(Sustainable) Urban Drainage

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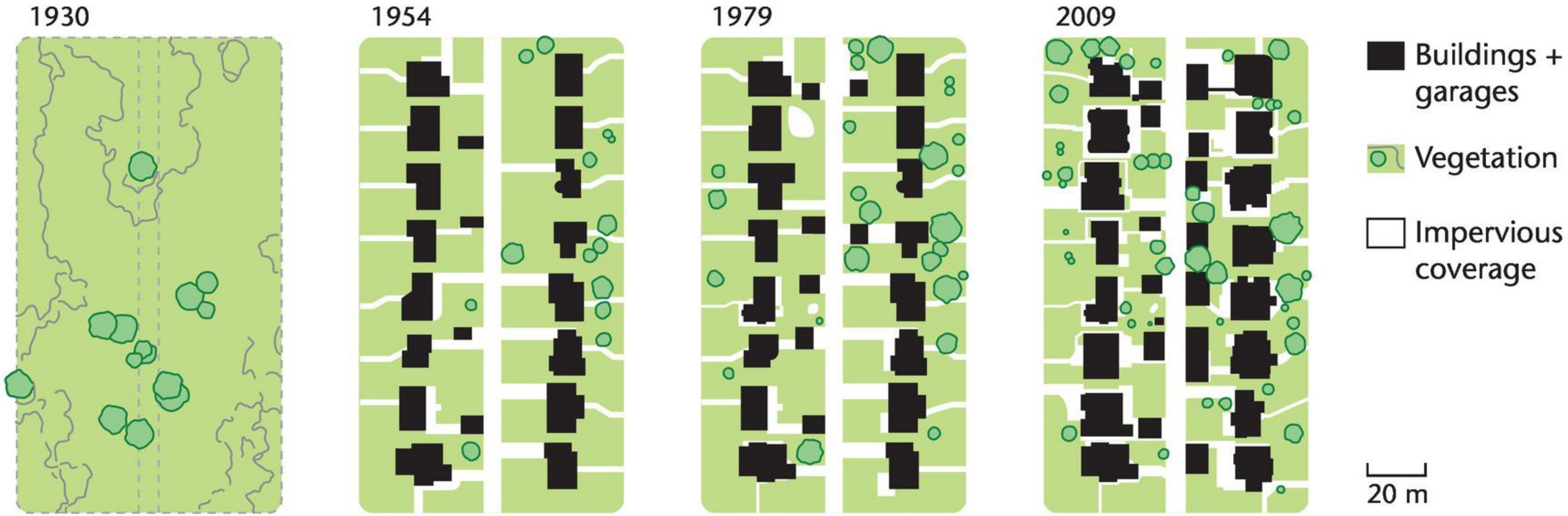
https://www.architecturaldigest.com/story/architect-new-yorks-central-park-incredibly-unexpected-legacy

Today's session

Outline

- **Conventional drainage**
  - Example
- Sustainable urban drainage
  - SuDS components
  - Example

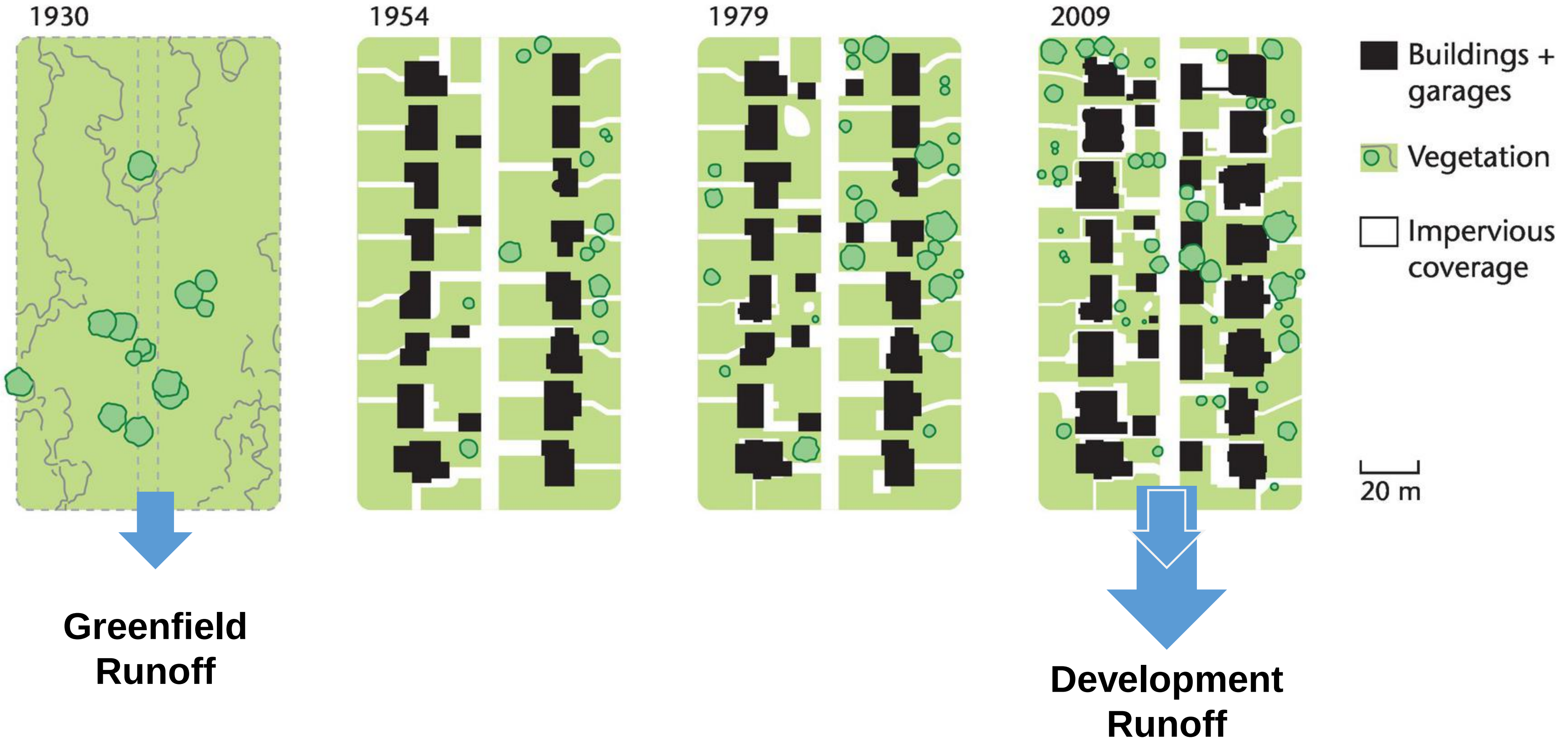
Urban Water Cycle



Replacement of vegetation (trees, shrubs) by impervious cover (roads, paths, buildings) due to initial development and subsequent densification in an urban block dominated by single-family residential houses in Vancouver, Canada

Oke et al. (2017)

Urban Water Cycle



Urban Water Cycle

Natural System

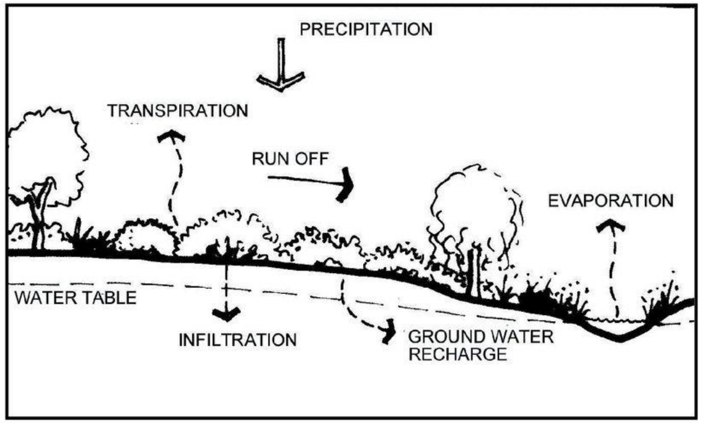


Figure 1: Natural hydrological system

Conventional Drainage

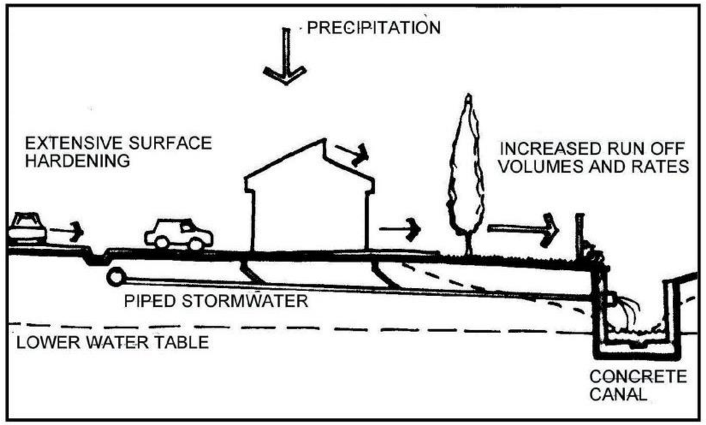


Figure 2: Stormwater management approach with little concern for the natural environment

SuDS

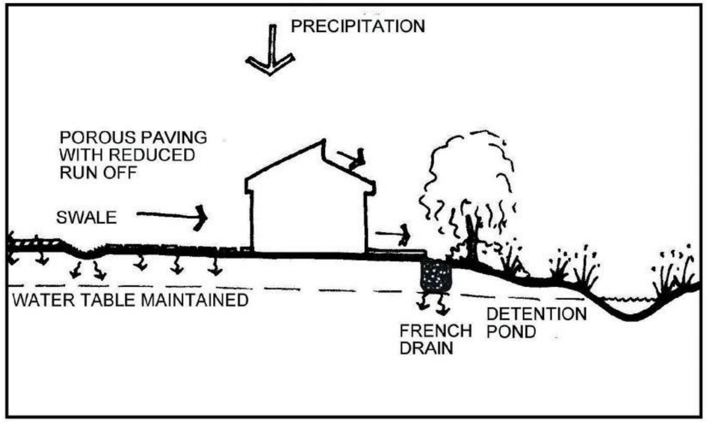


Figure 3 : Responsible approach to stormwater management

https://docplayer.net/21804199-Stormwater-management-planning-and-design-guidelines-for-new-developments.html

Flooding and drainage

Applied hydraulics (recap)

- For IE students: see **Chapter 8** in Butler and Davies (2011) – or any other Hydraulics book
- For IA students: optional

8.3 Pipe flow

8.3.1 Head (energy) losses

The head or energy losses in flow in a pipe are made up of *friction losses* and *local losses*. Friction losses are caused by forces between the liquid and the solid boundary (distributed along the length of the pipe), and local losses are caused by disruptions to the flow at local features like bends and changes in cross-section. Total head loss h_L is the sum of the two components.

The distribution of losses, and the other components in equation 8.7 can be shown by two imaginary lines.

The *energy grade line* (EGL) is drawn a vertical distance from the datum equal to the total head.

The *hydraulic grade line* (HGL) is drawn a vertical distance below the energy grade line equal to the velocity head.

The two lines are drawn for a pipe flowing full on Fig. 8.2. The lines allow all the terms in equation 8.7 to be identified.

8.3.2 Friction losses

A fundamental requirement in the hydraulic design and analysis of urban drainage systems is the estimation of friction loss. The basic representation

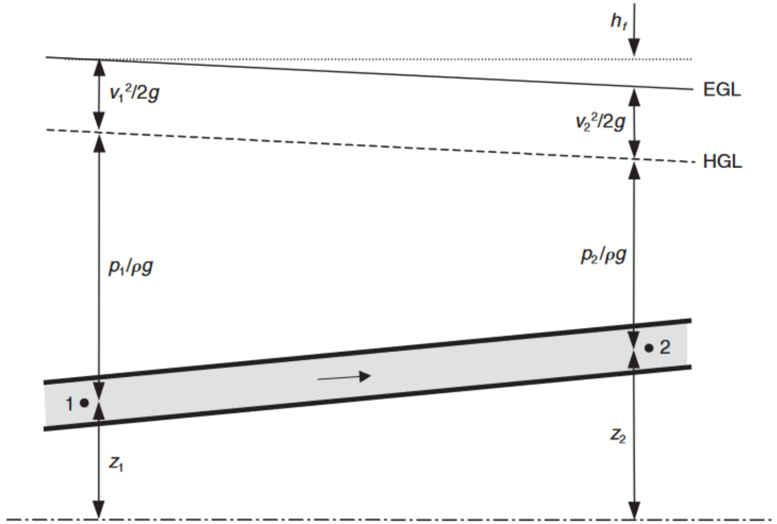


Fig. 8.2 EGL and HGL for a pipe flowing full

Butler and Davies (2011)

Conventional drainage

Stormwater

Definition: rainwater produced by a storm

- Major urban flow of concern to drainage engineers
- Efficient drainage to maintain public health and safety, and protect receiving water environments
- Rainwater and stormwater are **not 'pure'**:
  - Contaminated by range of pollutants (from atmosphere, vehicles, buildings, de-icing, spills, etc)
  - Variable from place to place, and from time to time
  - Sometimes stormwater can be as polluting as wastewater


SWI swissinfo.ch

Swiss perspectives in 10 languages

Researchers warn of 'huge' rubber pollution problem in Switzerland

es either side of the road. © Keystone /

Conventional drainage

Stormwater: System Components and Layout

- **Building Drainage**
  - Soil and waste drainage
  - Roof drainage
- Site Drainage
  - Sewers
  - Manholes
  - Gully Inlets

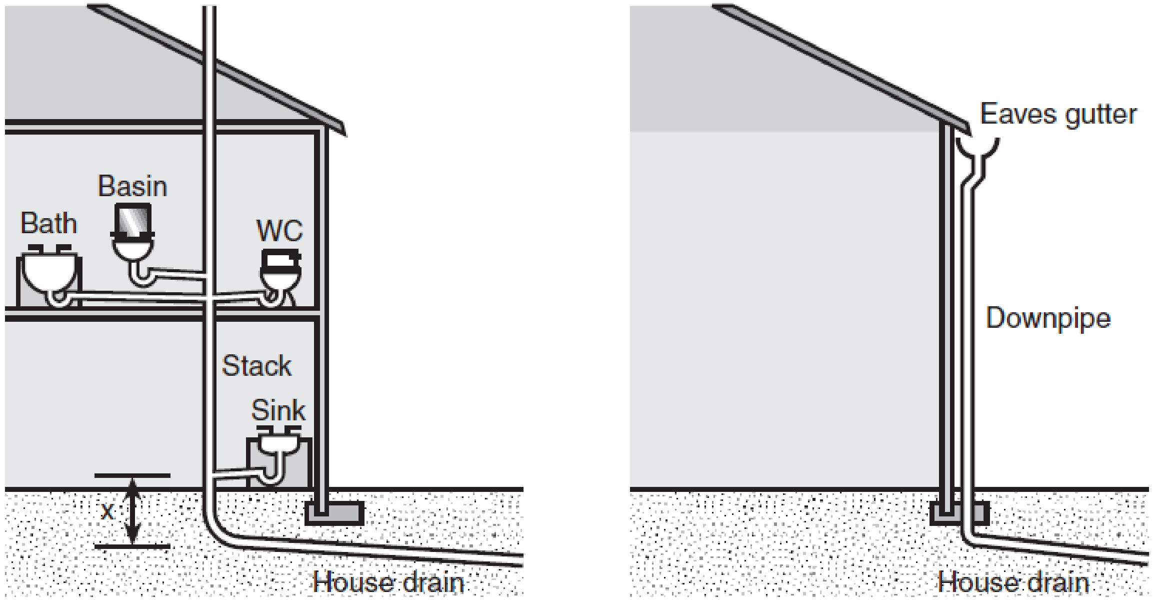


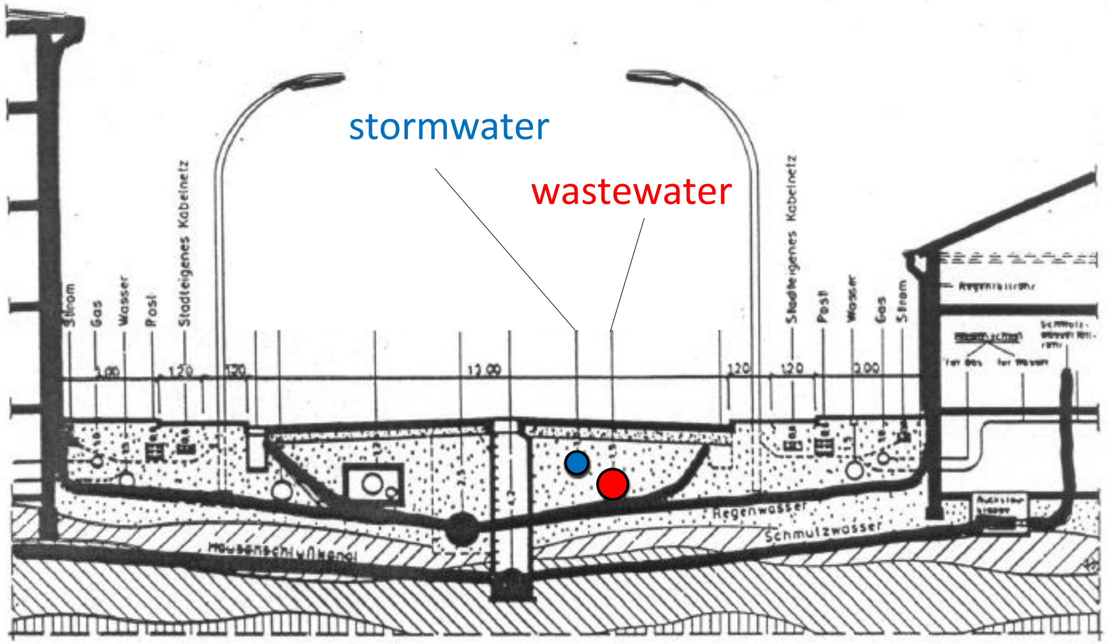
Fig. 7.1 Typical building drainage arrangement in a two-storey house

Butler & Davies (2011)

Conventional drainage

Stormwater: System Components and Layout

- **Building Drainage**
  - Soil and waste drainage
  - Roof drainage
- **Site Drainage**
  - Sewers
  - Manholes
  - Gully Inlets



Source: TU Delft

Conventional drainage

Stormwater: System Components and Layout

Vertical alignment

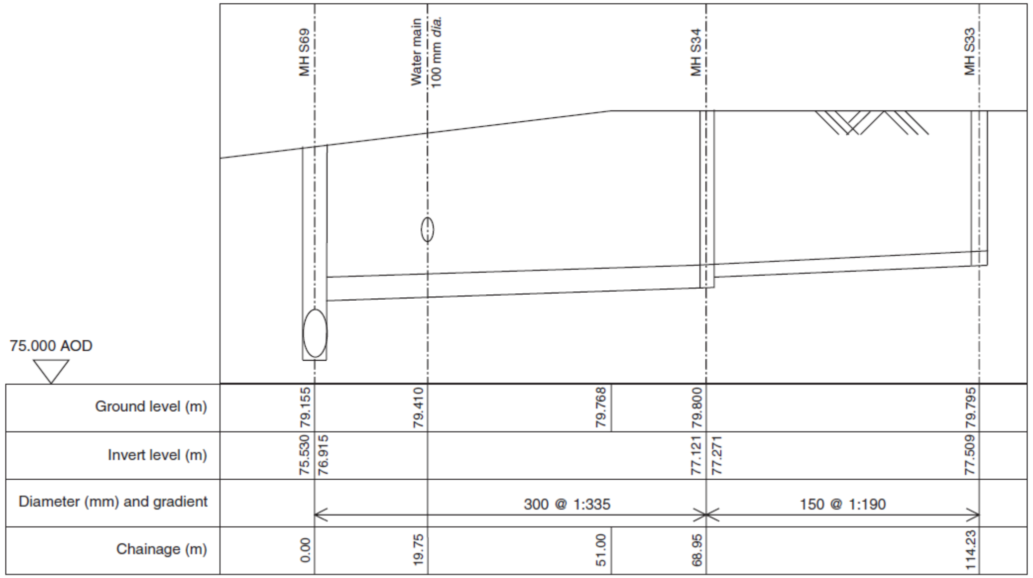
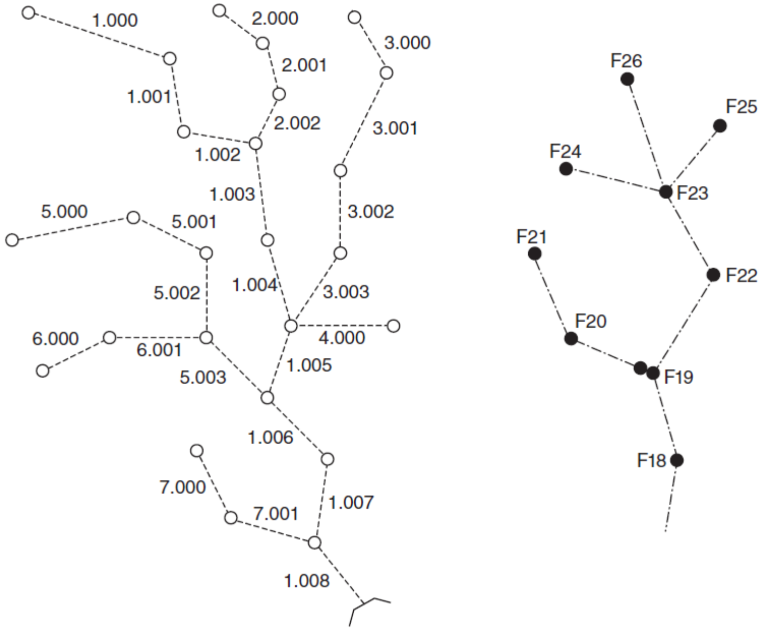


Fig. 7.3 Longitudinal profile of a sewer

Horizontal alignment



Butler & Davies (2011)

Conventional drainage

Stormwater: System Components and Layout

Sewer

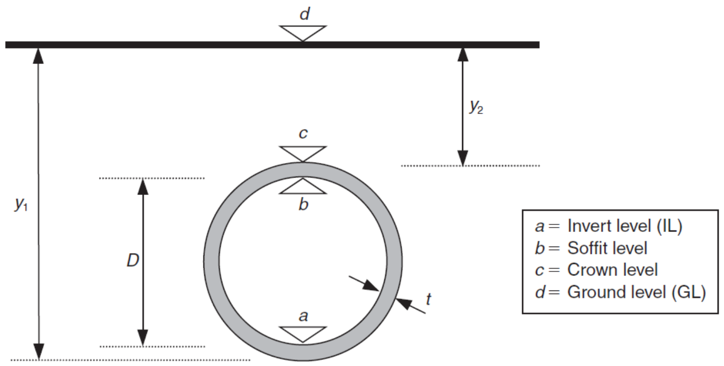


Fig. 7.2 Level definitions associated with sewers

Gully inlets

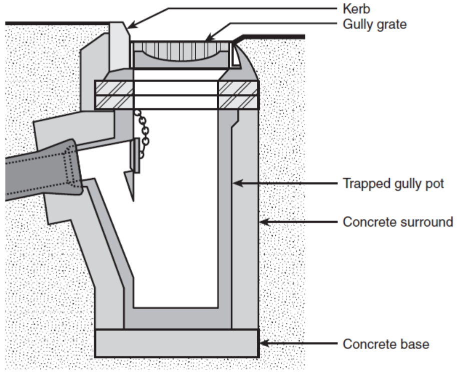


Fig. 7.7 Trapped road gully

Manholes

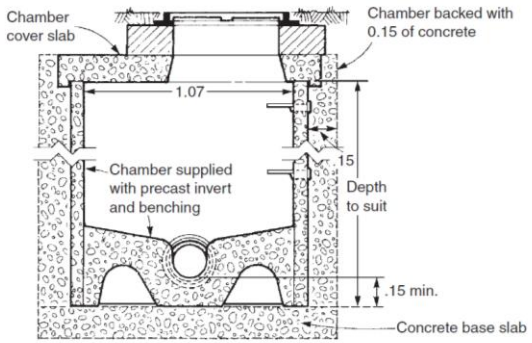


Fig. 7.5 Precast concrete ring manhole (reproduced from Woolley 1988 with permission of E & FN Spon)

Source: Butler & Davies (2011) & Google Images

Conventional drainage

Stormwater design

- Fundamental stages to follow to design a rational and cost-effective urban drainage system
- Key whether using **conventional** or **SuDS** approaches
- Stages are:
  1. Define the **contributing area**
  2. Produce a preliminary **horizontal alignment**
  3. Preliminary component **sizing** considering:
     - Peak discharge/velocity
     - Slope
     - Pipe size
  4. Preliminary **vertical layout**
  5. Revise as needed

STEP 1. Find out the average flowrate and maximum flow rate at present and after the design period

Time	Average flowrate	Peak factor	Peak flowrate
Present	50,000* 130*0.8 L/d=0.06 cum/s	2.5	0.15 cum/s
Design	100,000* 180*0.8 L/d= 0.167 cum/s	2.25	0.375 cum/s

STEP 2. Find out the optimum slope to be provided

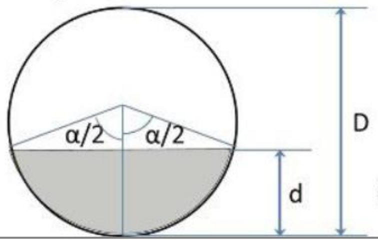
Slope to be provided = s=0.8 in 1000 = 0.8/1000 = 0.0008 (from the table)

STEP 3. Find out the size based on the ultimate peak flowrate.

