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DSD International Conference 2014

Extensive Green Roofs: first step towards Sustainable Urban Drainage System design in Hong Kong

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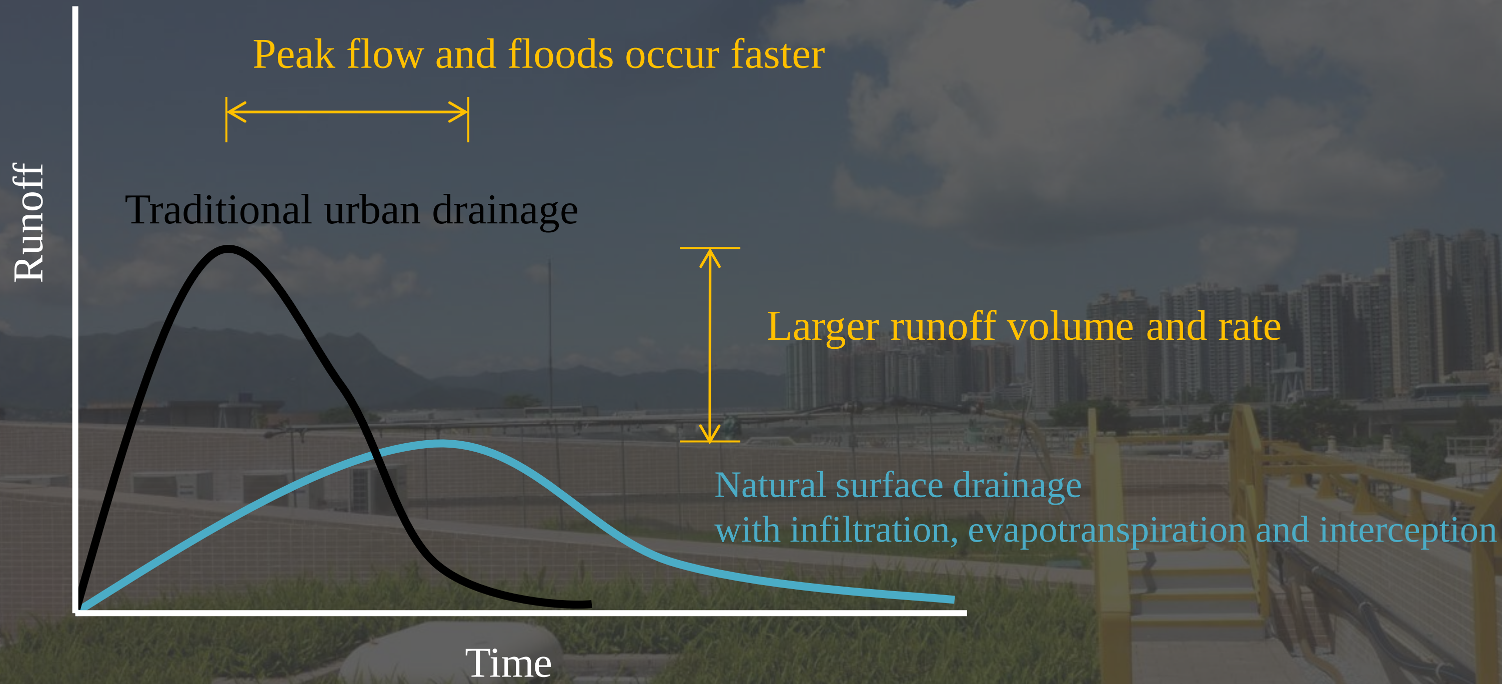
SUDS Terminology

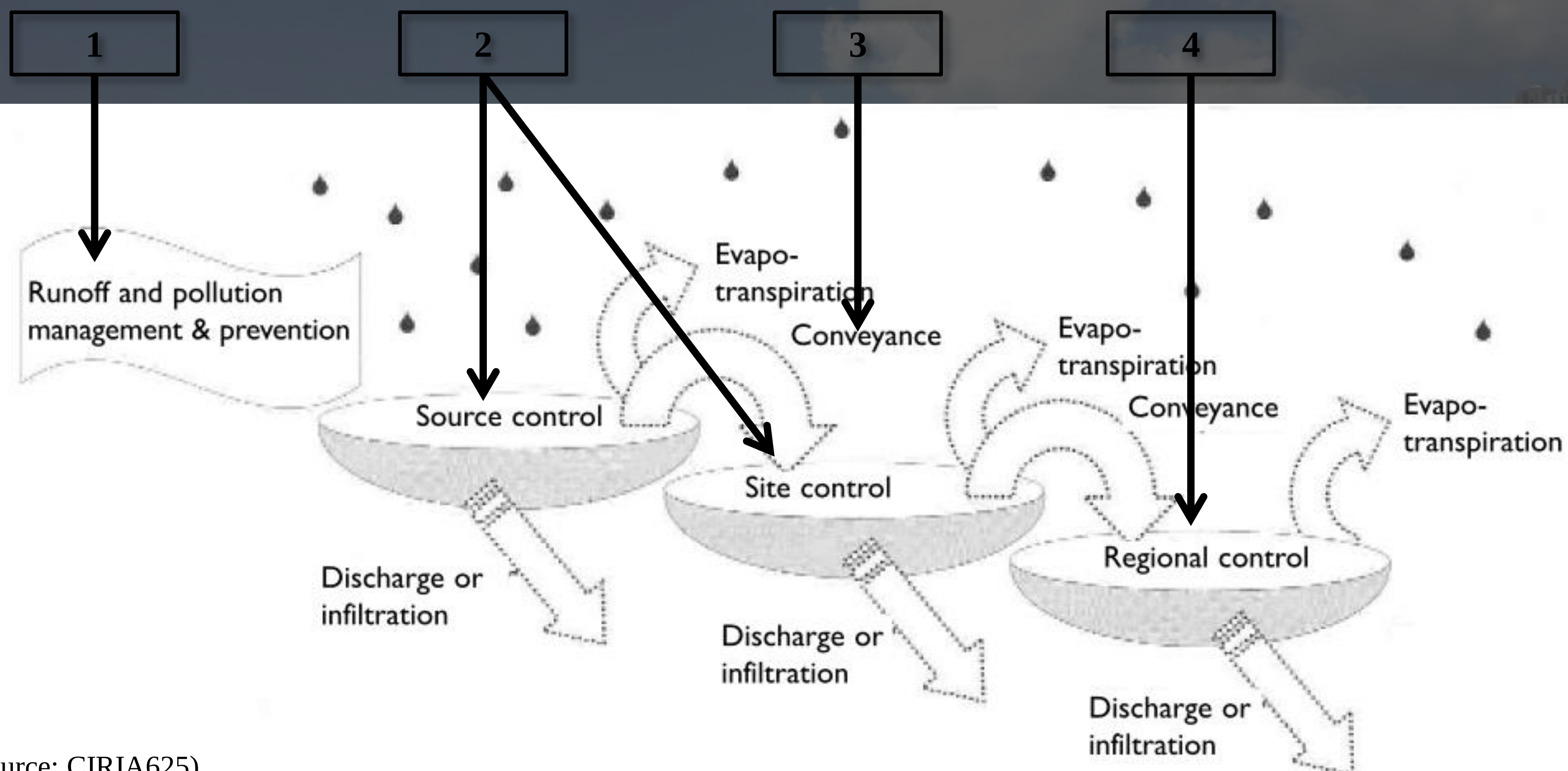
SUDS: **S**ustainable **U**rban **D**rainage **S**ystem (UK)
LID: **L**ow-**I**mpact **D**evelopment (US, Canada)
WSUD: **W**ater-**S**ensitive **U**rban **D**esign (Australia)
ABC-Waters: **A**ctive, **B**eautiful and **C**lean **W**aters (Singapore)
etc.

SUDS Concept
Hydrograph comparison:



SUDS: to restore the natural drainage system in urban setting for Quality, Quantity and Amenity improvements

SUDS Components
- A Holistic Approach of Water Management
- 4 major categories/levels of component:



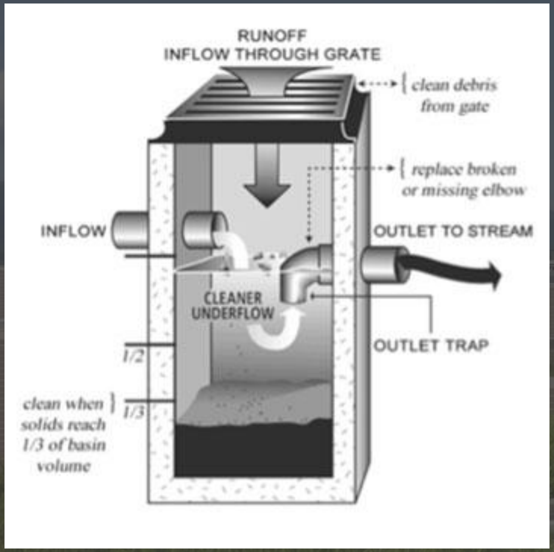
(Source: CIRIA625)

The "Treatment Train" in the SUDS Water Cycle

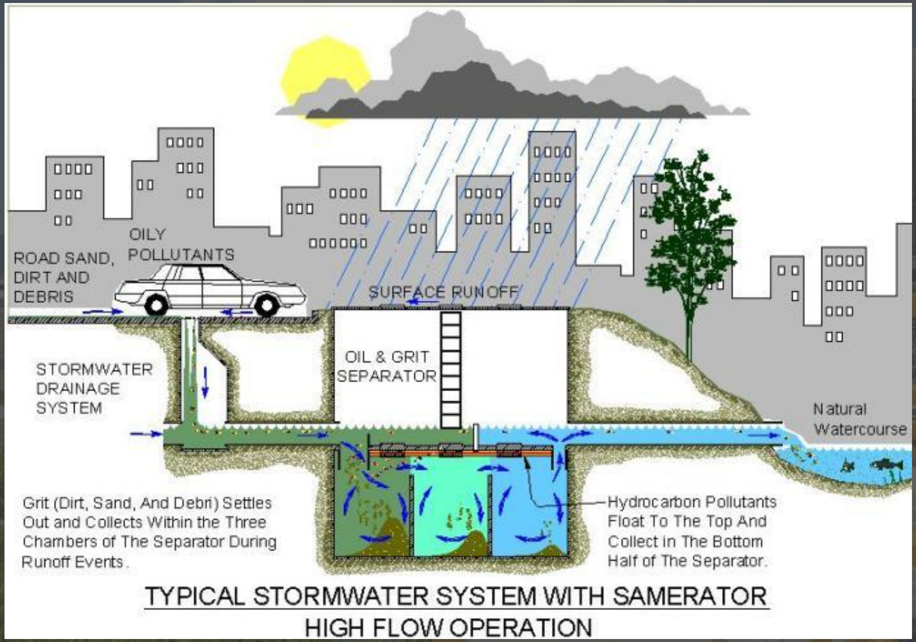
SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control

Examples of local runoff quality control or pre-treatment:



Sediment Sump



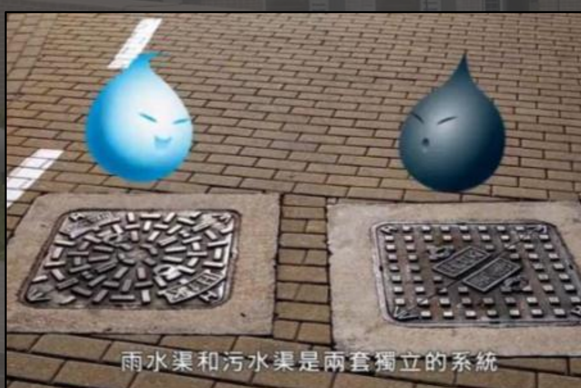
Oil and Grit Separator

(Source:
[left] http://www.theparkinglotguys.ca/catch-basin-cleaning
[right] http://www.sameng.com/2012/01/samerator-oilgrit-separator/)

SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control

2014 Government Commercial on Rainwater Pollution Prevention and Control

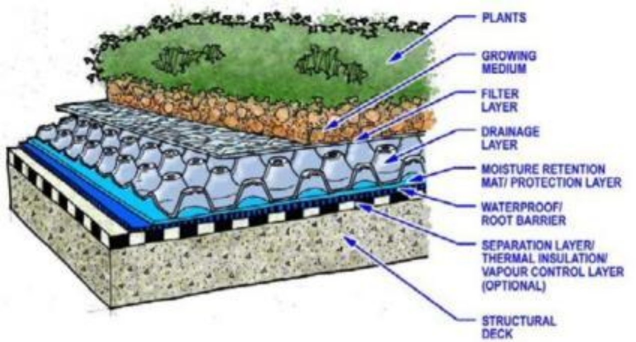


(Source: DSD, 2014)

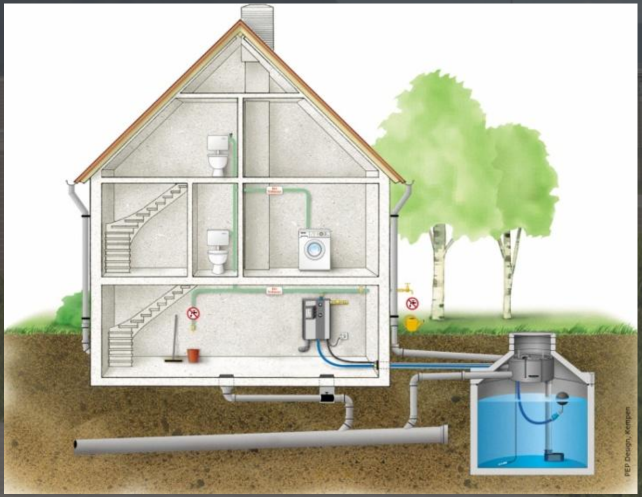
SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control

Examples of site / source control:



Green roof



(Source: http://www.tschernuth.co.at/76)

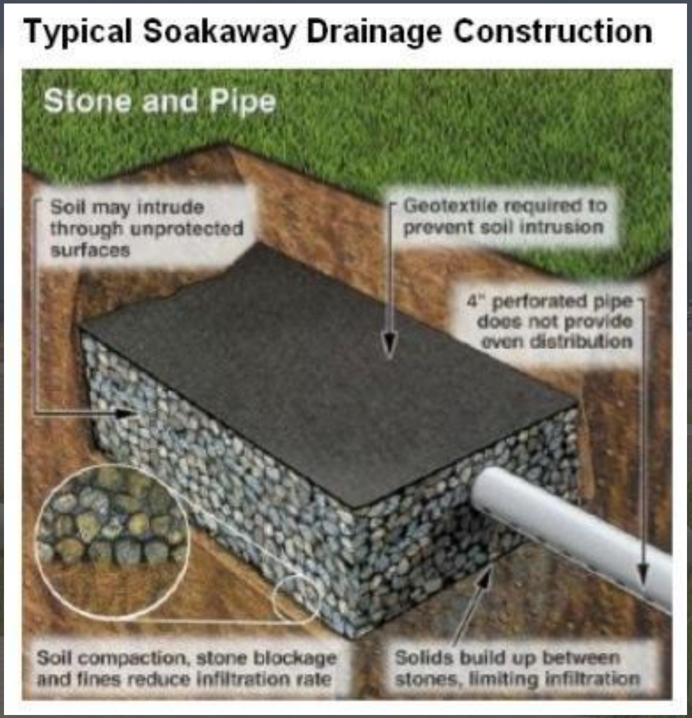
Rainwater harvesting system

(Source: 氣候變遷的因應與調適, 李鴻源)

Bio-retention area / Rain garden

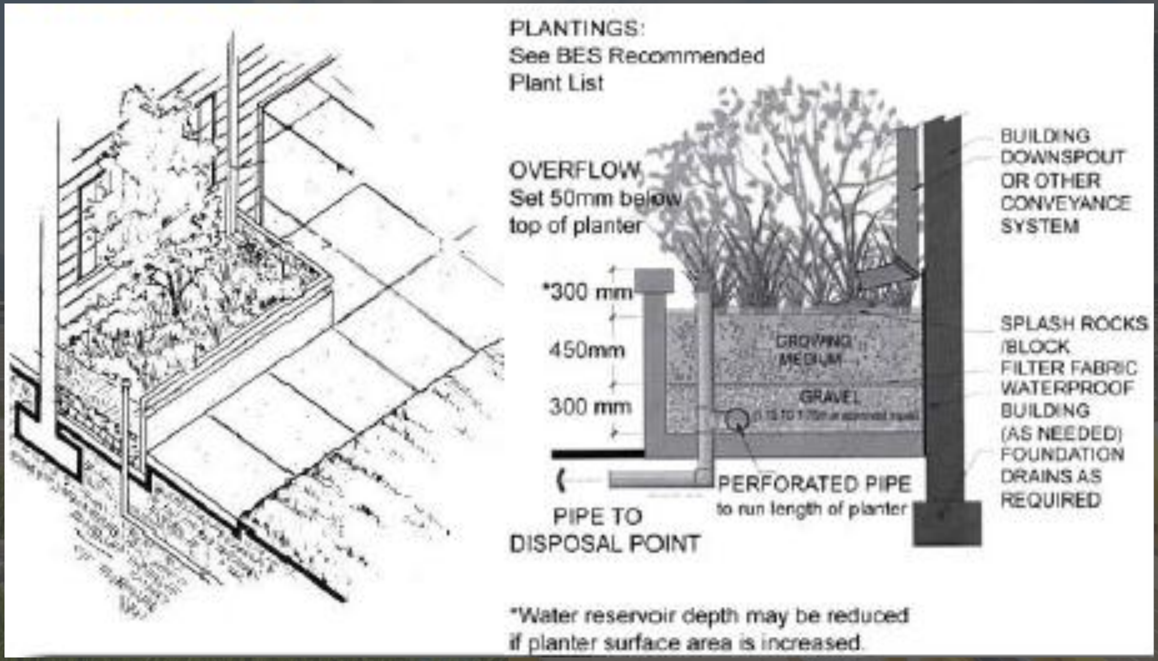
SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control



Soak away pit

Source: http://buildingindustry.org/soakaway



Bio-retention cell

Source: Ryerson University Low Impact Development Workshop 2009

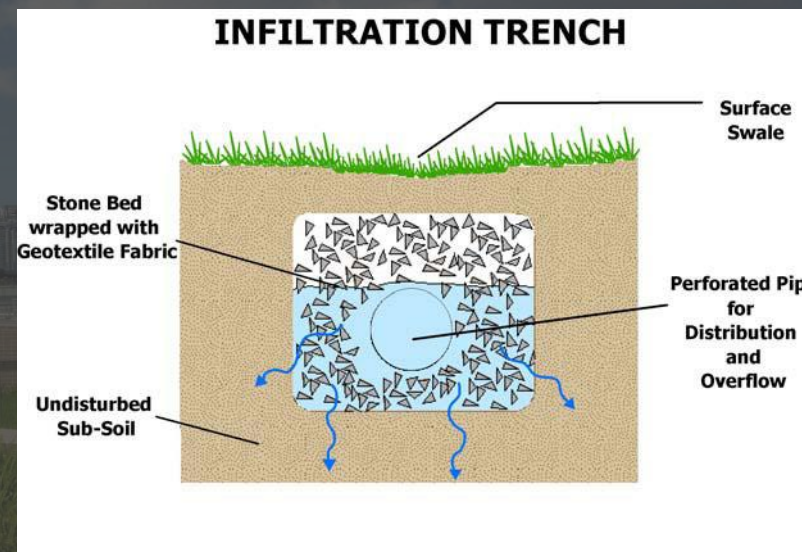
SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control

Examples of conveyance-level control:

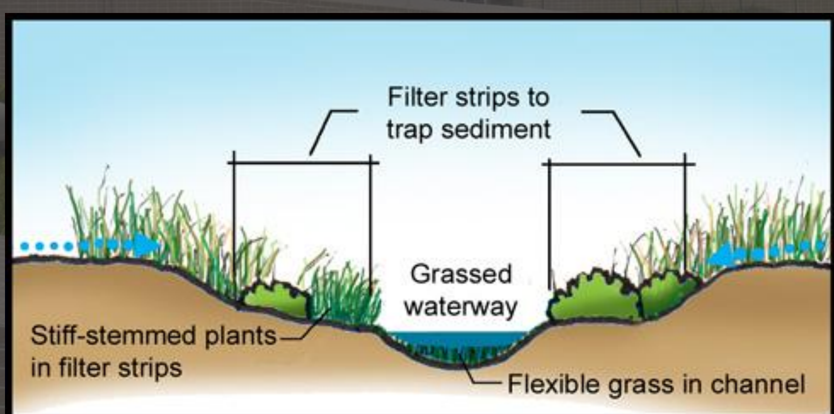
Swale

(Source: NFWF Hurricane Sandy presentation 2013)



Infiltration trench

(Source: http://acronymonline.org/times-calls-measures-stormwater-infiltration/)

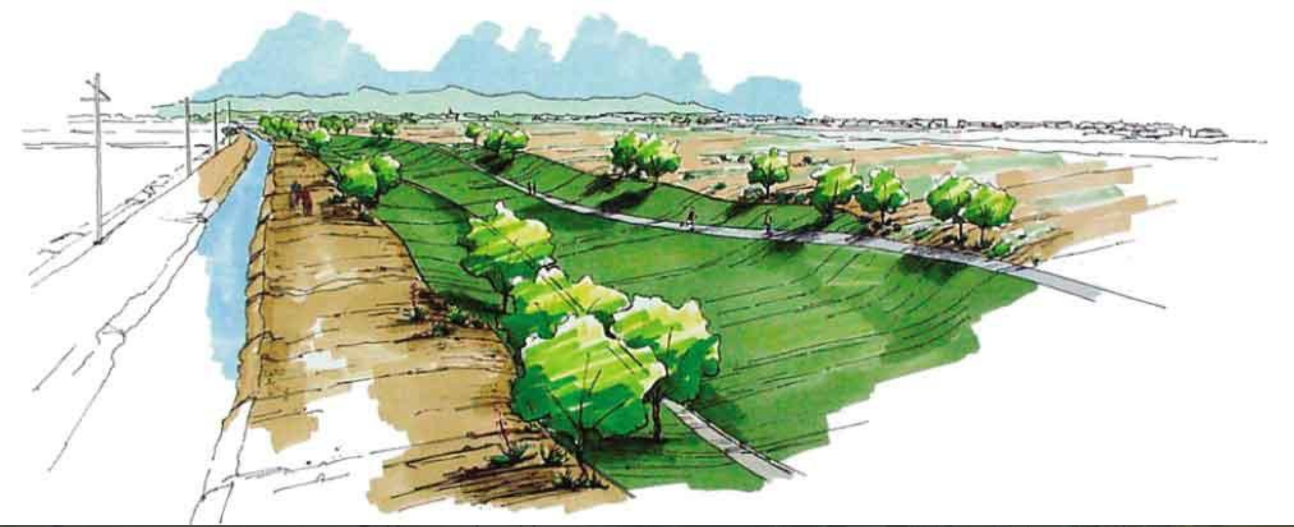


Filter strip

(Source: http://nac.unl.edu/buffers/guidelines/3_productive_soils/4.html)

SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control



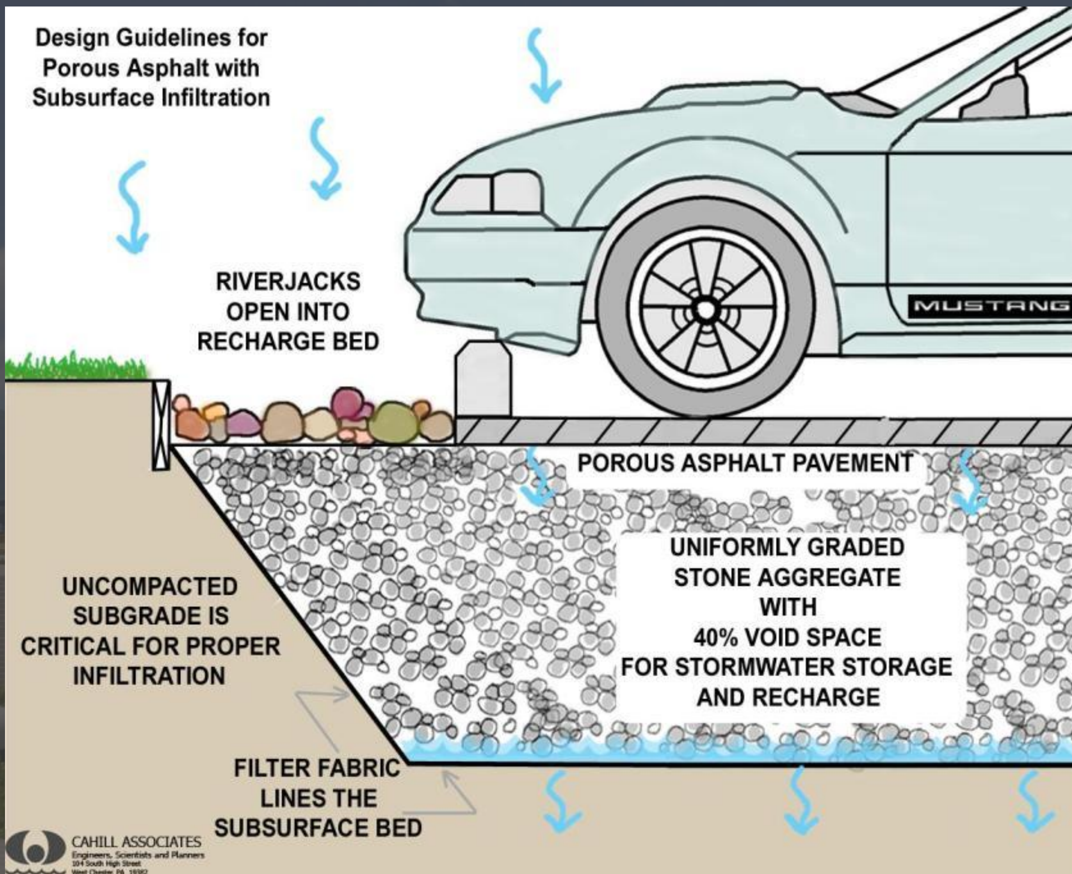
(Source: Ryerson University Low Impact Development Workshop 2009)

Grass channel

(Source: Kadoorie Farm and Botanic Garden, Fauna Conservation Department 2013)

SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control



(Source: Cahill Associates)

(Source: www.wsud.org)

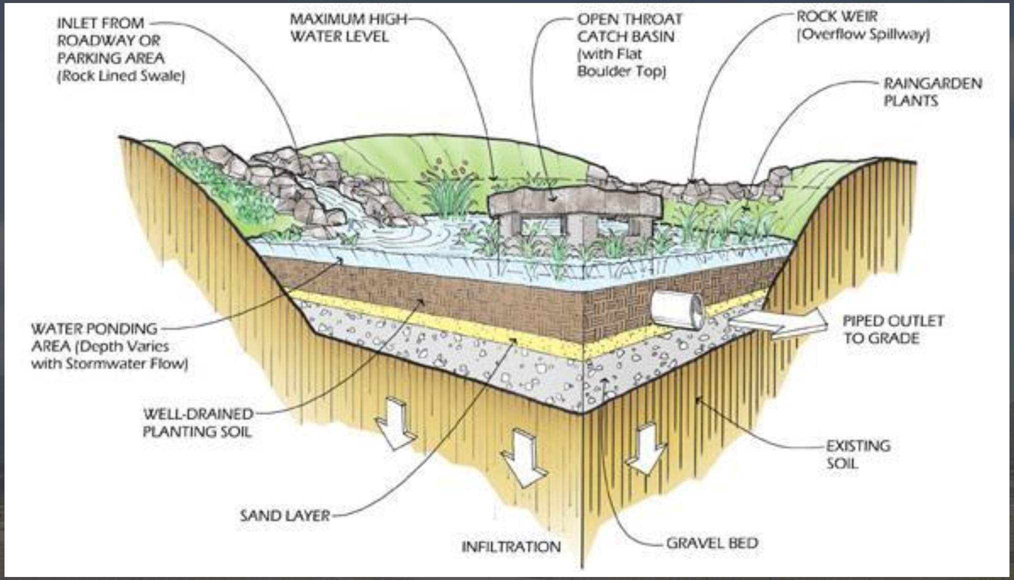
(Source: Ryerson University Low Impact Development Workshop 2009)

Permeable pavements

SUDS Components

1. Water Quality Control
2. Site/Source Control
3. Conveyance
4. Regional Control

Examples of regional control:



(Source: Ryerson University Low Impact Development Workshop 2009)

Detention / Retention basin

(Source: www.chelseama.gov, 2012)

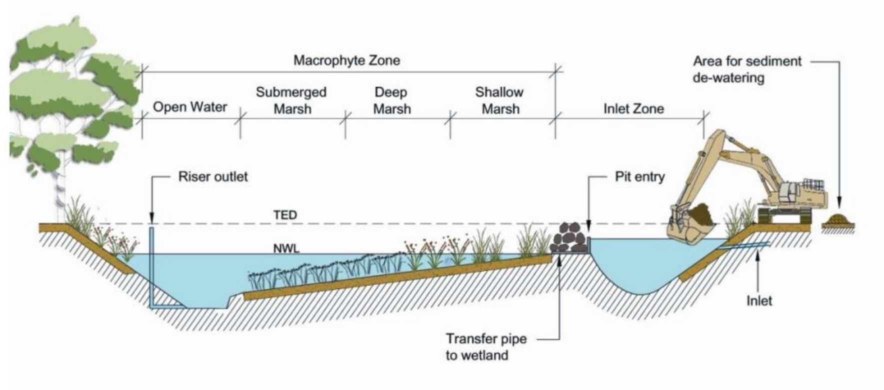


Figure 10.1 Layout of a constructed wetland system

Constructed wetland

(Source: PUB, Singapore 2014)

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Study of Extensive Green Roofs

Urbanized Wan Chai (roofs not being used)

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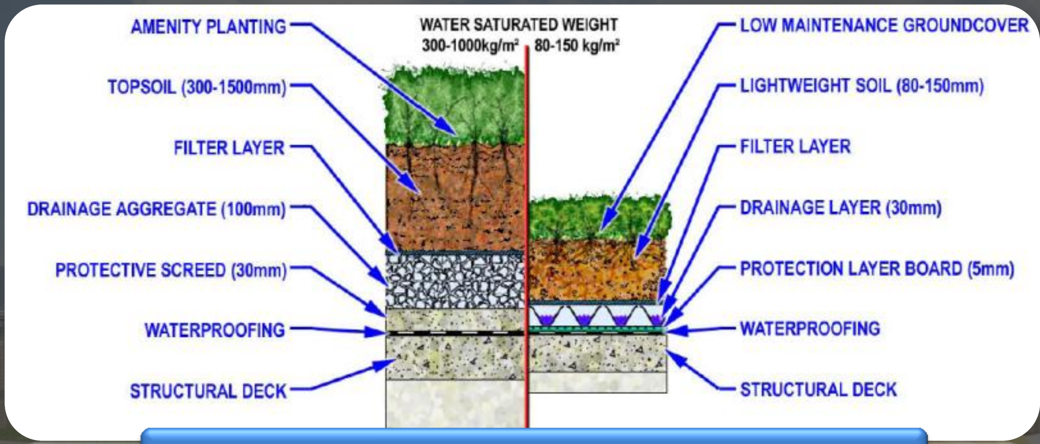
What about this?
Greening
Wan Chai

▪ Green Roof and Structure

○ Intensive and extensive green roof due to different thickness of substrate layer



Intensive and extensive green roof system [1]

○ Green roof consists of

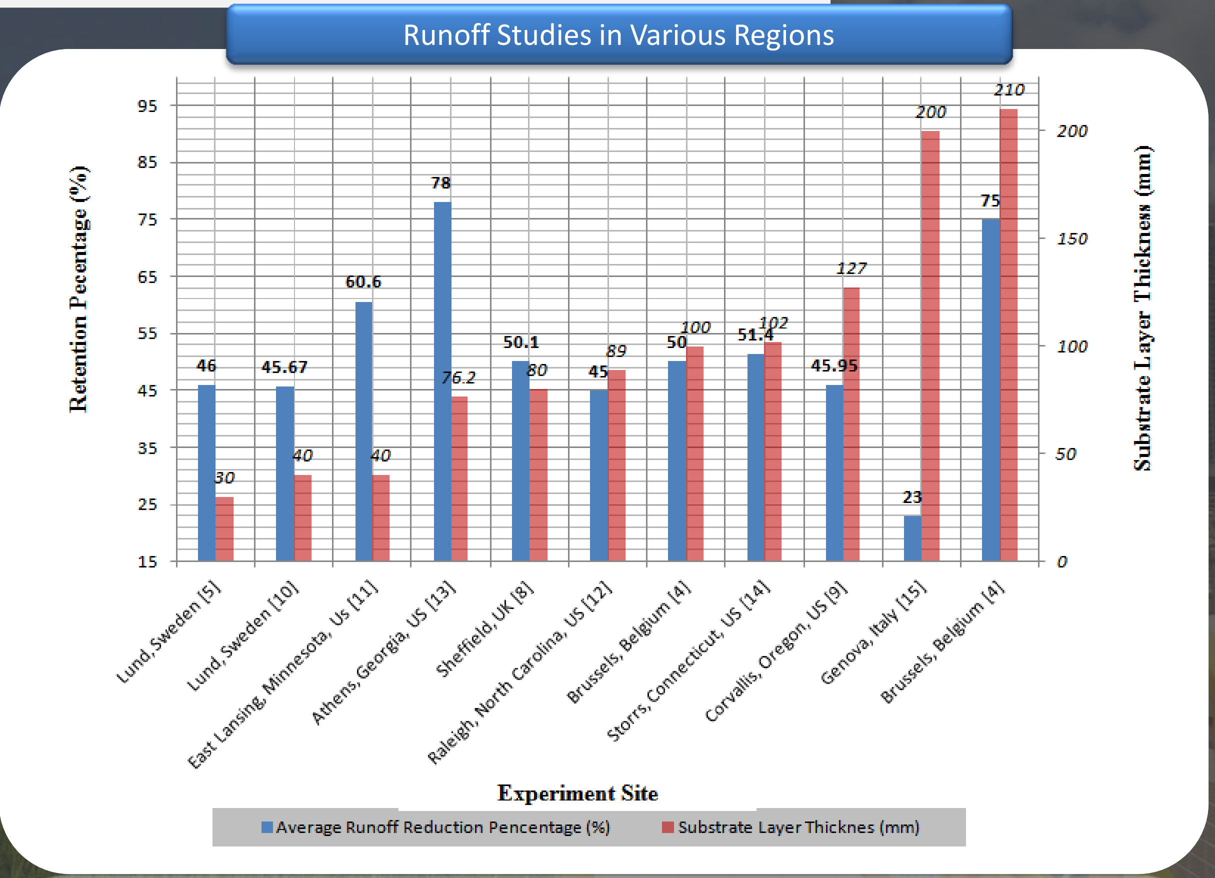
- Vegetation layer
- Substrate layer
- Filter layer
- Drainage layer
- Root barrier
- Water proofing

○ Benefits: stormwater management, air pollution abatement, heat island effect mitigation, noise reduction. etc.

Runoff Studies in Various Regions

- Different regions achieve different result of storm water retention percentage due to **climate and green roof configuration differences,** ranging from 23~78%.

- Thicker substrate layer, more storm water retention.



