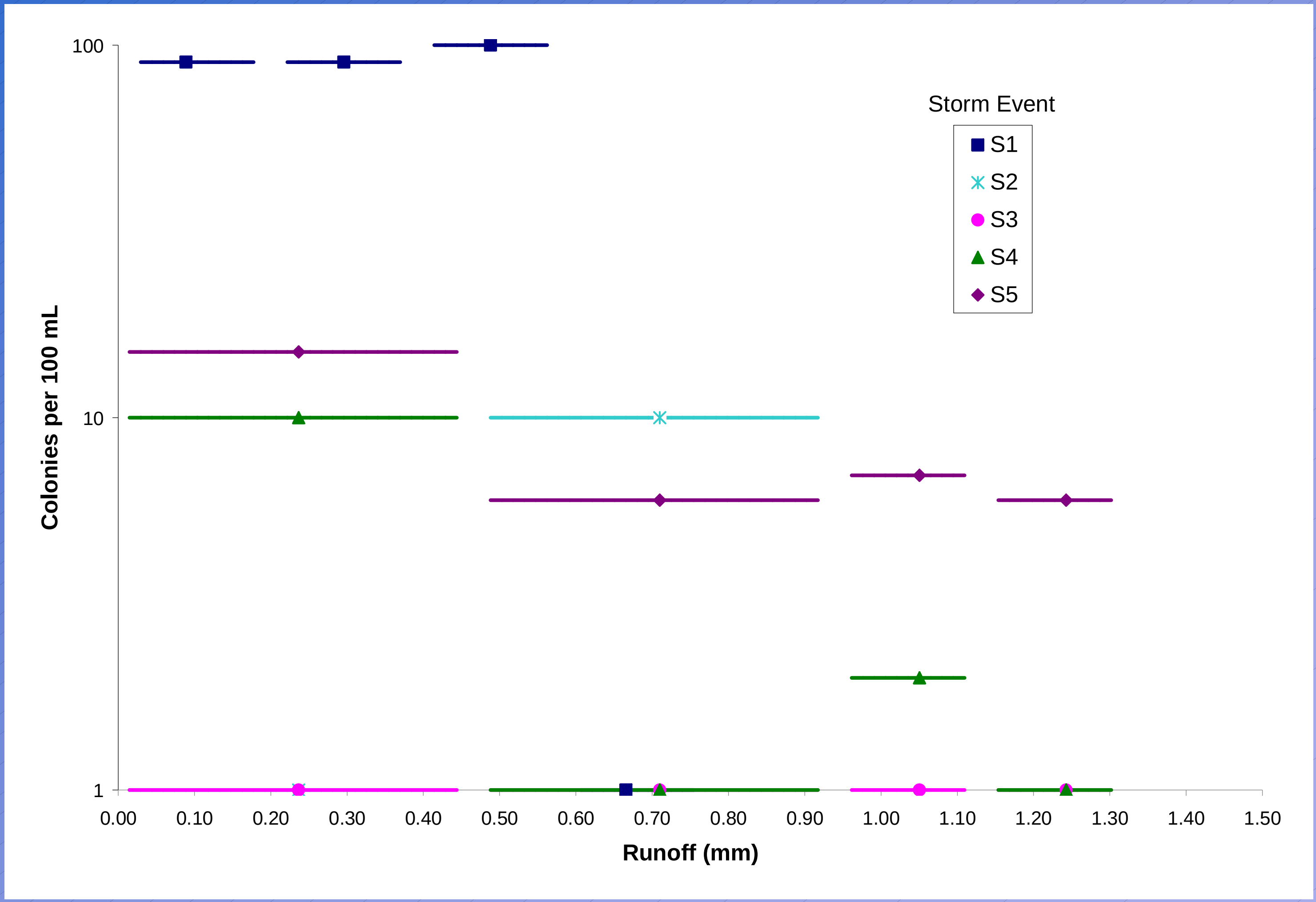
$$r' = -R_{wm} \ln(Z)$$

$$Z = aX + bX^2 + cX^3$$

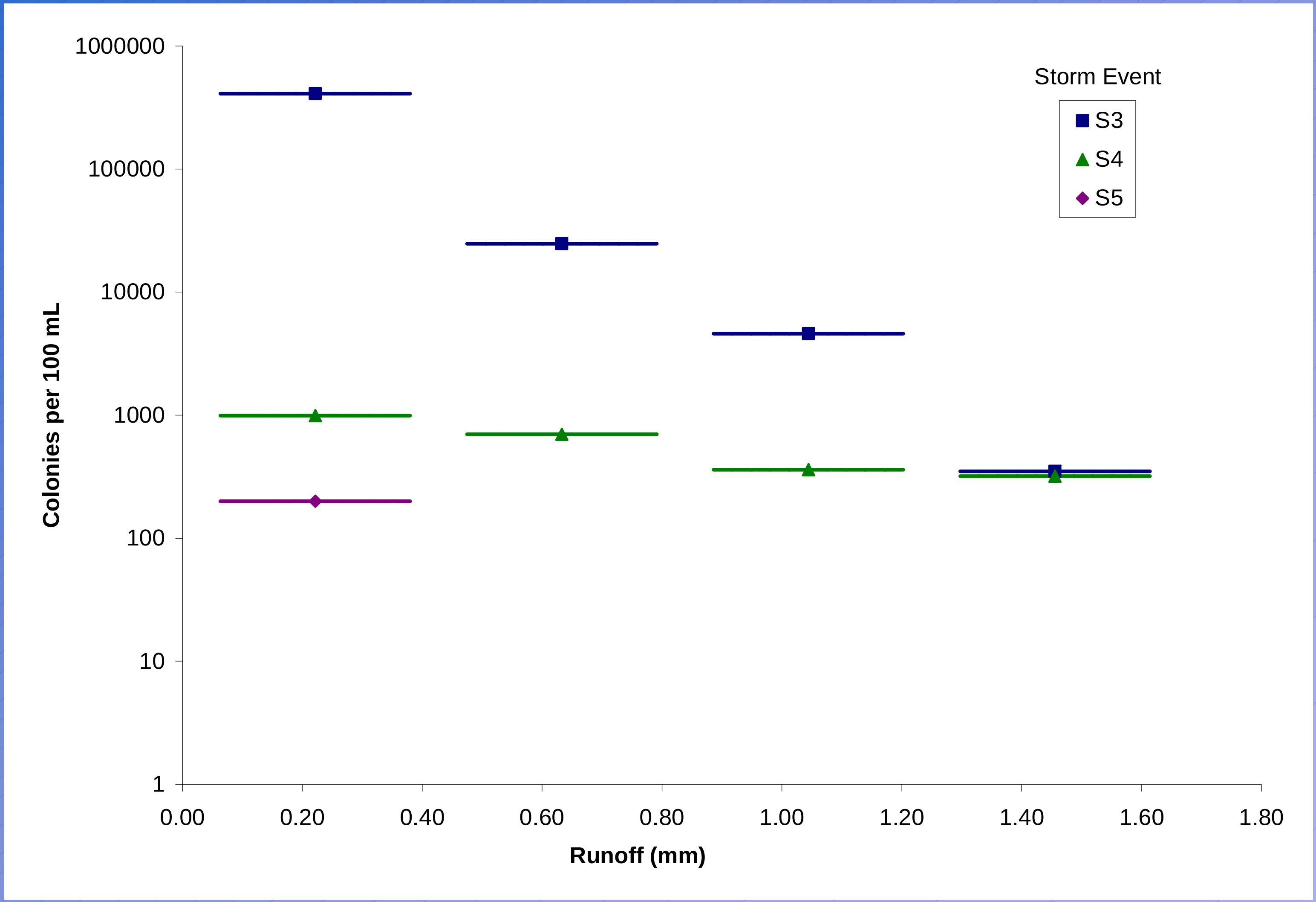
$$b = 3 - 3a$$

$$c = 2a - 2$$

Total Coliform Results-CL



Total Coliform Results: PT



"For each mm flushed away the contaminant load will halve" (Martinson and Thomas 2005)