We want the sewer to run 80% full at its ultimate peak flowrate so that maximum possible velocity can be attained). From the chart q/Q = 0.988 when d/D =0.8

Q = 0.375/0.988 = 0.380

Q = A.V



$$A = \pi\left(\frac{D}{4}\right)^2 \qquad V = \frac{1}{n}R^{2/3}s^{1/2}$$

$$R = \frac{A}{P} = \frac{\frac{\pi D^2}{4}}{\pi D} = \frac{D}{4}$$

$$Q = A.V = \frac{\pi D^2}{4} * \frac{1}{n}\left(\frac{D}{4}\right)^{2/3} * s^{1/2}$$

Today's session

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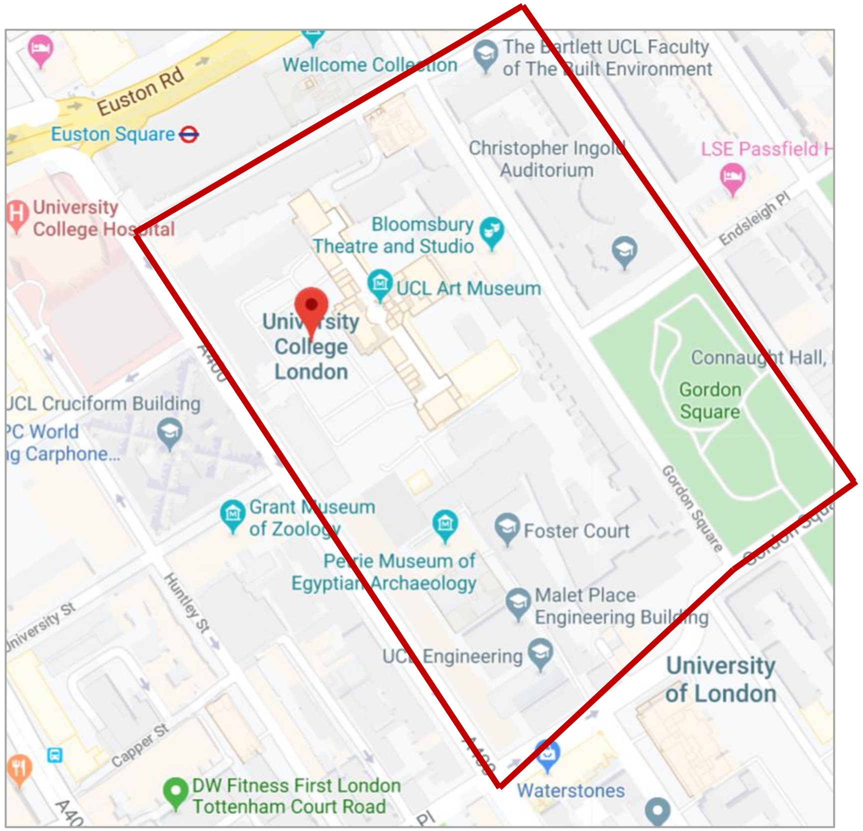
  - **Example**
- Sustainable urban drainage
  - SuDS components
  - Example

Conventional drainage

Example (University College London)

- Contributing area: $A_c = A_i + A_p$

Pervious:	$A_p \sim 9800\ m^2$
Impervious:	$A_i \sim 70700\ m^2$
Contributing:	$A_c \sim 80500\ m^2$



Conventional drainage

Example (University College London)

- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i \, i \, A_i + C_p \, i \, A_p$

EQ. 24.5 Modified rational method equation to determine peak flow rates

$$Q = 2.78\, C\, i\, A$$

where:

- Q = design event peak rate of runoff (l/s)
- C = non-dimensional runoff coefficient which is dependent on the catchment characteristics

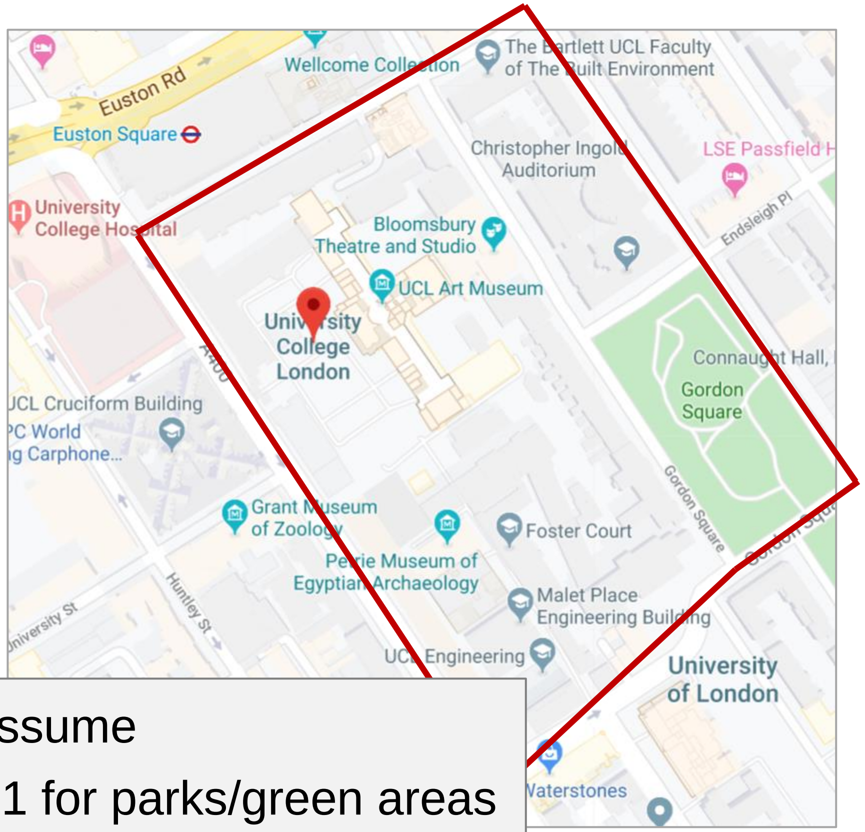
$$C = C_V\, C_R$$

where
- C_V = volumetric runoff coefficient
- C_R = dimensionless routing coefficient

- i = rainfall intensity for the design return period (in mm/hr) and for a duration equal to the "time of concentration" of the network
- A = total catchment area being drained (ha)

Note: 2.78 is a conversion factor to address the rainfall unit being in mm/hr.

CIRIA Manual (see Moodle)



We can assume

- $C_p = 0.1$ for parks/green areas
- $C_i = 0.9$ for roofs/roads

Conventional drainage

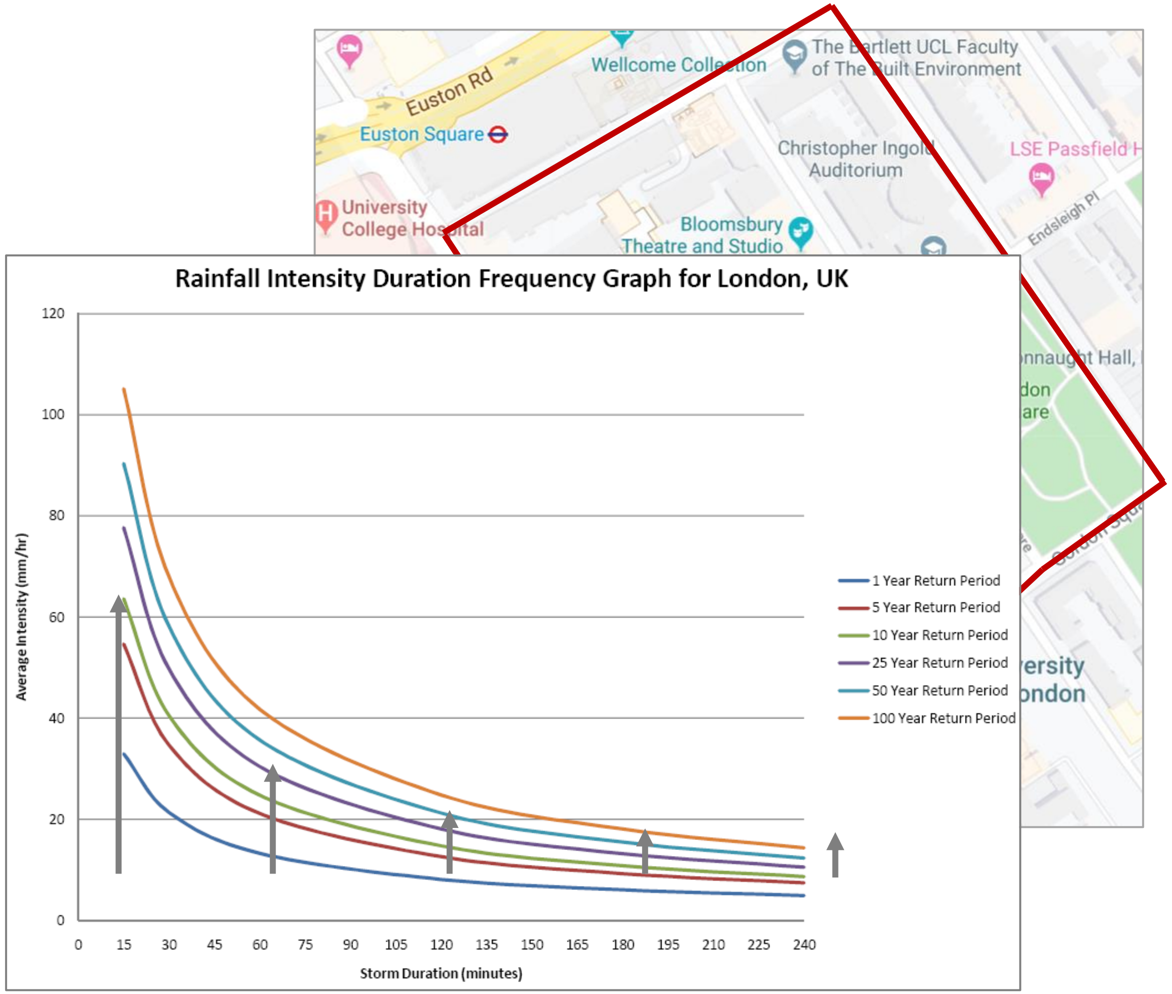
Example (University College London)

- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i \, i \, A_i + C_p \, i \, A_p$

T5years:
i (15m) = 55 mm/h
i (1h) = 22 mm/h
i (6h) = 6 mm/h

T30years:
i (15m) = 80 mm/h
i (1h) = 32 mm/h
i (6h) = 9 mm/h

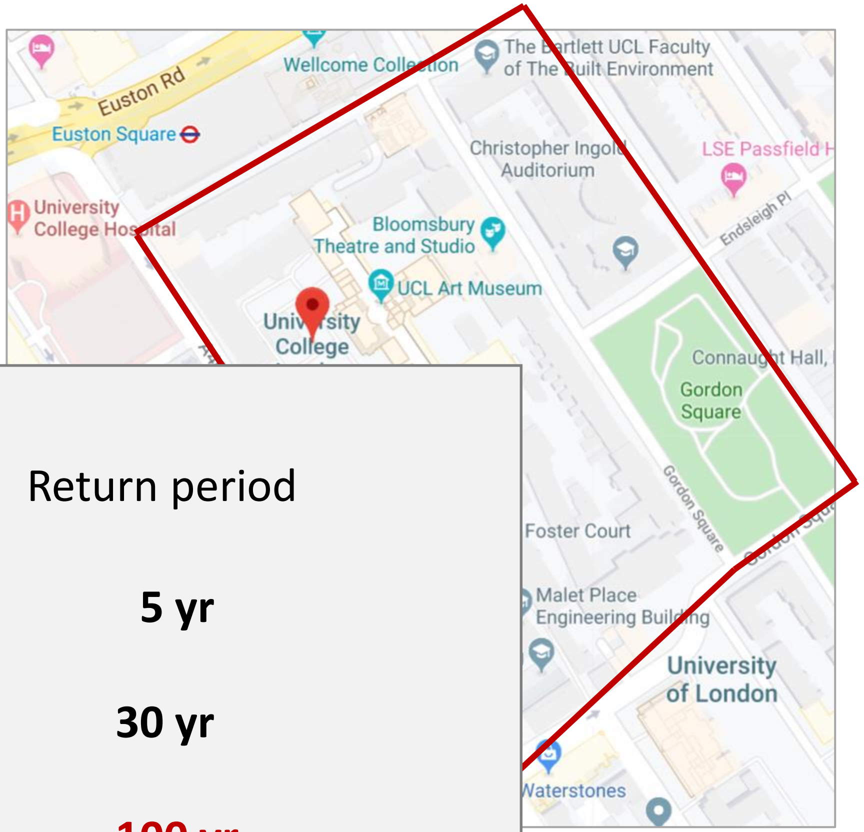
T100years:
i (15m) = 105 mm/h
i (1h) = 42 mm/h
i (6h) = 12 mm/h



Conventional drainage

Example (University College London)

- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i \, i \, A_i + C_p \, i \, A_p$



Greenfield

$Q = C_p \, i \, A_c$

Development

$Q = C_i \, i \, A_i + C_p \, i \, A_p$

Rational Method (1 hour)		
Runoff	(m3/s)	(l/s)
Qg05	0.05	49.19
Qd05	0.39	**394.84**
Qg30	0.07	71.56
Qd30	0.57	**574.31**
Qg100	0.10	100.71
Qd100	0.81	**808.27**

Return period

5 yr

30 yr

100 yr

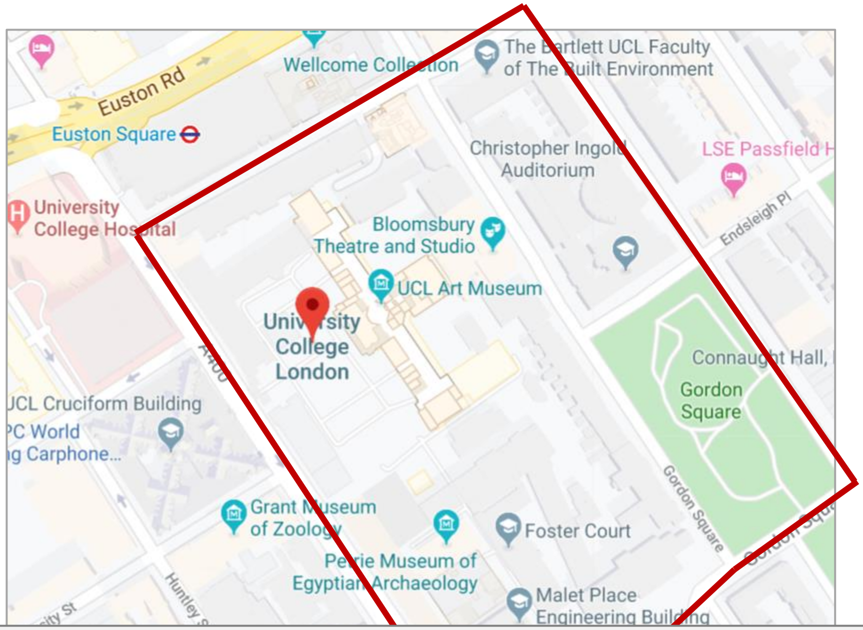
Conventional drainage

Example (University College London)

- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i\, i\, A_i + C_p\, i\, A_p$

TABLE 24.1 Summary of runoff estimation methods

Runoff estimation method	Reference	Greenfield site: Peak runoff rate	Greenfield site: Runoff volume	Developed site: Peak runoff rate	Developed site: Runoff volume	Section ref
FEH ReFH2	Kjeldsen (2007)	✓[1]	✓[1]	✓[3]	✓[3]	24.3.1
FEH statistical method	Kjeldsen *et al* (2008)	✓[1]				24.3.1
IH124	Marshall and Bayliss (1994)	✓[1,2]				24.3.2
FSSR16	NERC (1985)		✓[1,2]			24.4
Modified rational method	HR Wallingford (1981)			✓[3]		24.6.2
Wallingford – Fixed	HR Wallingford (1981)			[4]	[4]	24.6.3
Wallingford – Variable	Packman (1990), Osborne (2009)			✓	✓	24.6.3
UKWIR	UKWIR (2014)			✓	✓	24.6.3



Climate Change/Urban creep allowances can/should be included to account for future conditions. For example:

- 10% increase in rainfall (uplift factor = 1.1)
- 10% increase in paved surface area of 10%

Conventional drainage

Example (University College London)

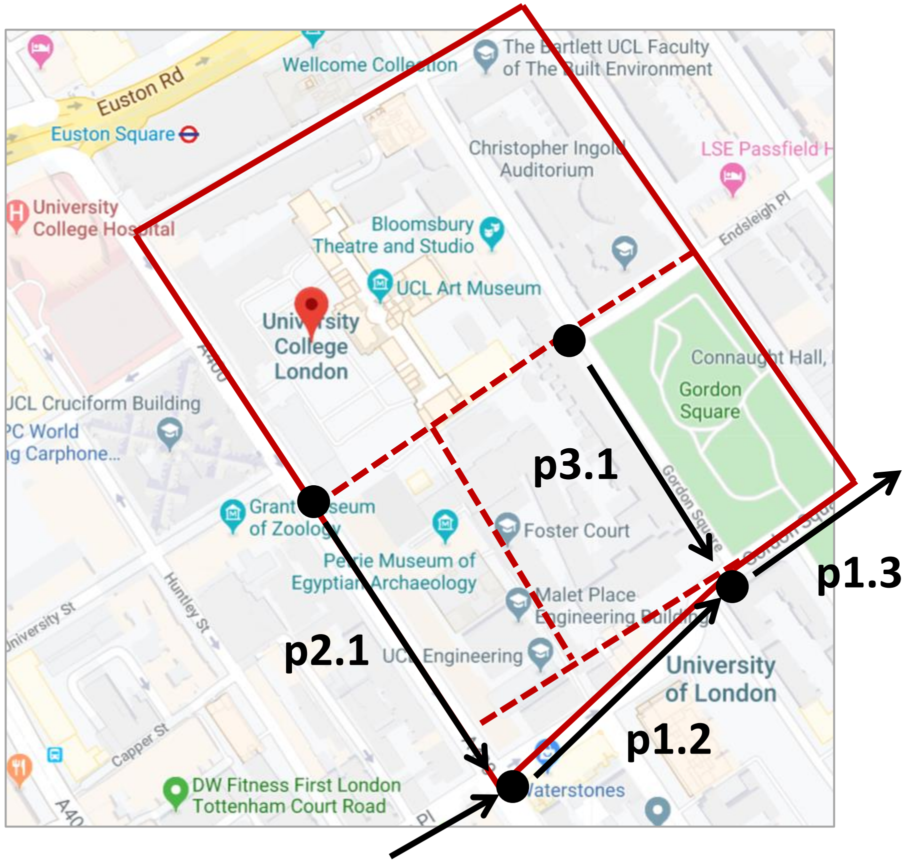
- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i\, i\, A_i + C_p\, i\, A_p$
- Design sewer system:

Full pipe discharge: $Q_f = \pi \frac{D^2}{4} v_f$

Flow velocity v_f : e.g., from ColebrookWhite equation

$$v = -2\sqrt{2gS_f D}\,\log_{10}\left(\frac{k_s}{3.7D} + \frac{2.51\nu}{D\sqrt{2gS_f D}}\right)$$

k_s	pipe roughness (m)
S_f	hydraulic gradient or friction slope, h_f/L (–)
ν	kinematic viscosity (m^2/s)



Conventional drainage

EPFL

Example (University College London)

- Contributing area: $A_c = A_i + A_p$
- Rational method: $Q = C_i\ i\ A_i + C_p\ i\ A_p$
- Design sewer system:

For those who are interested:
see Butler & Davies (2011) and **example in Moodle**

Calculations:

ks (m)	0.0006
v (m2/s)	0.00000114

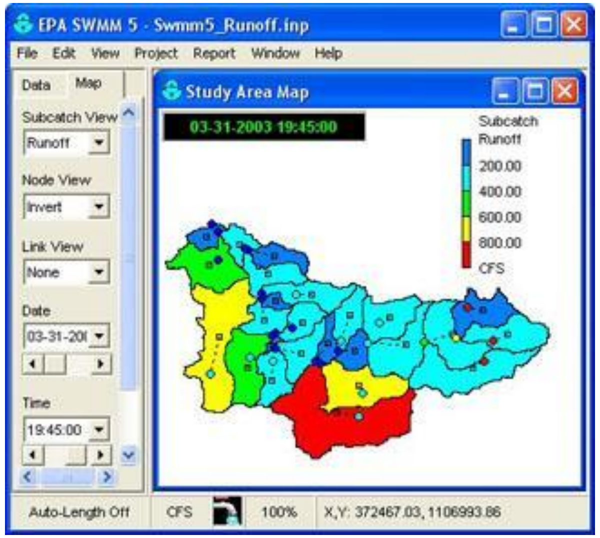
Pipe Number	Length (m)	Gradient (-)	Contributing Area (m2)	Sum Area (m2	Diameter (mm)	Pipe Velocity (m/s)	Pipe capacity Qf (l/s)	tf (min)	t conc = te + tf (min)	Rainfall intensity (mm/h)	Qp (l/s)	Qf>Qp?	vf>1 m/s?
1.1	200	0.01	10000	10000	750	2.80	**1235.63**	1.19	6.19	159.30	**442.49**	Yes	Yes
2.1	190	0.005	9800	9800	450	1.43	**227.78**	2.21	7.21	149.28	**406.38**	No	Yes
	190	0.01	9800	9800	500	2.17	**426.21**	1.46	6.46	156.54	**426.15**	Yes	Yes
1.2	170	0.01	1750	19800	750	2.80	**1235.63**	1.01	12.20	114.12	**904.34**	Yes	Yes
3.1	140	0.005	14000	14000	300	1.11	**78.21**	2.11	7.11	150.23	**584.22**	No	Yes
	140	0.01	14000	14000	600	2.43	**688.08**	0.96	5.96	161.78	**629.14**	Yes	Yes
1.3	70	0.01	9800	33800	750	2.80	**1235.63**	0.42	17.62	90.90	**1736.02**	No	Yes
	70	0.02	9800	33800	750	3.96	**1750.15**	0.29	17.50	91.32	**1737.16**	Yes	Yes

Sewer design method

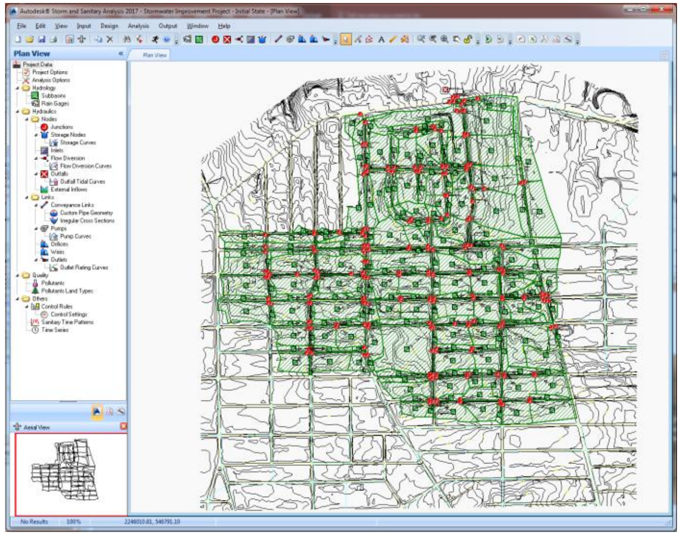
1. Assume design rainfall return period (T), pipe roughness (ks), time of entry (te) and runoff coefficients (Ci, Cp).
2. Prepare a preliminary layout of sewers, including inlet locations.
3. Mark pipe numbers on plan according to convection.
4. Estimate contributing areas (impervious) for each pipe.
5. First attempt at setting gradients and diameters of each pipe.
6. Calculate the pipe-full velocity (Vf) and full discharge (Qf)
7. Calculate time of concentration tc = te + tf, tf = L/Vf.
8. Obtain rainfall intensity from IDF curves/equations/methods/data.
9. Estimate the cumulative contribution area.
10. Calculate Peak flow Qp from Rational Method eq. Qp = C*i*A
11. Check Qp < Qf and vmax > vf > vmin (vmax = 3 m/s, vmin = 1m/s)
12. Adjust Pipe diameters and gradients to meet conditions.

Conventional drainage

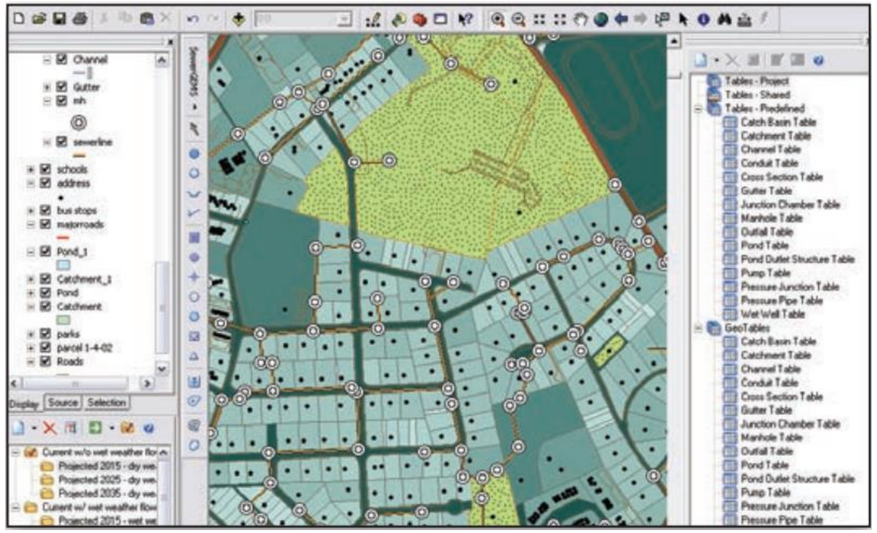
Storm water management: models



[SWMM](#) developed by US EPA (see: [Storm Water Management Model – Wikipedia](#))



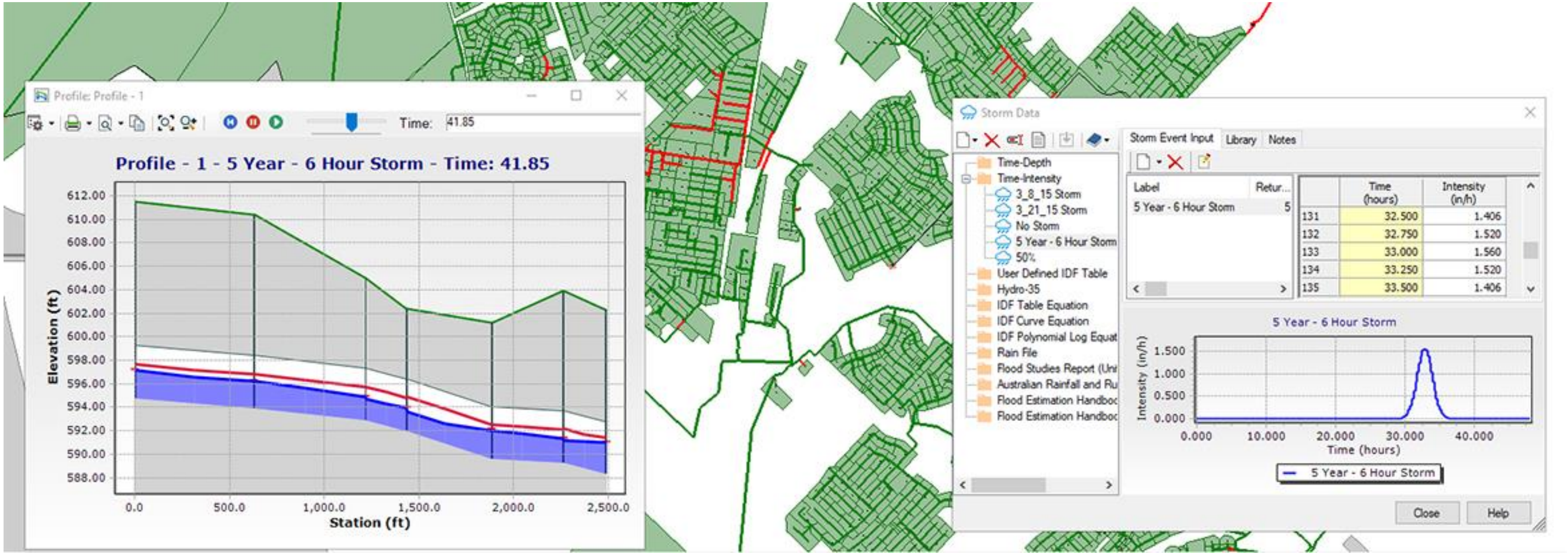
[Autodesk® Storm and Sanitary Analysis](#) in AutoCAD Civil 3D
Developed by Autodesk