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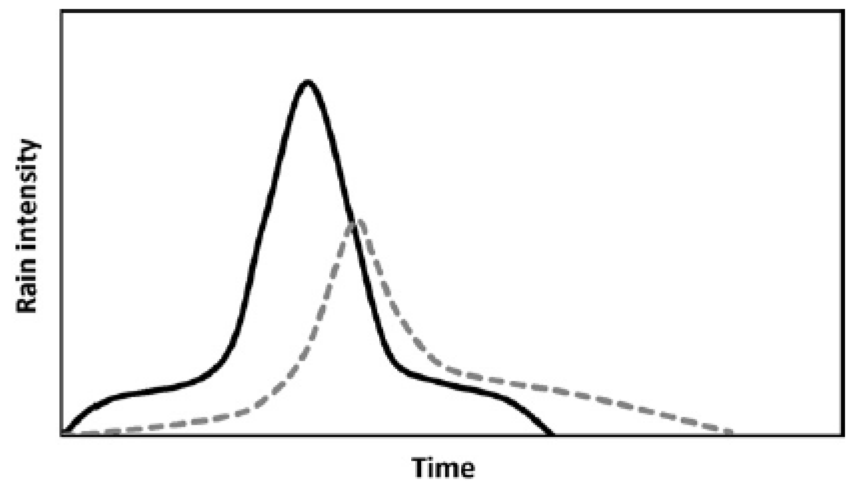
▪ Factors Affecting Runoff Results

○ Substrate Layer Thickness

Intensive green roof reduced annual runoff as **85-86%** of normal precipitation while the **extensive achieved 27-81%**

○ Rainfall Intensity

For small storms (<25.4mm) 88% retained, for medium storms (25.4–76.2mm) more than 54% retained and for large storms (>76.2mm) 48% retained.



Example runoff from a green roof (dashed line) generated by a given rain event (black line) [16]

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Factors Affecting Runoff Results

○ Slope

2° slope **double** the retention capacity as compared to 14° slope [10].

○ Season

For the substrate thickness between 50 and 150 mm, season-wise runoff reductions were: 70% for the warm season, 49% for the in-between seasons, and 33% for the cold season [4].

Rainfall retention by *Sedum* extensive green roof under different slopes [10]

Rain (mm/min)	Duration (min)	Total precipitation, *P* (mm)	Rain to start runoff (mm)	Total runoff	Retention (mm)
Slope 2°					
0.4	60	24	12	9.2 (38%)	14.8 (62%)
0.8	30	24	10	11.0 (46%)	13.0 (54%)
1.3	30	39	9	31.0 (79%)	8.0 (21%)
Slope 8°					
0.4	50	20	8	11.4 (57%)	8.6 (43%)
0.8	30	24	7	16.7 (70%)	7.3 (30%)
Slope 14°					
0.4	60	24	8	14.6 (61%)	9.4 (39%)
0.8	60	48	7	38.0 (79%)	10.0 (21%)
1.3	60	78	6	70.0 (90%)	8.0 (10%)

Factors Affecting Runoff Results

Vegetation

Vegetated roofs retained 60.6% rainfall; the media-only roofs retained 50.4% rainfall and the gravel ballast roof retained 27.2% rainfall [11] .

Vegetation is likely to have the greatest impact on stormwater management (about 40% better than medium-only roofs) under conditions characterized by frequent relatively small rain events [17] .

The incredible green roof at the School of Art, Design and Media at Nanyang Technical University in Singapore [18]

Issues Arise

Runoff is weather specific, study based on HK weather conditions is required.

Plants used in various studies are different, study on local plant species in HK should be carried out.

Substrate constituent varied in different studies, study of commercial substrate in HK is needed.

Intensive (Left) and extensive (Right) green roofs in Hong Kong

Scope of Work

1. To design 2 real green roofs for the purposes of demonstration, testing and monitoring.
2. To carry out in-situ measurements and laboratory experiments to investigate the stormwater retention performance of different green roof systems under different growing medium depths, roof slopes, antecedent moisture conditions and number of layers.

Real Green Roof Design

Roof of Sludge Thickening House (STH), Shatin Sewage Treatment Works


1. Original roof


2. Staircase construction to STHE


3. Paving green roof layers


4. Adding soil substrate


5. Completed green roof

Roof Area: 840m^2
Plants: 12 species
Soil Thickness: 150mm

Another building -- Sludge Thickening House Extension (STHE)


1. Original roof


3. Paving green roof layers


5. Completed green roof

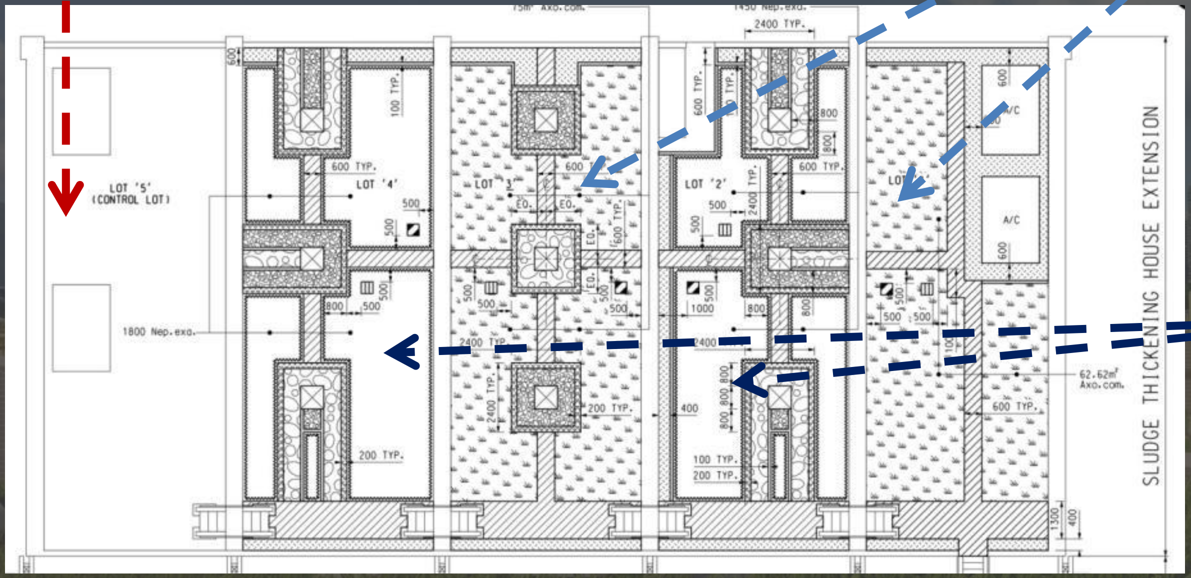

1. Wall tiles and stairs construction


4. Adding soil and plants

Roof Area: 602m^2
Area of each lot: 108 to 113m^2
Plants: 2 species
Soil Thickness: 100mm, 150mm and 0mm (control)

Sludge Thickening House Extension (STHE) (cont.)

Lot 5: Control Lot
(original roof unchanged)



Lot 3, 4: Soil Thickness 150mm

Lot 1, 2: Soil Thickness 100mm

Lot 1, 3:
Axonopus comperssus
(Carpet Grass)

Lot 2, 4:
Nephrolepis exaltata
(Boston Fern)

Growth Performance: Carpet Grass (Lot1, 100mm soil)

13-2-2012: Early establishment

10-8-2012: 1st Summer

21-12-2012: 1st Winter

15-5-2013: 2nd Summer

Growth Performance: Sword Fern (Lot2, 100mm soil)

13-2-2012: Early establishment

18-7-2012: 1st Summer

7-1-2013: 1st Winter

15-5-2013: 2nd Summer

Growth in STH Green Roof

14-3-2012: Early establishment

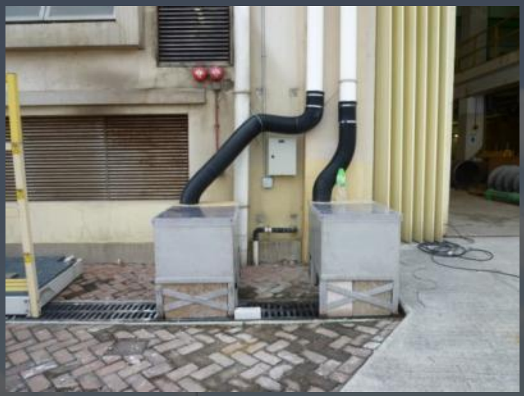
22-5-2012: Quick growth after Spring

7-11-2012: 1st Winter

29-5-2013: 2nd Summer

Sensors and equipments

Weather station sensor suite



V-notch weir chamber (runoff measurement)

Runoff experiment setup (left) and ultrasonic flow meter (right)

3D anemometer

Thermocouple and data logger

Soil temperature and moisture sensor (right) and data logger (left)

Sensors and Equipments - V-notch calibration example: Lot 1

Discharge expression of a V-notch weir:

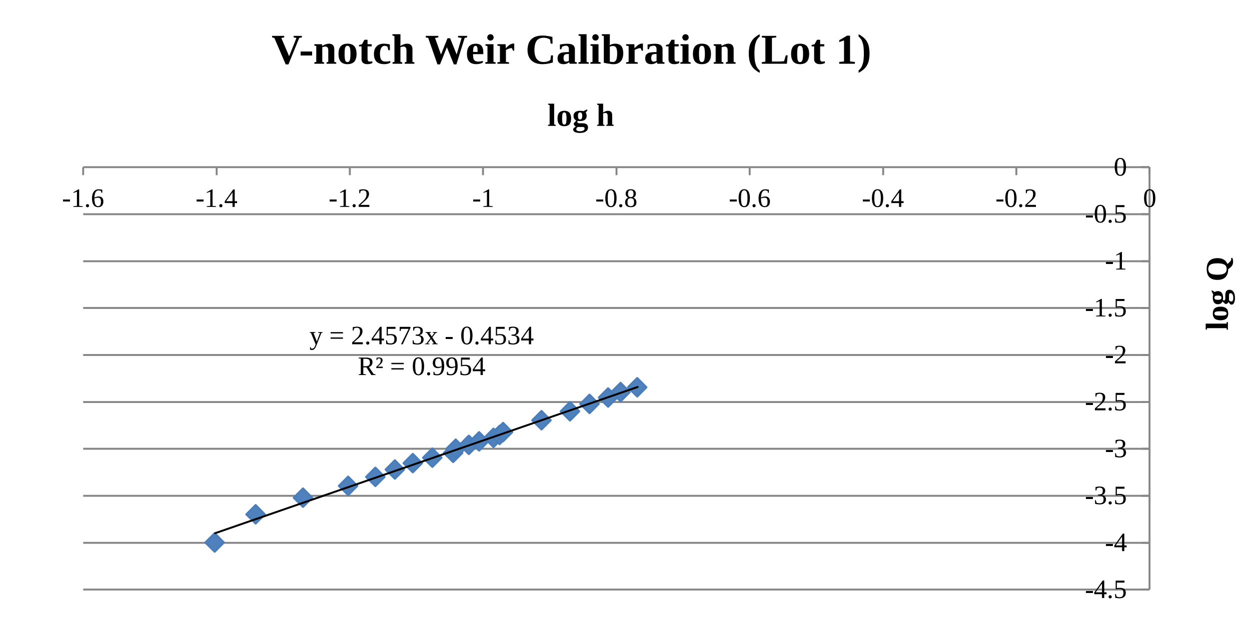
$$Q = \left(\frac{8}{15}\sqrt{2g}C_d \tan\frac{\theta}{2}\right)h^{\frac{5}{2}}$$

Q = discharge
C_d = coefficient of discharge of the V-notch
ө = angle of the V-notch (30 in this case)
h = water level from vertex of the V-notch
g = standard gravity (9.8m/s^2)

By measuring Q and h,
C_d can be calculated through a calibration plot of log Q against log h

$$\log Q = \log\left(\frac{8}{15}\sqrt{2g}C_d \tan\frac{\theta}{2}\right) + \frac{5}{2}\log h$$