[SewerCAD/SewerGEMS/CivilStorm/StormCAD](#) developed by [Bentley](#)'s Haestad Methods (Hydraulics & Hydrology group)

Conventional drainage

Storm water management: models



[A Deep Dive into SWMM Modeling| Burgess & Niple]

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- **Sustainable urban drainage**
  - SuDS components
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Urban Water Cycle

Natural System

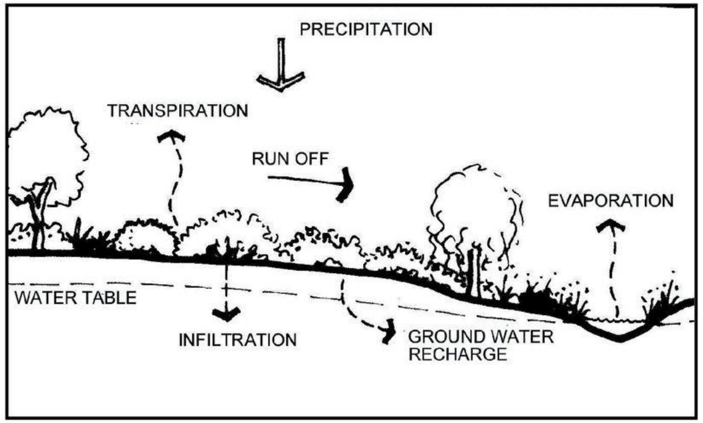


Figure 1: Natural hydrological system

Conventional Drainage

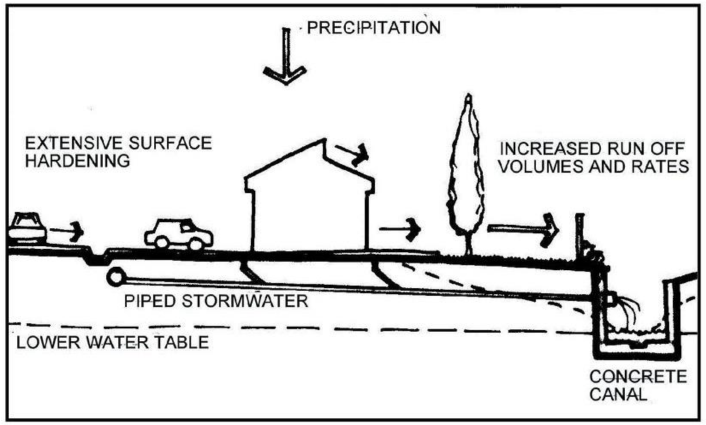


Figure 2: Stormwater management approach with little concern for the natural environment

SuDS

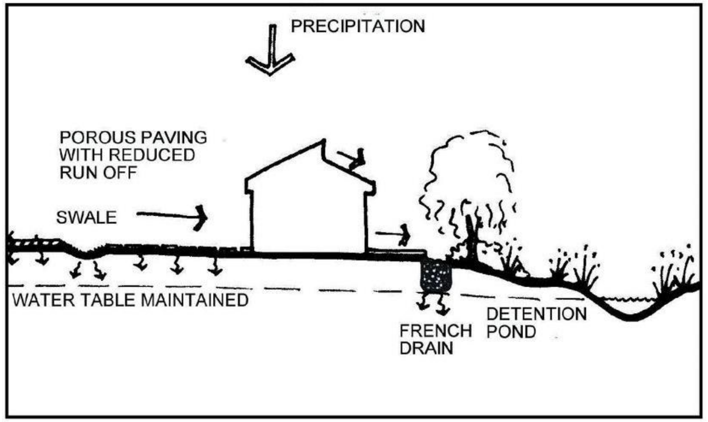


Figure 3 : Responsible approach to stormwater management

https://docplayer.net/21804199-Stormwater-management-planning-and-design-guidelines-for-new-developments.html

Sustainable Urban Drainage (SuDS)

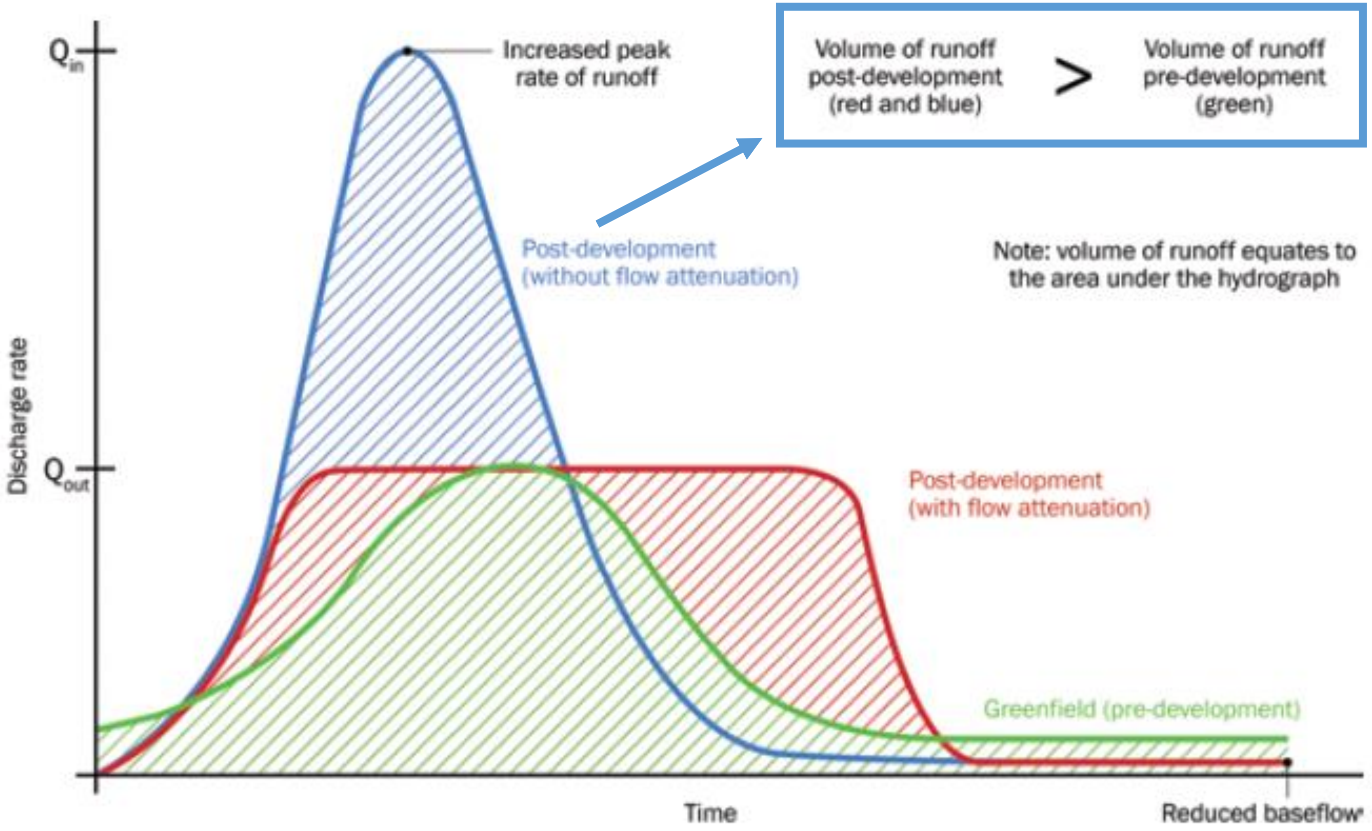


Figure 3.1 Example of a runoff hydrograph

CIRIA (2015)

Sustainable Urban Drainage (SuDS)

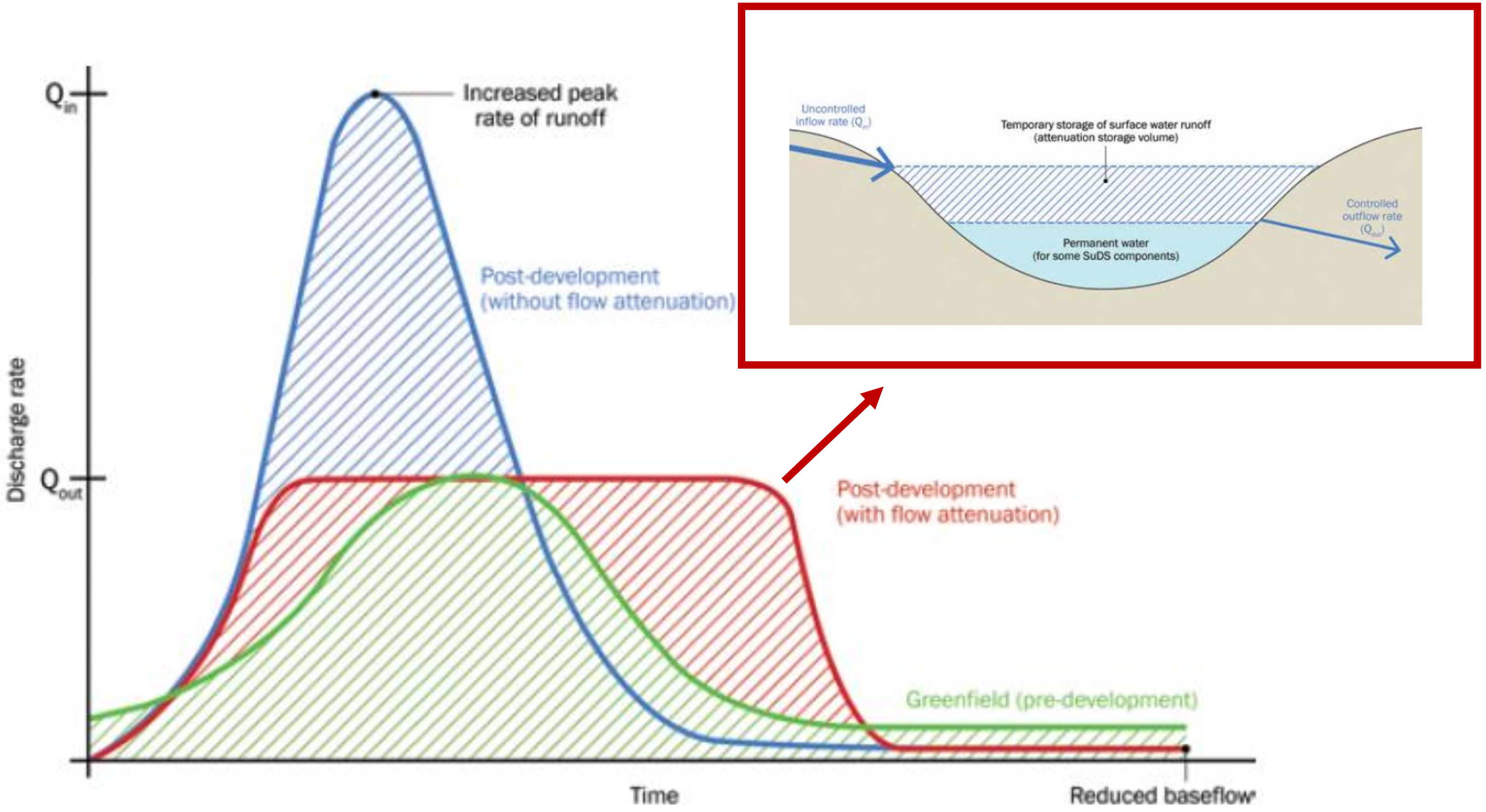


Figure 3.1 Example of a runoff hydrograph

CIRIA (2015)

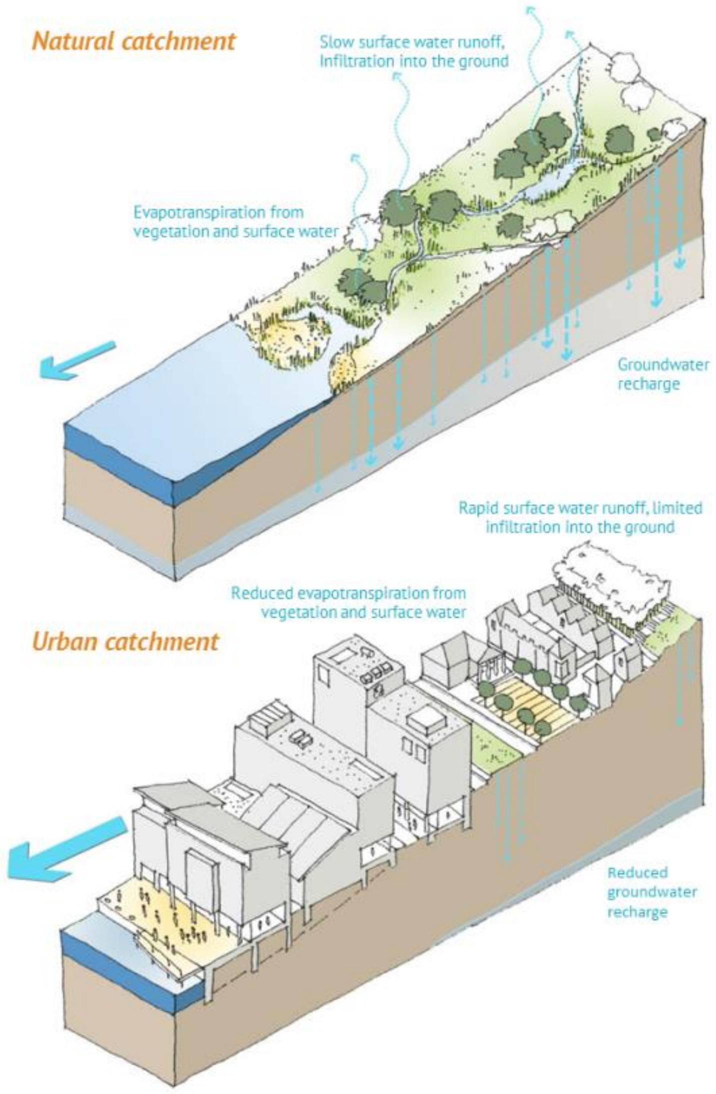
Sustainable Urban Drainage (SuDS)

SuDS design: introduction and background

- In **flood risk assessments** (FRAs), the relevant authority (e.g., Environment Agency) requests that a development should not increase the risk of flooding to other properties

- To understand this risk, we need to know:
  - An estimate of the peak runoff rates and runoff volumes from the site in its **greenfield state** (and **previously developed state**, if the case)
  - An estimate of the runoff rates and volumes from the site in its **developed state**

- In some countries, this is now a requirement for sustainable home developments



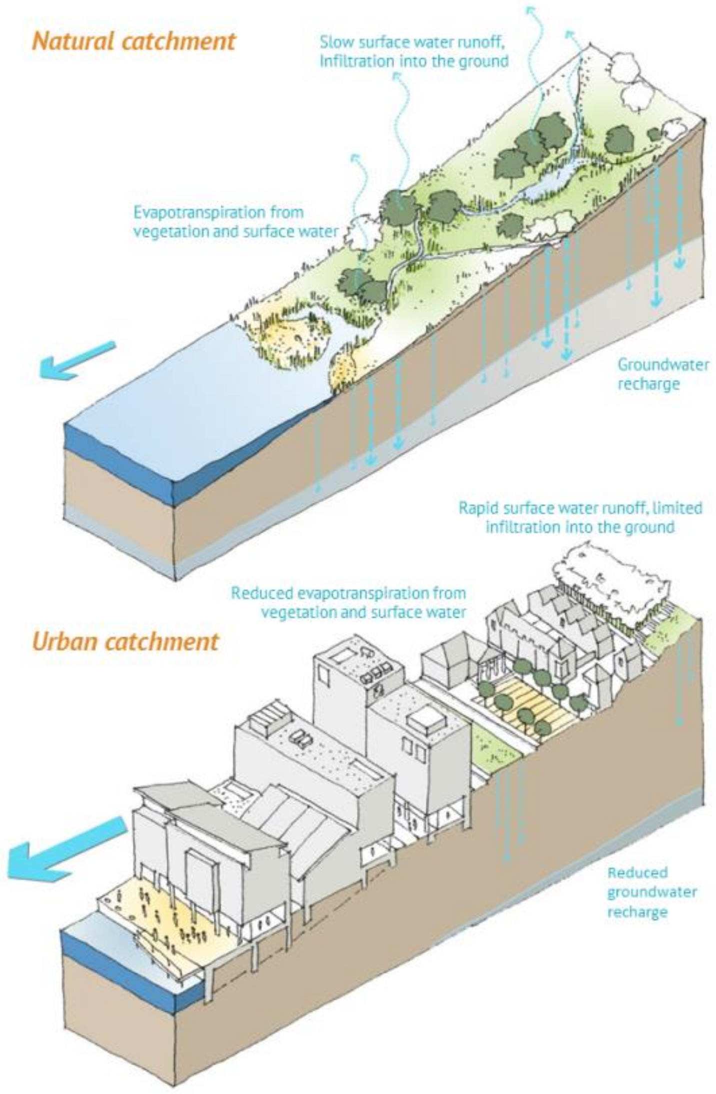
Sustainable drainage (susdrain.org)

Sustainable Urban Drainage (SuDS)

SuDS design: introduction and background

For any new development:

- Runoff rates calculated for a proposed development will exceed the **allowable discharge rates (how fast)**
  - therefore SuDS design will need to include attenuation storage / infiltration
- The volume of runoff from a proposed development will also exceed **allowable discharge volumes (how much)**
  - therefore SuDS designs will need to 'use' the runoff, infiltrate it and/or store and tightly control any additional storage volume (long term storage)



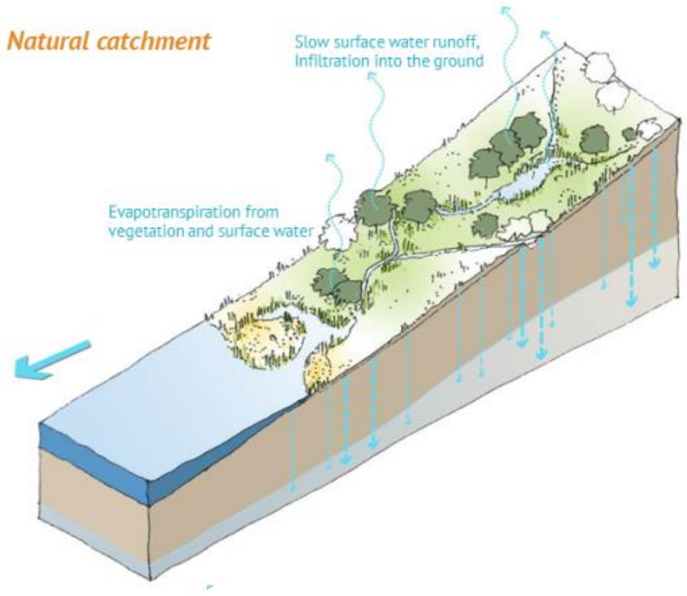
[Sustainable drainage (susdrain.org)](https://www.susdrain.org)

Sustainable Urban Drainage (SuDS)

Greenfield flows

<u>**Definition:** This is the measure of the runoff that would have been produced from the site prior to any development</u>

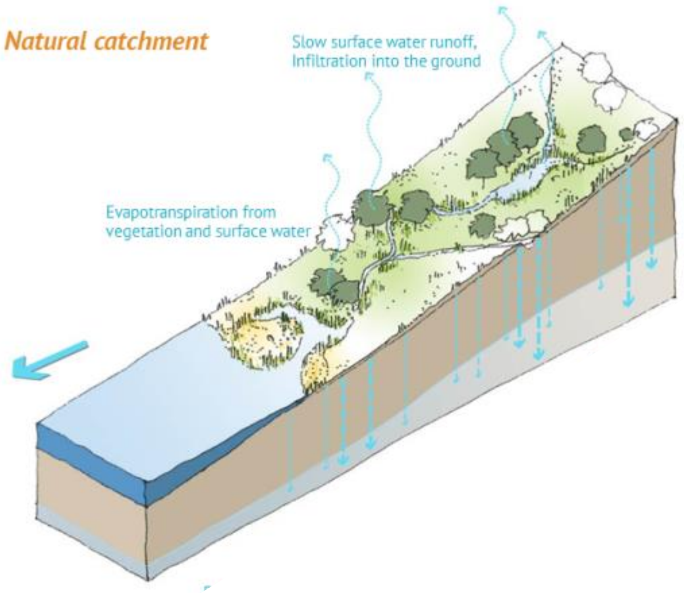
In order to reduce the chance of flooding due to the increased runoff from developed areas, **rainwater should somehow be stored or delayed** when it runs off the building and impermeable area.



- The green field runoff rate therefore gives an allowance of rainfall that can flow directly form the buildings or roads, to the water course without increasing the natural water level rise that would result from a storm.
- The green field runoff is related to the size and soil properties of the catchment

Sustainable Urban Drainage (SuDS)

Greenfield flows



Design guidelines:

- Estimated peak runoff rates of a development site in its greenfield condition for a **range of return periods** is normally used to define the discharge limits for a new development site
- More commonly now an additional 30%, sometimes 40% needs to be accounted for to allow for **climate change**.

Note that:

- Values derived from any analysis should be regarded as **approximate**
- Overall objective of using an **agreed method** is to provide a consistent and reasonable estimate upon which storage design can be based, rather than finding the exact runoff rate for any specific site which is not possible

Sustainable Urban Drainage (SuDS)

EPFL

Greenfield flows: peak runoff rate

TABLE 24.1 Summary of runoff estimation methods

Runoff estimation method	Reference	Greenfield site		Developed site		Section ref
		Peak runoff rate	Runoff volume	Peak runoff rate	Runoff volume	
FEH ReFH2	Kjeldsen (2007)	✓[1]	✓[1]	✓[3]	✓[3]	24.3.1
FEH statistical method	Kjeldsen *et al* (2008)	✓[1]				24.3.1
IH124	Marshall and Bayliss (1994)	✓[1,2]				24.3.2
FSSR16	NERC (1985)		✓[1,2]			24.4
Modified rational method	HR Wallingford (1981)			✓[3]		24.6.2
Wallingford – Fixed	HR Wallingford (1981)			[4]	[4]	24.6.3
Wallingford – Variable	Packman (1990), Osborne (2009)			✓	✓	24.6.3
UKWIR	UKWIR (2014)			✓	✓	24.6.3

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Sustainable Urban Drainage (SuDS)

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Greenfield flows: peak runoff rate

EQ. 24.5 **Modified rational method equation to determine peak flow rates**

$$Q = 2.78\, C\, i\, A$$

where:

Q = design event peak rate of runoff (l/s)

C = non-dimensional runoff coefficient which is dependent on the catchment characteristics

$$C = C_V\, C_R$$

where C_V = volumetric runoff coefficient

C_R = dimensionless routing coefficient

i = rainfall intensity for the design return period (in mm/hr) and for a duration equal to the "time of concentration" of the network

A = total catchment area being drained (ha)

Note: 2.78 is a conversion factor to address the rainfall unit being in mm/hr.

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Sustainable Urban Drainage (SuDS)

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Greenfield flows: peak runoff rate

- The manual for peak flow estimation in **Switzerland** (Spreafico et al., 2003) distinguishes between small (< 10 km2) and medium-sized (10-500 km2) catchments.
- The **required flood** depends on the purpose of the study. Where the 1000-year event return period is required it is usually derived from an estimate of the 100-year event, for instance by multiplication with a safety factor of 1.3 – 2 depending on the catchment size.
- **Different methods** for flood estimation in ungauged catchments have been tested and applied:
  - an empirical method using envelope curves, which considers catchment area and the peak-flow-runoff coefficient
  - a modified version of the SCS-method
  - Two different modifications of the rational formula,
  - Clark-WSL method
  - HYDREG method (independent of catchment size)
  - boundary-regional-model

Note: the tested methods do not provide accurate estimates of runoff rates. It is therefore recommend to use all methods and assess the spread of possible flood estimates.