V-notch calibration : Lot 1



(Lot 1) $C_d = 0.556$

V-notch calibration setup in Hydraulics Laboratory

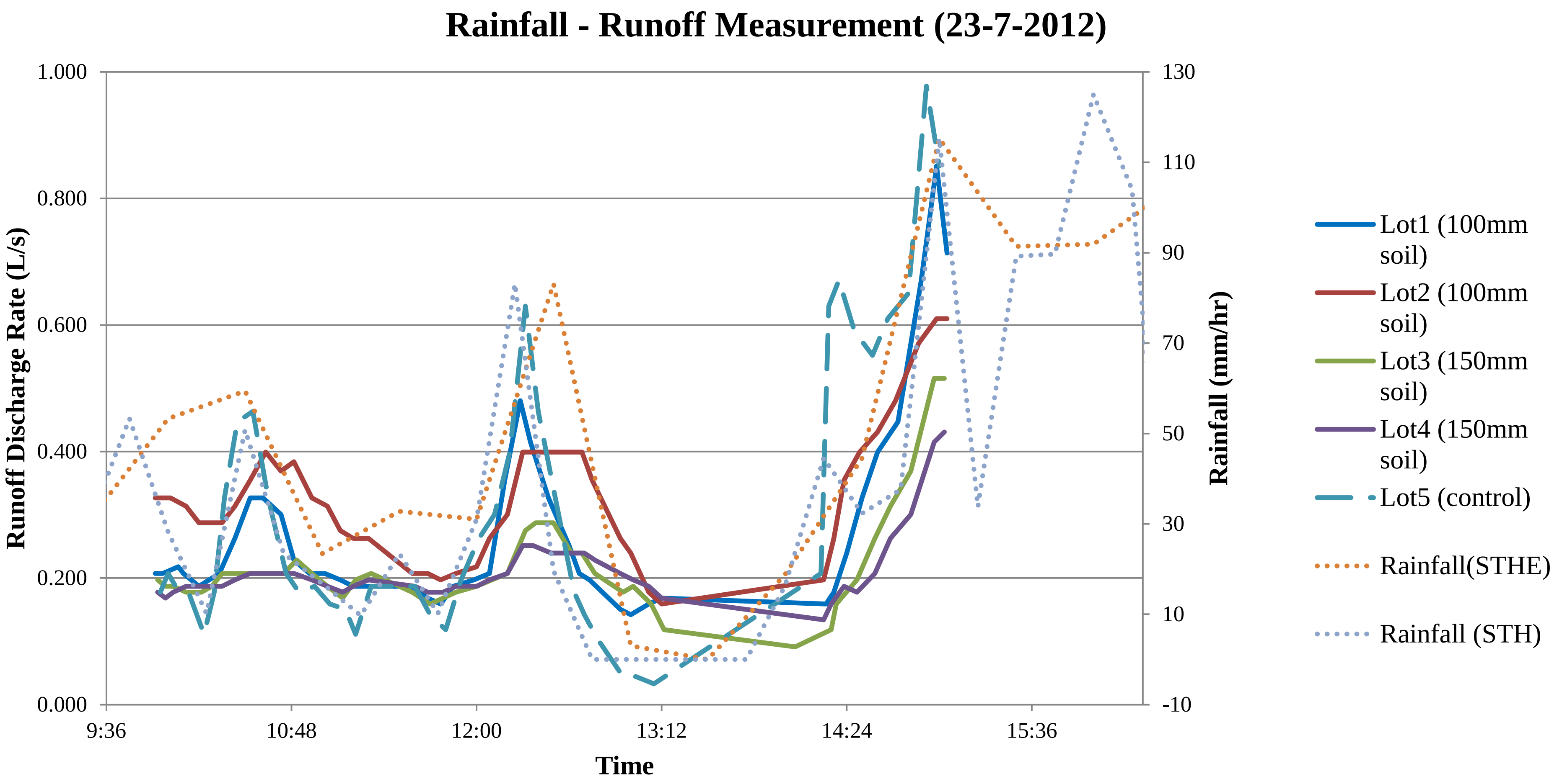
Field Measurement - Runoff Measurement

Drainage Inspection Chamber

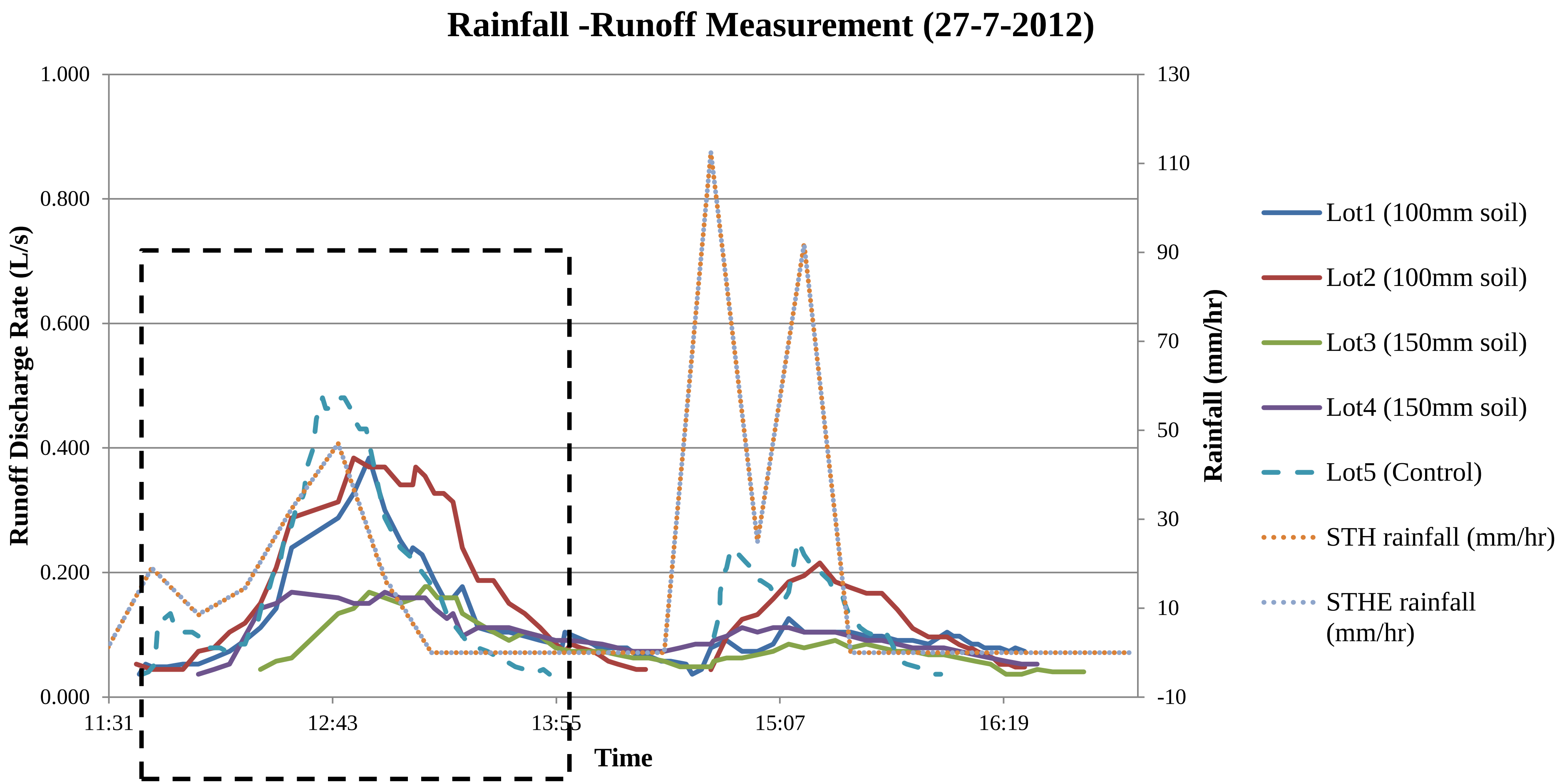
Each green roof lot is connected to the corresponding V-notch chamber through an individual downpipe

V-notch weir chamber

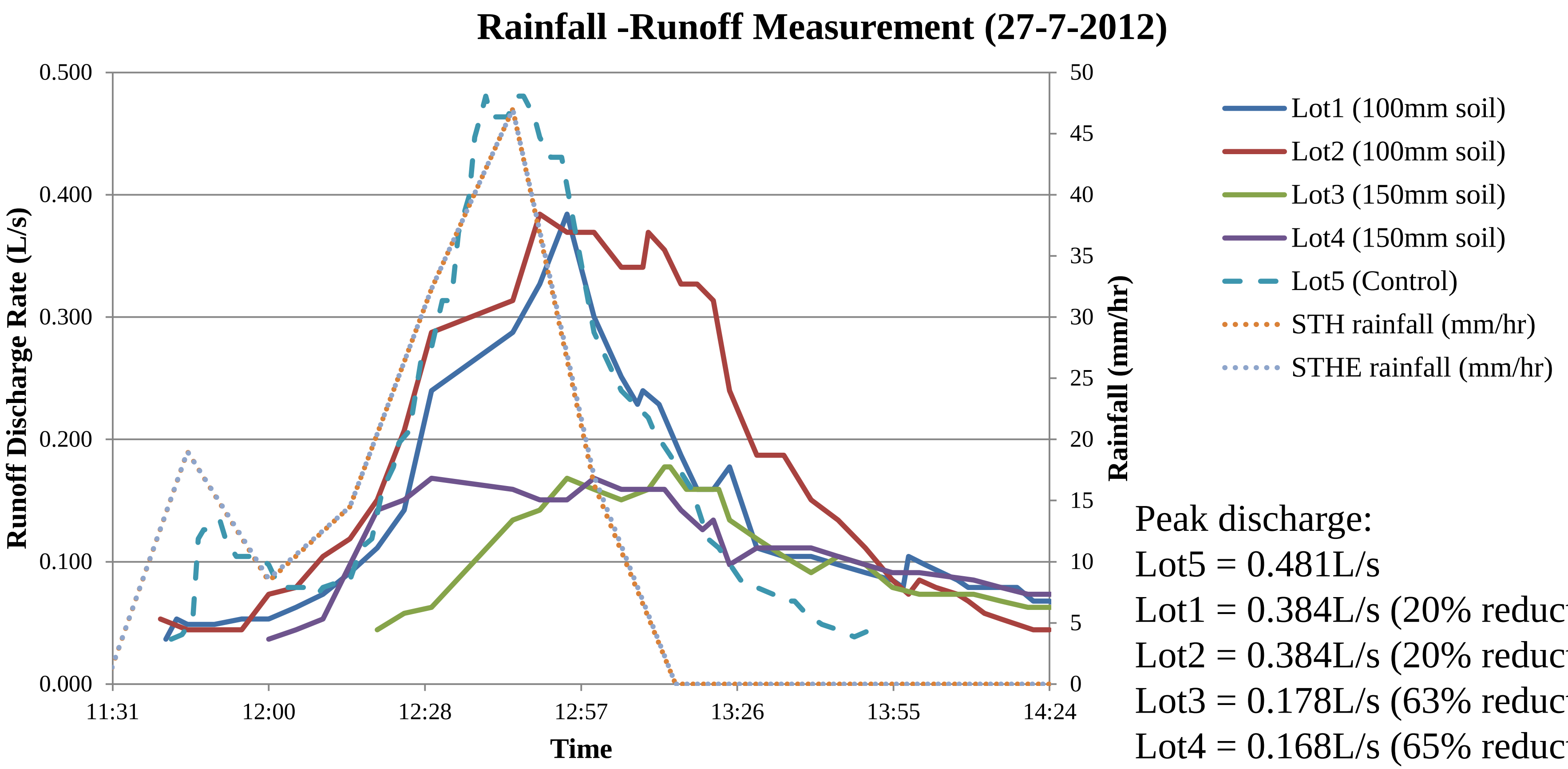
Runoff Measurement 23 July 2012 (Typhoon Vicente)