Source: Fleig & Wilson (2013)

Sustainable Urban Drainage (SuDS)

Greenfield flows: runoff volume

Greenfield runoff volume defines the allowable volume that can be discharged from development site, in order to protect downstream areas from increased flood risk. Greenfield runoff volumes can be calculated from design event runoff hydrographs (using previous rainfall-runoff methods) for e.g. a 100 year, 6 hour duration design storm:

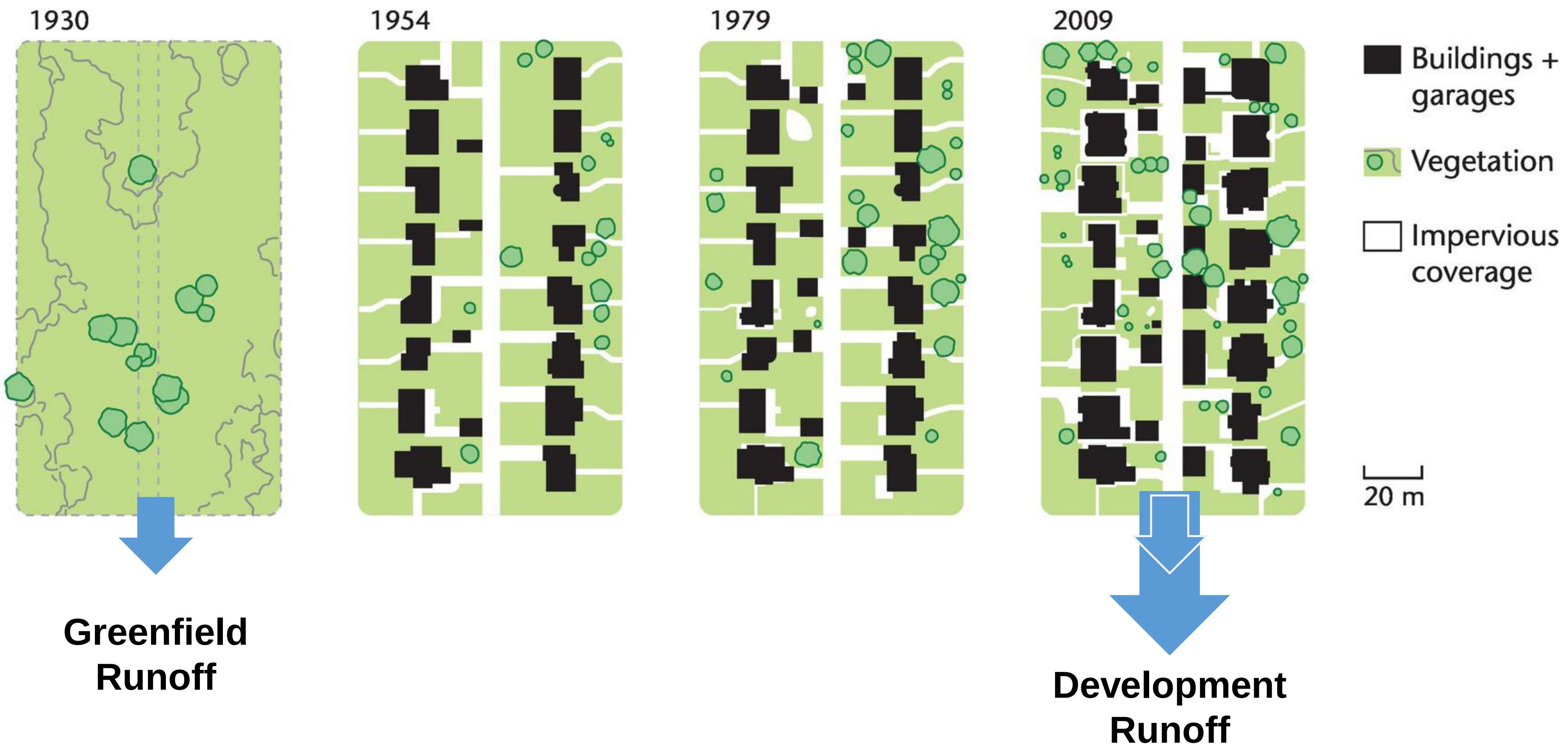
Volume = Q x duration

Development runoff rates/volumes

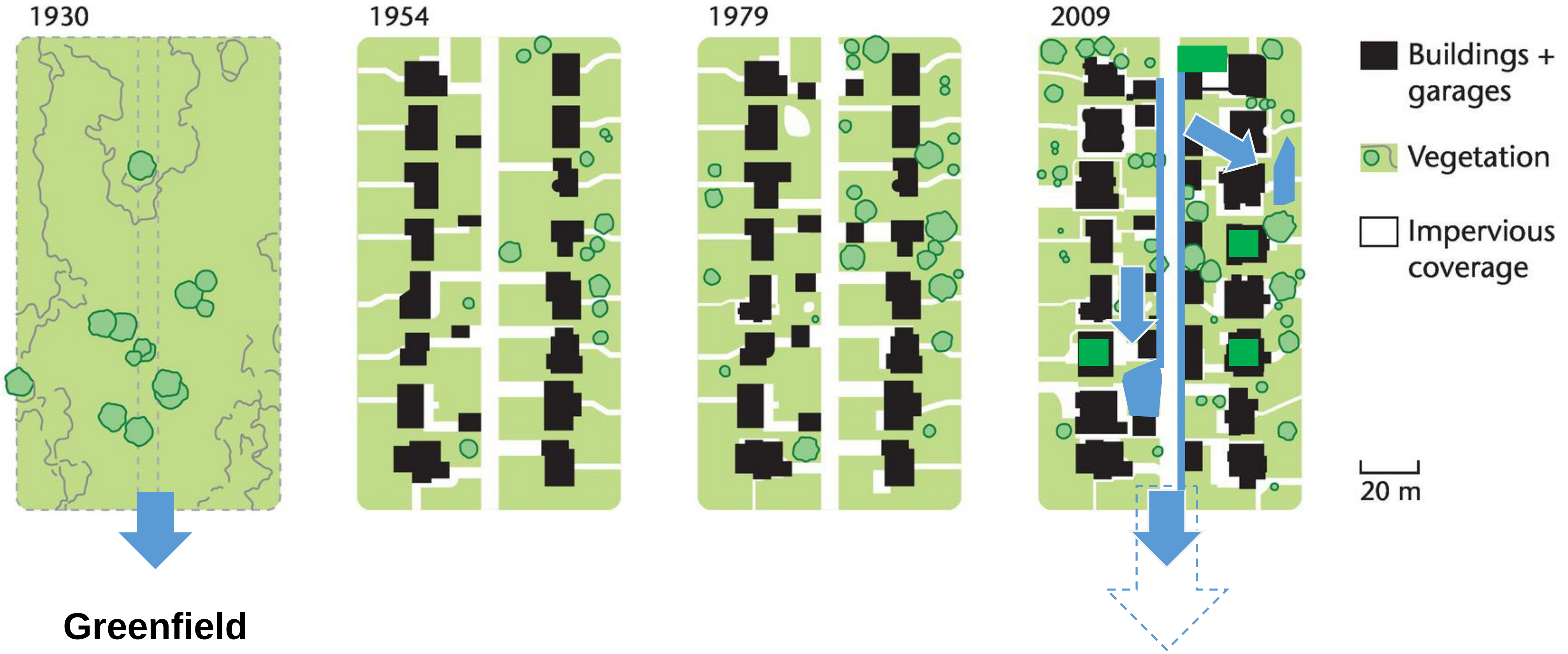
- Runoff will be required as inflows to the drainage system
  - Need to design storage systems to reduce these runoff rates/volumes
- Site developments have 2 types of surfaces (different runoff):
  - permeable + impermeable
- Climate Change + Future urban creep allowances.

The objective is to meet greenfield runoff rates/volumes

Sustainable Urban Drainage (SuDS)



Sustainable Urban Drainage (SuDS)



Greenfield Runoff

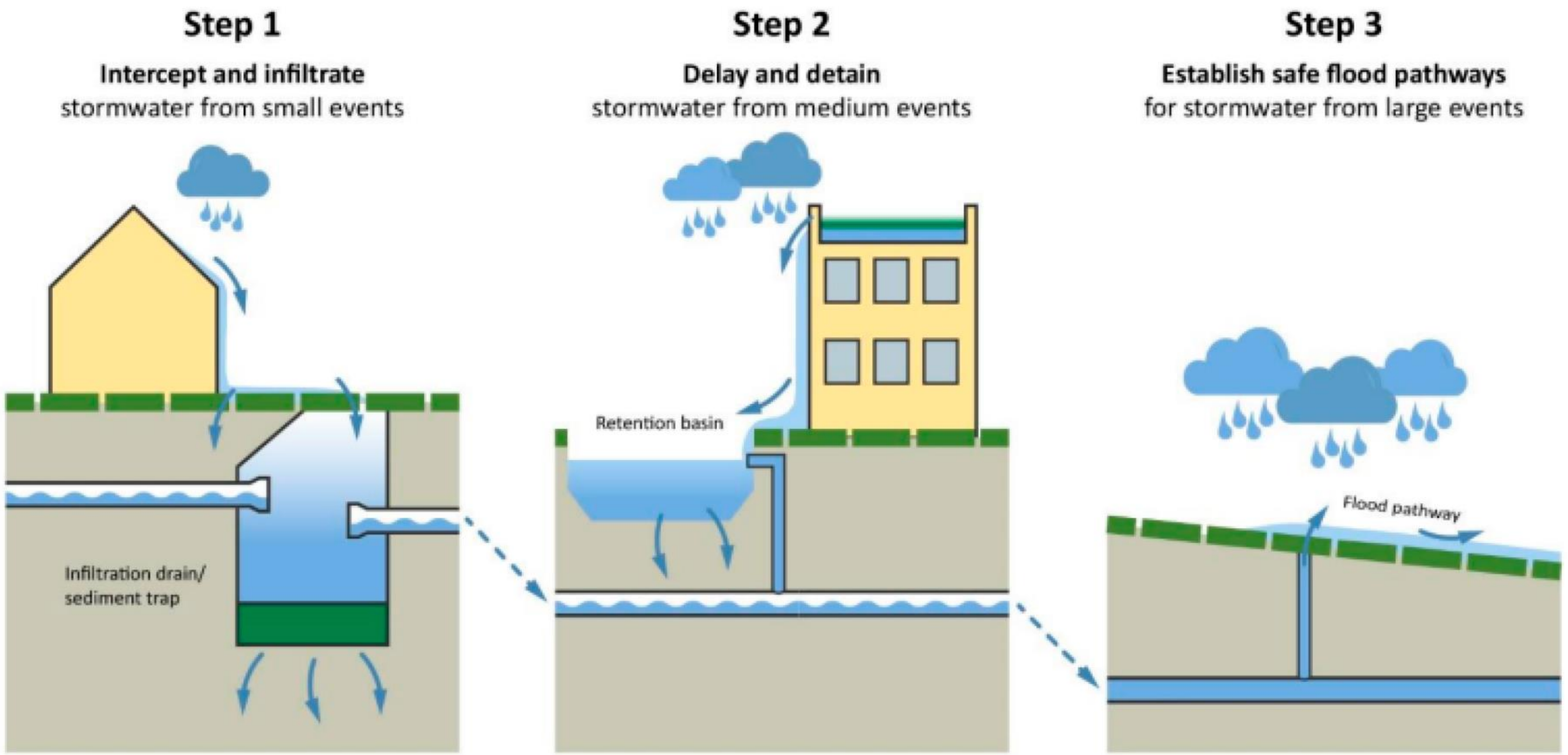
Development Runoff (with SuDS)

Today’s session

Outline

- Conventional drainage
  - Example
- Sustainable urban drainage
  - **SuDS components**
  - Example

SuDS Hydraulic Design

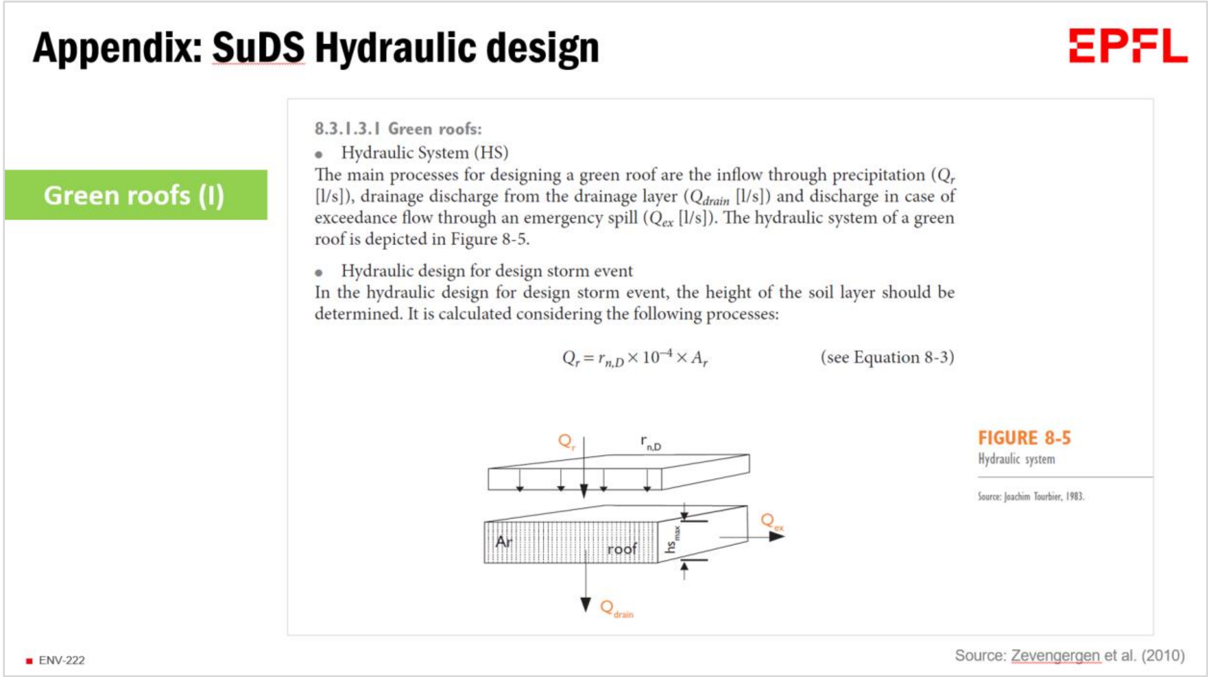


Source: [Sustainable Urban Drainage Systems]

SuDS Hydraulic Design

CIRIA Manual (available in Moodle)

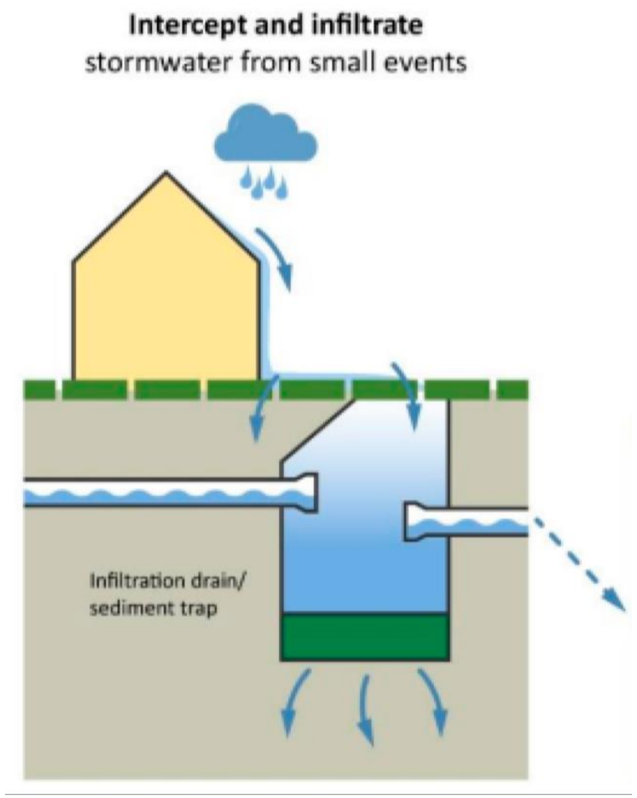
Course material (see Appendix)



SuDS Hydraulic Design

Interception (source control)

- It's the capture and retention on site of the first 5 mm of the majority of rainfall events. Runoff will not occur for the majority of small rainfall events.
- Interception is delivered by one or combination of processes:
  - **Rainwater harvesting**
  - **Infiltration**
  - **Evapotranspiration** using shallow ponding/storage within upper soil layer.
- Worst scenarios are better simulated with <u>no interception</u>



SuDS Hydraulic Design

Attenuation storage (site control)

- Attenuation storage is used to **temporally store water** when the runoff rates exceed the **allowable discharges**. Attenuation volumes are designed to drain at a rate controlled by the outlet structure.
- Attenuation Storage can be provided by:
  - a **dry storage** component
  - a **pond/wetland**

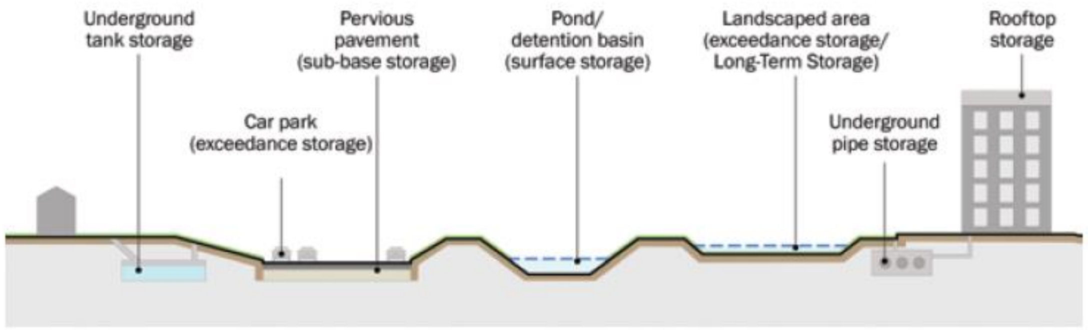


Figure 24.5 Examples of attenuation storage locations

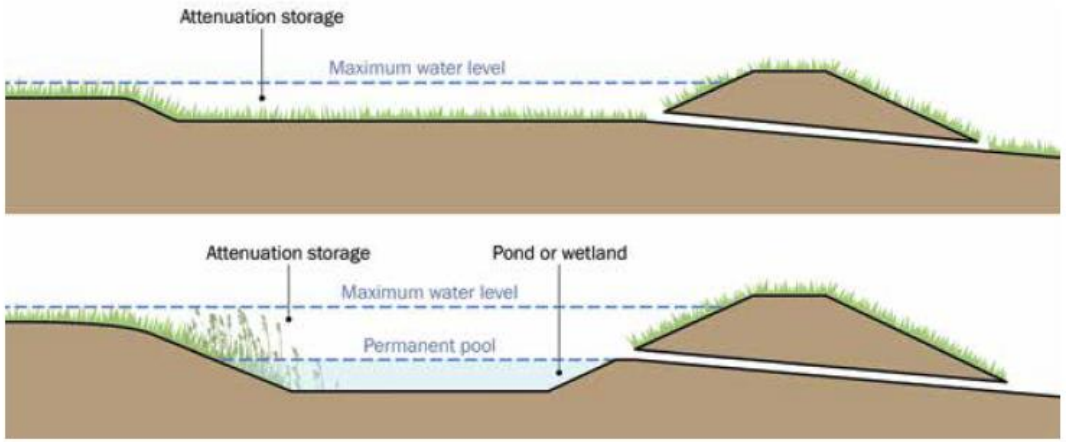


Figure 24.4 Attenuation storage in dry or wet components

CIRIA (2015)

SuDS Hydraulic Design

Attenuation storage (site control)

- A stage-storage curve defines the relationship between the depth of water and storage volume in a storage facility.
- The storage volume may be evaluated using a topographic map and integrating the depth-area relationship of the storage unit.

EQ. 24.9 **Integration of storage volume from depth/area relationship**

$$V_{1,2} = \left(\frac{A_1 + A_2}{2}\right) d$$

where:

$V_{1,2}$ = storage volume (m^3) between elevations 1 and 2
A_1 = surface area at elevation 1 (m^2)
A_2 = surface area at elevation 2 (m^2)
d = change in elevation between points 1 and 2 (m)

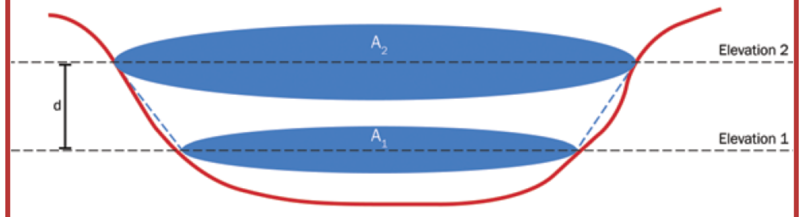


Figure 24.8 Schematic for estimating storage volume

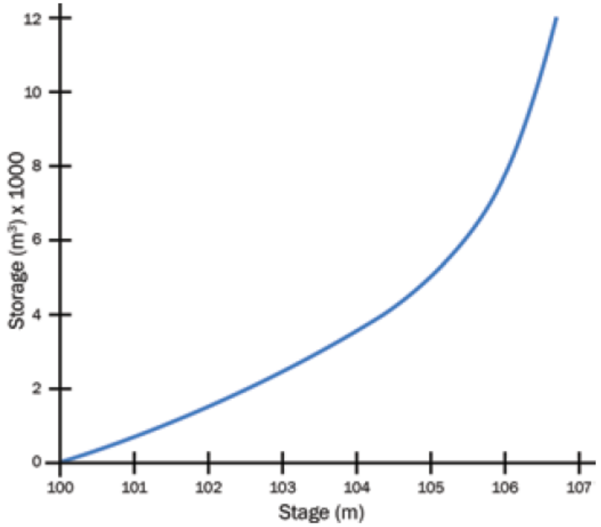


Figure 24.7 Example of a stage-storage curve

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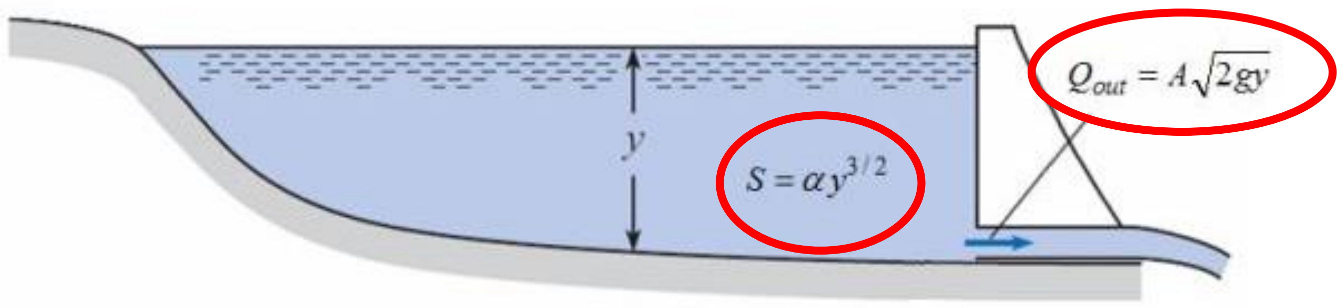
SuDS Hydraulic Design

Attenuation storage (site control)

- Simple outlet structures will <u>only discharge the max. discharge rate at the max. level</u>.
- A **stage-discharge curve**: relationship between depth of water and the discharge or outflow.
- A secondary or emergency outlet route should be designed.



Google Images & CIRIA (2015)

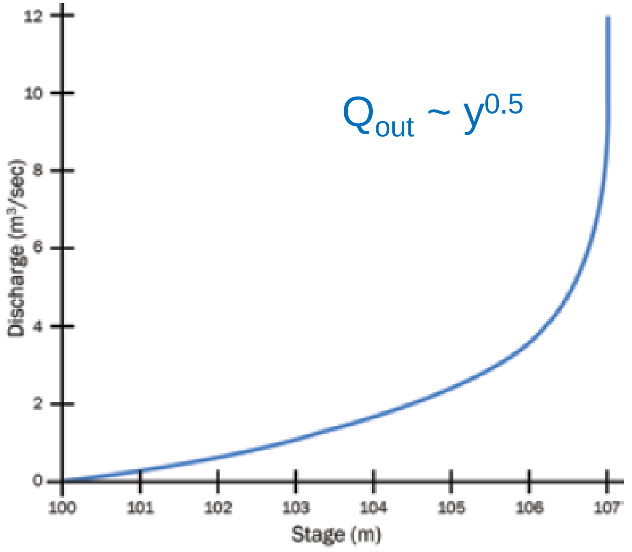


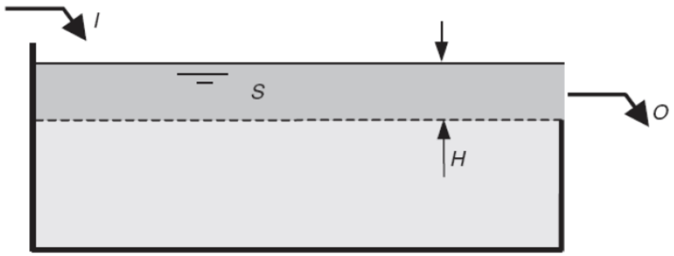
Figure 24.9 Example of a stage discharge curve

SuDS Hydraulic Design

Attenuation storage (site control)

- Sizing: **Storage volume = inflow volume – outflow volume**
  - Inflow: e.g., use rational method to estimate runoff from contributing area
  - Outflow: discharge at greenfield conditions or discharge capacity of downstream sewer
  - Design storm: e.g., 2-5 years storm for small areas, 100 years for large areas (see next slides)

- Performance: storage routing



See Butler and Davies (2011)

$$\frac{dS(t)}{dt} = Q_{in}(t) - Q_{out}(t)$$

Solution of differential equation, e.g. with:

$$\frac{dS(t)}{dt} = A\frac{dH(t)}{dt} \quad \text{and} \quad Q_{out}(t) \sim H^{\beta}$$

SuDS Hydraulic Design

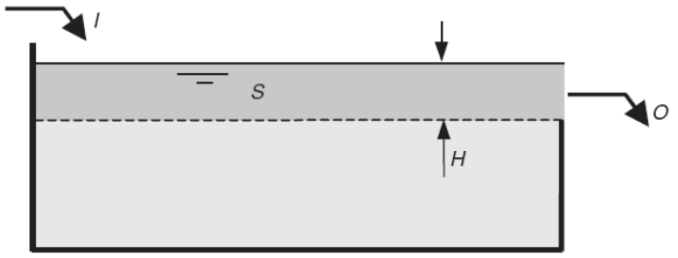
EPFL

Attenuation storage (site control)

Example 13.3

An on-line balancing pond is needed to limit the peak storm runoff from the site to 100 l/s. Design a suitable vertically sided storage tank using an orifice plate ($C_d = 0.6$) as the outflow regulator. The maximum head available on the site is 1.5 m. The inflow hydrograph is given below.

Time (h)	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75
Flow (l/s)	0	75	150	225	300	375	450	525
Time (h)	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75
Flow (l/s)	600	525	450	375	300	150	75	0



See Butler and Davies (2011)

Example 13.2

Outflow from a detention tank is given by $O = 3.5\,H^{1.5}$. The tank has vertical sides and a plan area of 300 m^2. Inflow and outflow are initially 0.6 m^3/s, then inflow increases to 1.8 m^3/s at a uniform rate over 6 minutes. Inflow then decreases at the same rate (over the next 6 minutes) back to a constant value of 0.6 m^3/s. Using a time step of 1 minute, determine the outflow hydrograph.

Solution

We first use the way O and S vary with H to create a relationship between $\frac{S}{\Delta t} + \frac{O}{2}$ and O, as on Table 13.2.

Table 13.2 Variation with H

H	O $3.5\,H^{1.5}$	S $300\,H$	$\frac{S}{\Delta t} + \frac{O}{2}$
(m)	*(m^3/s)*	*(m^3)*	*(m^3/s)*
0	0	0	0
0.2	0.31	60	1.16
0.4	0.89	120	2.44
0.6	1.63	180	3.81
0.8	2.50	240	5.25

We can use the data in Table 13.2 to plot $\frac{S}{\Delta t} + \frac{O}{2}$ against O (Fig. 13.6).

SuDS Hydraulic Design

Long-term storage (site control)

- Long-Term Storage is the difference in runoff volume between development and greenfield states. Design for long-term storage is needed for developments that can increase flood risk downstream.
- The greenfield runoff volume is calculated using the 1:100 year 6 hour event. This volume is the amount that can be discharged at the 1:100 year greenfield runoff rate
- The additional runoff volume should be discharged from the site at a flow rate less than 2l/s/ha for this event (UK guidelines, see CIRIA manual)

SuDS components

SuDS components could be….

- **Rainwater Harvesting**
- Green Roofs
- **Infiltration Systems (trenches)**
- Proprietary Treatment
- Filter Strips
- Filter Drains
- **Swales**
- Bio-retention Systems
- Trees
- **Pervious Pavements**
- **Detention Basins**
- **Ponds and Wetlands**

Source: Google Images

SuDS components

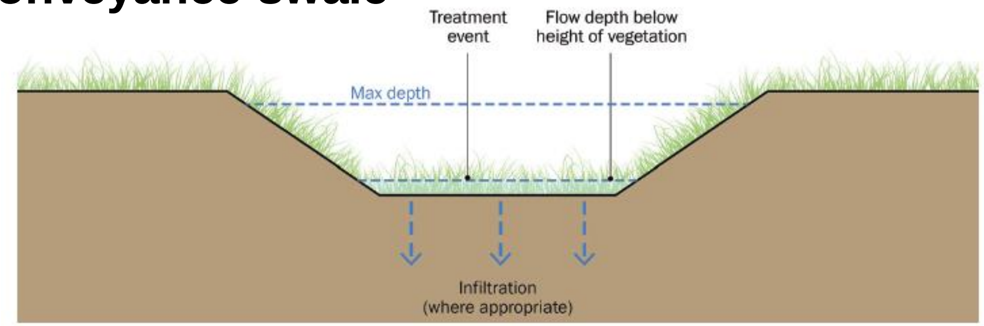
Swales

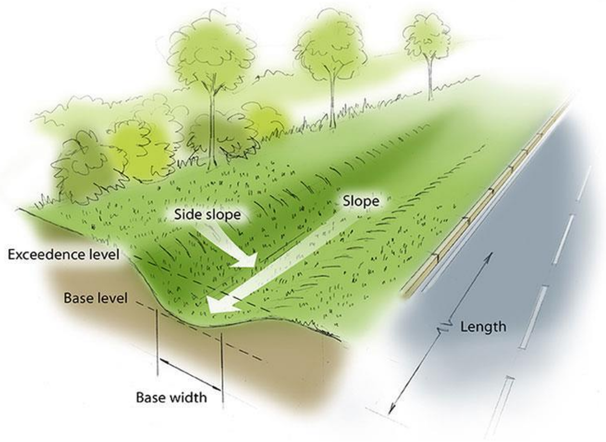
- **Definition:** “Shallow, flat bottomed vegetated open channels designed to convey, treat and (often) attenuate surface water runoff” (CIRIA 2015)
  - Enhance natural landscape
  - Drain roads, paths, car parks
  - Can replace conventional pipework
- **Types of swales:**
  - Conveyance and attenuation swale
  - Dry swale
  - Wet swale

https://www.susdrain.org/

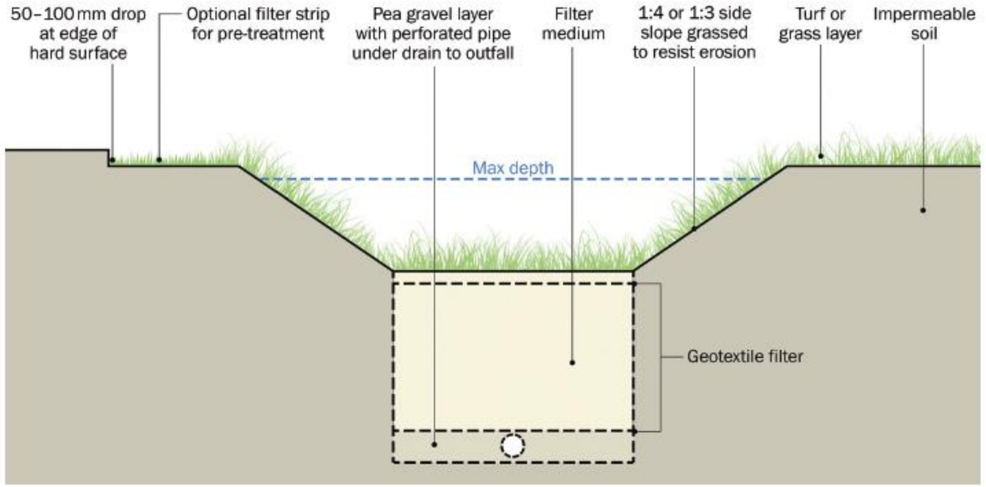
SuDS components

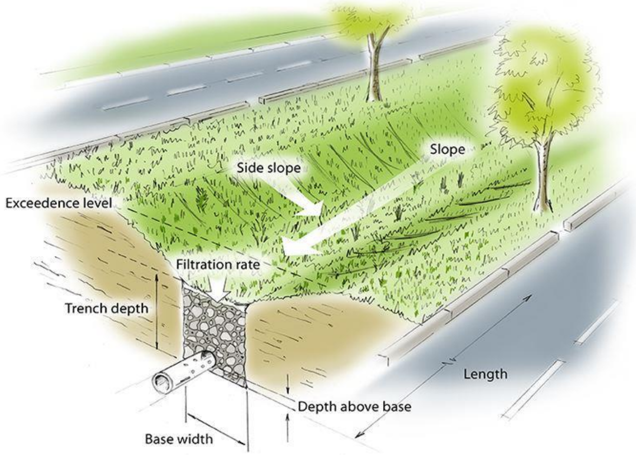
- **Conveyance swale**





- **Dry (enhanced) Swale**





CIRIA (2015)

SuDS components

- **Wet Swale**

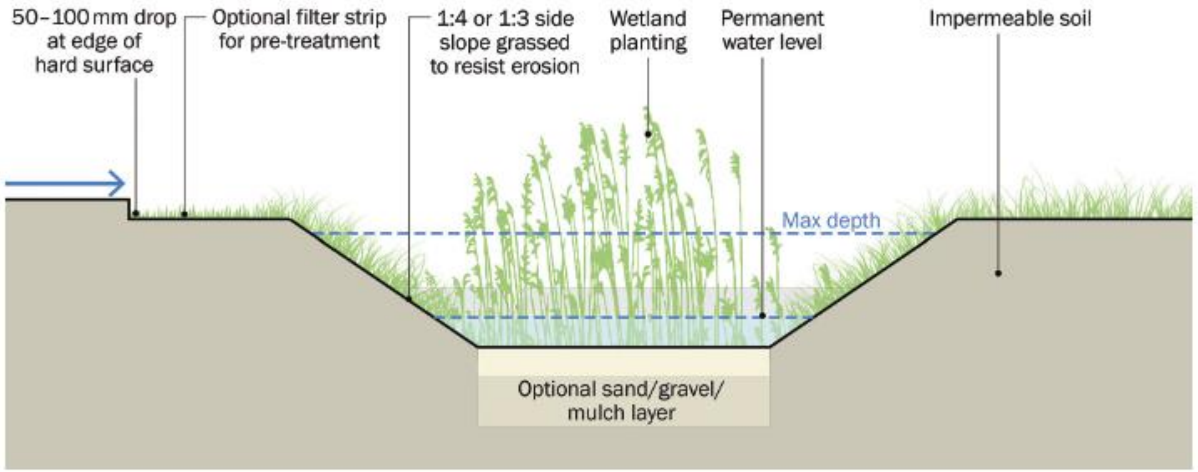
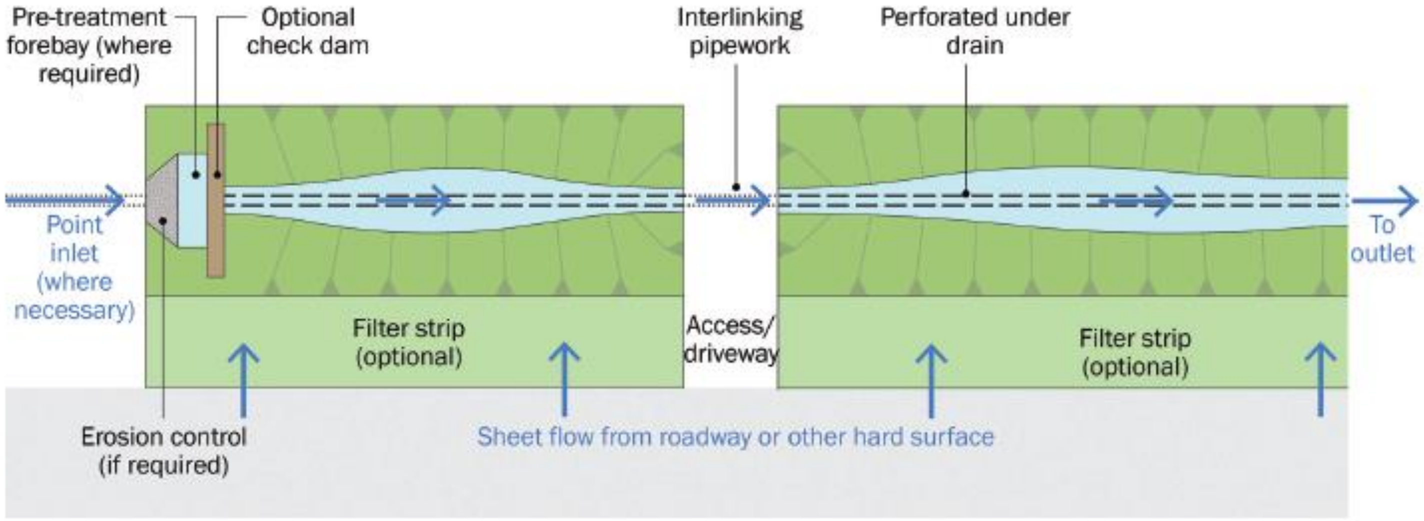


Figure 17.3 Typical wet swale

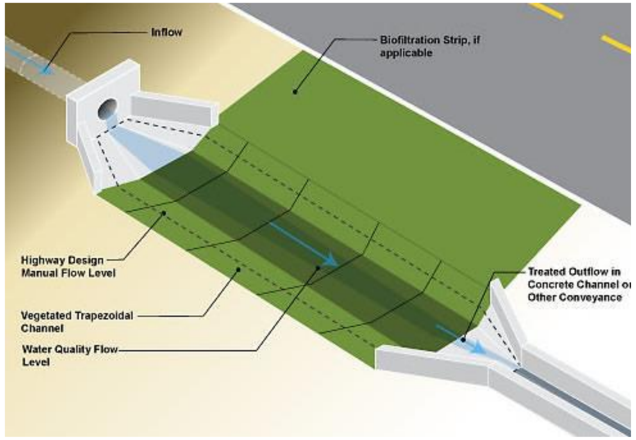
CIRIA (2015)

SuDS components

Swales: plan view



CIRIA (2015)



Google Images

SuDS components

Swales: considerations

- **Trapezoidal** / parabolic best for hydraulic performance, construction and maintenance
- **Bottom width**, generally = 0.5-2.0m
- **Longitudinal slope**: 0.5-6%. Check dams where slope is >3% (vs erosion)
- **Side slopes** flat as possible to aid pre-treatment. Also safety / easy access for mowing. **1V:3H** recommended
- **Depth**: 400-600mm; deeper could mean higher land take, deeper water, costly excavations

Expressions for A, P and R_h for important channel shapes are given below.

	rectangle	trapezoid	circle
cross-sectional area A	bh	$bh + \frac{h^2}{\tan\alpha}$	$R^2(\theta - \frac{1}{2}\sin 2\theta)$
wetted perimeter P	$b + 2h$	$b + \frac{2h}{\sin\alpha}$	$2R\theta$
hydraulic radius R_h	$\frac{h}{1+2h/b}$	$h\frac{b+h/\tan\alpha}{b+2h/\sin\alpha}$	$\frac{R}{2}\left(1 - \frac{\sin 2\theta}{2\theta}\right)$

Source: Google Images

SuDS components

Swales: considerations

- Ability to safely convey extreme event flows for design return period
- Design event runoff flows should half-empty within 24 hours
- Average velocity calculated using Manning’s equation:

$$V = \frac{R^{2/3}\, s^{1/2}}{n}$$

< 1.0 m/s to prevent erosion

- *Q* = flow rate
- *s* = slope
- *R* = hydraulic radius
- *n* = roughness coefficient (value of 0.30-0.35 recommended for depth of water below or equal to the height of the grass)

SuDS components

Swales: considerations

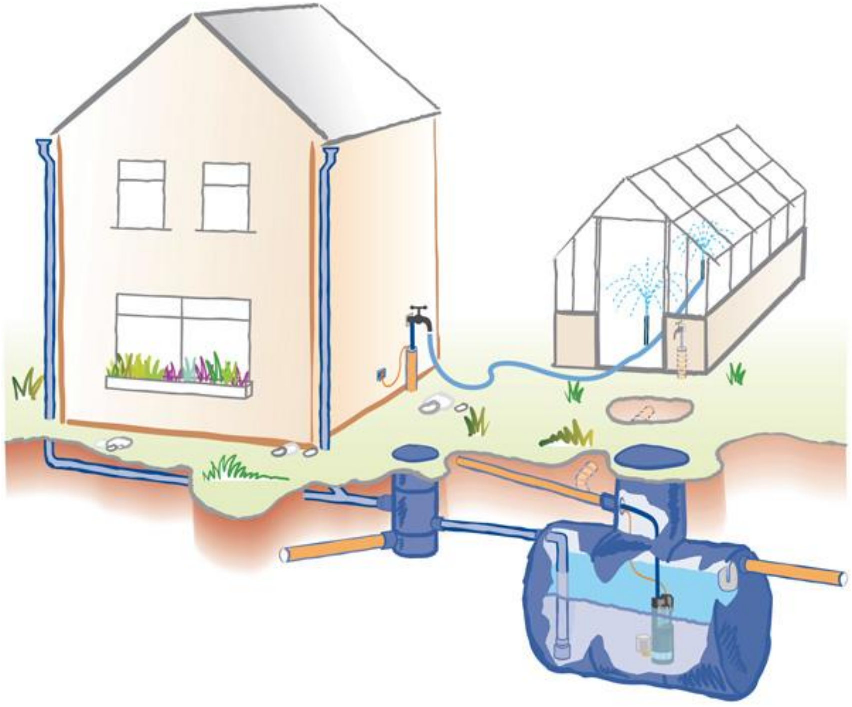
- Additional storage e.g. beneath swale base (e.g. for dry swale), in filter media and drainage layer of swale system:
  - Storage = Vol x Θ (= volume of systems x void ratio of drainage layer)
- Flow route required for rainfall events that exceed design capacity of swale
  - Overflow pipe
  - Weir structure
- Weir, orifice, pipe flow hydraulics design required for each component

Source: Google Images

SuDS components

Rainwater harvesting

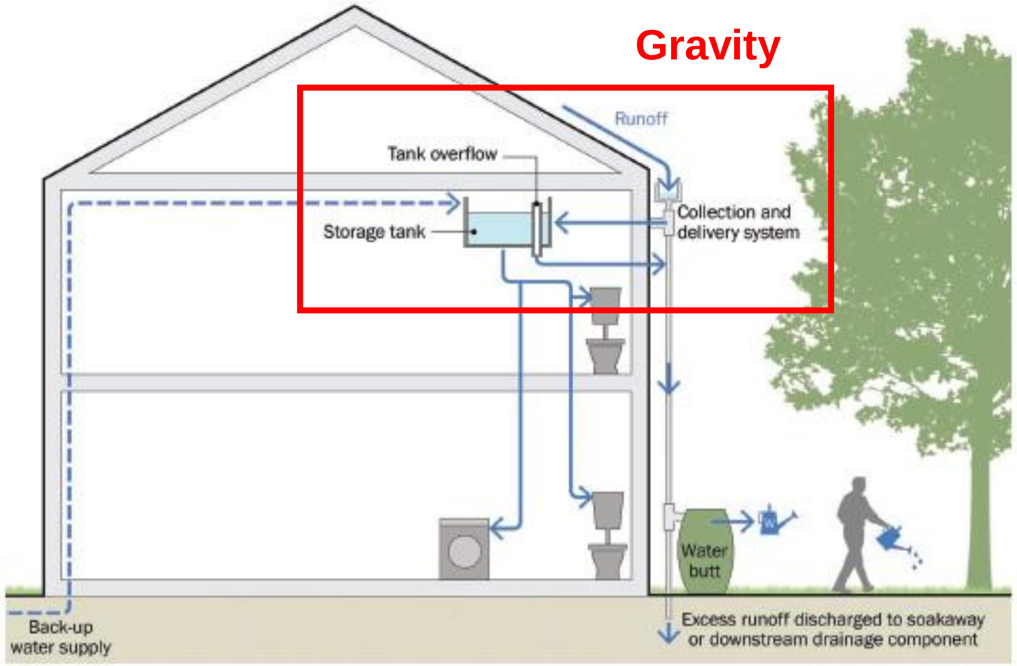
- Rainwater Harvesting (RWH) is the collection of rainwater runoff for use (from roofs and other impermeable areas)
- Water is stored, treated (if required), and used as needed
- **Types** of RWH
  - Gravity
  - Pumped
  - Composite (gravity + pumped)

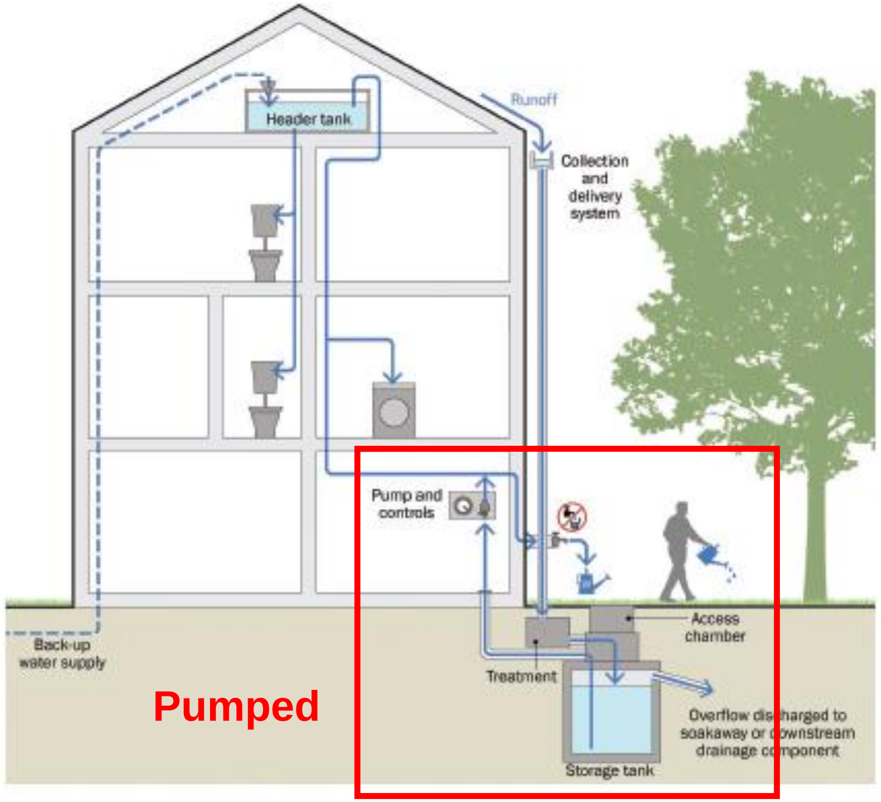


https://www.rainharvesting.co.uk/

SuDS components

Rainwater harvesting





CIRIA (2015)

SuDS components

Rainwater harvesting

Parameters for calculating size of storage are:

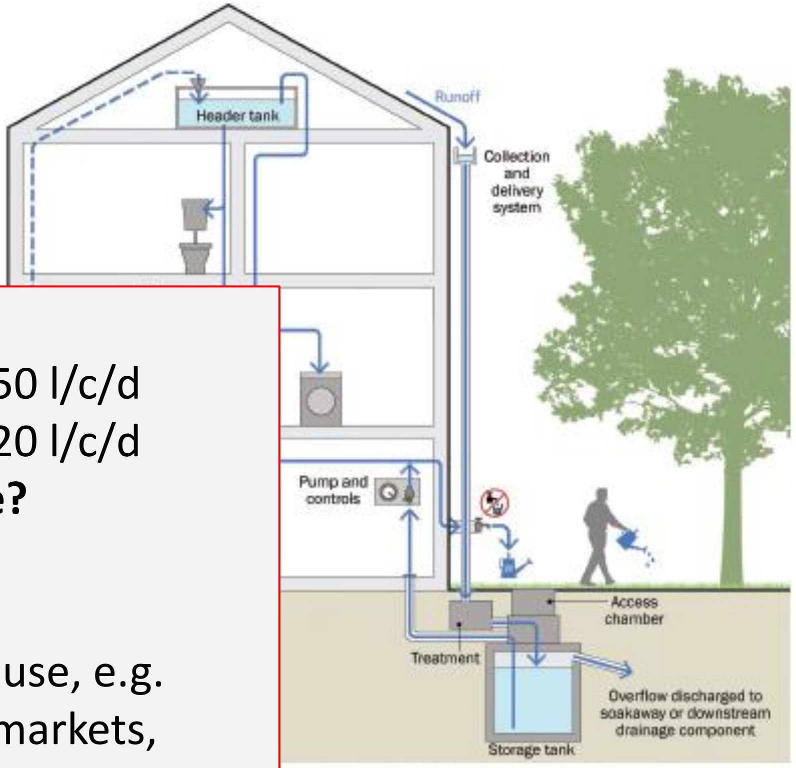
- Storm rainfall depth to be captured
- Average annual demand
- **Daily demand for non-potable water**
- Building occupancy
- Contributing surface area
- Runoff factor
- Filter efficiency factor

(See CIRIA Manual)

Toilet flushing?
- 9 litre cistern, 50 l/c/d
- 6 litre cistern, 20 l/c/d

Washing Machine?
- 20 l/c/d

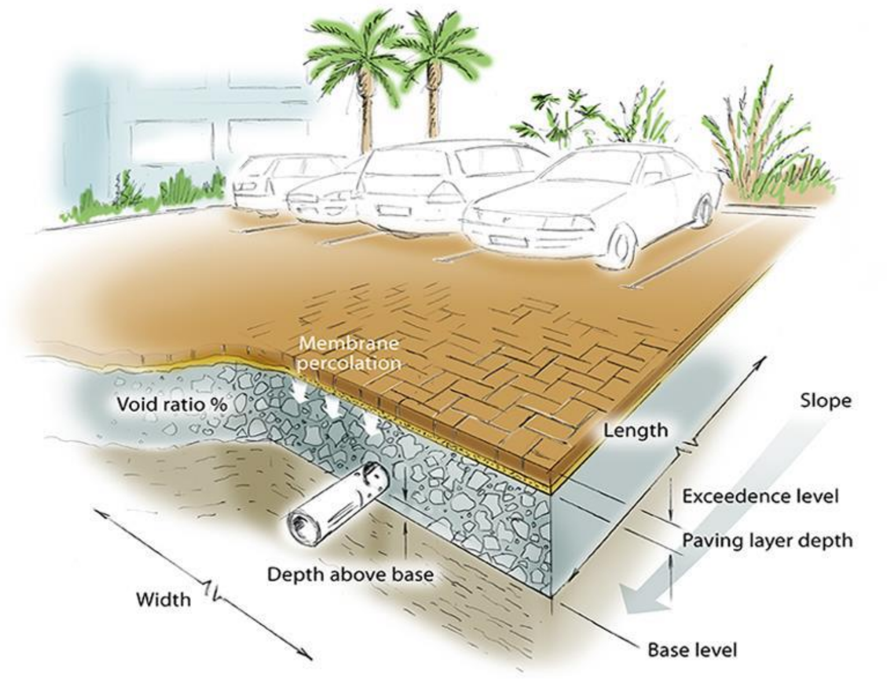
Commercial:
- Dependent on use, e.g. schools, supermarkets, offices different.



SuDS components

Pervious pavements

- Pervious pavements are suitable for pedestrian and/or vehicular traffic, while allowing rainwater to **infiltrate** through the surface and into the underlying layers.
- The water is **temporarily stored** before infiltration to the ground, reuse, or discharge to a watercourse or other drainage system.
- Pervious Pavements with aggregate sub-bases manage surface water runoff close to its source:
  - Intercepting runoff
  - Reducing the volume and frequency of runoff
  - Providing a treatment medium



Source: Google Images

SuDS components

Pervious pavements: typologies

- **Porous pavements**: infiltrate water across their entire surface material, e.g. reinforced grass or gravel surfaces, porous concrete and porous asphalt
- **Permeable pavements**: are formed of material that is itself impervious to water. The materials are laid to provide void space through the surface


Source: Google Images

SuDS components

Pervious pavements: typologies



Source: Google Images

SuDS components

Pervious pavements: typologies

Type A - Total Infiltration

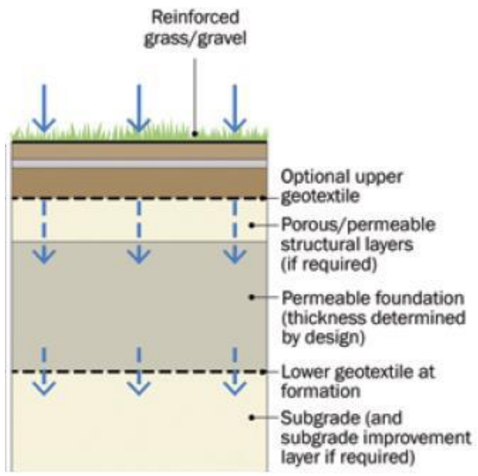
- all the rainfall passes through the sub-structure
- No discharge to a sewer/river.
- An emergency overflow is required

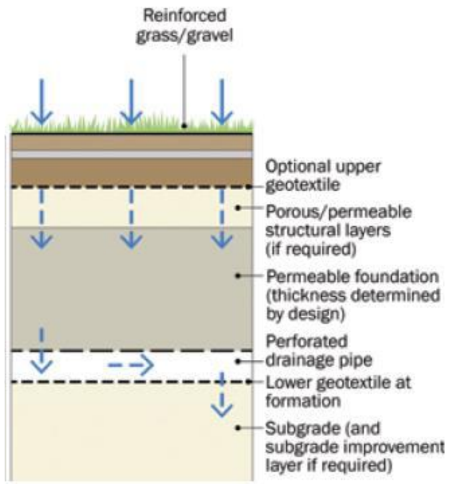
Type B - Partial Infiltration

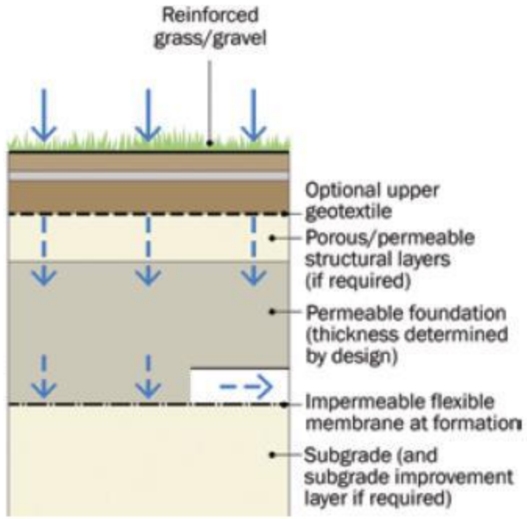
- the proportion of rainfall that exceeds the infiltration capacity of the subsoils flows to the **drainage system** (e.g., by direct drainage or perforated pipes)

Type C - No Infiltration

- the system is generally wrapped in an **impermeable** membrane
- The water is conveyed to the outfall via perforated pipes or fin drains
- Employed, e.g., when water is reused, or site is contaminated







CIRIA (2015)

SuDS components

Pervious pavements: design criteria

- Any pervious pavement (PP) need to be able to **capture the required design storm event** and discharge it in a controlled manner to the subgrade/drainage system.
- pervious surface and sub-base to be structurally designed (**vehicular loading**)
- **surface infiltration rate** > design rainfall intensity (order of magnitude)
- temporary **subsurface storage volume** to meet requirements for infiltration and/or controlled discharge

TABLE 20.1 Guidance on selection of a pavement system type (after Interpave, 2010)

Ground characteristics		Type A: total infiltration	Type B: partial infiltration	Type C: no infiltration
Permeability of subgrade defined by coefficient of permeability k (m/s)	1×10^{-6} to 1×10^{-3}	✓	✓	✓
	1×10^{-8} to 1×10^{-6}	×	✓	✓
	1×10^{-10} to 1×10^{-8}	×	× (1)	✓
Highest expected water level within 1000 mm of formation level		×	×	✓
Pollutants present in subgrade		×	×	✓
Ground conditions such that infiltration of water is not recommended (solution features, old mine working etc, Chapter 8)		×	×	✓

Note

1 Partial infiltration systems may be used in soils with permeability less than 10^{-8} m/s but the infiltration of water is not allowed for in the storage design. This helps with the provision of Interception.