Runoff Measurement 27 July 2012



Runoff Measurement 27 July 2012
Highlight – Runoff reduction of green roofs



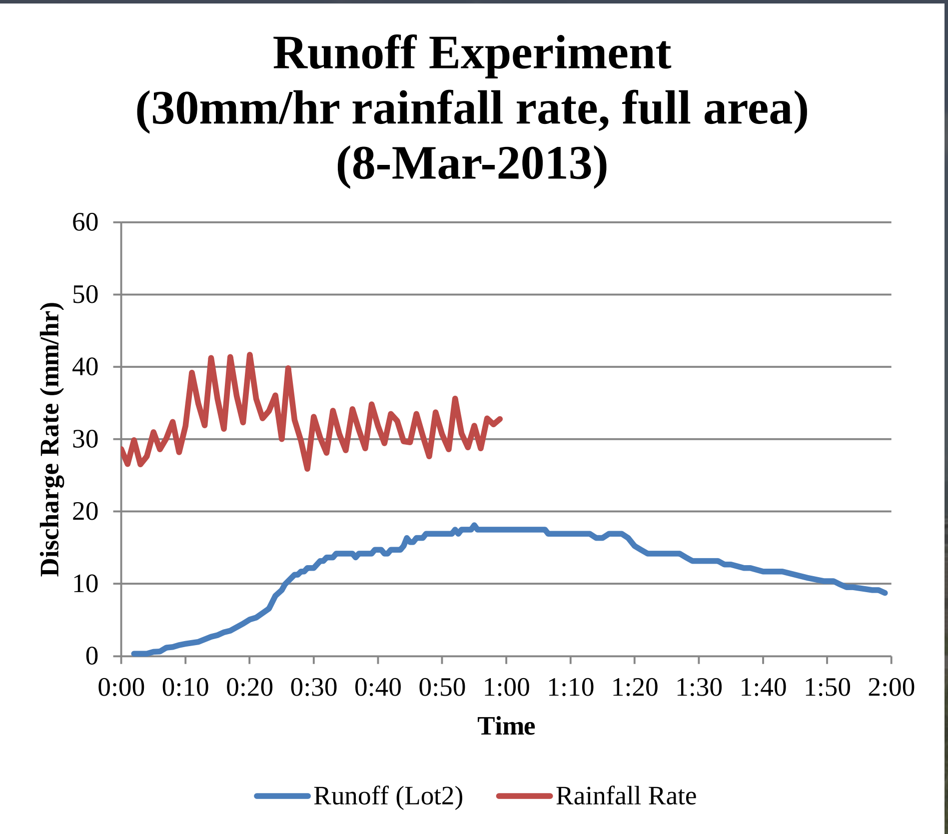
Peak discharge:
Lot5 = 0.481L/s
Lot1 = 0.384L/s (20% reduction)
Lot2 = 0.384L/s (20% reduction)
Lot3 = 0.178L/s (63% reduction)
Lot4 = 0.168L/s (65% reduction)

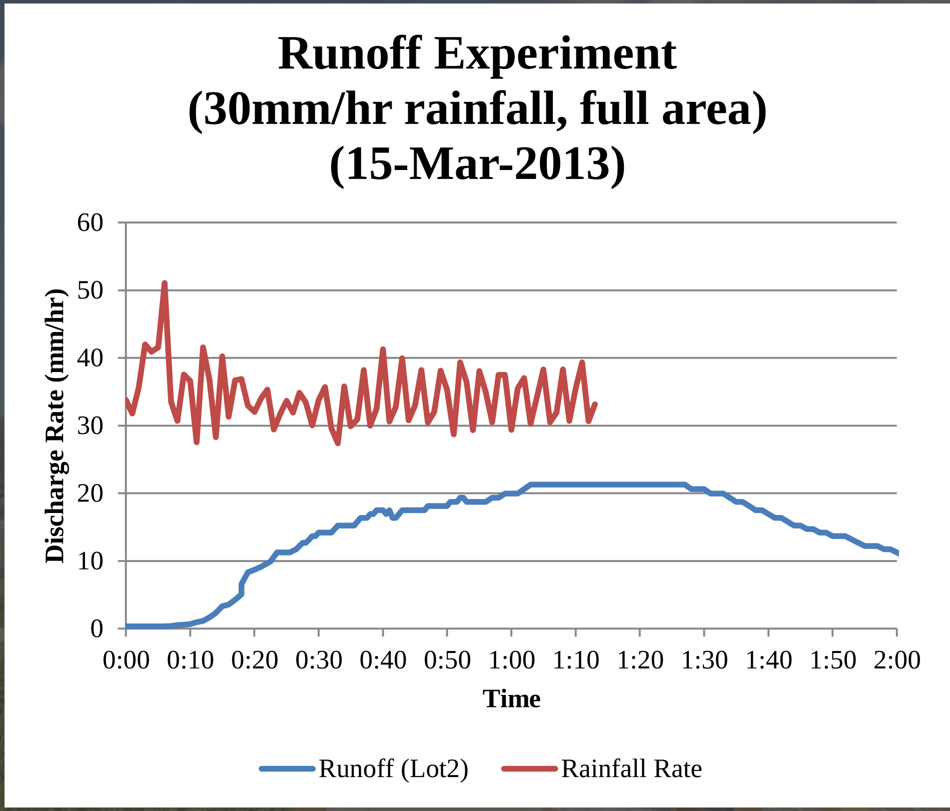
Field Runoff Experiments

Rainfall simulator

Water ponding in part of the roof (pebble path)

Field Runoff Experiments





Field Runoff Experiments

For 1hr long 30mm/hr rainfall events

- Very consistent 30% peak reduction
- Peak-to-peak detention time: about 50min

Laboratory Experiments

Laboratory runoff experiments

- 36 test plots (0.6m x 0.45m x 0.4m plastic container)
- Test parameters:
    - 2 types of soil substrate
    - 3 types of vegetations
    - Rainfall rate (10, 30, 50, 70, 100 mm/hr)
    - Gradient (1^{o}, 3^{o}, 6^{o})
    - Antecedent soil moisture content (1, 3, 7days after watering)

Laboratory runoff experiments (cont.)

Soil A:
50% sand
50% peat moss

Soil B:
Commercial potting soil (Taiwan brand)

Test Plot 1-12:
Zoysia matrella
(manila grass, 台北草)

Test Plot 13-24:
Sedum lineare
(needle stonecrop, 佛甲草)

Test Plot 25-36:
Veronica serpyllifolia
(Thyme-leaf speedwell, 水藍星)

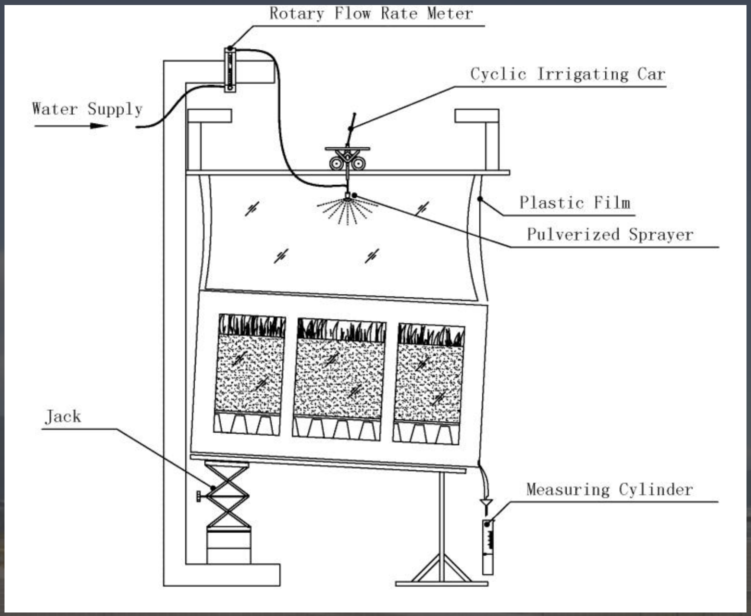
Laboratory runoff experiment (cont.)

	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B
2nd month	1	7	13	19	25	31
4th month	2	8	14	20	26	32
6th month	3	9	15	21	27	33
8th month	4	10	16	22	28	34
10th month	5	11	17	23	29	35
12th month	6	12	18	24	30	36

Configuration of the soil/plant combinations

Actual setup on the roof of PolyU, building-P
8 October 2012

I. Laboratory runoff experiment (cont.)



Experiment setup drawing (left) and photo (right)

Runoff measurement using tipping bucket setups

Growth Performance (*Zoysia matrella*)

In Soil A: 12-9-2012

22-11-2012

10-1-2013

17-6-2013

In Soil B: 12-9-2012

22-11-2012

10-1-2013

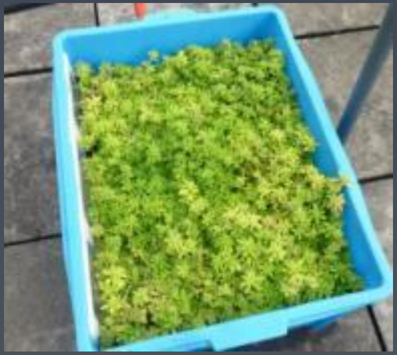
17-6-2013

-Very good condition throughout the season; no weed problem

- Same as carpet grass, dead grass layer accumulates quickly and needs clearing

Laboratory Experiment – Growth Performance (*Sedum lineare*)

In Soil A: 12-9-2012



22-11-2012

10-1-2013

17-6-2013

In Soil B: 12-9-2012

22-11-2012

10-1-2013

17-6-2013

- Weak during winter and may not recover; rotting problem in wet condition
- Requires specific configuration and maintenance

Laboratory Experiment – Growth Performance (*Veronica serpyllifolia*)

In Soil A: 12-9-2012

22-11-2012

10-1-2013

17-6-2013

In Soil B: 12-9-2012

22-11-2012

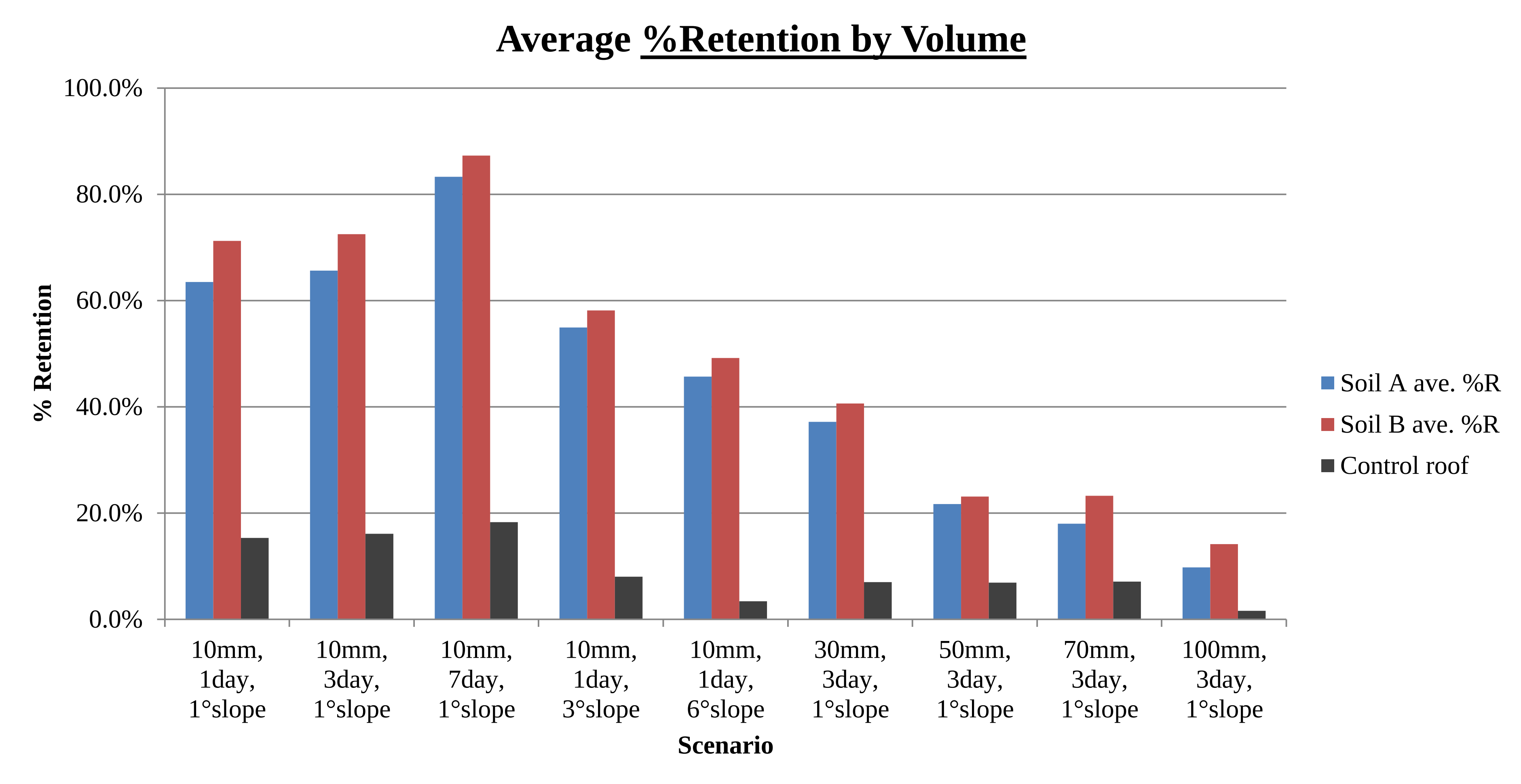
10-1-2013

17-6-2013

-Growth is not stable: may wilt and recover over and over

- Produces small flowers attracting flying insects

Averaging the results from all groups



Averaging the results from all groups

Rainfall Rate	**Ave. % retention <u>improvement</u> by the green roof system**
10 mm/hr (*most common scenario)	53.5%
30 mm/hr	31.9%
50 mm/hr	15.5%
70 mm/hr	13.5%
100 mm/hr	10.4%

*92% of the rainfall events in HK were <30mm/hr, in the past 16 years according to HKO record

Laboratory runoff experiment (cont.)