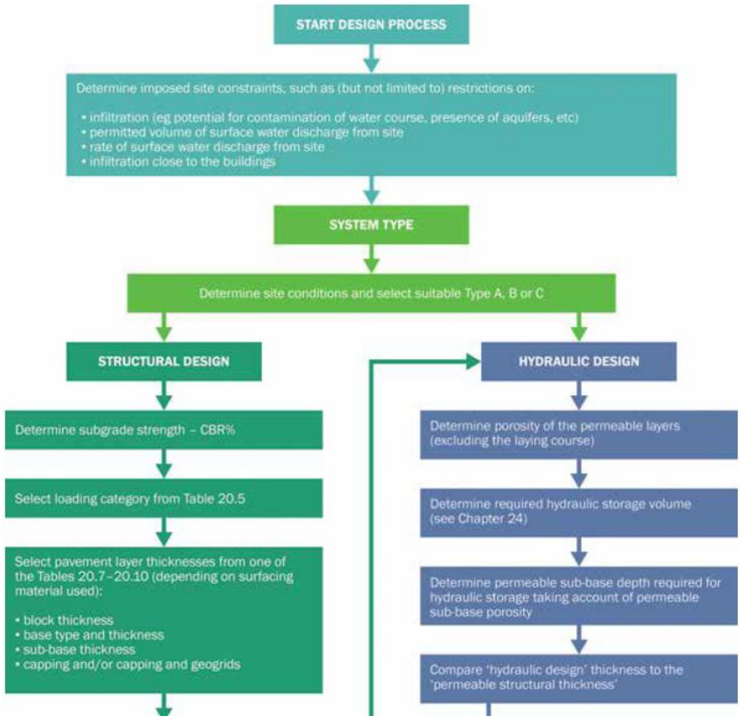
CIRIA (2015)

SuDS components

Pervious pavements: hydraulic design

1. Adequate **rate of infiltration** of rainwater through the pavement surface.
2. **Storage volume** required for design storm rainfall event management.
3. Adequacy of **outfall capacity** to convey water from the pavement structure.
4. Management of **extreme events** (excess of the design storms – e.g., gullies slightly above the pavement)

Note: a safety factor of 10 is recommended to allow effect of clogging over the design life.



See CIRIA Manual (Moodle)

SuDS components

Pervious pavements: hydraulic design

EQ. 25.2	Procedure for design of plane infiltration systems

1 Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety

2 Find the porosity of granular fill material

3 (i) Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)

(ii) Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$

4 (i) Select a storm duration, D (h)

(ii) Determine the corresponding rainfall intensity, i (m/h)

5 (i) Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case $h_{max} = 0$

(ii) Otherwise, calculate the value of h_{max} (m)

6 Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results

7 Select the largest value of h_{max}

CIRIA (2015)

Table 22.1 Typical soil infiltration rates (after Bettess, 1996)

Soil type	*Rate (mm/h)*
Gravel	10–1000
Sand	0.1–100
Loam	0.01–1
Chalk	0.001–100
Clay	<0.0001

TABLE 25.2 Suggested factors of safety, F, for use in hydraulic design of infiltration systems (designed using Bettess (1996). Note: not relevant for BRE method)

Size of area to be drained	Consequences of failure		
	No damage or inconvenience	Minor damage to external areas or inconvenience (eg surface water on car parking)	Damage to buildings or structures, or major inconvenience (eg flooding of roads)
< 100 m^2	1.5	2	10
100–1000 m^2	1.5	3	10
> 1000 m^2	1.5	5	10

SuDS components

Pervious pavements: hydraulic design

EQ. 25.2	Procedure for design of plane infiltration systems		
	1		Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety
	2		Find the porosity of granular fill material
	3	(i)	Decide on the area to be drained, A_D,(m²) and the infiltration surface area, A_b (m²)
		(ii)	Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$
	4	(i)	Select a storm duration, D (h)
		(ii)	Determine the corresponding rainfall intensity, i (m/h)
	5	(i)	Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case h_{max} = 0
		(ii)	Otherwise, calculate the value of h_{max} (m)
	6		Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results
	7		Select the largest value of h_{max}

CIRIA (2015)

Material	Porosity, n
geocellular systems	0.9–0.95
uniform gravel	0.3–0.4
graded sand or gravel	0.2–0.3

SuDS components

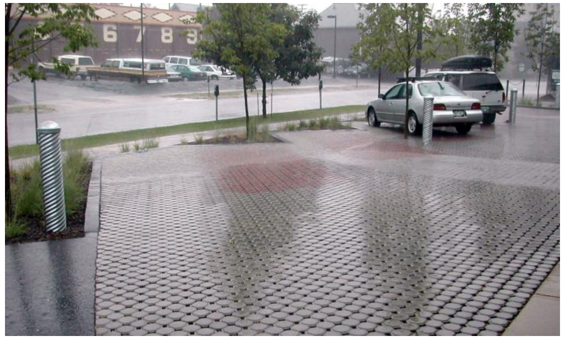
Pervious pavements: hydraulic design

EQ. 25.2	Procedure for design of plane infiltration systems		
	1		Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety
	2		Find the porosity of granular fill material
	3	(i)	Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)
		(ii)	Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$
	4	(i)	Select a storm duration, D (h)
		(ii)	Determine the corresponding rainfall intensity, i (m/h)
	5	(i)	Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case $h_{max} = 0$
		(ii)	Otherwise, calculate the value of h_{max} (m)
	6		Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results
	7		Select the largest value of h_{max}

CIRIA (2015)

Pre-Design

Usually R = 1



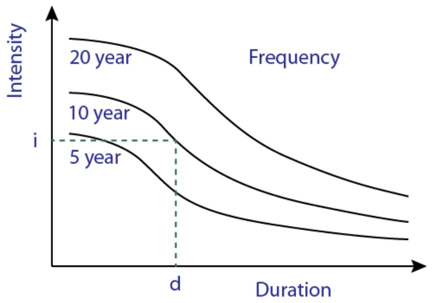
SuDS components

Pervious pavements: hydraulic design

EQ. 25.2	Procedure for design of plane infiltration systems		
1	Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety		
2	Find the porosity of granular fill material		
3	(i)	Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)	
	(ii)	Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$	
4	(i)	Select a storm duration, D (h)	
	(ii)	Determine the corresponding rainfall intensity, i (m/h)	
5	(i)	Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case h_{max} = 0	
	(ii)	Otherwise, calculate the value of h_{max} (m)	
6	Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results		
7	Select the largest value of h_{max}		

CIRIA (2015)

Design storm



SuDS components

Pervious pavements: hydraulic design

EQ. 25.2 Procedure for design of plane infiltration systems

1. Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety
2. Find the porosity of granular fill material
3. (i) Decide on the area to be drained, A_D,(m²) and the infiltration surface area, A_b (m²)

   (ii) Calculate the drainage ratio, R, where $R = \dfrac{A_D}{A_b}$
4. (i) Select a storm duration, D (h)

   (ii) Determine the corresponding rainfall intensity, i (m/h)
5. (i) Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case $h_{max} = 0$

   (ii) Otherwise, calculate the value of h_{max} (m)
6. Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results
7. Select the largest value of h_{max}

CIRIA (2015)

Maximum depth of water for plane infiltration

$$h_{max} = \frac{D(Ri - q)}{q}$$

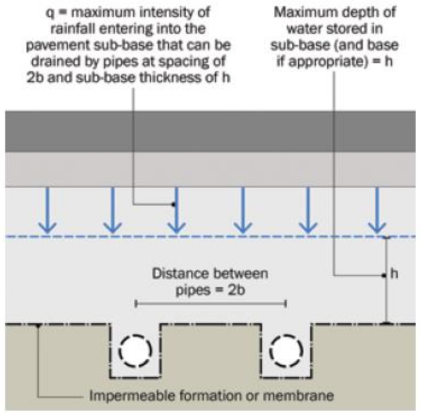


Figure 20.22 Outfall pipe spacing (after Interpave, 2010)

SuDS components

Pervious pavements: hydraulic design

EQ. 25.2 Procedure for design of plane infiltration systems

1 Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety

2 Find the porosity of granular fill material

3 (i) Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)

(ii) Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$

4 (i) Select a storm duration, D (h)

(ii) Determine the corresponding rainfall intensity, i (m/h)

5 (i) Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case $h_{max} = 0$

(ii) Otherwise, calculate the value of h_{max} (m)

6 Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results

7 Select the largest value of h_{max}

CIRIA (2015)

Maximum depth of water for plane infiltration

$$h_{max} = \frac{D(Ri - q)}{q}$$

Storage = VOL rain – VOL Infiltration

Storage = $A_b \cdot n \cdot hmax$

VOL rainfall = $A_D \cdot i \cdot D$

VOL infiltration = $A_b \cdot q \cdot D$

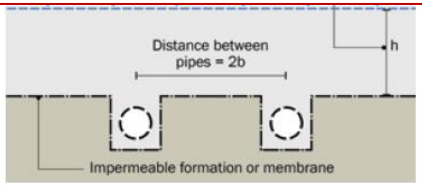


Figure 20.22 Outfall pipe spacing (after Interpave, 2010)

SuDS components

Pervious pavements: hydraulic design

EQ. 25.2	Procedure for design of plane infiltration systems	
1	Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety	
2	Find the porosity of granular fill material	
3	(i)	Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)
	(ii)	Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$
4	(i)	Select a storm duration, D (h)
	(ii)	Determine the corresponding rainfall intensity, i (m/h)
5	(i)	Check whether q exceeds R_i. If so, the rate of infiltration exceeds the potential rate of runoff, in which case $h_{max} = 0$
	(ii)	Otherwise, calculate the value of h_{max} (m)
6	Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadsheet or table of results	
7	Select the largest value of h_{max}	

CIRIA (2015)

Iterative process
(hmax → reSize)

SuDS components

Pervious pavements: hydraulic design

EQ. 25.2 Procedure for design of plane infiltration systems

1 Obtain the infiltration coefficient, q, (m/h) by dividing the infiltration rate found from field tests by the appropriate factor of safety

2 Find the porosity of granular fill material

3 (i) Decide on the area to be drained, A_D,(m^2) and the infiltration surface area, A_b (m^2)

(ii) Calculate the drainage ratio, R, where $R = \frac{A_D}{A_b}$

4 (i) Select a storm duration, D (h)

(ii) Determine the corresponding rainfall intensity, i (m/h)

5 (i) Check whether q exceeds R_i. If so, the rate of infiltration exceeds the po
in which case $h_{max} = 0$

(ii) Otherwise, calculate the value of h_{max} (m)

6 Repeat steps 4 and 5 for a range of rainfall durations, constructing a spreadshe

7 Select the largest value of h_{max}

8. Check half-empty time (<24h)

EQ. 25.6 Equations to calculate the time to empty an infiltration system

1 Time for half-emptying a plane infiltration system:

$$\frac{n\,h_{max}}{2q}$$

If the time for half-emptying is stipulated to be less than 24 hours and q is measured in m/h, then an acceptable infiltration coefficient is determined by:

$$q \geq \frac{n\,h_{max}}{48}$$

SuDS components

Pervious pavements: hydraulic design (given the maximum depth)

EQ. 25.3 Procedure to determine the base area required for a given maximum depth

The equation for the base area A_b (m^2) is given by:

$$A_b = \frac{A_D\, i\, D}{n\, h_{max} + q\, D}$$

1 Obtain the infiltration coefficient, q, by dividing the infiltration rate found from field tests by the appropriate factor of safety

$$h_{max} = \frac{D\,(R\, i - q)}{n}$$

where R is the ratio of the drained area to the infiltration area, $R = A_D/A_b$

2 Find the porosity of granular fill material

3 (i) Decide on the area to be drained, A_D (m^2)

(ii) Decide on the maximum allowable water level, h_{max} (m)

4 (i) Select a storm duration, D (h)

(ii) Determine the corresponding rainfall intensity, i (m/h)

5 (i) Calculate $A_D.i.D$, $n.h_{max}$, and $q.D$

(ii) Calculate A_b (m_2)

6 Repeat steps 4 and 5 for a range of rainfall durations constructing a spreadsheet or a table of results

7 (i) Find the largest infiltration surface area required

(ii) If this area is unacceptably large then increase h_{max} or decrease A_D and repeat from step 3

CIRIA (2015)

SuDS components

Pervious pavements: hydraulic design (outflow from pavement structure)

EQ. 20.1 Equation to estimate outfall pipe spacing

$q = k\,(h/b)^2$

q = maximum intensity of rainfall entering into the pavement sub-base that can be drained by pipes at spacing of 2b and sub-base thickness of h (m/s)

k = coefficient of permeability of sub-base (m/s) (minimum value is specified in **Section 20.11**)

h = maximum depth of water stored in sub-base (and base if appropriate) above impermeable formation or membrane (m)

2b = distance between pipes (m)

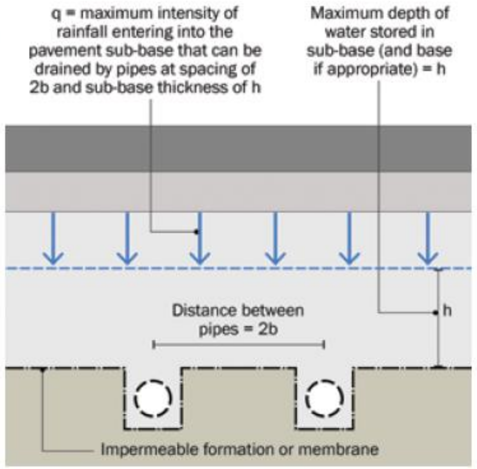


Figure 20.22 Outfall pipe spacing (after Interpave, 2010)

EQ. 20.2 Darcy's law to calculate sub-base flow

$Q = A.k.i$

Where

Q = flow capacity of sub-base (m^3/s)

A = cross-sectional flow area, ie height × width of sub-base through which water is flowing (m^2)

k = coefficient of permeability of sub-base (m/s) (minimum value is specified in **Section 20.11**.)

i = hydraulic gradient (m/m) (The hydraulic gradient is the head of water driving the flow. For this purpose, it is assumed to be the slope of the subgrade towards the outlet. This is not the true hydraulic head, but is a simple approximation which is generally conservative.)

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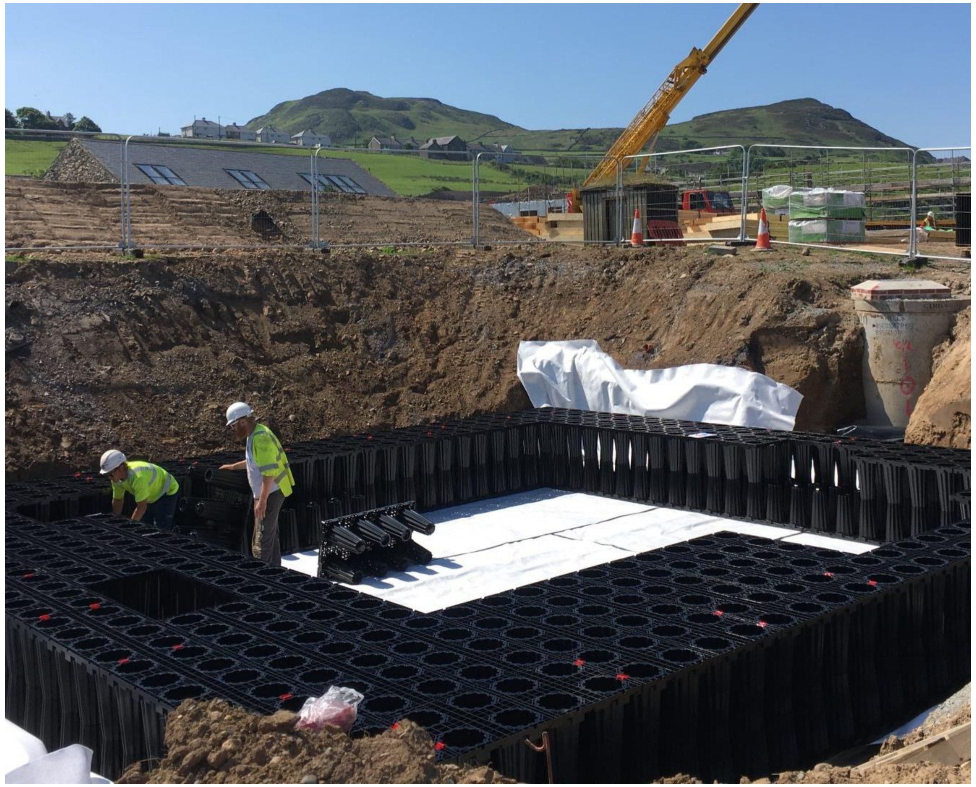
SuDS components

Infiltration systems

Infiltrations Systems (IS) facilitate the discharge of stormwater runoff to the ground and ultimately into groundwater.

There are different types of drainage components to facilitate infiltration:

- Soakaways
- Infiltration trenches/blankets
- Infiltration basins
- Others (bioretention systems and pervious pavement)



Source: Google Images

SuDS components

Infiltration systems

- **Soakaways** are excavations filled with a void-forming material that allows temporary storage of water before it soaks into the ground.

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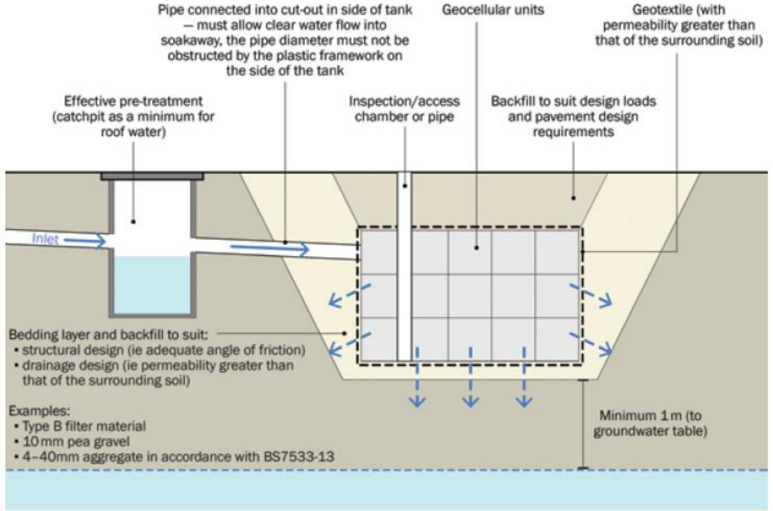

Figure 13.1 Soakaway details (including a pre-treatment system)

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SuDS components

Infiltration systems

- **Infiltration trenches** are simply linear soakaways. They can be shallower and they distribute the infiltration area so that the impact of less permeable areas of soil is lower

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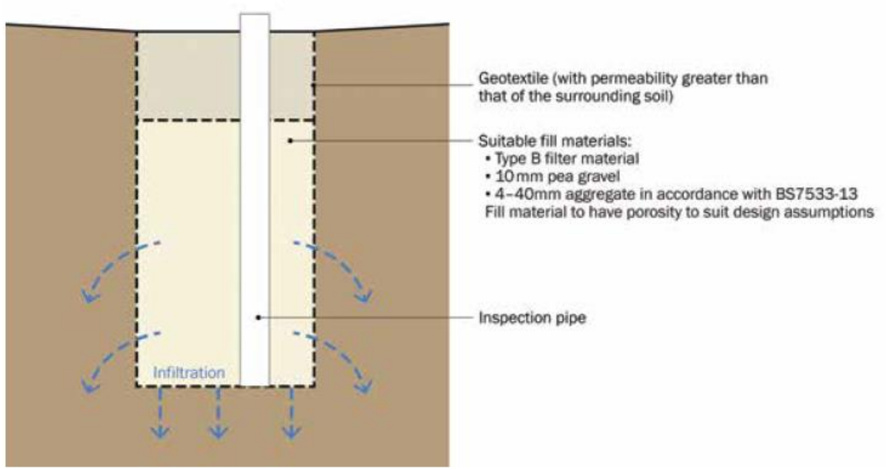

Figure 13.3 Infiltration trench

CIRIA (2015)

SuDS components

Infiltration systems

- **Infiltration basins** are flat-bottomed, shallow landscape depressions that store runoff before infiltration into the subsurface soils. Generally vegetated and with sediment and contaminants treatment.

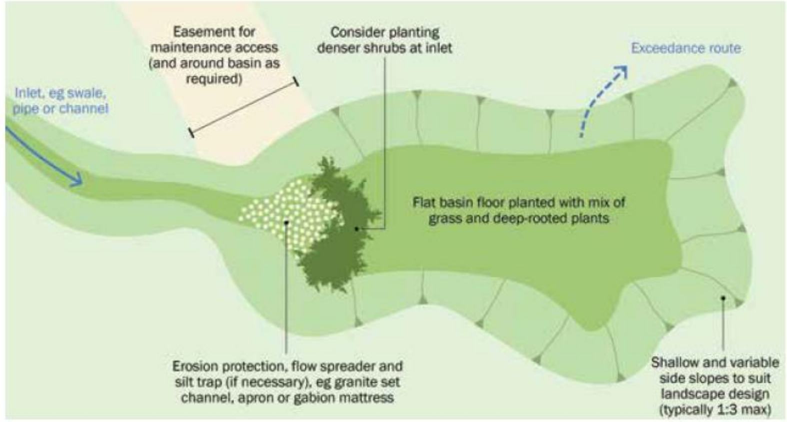

Figure 13.4 Plan view of infiltration basin

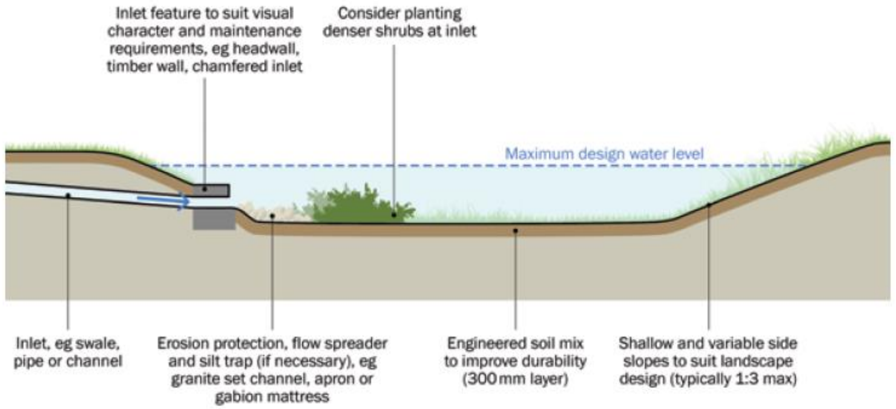

Figure 13.5 Elevation of infiltration basin

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SuDS components

Infiltration systems: design criteria

- It is crucial that any **runoff be clean** before entering the IS to avoid groundwater is not put at risk of contamination.
- The performance is dependent on the **infiltration capacity** of the surrounding soils and the depth to **groundwater** (a minimum 1 m between the base of the IS and the Groundwater level is usually adopted)
- The bottom should be **flat** and the side slopes should not be steeper than **1H:3V** (for vegetative stabilisation and public safety reasons)
- Infiltrations Systems should manage storms up to the design standard of service: **T = 10 or 30 years** (but the 100 years performance also needs to be known)
- The IS should discharge to **half empty within 24 hours**
- Overflow pipe should convey exceedance flow downstream (in case of extremes)

SuDS components

Infiltration systems: hydraulic design (3D systems)

EQ. 25.5 Procedure for design of 3D infiltration systems

1. Obtain the infiltration coefficient, q, by dividing the infiltration rate found from field tests by the appropriate factor of safety
2. Find the porosity of granular fill material; if the structure is open, n = 1, but if it is part-filled with gravel then the effective porosity, n', is used
3. (i) Decide on the area to be drained, A_D
   (ii) Choose the type and shape of infiltration system, ie cylindrical soakaway, infiltration trench
4. (i) Select the proposed dimensions for the infiltration system, ie the radius of a cylindrical soakaway, the width and length of a rectangular plan system
   (ii) Calculate the base area, A_b, and the perimeter, P, of the soakaway base from the proposed dimensions
   (iii) Determine the value of b from $b = \frac{P\,q}{n\,A_b}$
5. (i) Select a storm duration, D
   (ii) Determine the corresponding rainstorm intensity, i
6. Determine the value of a from $a = \frac{A_b}{P} - i\,\frac{A_D}{P\,q}$
7. Either calculate h_{max} or read off the value of h_{max} from **Figure 25.8**
8. Repeat steps 5 to 7 for a range of rainfall durations
9. (i) Find the largest value of h_{max}
   (ii) If hmax is unacceptably high, return to step 4 and increase the dimensions
   (iii) If h_{max} is still unacceptably high, either:
   (a) return to step 3(i) and reduce the area drained to an individual system
   or
   (b) return to step 3(ii) and choose a different type of system

EQ. 25.4 Determination of maximum depth of water for 3D infiltration systems

$$h_{max} = a\left[e^{(-bD)} - 1\right]$$

Where:

$$a = \frac{A_b}{P} - i\,\frac{A_D}{P\,q}$$

P = perimeter of the base of the infiltration system (m).

$$b = \frac{P\,q}{n\,A_b}$$

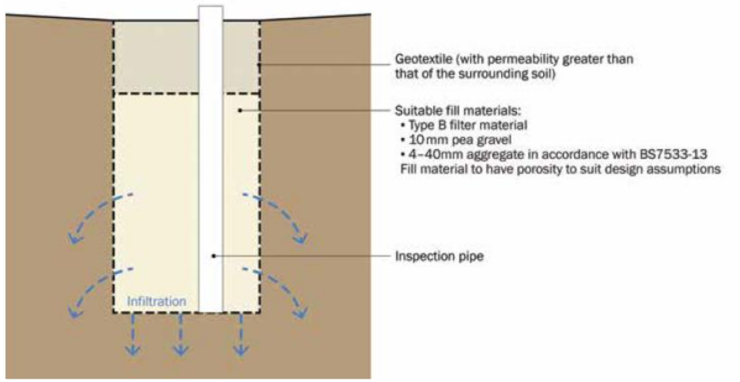

Figure 13.3 Infiltration trench

SuDS components

Infiltration systems: hydraulic design (3D systems)

EQ. 25.5 **Procedure for design of 3D infiltration systems**

1 Obtain the infiltration coefficient, q, by dividing the infiltration rate found from field tests by the appropriate factor of safety

2 Find the porosity of granular fill material; if the structure is open, n = 1, but if it is part-filled with gravel then the effective porosity, n', is used

3 (i) Decide on the area to be drained, A_D

(ii) Choose the type and shape of infiltration system, ie cylindrical soakaway, infiltration trench

4 (i) Select the proposed dimensions for the infiltration system, ie the radius of a cylindrical soakaway, the width and length of a rectangular plan system

(ii) Calculate the base area, A_b, and the perimeter, P, of the soakaway base from the proposed dimensions

(iii) Determine the value of b from $b = \frac{P\,q}{n\,A_b}$

5 (i) Select a storm duration, D

(ii) Determine the corresponding rainstorm intensity, i

6 Determine the value of a from $a = \frac{A_b}{P} - i\frac{A_D}{P\,q}$

7 Either calculate h_{max} or read off the value of h_{max} from Figure 25.8

8 Repeat steps 5 to 7 for a range of rainfall durations

9 (i) Find the largest value of h_{max}

(ii) If hmax is unacceptably high, return to step 4 and increase the dimensions

(iii) If h_{max} is still unacceptably high, either:

(a) return to step 3(i) and reduce the area drained to an individual system

or

(b) return to step 3(ii) and choose a different type of system

10. Check half-empty time (<24h)

EQ. 25.6 **Equations to calculate the time to empty an infiltration system**

1 Time for half-emptying a plane infiltration system:

$$\frac{n\,h_{max}}{2q}$$

If the time for half-emptying is stipulated to be less than 24 hours and q is measured in m/h, then an acceptable infiltration coefficient is determined by:

$$q \geq \frac{n\,h_{max}}{48}$$

2 Time for half-emptying a 3D infiltration system.

$$\frac{n\,A_b}{q\,P}\log_e\left[\frac{h_{max} + \frac{A_b}{P}}{\frac{h_{max}}{2} + \frac{A_b}{P}}\right]$$

If the time for half-emptying is stipulated to be less than 24 hours and q is measured in m/h, then an acceptable infiltration coefficient is given by:

$$q > \frac{n\,A_b}{24P}\log_e\left[\frac{h_{max} + \frac{A_b}{P}}{\frac{h_{max}}{2} + \frac{A_b}{P}}\right]$$

SuDS components

Detention basins

- Detention basins (DB) are surface storage basins/facilities that provide flow control through attenuation of stormwater runoff (settling pollutants)
- DB are normally **dry** (certain situations: recreational facility)

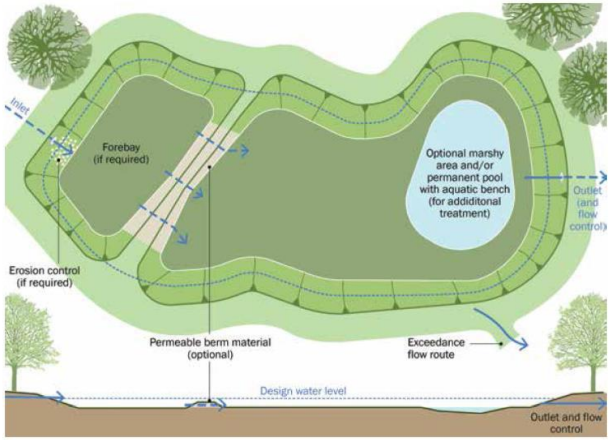

Figure 22.2 Plan and elevation of vegetated detention basin

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Source: Google Images

Watersquare, Rotterdam (Google Images)

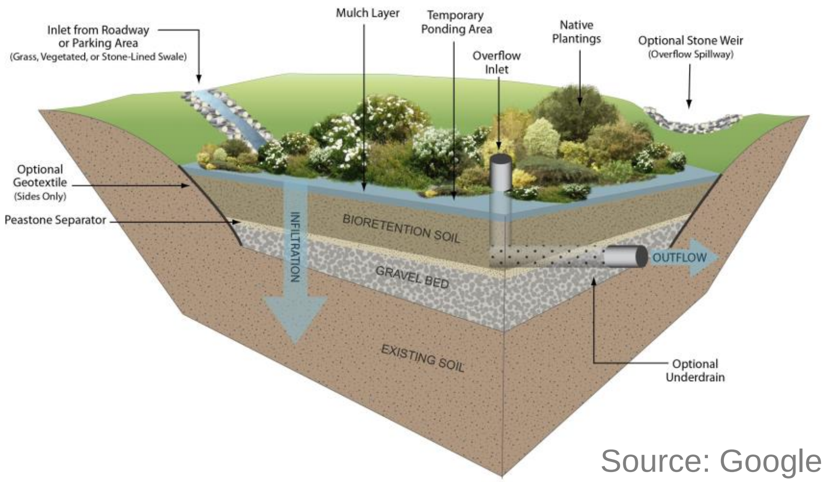
SuDS components

Detention basins: design criteria

- **detention volume** to manage design storms via constrained outflow
- minimum **length:width** ratio of **2:1** (3:1 to 5:1)
- maximum **side slopes** of **1V:3H** for maintenance and safety reasons, (steeper slopes only in special situations)
- Maximum **depth** should not exceed **2m**.
- Bioretention and/or wetland/micropools at outlets is desirable for **enhanced pollution control**

Bioretention areas are shallow landscaped depressions, typically underdrained and rely on engineered soils and enhanced vegetation and filtration to remove pollution and reduce runoff downstream.

Water Quality Treatment (not covered in this course)



Source: Google Images

SuDS components

Ponds: design criteria

- **permanent pool** volume for water quality treatment
- temporary storage volume for flow attenuation
- sediment forebay or upstream pre-treatment
- **length:width** ratio between 3:1 and 5:1
- **minimum depth** for open water areas of **1.2 m**
- **maximum depth** of permanent pool of **2 m**
- **side slopes** > **1V:3H** for slopes.

Source: Google Images

Today’s session

Outline

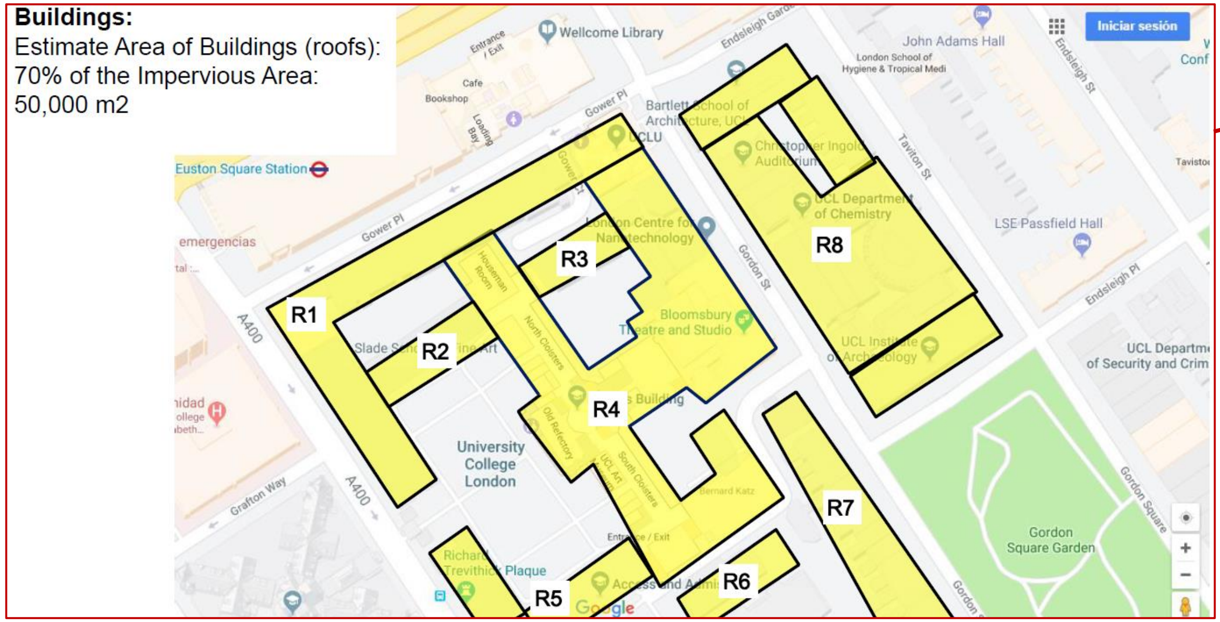
- Conventional drainage
  - Example
- Sustainable urban drainage
  - SuDS components
  - **Example**

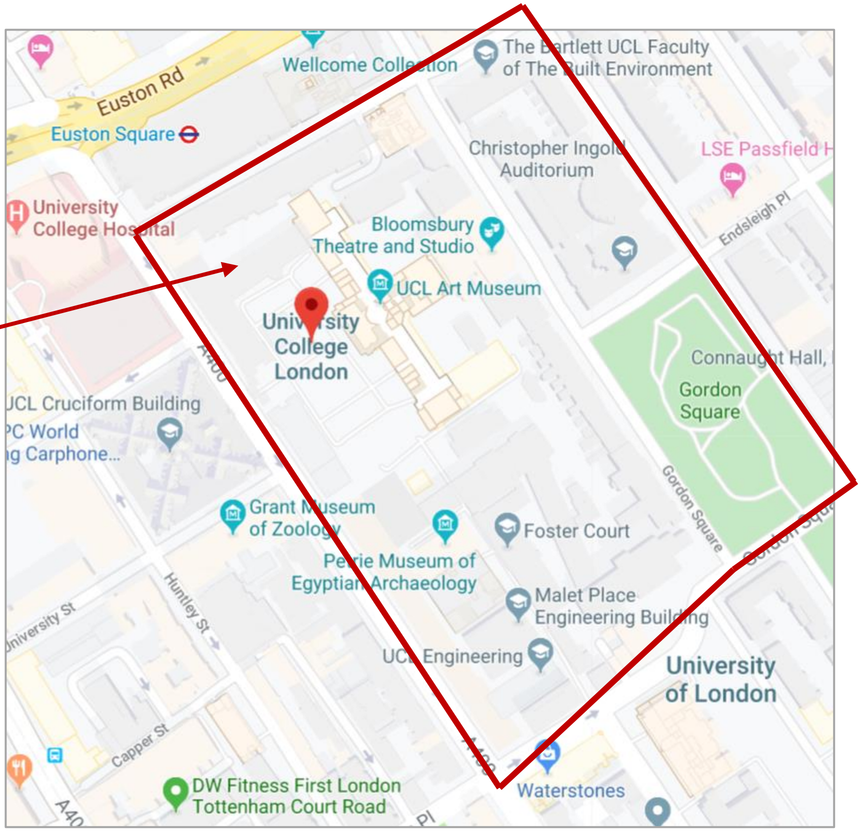
Sustainable Urban Drainage (SuDS)

Example (University College London)

Status quo (developed conditions)

Buildings:
Estimate Area of Buildings (roofs):
70% of the Impervious Area:
50,000 m2

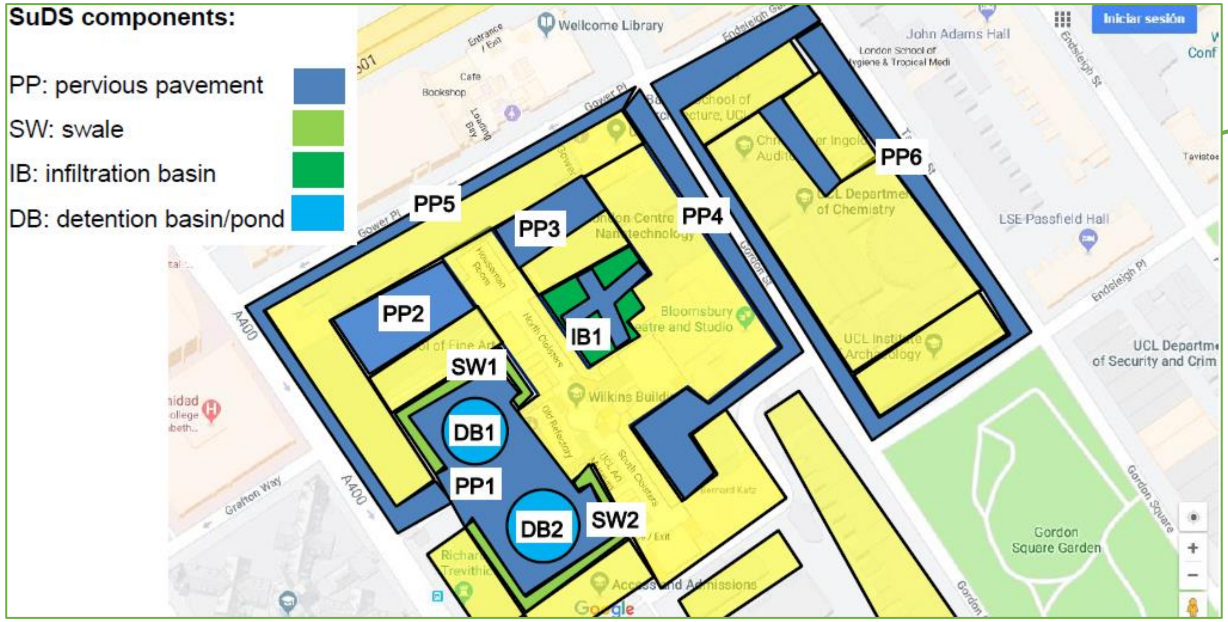


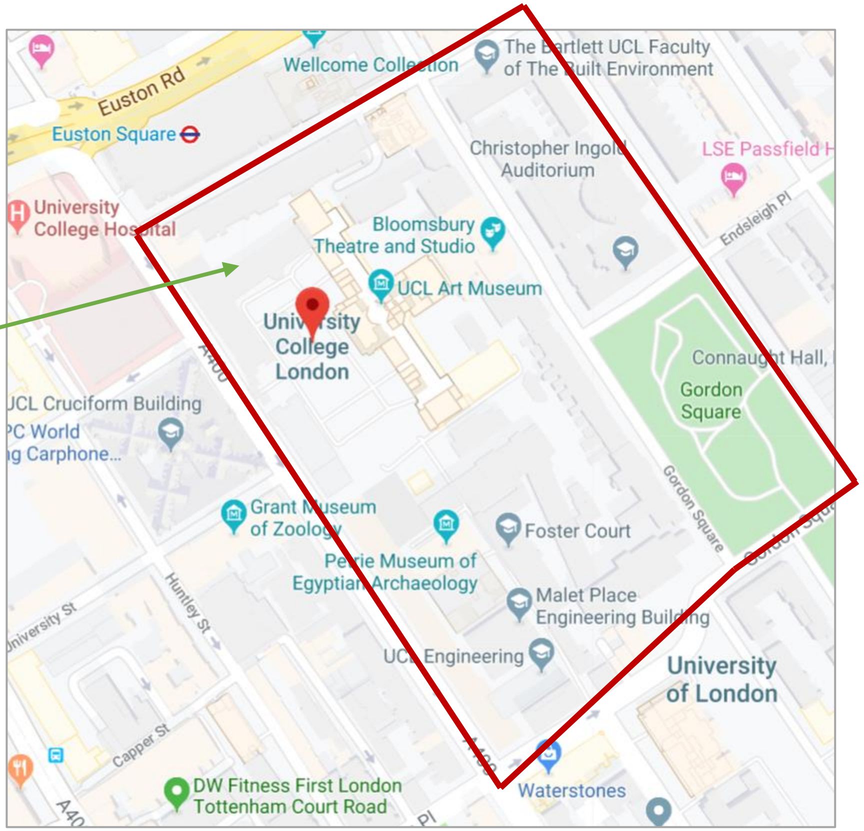


Sustainable Urban Drainage (SuDS)

Example (University College London)

Proposed interventions (SuDS)

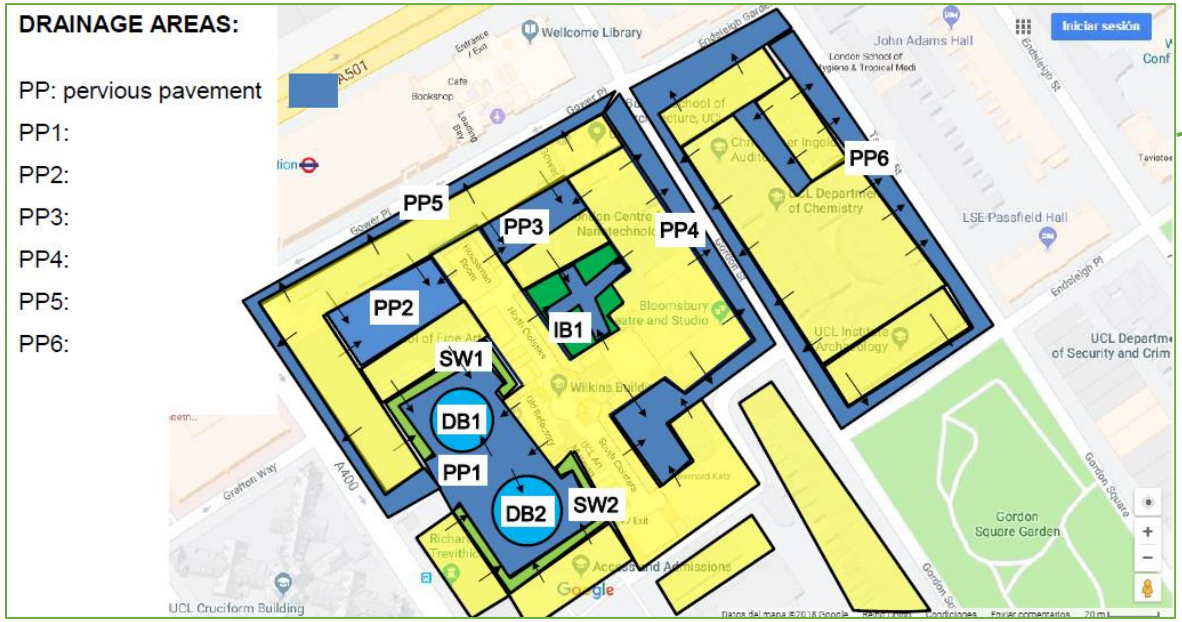


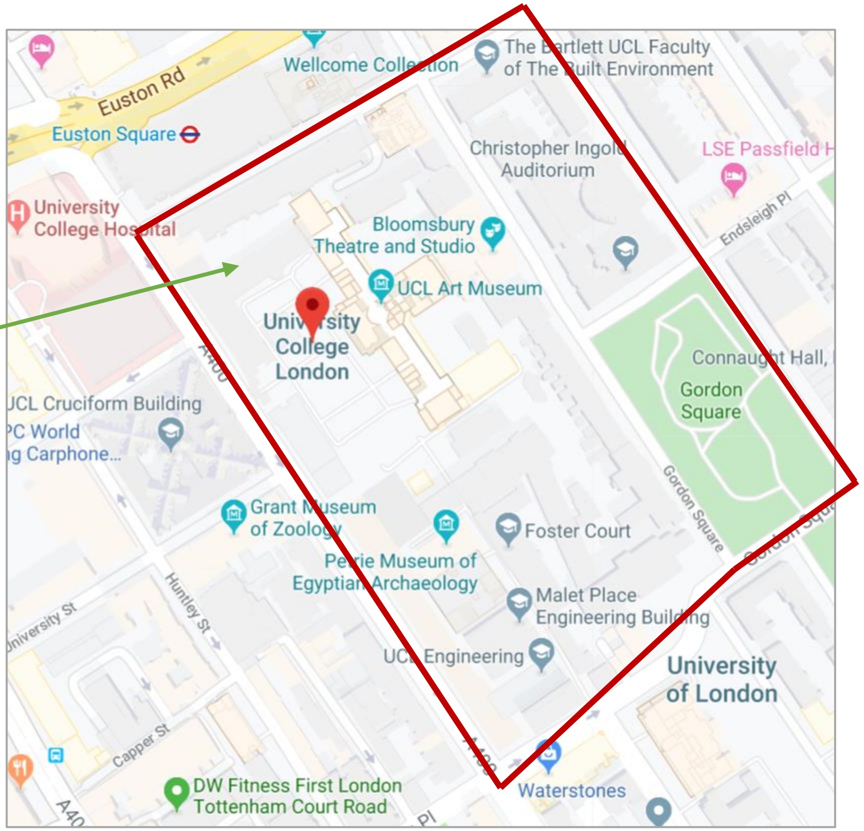


Sustainable Urban Drainage (SuDS)

Example (University College London)

Proposed interventions (SuDS)





See calculations in Moodle

Sustainable Urban Drainage (SuDS)

SuDS Design Process

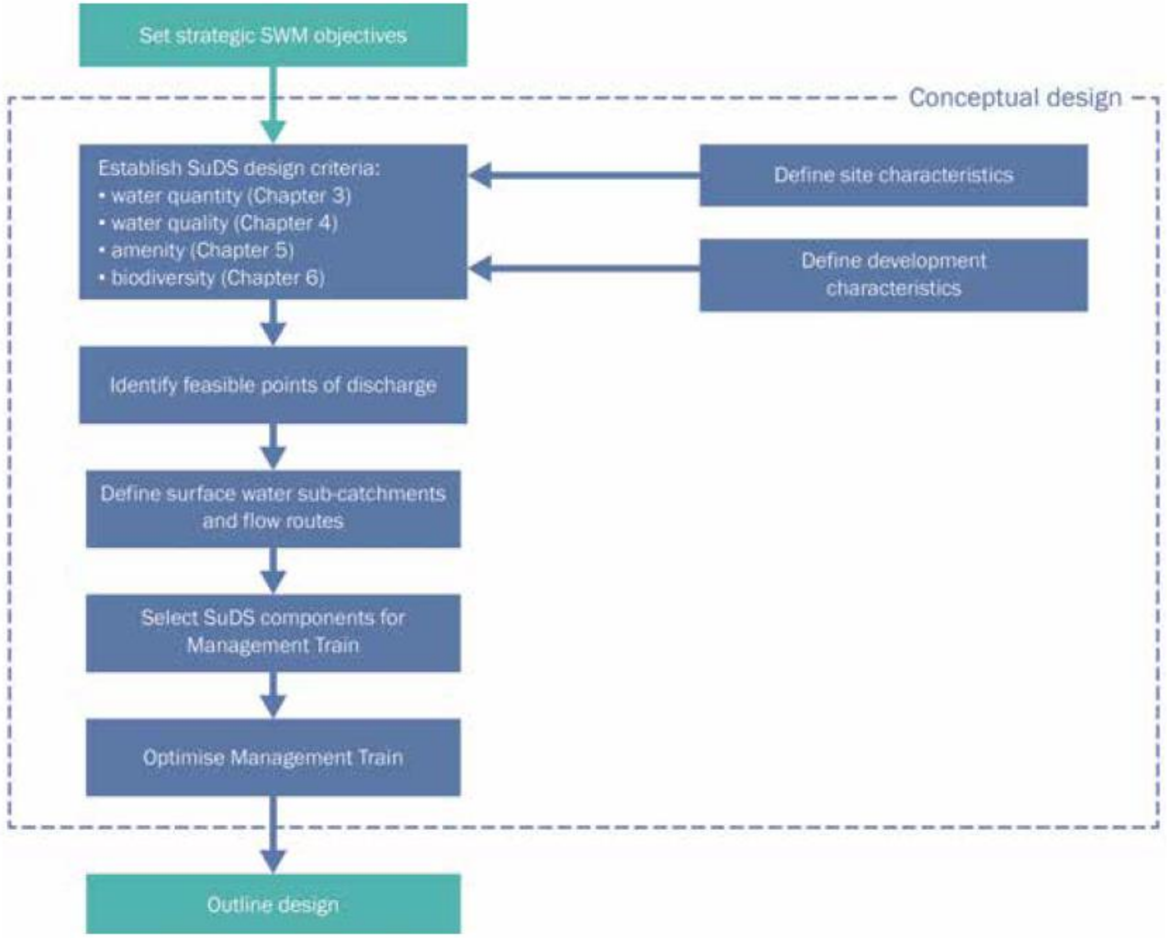


Figure 7.3 The conceptual design process

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Sustainable Urban Drainage (SuDS)

SuDS Design Process

Appendix C

Design example: Rosetree Estate

This design example is based on a hypothetical site, developed to demonstrate:

1. *the design process (Chapter 7)*
2. *the detailed hydraulic and treatment design of individual components (Chapters 11–23).*

It does not cover landscape works, amenity or biodiversity design, construction programming and processes, costs and benefits or operation and maintenance requirements, health and safety, community engagement etc. It does not include appraisal of different design options or the evaluation of alternative SuDS components in delivering the required design criteria. The site layout and features have been developed specifically to allow the incorporation of a range of preselected SuDS components and it does not purport to be a realistic development layout.

The example works through the conceptual design of the scheme to meet the design criteria, as presented in this manual, and sizing of a number of representative SuDS components. It does not cover detailed scheme design or component detailing.