Insights from overseas studies:

Source/Location	Retention Vol.	Source/Location	Retention Vol.
(Bliss 2009)/Pittsburgh, US	**70%** of total volume (13 events in 5 month)	Gregoire and Clausen 2011/Connecticut, US	**51.4%** of total volume (97 events in 13 months)
Mentens et al. 2006/Germany	**27-81%** average annual volume (in 16 years data)	Auckland Technical Report 2010/New Zealand	**66-69%** total volume (183 events in 13 months); Mean event-based retention 77%
VanWoert 2005/Michigan, US	**60.6%** of total volume (83 events in 14 months)	EPA 2009/Pennsylvania, US	**50%** of total volume (111 events in 11 months)

How much runoff possibly reduced in urban district?

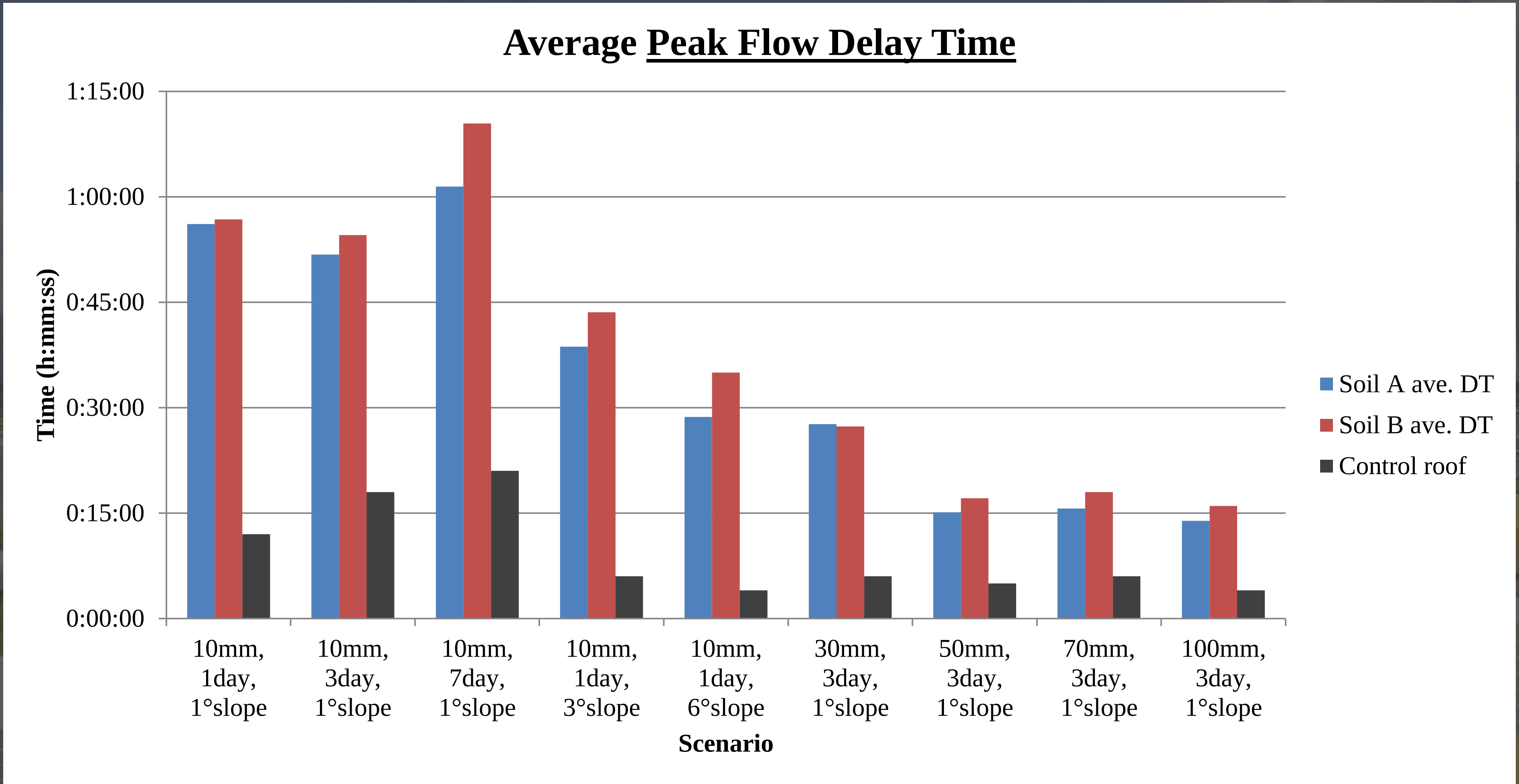
- From a numerical model of Tsim Sha Tsui and Hung Hom:

Total study area = 3.43 km^2
Total roof area = 1.16 km^2
(% roof area = 33.86%)

Ave. annual total rainfall in TST (2000-2013) = 2388.1mm

If ALL rooftops are covered with extensive green roofs, annual total runoff reduction estimation: 0.3 – 0.5 million m^3

Laboratory runoff experiment (cont.)



Laboratory runoff experiment (cont.)

Rainfall Rate	Ave. peak flow delay time improvement by green roof system (±5% in calculation of peaks)
10 mm/hr	35 min
30 mm/hr	21min
50 mm/hr	11min
70 mm/hr	10min
100 mm/hr	10min

Under different slopes:

Gradient of Green Roof System under 10mm/hr Rainfall	Ave. % retention	Ave. peak flow delay time (±5% in peak calculation)
1° (1.75%)	67.4	56 min
3° (5.24%)	56.5	41 min
6° (10.47%)	47.4	32 min

This result is comparable to the 2005 study by Villarreal and Bengtsson:

retention under 2% slope = 2 times of retention under 14% slope

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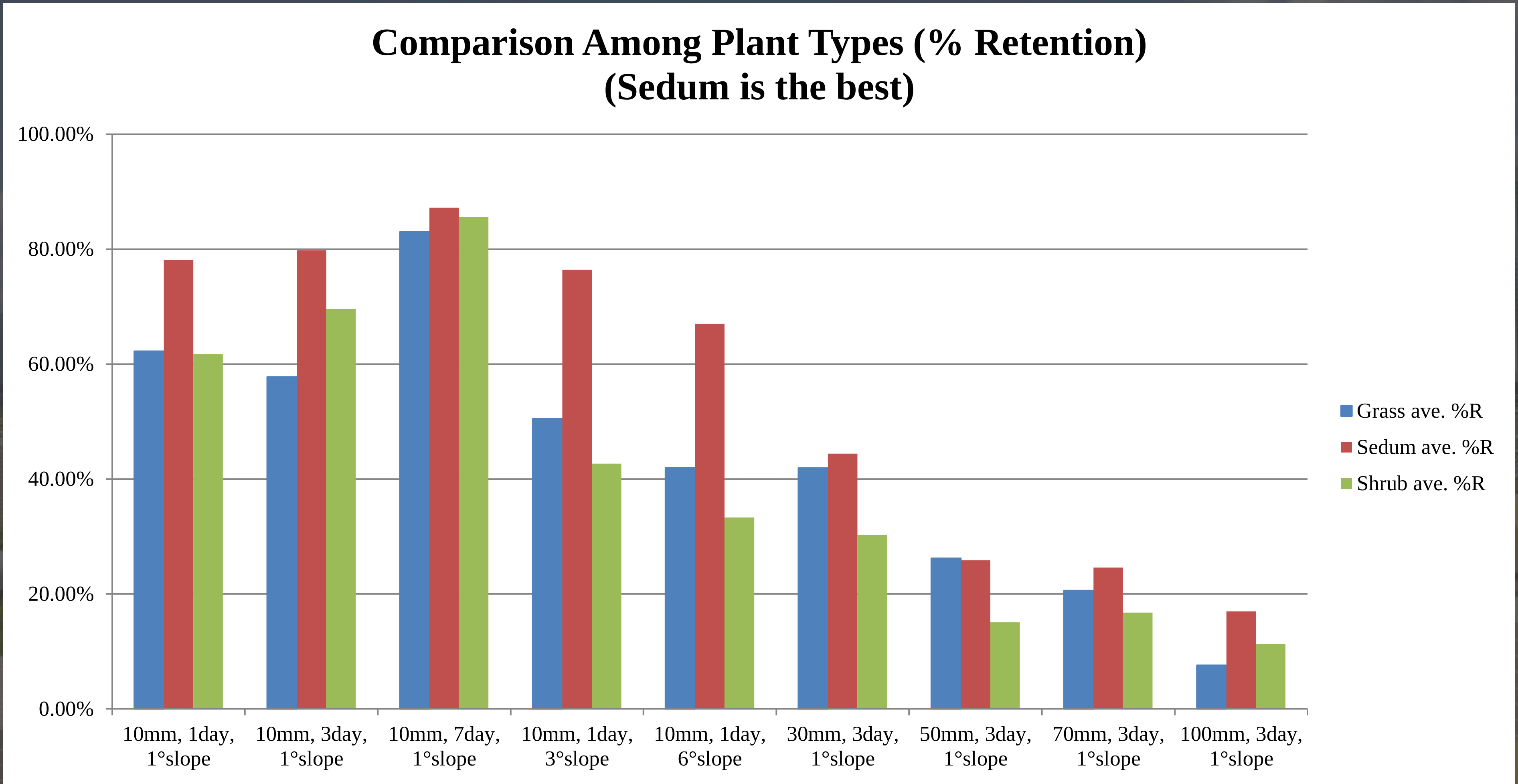
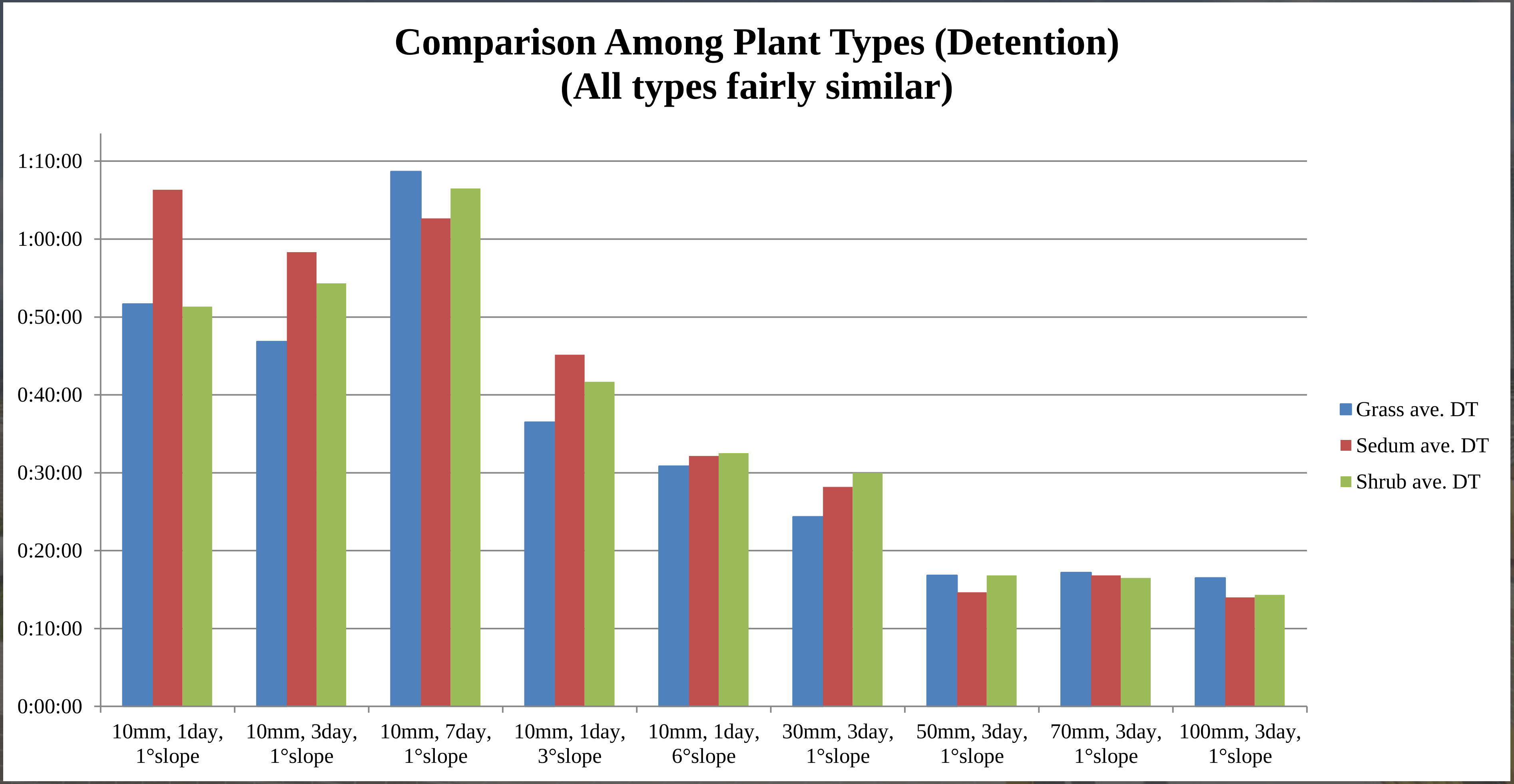
Among different plant types:



Among different plant types:



▪Soil Moisture Transport Model (HYDRUS-1D)

-To simulate STHE green roofs performance under rainstorm up to 200mm/hr

Important parameters:

Step	Selection/Parameter(s)
Main Process	Water flow, root water uptake
Soil hydraulic model	Van Genuchten-Mualem model
Soil hydraulic parameters	Measured values
Water flow boundary conditions	Upper boundary: atmospheric BC with surface runoff Lower boundary: horizontal drainage
Root water uptake model	Water uptake reduction model: Feddes Root water uptake parameters: Grass type
Time variable boundary conditions	Precipitation (10, 30, 50, 70, 100, 150, 200mm/hr) for 1hr

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Model Governing Equations

- The HYDRUS models numerically solve the Richards' equation:

$$C_w(h)\frac{\partial(h)}{\partial t}=\frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right)+\frac{\partial K(h)}{\partial z}-S(h)$$

$C_w(h)$ = soil water retention
K = hydraulic conductivity
h = pressure head
z = elevation above datum
t = time

which means water flux into this volume during time interval, ∂t, equals
changes of water capillarity movement (first term on right hand side)
plus changes of water gravity movement (second term)
minus a sink function of root water uptake (last term)

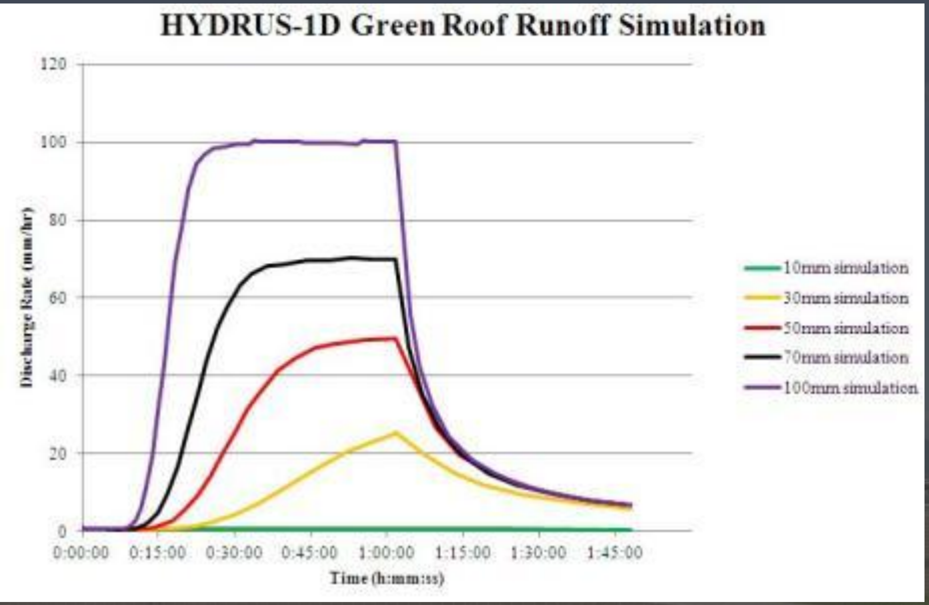
- Soil water retention function, $C_w(h)$, is solved using the van Genuchten equation:

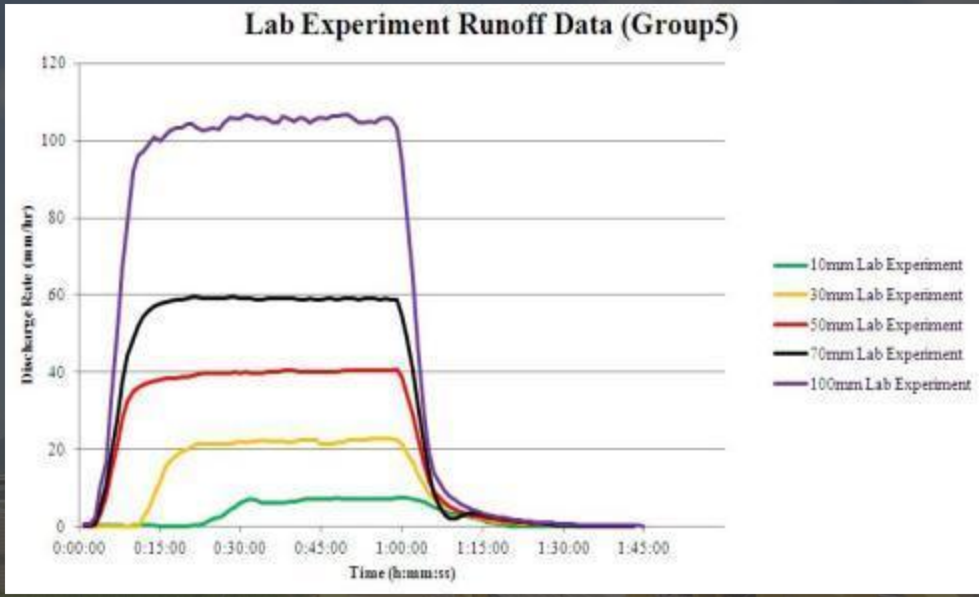
$$C_w(h)=\frac{\alpha^n(\theta_s-\theta_r)mn(-h)^{n-1}}{\left[1+(-\alpha h)^n\right]^{m+1}}$$

α = inverse of air entry suction
θ_s = saturated water content
θ_r = residual water content
n = pore-size distribution
$m = 1\text{-}n^{-1}$

- Soil hydraulic parameters (e.g. α, θ_s θ_r) can be predicted in HYDRUS-1D given the soil textural characteristics, such as the sand/silt/clay fractions, and bulk density

Hydrus-1D Results





- The numerical model tends to over-estimate runoff retention/detention performance

-Simulation for large rainfall events are closer to experimental/field results

- More verifications of the model are needed to conduct before practical predictions

Runoff Water Quality Analysis

- To compare the difference between the runoffs from the green roofs and the conventional roof

- Also, to examine the chemical characteristics of the runoff as effluent (purifying or polluting)

Atomic Absorption (AA) Spectrometer used for heavy metal analysis

Runoff Analysis –Results

Parameter	Inflow	Green Roof	Control Roof
Total suspended solid (g/L)	0.003	0.010 - 0.042	0.010
Nitrite nitrogen (mg/L) Nitrate nitrogen (mg/L) Ammonium nitrogen (mg/L)	0.091 0.8 0.04	0.049 – 0.105 0.55 – 1.15 0.01 – 0.07	0.062 0.75 0.03
BOD (mg/L)	0.18	0.09 – 0.42	0.25
Reactive phosphorus (PO4) (mg/L)	0.12	0.18 – 0.35	0.11
Residual chlorine (mg/L)	0.03	0.03 – 0.04	0.03
pH	6.16	6.76 – 6.99	6.87
Total Cu (mg/L) Total Pb (mg/L) Total Zn (mg/L)	0.006 0.08 0.004	0.006 – 0.014 0.04 – 0.07 0.000 – 0.102	0.019 0.12 0.2283

Runoff Analysis

Parameters	Findings (source)
Phosphorus	- 2 to 3mg/L from green roof vs. negligible from rainfall and control roof (Bliss 2007) -Reactive phosphorus in green roof runoff : 0.003-0.079mg/L, higher than in rainfall (Gregoire 2011) - Related to the presence of fertilizers and birds and animals' droppings (Berndtsson et al. 2009)
Nitrogen	-Total nitrogen is 0.275-1.264mg/L in green roof runoff, higher than in rainfall (Gregoire 2011) - Related to soil type, age of green roof, and fertilization (Berndtsson et al. 2009)
Lead	- Pb found from all roofs and rainfall in no pattern at 0.1mg/L level (Bliss 2007)
Zinc	- Zn found from all roofs and rainfall in no pattern at 0.1mg/L level (Bliss 2007) - Over 65% Zn retained by green roof , 6-54ug/L in green roof runoff (Gregoire 2011)
Copper	-Detected more frequently in green roof runoff (74%) than in rainfall (27%) or control roof runoff (43%), with mean total Cu of 6ug/L, in the form of CuSO4 from fertilizers (Gregoire 2011)
pH	Green roof reduces the acidity of rainfall, and therefore can mitigate mild acid rains (Bliss 2007; Berndtsson et al 2009)

Concluding Remarks

Experimental results show that peak flow delay time in 1° slope doubles that in 6°.

The average detention and retention performance are the best 7 days after irrigation.

In 30 mm/hr or lower rainfall intensities, the peak flow delay time and retention percentage are 21-35min and 31.9-53.5%, respectively. In Hong Kong, nearly 90% of the rainfall events have an intensity less than 30 mm/hr. This suggests that extensive green roofs are effective to regulate rainfall runoff for most of the time in Hong Kong.

Water quality parameter concentrations are found to be lowered or unchanged in green roof runoffs

- -Lowered heavy metals (Cu, Pb and Zn) concentration in green roof runoff
- -pH becomes less acidic than inflow
- - Residual chlorine was at low level in both inflow and runoffs

Some water quality parameter concentrations increase in green roof runoffs (and possible reasons)

- - Total suspend solid (from soil substrate)
- - BOD (from vegetation and soil substrate)
- - Phosphorus (from soil and fertilizer)
- - Nitrogen (from soil and fertilizer)

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