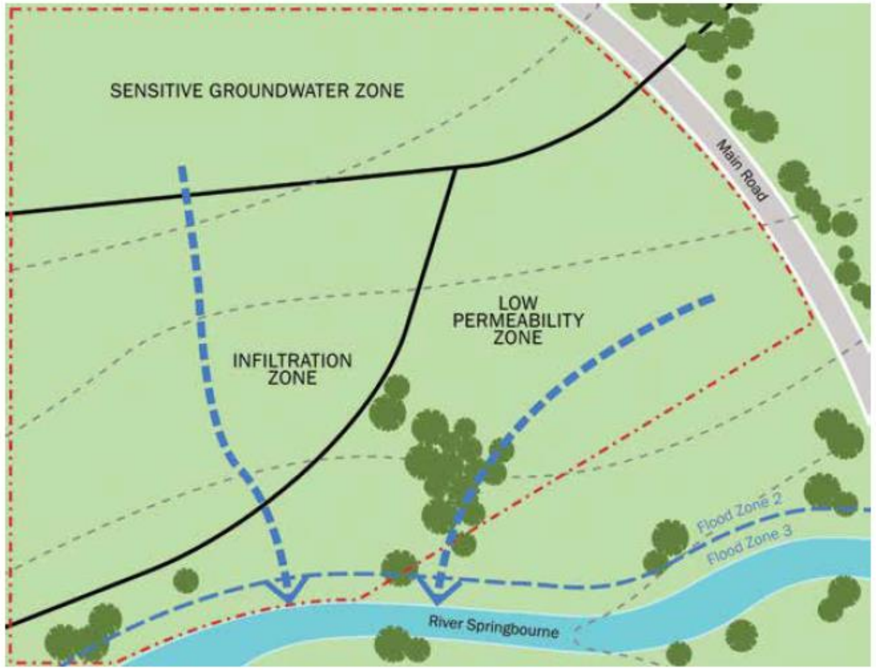


Figure C.1 Site characterisation

CIRIA (2015)

Sustainable Urban Drainage (SuDS)

SuDS Design Process

Identify flow paths

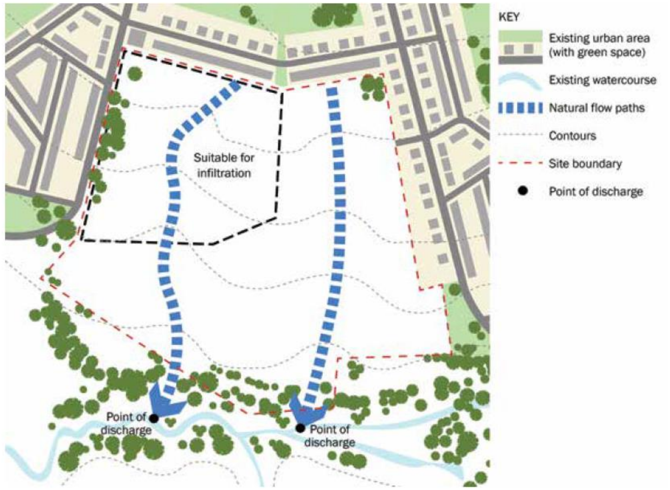


Figure 7.4 Characterising flow routes and discharge points

Define sub-catchments

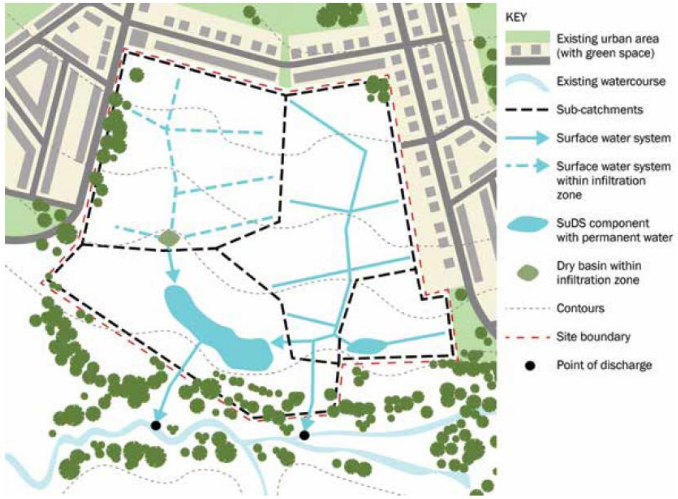


Figure 7.6 Defining surface water sub-catchments

Define green spaces

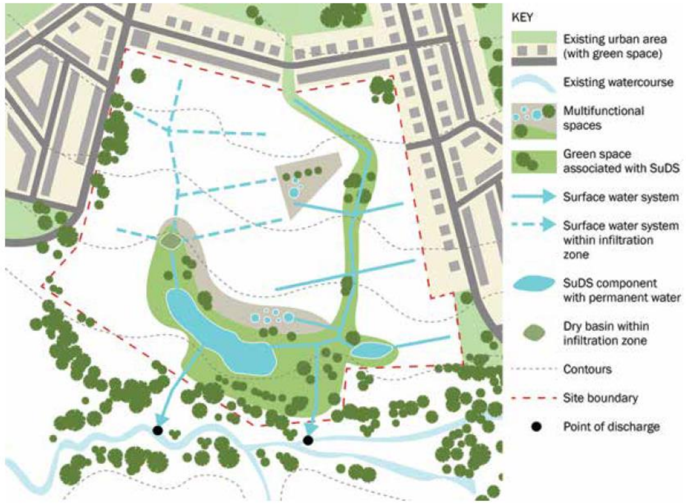


Figure 7.7 Defining parks, open spaces and corridors

CIRIA (2015)

Sustainable Urban Drainage (SuDS)

SuDS Design Process

Define roads

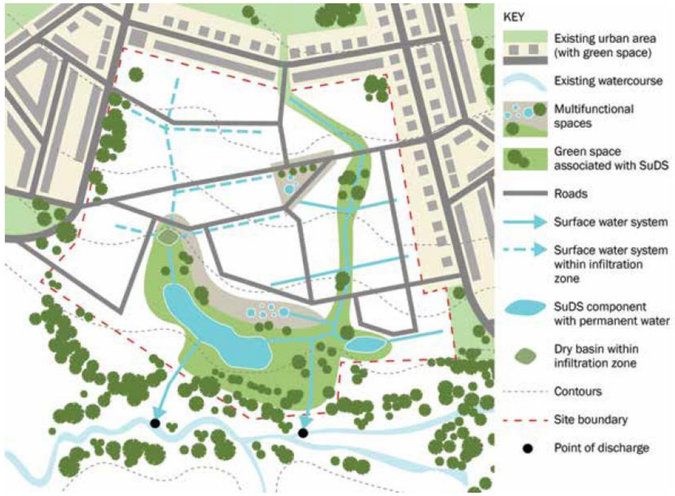


Figure 7.8 Defining the road network

Define exceedance

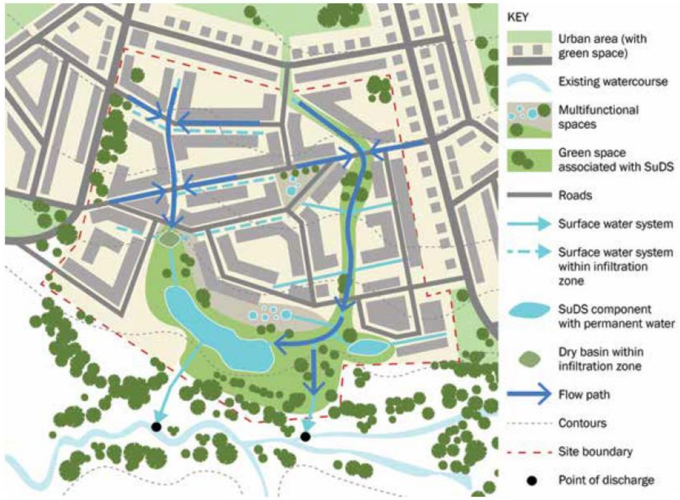


Figure 7.10 Defining exceedance routes

CIRIA (2015)

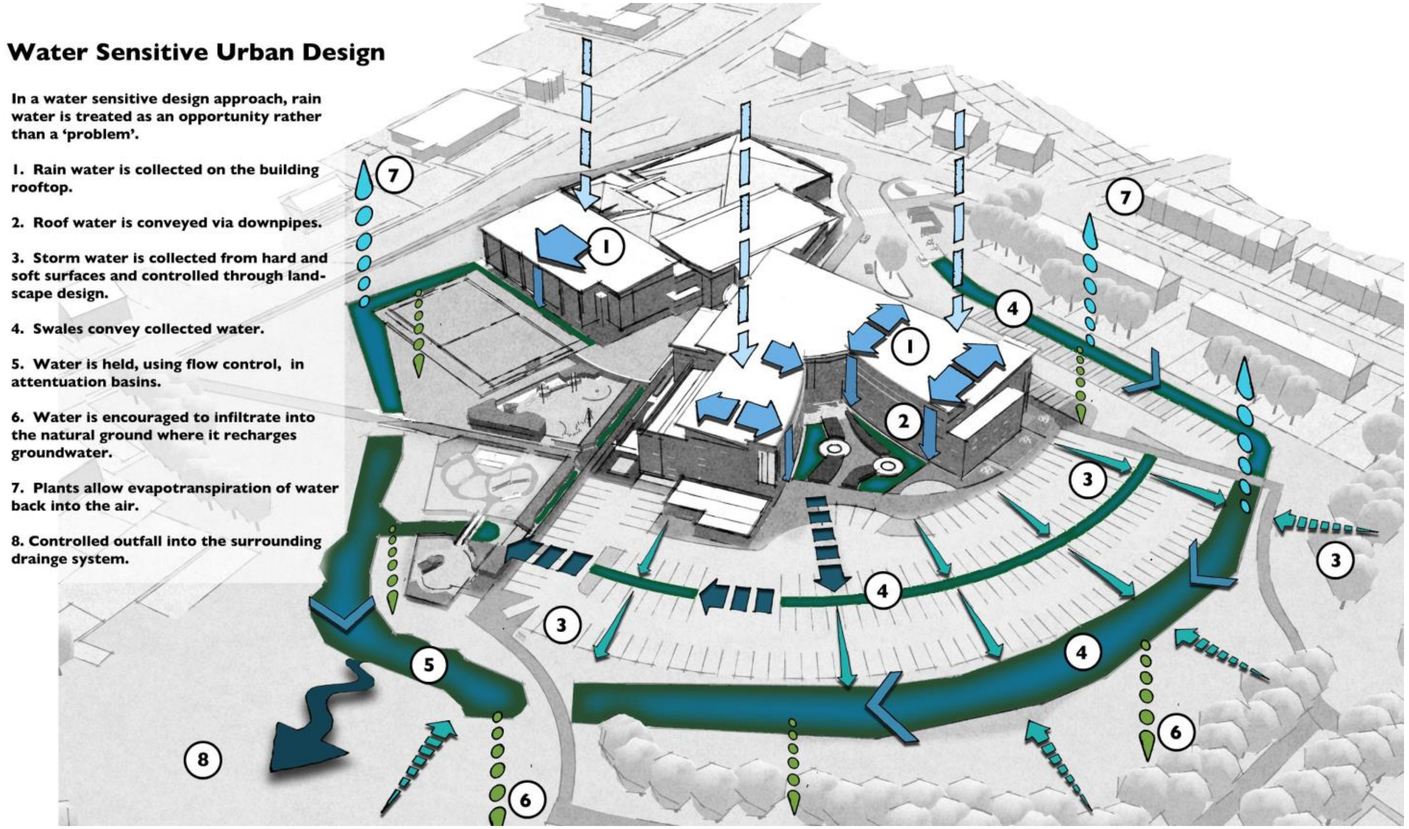
Sustainable Urban Drainage (SuDS)

SuDS Design Process (case studies)

https://www.susdrain.org/case-studies/case_studies/lamb_drove_residential_suds_scheme_cambourne.html

Sustainable Urban Drainage (SuDS)

SuDS Design Process (case studies)



https://www.susdrain.org/case-studies/case_studies/moor_park_blackpool.html

Sustainable Urban Drainage (SuDS)

SuDS Design Process (case studies)

Appendix: SuDS hydraulic design

Prof. Gabriele Manoli
gabriele.manoli@epfl.ch

https://www.architecturaldigest.com/story/architect-new-yorks-central-park-incredibly-unexpected-legacy

Appendix: SuDS Hydraulic design

The following slides provide additional material on the hydraulic design of SuDS components (to complement the CIRIA manual)

Appendix: SuDS Hydraulic design

Basics (I)

8.3.1.1 Definition of design storm events

SUDS are typically dimensioned for a defined 'design storm event'. It is given as precipitation height (h_N in mm) for a defined frequency of occurrence (n) and a precipitation duration (D in min). Based on those values the rainfall intensity ($r_{D;n}$ in [l/(s∗ha)] of a storm event can be calculated as:

$$r_{D,n} = 166.7 * \frac{h_N}{D} \quad [\mathrm{l/(s*ha)}] \qquad (8\text{-}1)$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Basics (II)

8.3.1.2 Definition of the runoff from sealed areas

Within urban catchments, the whole area does not contribute equally to the formation of runoff. Specific losses have to be taken into account, which reduce the runoff. For a defined area A_{total}, discharge Q_{runoff} can be calculated as:

$$Q_{runoff} = r_{D,n} \times \Psi_m \times A_{total} \times 10^{-4} \qquad (8\text{-}2)$$

where:

Q_{runoff}	Runoff (l/s)
A_{total},	Catchment area (m^2)
$r_{D,n}$	Rainfall intensity [l/(s*ha)]
Ψ_m	Runoff coefficient (–)

The runoff coefficient ψ_m for an area A_{total} defines the percentage of precipitation that results in surface runoff and as such depends on the material and the structure of the surface as well as on the gradient. It can be calculated by summation of proportions of the specific surface types and corresponding specific runoff coefficients as.

$$\Psi_m = \sum_{i=1}^{n} \frac{\psi_i \times A_i}{\sum A_i} \qquad (8\text{-}3)$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Green roofs (I)

8.3.1.3.1 Green roofs:

- Hydraulic System (HS)

The main processes for designing a green roof are the inflow through precipitation (Q_r [l/s]), drainage discharge from the drainage layer (Q_{drain} [l/s]) and discharge in case of exceedance flow through an emergency spill (Q_{ex} [l/s]). The hydraulic system of a green roof is depicted in Figure 8-5.

- Hydraulic design for design storm event

In the hydraulic design for design storm event, the height of the soil layer should be determined. It is calculated considering the following processes:

$$Q_r = r_{n,D} \times 10^{-4} \times A_r \qquad \text{(see Equation 8-3)}$$

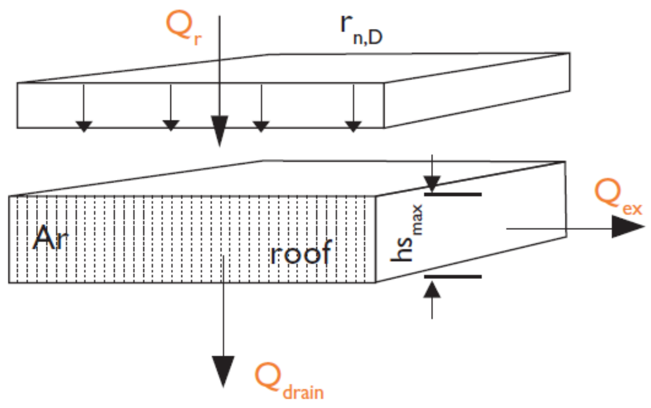


FIGURE 8-5
Hydraulic system

Source: Joachim Tourbier, 1983.

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Green roofs (II)

Q_{drain} can be calculated applying the POLENI Formula:

$$Q_{drain} = \frac{2}{3} \times \mu \times \sqrt{2g \times h_{drain}{}^{3}} \tag{8-4}$$

In practice, this discharge is usually set to a certain value (e.g. 0.5 l/s) beforehand. To prove whether this discharge in the drainage layer can be reached, Darcy's law should be applied.

The volume of the soil layer is determined for the design storm event as:

$$V_s = A_r \times h_s \times n_{pors} \tag{8-5}$$

$$V_s = (Q_p - Q_{drain}) \times 10^{-3} \times D \times 60 \tag{8-6}$$

The height of the soil and substrate layer (*hs*) results in:

$$h_s = D \times 60 \times 10^{-3} \times \frac{r_{n,D} \times A_r \times 10^{-4} - Q_{drain}}{A_r \times n_{pors}} \tag{8-7}$$

where:

V_s	Volume of the soil layer (m^3)
h_s	Height of the soil and substrate layer (m)
$r_{D,n}$	Rainfall intensity [l/(s*ha)]
D	Duration of the design storm (min)
Q_{drain}	Drainage discharge (l/s)
A_r	Storage area of the roof (m^2)
n_{pors}	Porosity of the soil layer (–)

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Green roofs (III)

- Hydraulic design and proof for exceedance

Green roofs, although designed for precipitation events of T = 5-30a, have to be equipped for the case of an extreme event. For that purpose, emergency spills are used and designed for at least 100-year precipitation events.

For calculation of the height of the storage above the soil layer of the roof and under the height of the emergency spill, the following approach is recommended (see Figure 8-5).

$$\Delta h_{sl} = \Delta t \times 60 \times 10^{-3} \times \frac{r_{100,D} \times A_r \times 10^{-4} - Q_{drain} - Q_{ex}}{A_r} \qquad (8\text{-}8)$$

where:

Δh_{sl}	Height above the soil substrate layer (m)
$r_{100,D}$	Rainfall intensity [l/(s*ha)] n = 0.01
Q_{drain}	Drainage discharge (l/s)
Q_{ex}	Discharge through emergency spill (l/s)
A_r	Storage area of the roof (m^2)

The emergency spill discharge is generated when the water level on the roof reaches a specific critical level and ensures that the roof is not 'overfilled', or:

$$\text{If } h_{sl,i} < h_{crit} \text{ (with } n_{pors} < 100\%) \; Q_{ex} = 0$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Green roofs (IV)

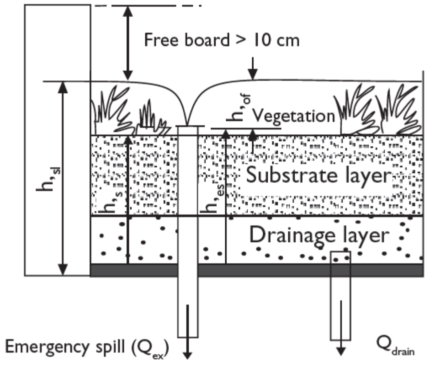


FIGURE 8-6
Cross section of a green roof

Source: Joachim Tourbier.

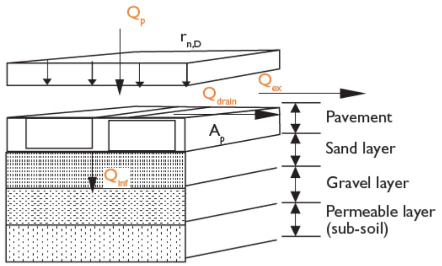


FIGURE 8-7
HS of a pervious pavement

Source: Joachim Tourbier.

$$\text{If } h_{sl,i} > h_{crit} \text{ (with } n_{pors} = 100\%) \text{ then } Q_{ex} = l_u \times \frac{2}{3} \times \sqrt{2g} \times \mu \times \sqrt{h_{of}^{\;3}} \qquad (8\text{-}9)$$

where:

- l_u Perimeter of emergency spill (m)
- g 9.81 m/s^2
- μ Overflow coefficient = ca. 0.7
- h_{of} Overflow height (m)
- $h_{sl,i}$ Actual water level on the green roof (m)
- n_{pors} Porosity of the soil layer on the green roof (–)

The calculation of the critical overflow height is an iterative process as shown in example in Textbox 8-2).

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Pavements (I)

8.3.1.3.2 Pervious pavements

The main processes for design of pervious pavements are direct inflow through precipitation (Q_p [l/s]), runoff from the pervious pavement (Q_{drain} [l/s]) and discharge into ground (infiltration) (Q_{inf} [l/s])

- Hydraulic System (HS)
- Hydraulic design for design event

For the case that the permeable pavement should only improve the infiltration characteristics of the soil, the improved runoff from the area and the infiltration discharge can be calculated as follows:

$$Q_{drain} = \psi'_m \times Q_p \tag{8-10}$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Pavements (II)

where
ψ'_m is the modified runoff coefficient calculated for the unsealing plan (see Equation 8-4).

$$Q_p = r_{n,D} \times 10^{-4} \times A_p \qquad \text{(see Equation 8-3).}$$

and

$$Q_{inf} = Q_p - Q_{drain} \tag{8-11}$$

In case that an additional sealed area drains onto the pervious surface, the area A_p required to receive the runoff from the connected sealed surface can be calculated as:

$$A_p = \frac{A_{red}}{\frac{10^7 \times k_{f,sat} \times (1-\psi_{m'})}{2 \times r_{D;n}} - 1} \tag{8-12}$$

where:

A_p	Area of pervious pavement (m^2)
A_{red}	Drained sealed area (m^2)
$k_{f,sat}$	Permeability coefficient (m/s): if the infiltration area is used as parking place, the kf-value is reduced by the compaction of the soil.
$r_{D;n}$	Rainfall intensity [l/(s*ha)]

- Hydraulic design and proof for exceedance

Pervious pavements are designed for a design storm event, but in the case of an exceedance flow, the Q_{ex}, has to be considered for design of the conveyance systems.

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (I)

8.3.1.3.3 Swales

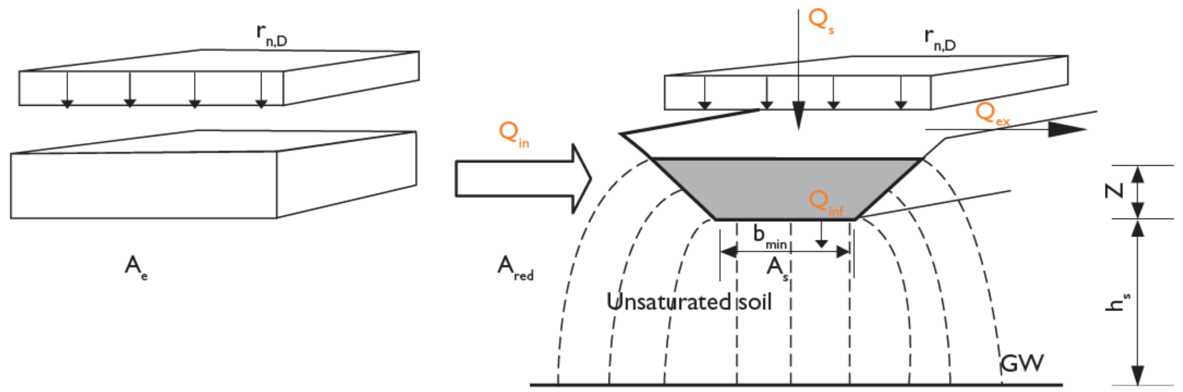
Three main processes are decisive for the design of swales. These are: inflow from the drained area (Q_{in} [l/s]) during a storm event with the duration D from the area A_e; inflow into the swale during a storm event with the duration D from the area A_e (Q_s [l/s]); and infiltration rate from the swale into the soil (Q_{inf} [l/s]).

- Hydraulic system of a swale
- Hydraulic design of a swale for design event

The objective of the hydraulic design for design event is to calculate the area A_s and height (z)

$$Q_{in} = (\Psi_m \times A_e) \times r_{n,D} \times 10^{-4} + Q_{rill} \qquad (8\text{-}13)$$

where can be calculated using Equation 8-4.



Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (II)

Q_{rill} is the discharge coming from rills (e.g. conveying water from the green roofs).

$$Q_s = r_{n,D} \times A_s \times 10^{-4} \tag{8-14}$$

where:

$r_{D;n}$ Rainfall intensity [l/(s*ha)]
A_s Area of the swale (m^2)

The infiltration into the ground is described by Darcy's equation:

$$Q_{inf} = k_f \times I_{hyd} \times A_s \tag{8-15}$$

whereby:

Q_{inf} Infiltration discharge from the swale into soil (m^3/s)
K_f Permeability (Darcy's) coefficient (m/s)
I_{hyd} Hydraulic gradient (m/m)
A_s Infiltration area of the swale (m^2)

The infiltration into ground takes place on both horizontal and inclined sidewalls. The hydraulic gradient is defined as (DWA-A 138):

$$I_{hyd} = \frac{\Delta h}{\Delta l} = \frac{(h_s + z)}{\left(h_s + \frac{z}{2}\right)} \tag{8-16}$$

where:

h_s Distance between the bottom of the swale and the GW level (m)
z Water level within the swale (m)

When the infiltration through the sidewalls can be neglected in comparison to the infiltration through the bottom of the swale, the hydraulic gradient becomes: (DWA-A 138):

$$I_{hyd} = \frac{\Delta h}{\Delta l} = \frac{\left(h_s + \frac{z}{2}\right)}{h_s} \tag{8-17}$$

In swales with a small depth, the hydraulic gradient is almost 1.

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (III)

The infiltration rate within the swales is calculated as:

$$Q_{inf} = v_{f,u} \times A_s = \frac{k_f}{2} \times A_s \qquad (8\text{-}18)$$

where:

- kf Permeability coefficient (m/s) in the saturated soil
- Q_{inf} Infiltration rate of the swale (m^3/s)
- A_s Infiltration area of the swale (m^2)
- $v_{f,u}$ Infiltration (m/s)

with the assumption: that $k_{f,unsat}$ equals $k_f/2$ that of the saturated soil.

The infiltration area A_s, is related to the water level within the swale (DWA-A 138) as:

$$A_{s,average} = \frac{A_{s,\min} + A_{s,\max}}{2} \qquad (8\text{-}19)$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (IV)

or

$$A_{s,average} = \frac{b_{\max} + b_{\min}}{2} \times L_s \qquad (8\text{-}20)$$

The storage volume of the swale is calculated as (DWA-A 138):

$$V_s = (Q_{in} + Q_s - Q_{inf}) \times D \times 60 \times f_z \times f_A \qquad (8\text{-}21)$$

where:

- V_s Required storage volume in swale (m^3)
- Q_{in} Inflow into the swale during a storm event with the duration D from the area A_e (m^3/s)
- Q_s Inflow into swale due to precipitation (m^3/s)
- D Duration of storm event (min)
- f_Z Safety parameter (1.1 to 1.2 according to DWA-A 117)
- f_A Attenuation parameter runoff (≤1.0 according to DWA-A 117)

Determination of the swale volume is an iterative process and depends on the local conditions and available space for swales. In general the water depth in swales (h_s) should not exceed 0.3 m (DWA-A 138).

To achieve this requirement, the swale area (A_s) has to be maximised. Replacing V_s in Equation 3-9 gives the following equation:

$$z = \Delta t \times 60 \times 10^{-3} \times \frac{Q_{in} + Q_s - Q_{inf}}{A_s} \qquad (8\text{-}22)$$

where:

- z Water level in the swale (m)
- Δt Time step (min)
- Q_{in} Flow into the swale (l/s)
- Q_s Inflow into swale due to precipitation (l/s)
- Q_{inf} Infiltration rate from the swale (l/s)
- A_s Area of the swale (m^2)

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (V)

8.3.1.3.4 Swales with filter drains

In case that the soil permeability is not sufficient for the required infiltration rates, it can be improved by applying a filter layer below the swale and a perforated drainage pipe.

- Hydraulic system

The system is composed of two main elements: swales and filter drains. The design principle of those systems is as depicted in Figure 8-9.

- Hydraulic design

Swales can be designed as shown in the section above.

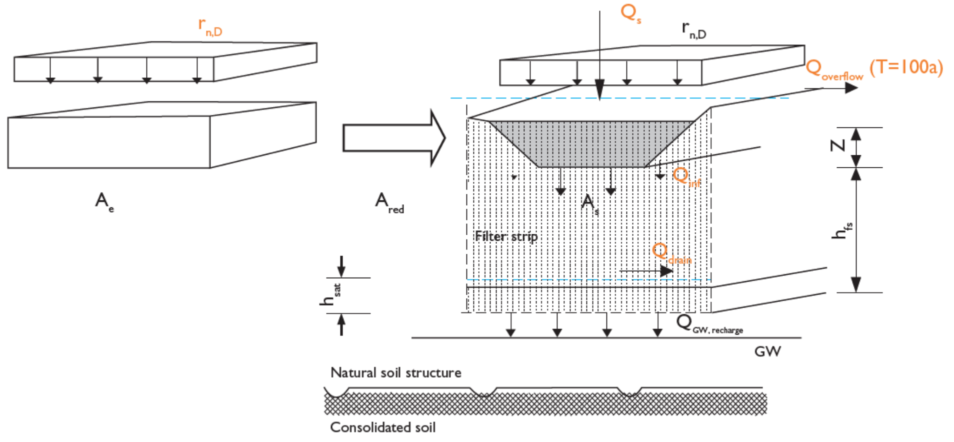
Filter drain:
The volume of the filter drain can be calculated as:

$$V_f = A_f \times h_f \times n_{pors} \tag{8-23}$$

Source: Zevengergen et al. (2010)

Appendix: SuDS Hydraulic design

Swales (VI)



assuming that $A_f = A_s$.
Further, the volume of the filter drain can be defined as:

$$V_f = (Q_{\inf} - Q_{GW,recharge} - Q_{drain}) \times D \times 60 \qquad (8\text{-}24)$$

where:

Q_{inf}	Infiltration rate from the swale (m^3/s)
$Q_{GW,recharge}$	Recharge from the filter drain into the ground water aquifer (m^3/s)
Q_{drain}	Discharge through the drainage pipe (m^3/s)
A_s	Area of the swale (m^2)
D	Duration of storm event (min)

Recharge from the filter drain into the groundwater aquifer can be calculated as:

$$Q_{GW,recharge} = k_{f,saturated} \times I_{hy} \times A_f \qquad (8\text{-}25)$$

with the following assumptions:

$$I_{hy} = 1 \quad \text{and} \quad A_f = A_s$$

Discharge through the drainage pipe can be calculated according to POLENI as:

$$Q_{drain} = \frac{2}{3} \times \mu \times \sqrt{2 \times g} \times h^{2/3}{}_{drain} \qquad (8\text{-}26)$$

Source: Zevengergen et al. (2010)