CIV3285 – Engineering Hydrology (Part 1 - Physical Hydrology)

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1. Introduction to Hydrology

1.1 Motivation for Hydrology

- Water is our most important resource, we must: manage its use & quality also control its power
- Hydrology is defined as the study of the movement, distribution, and quality of water on Earth, including the hydrologic cycle, water resources and environmental watershed sustainability
  "is the science that treats the waters of the earth, their occurrence, circulation and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things. The domain of hydrology embraces the full life history of water on the earth"
- Planet Earth Components:
  Lithosphere: (Solid) = Geology
  Hydrosphere: (Water) = Hydrology
  Atmosphere: (Air) = Meteorology

- We need to **manage water use:**
  - We extract water from lakes, rivers, aquifers, and oceans ∴ need to manage how we do this to ensure a certain level of water supply reliability, while still ensuring ecosystem is protected
  - We are called upon to understand water and constituent inflows into and out of these systems

- We need to **control water power:**
  - We need to live with water, so we must control its power and protect us from floods and droughts

- We need to **manage water quality**
  - We control the source of pollution to receiving water bodies, to make them fit for human use & protect our environment i.e water needs a certain quality free of pollution

- Problems of interest
  Environmental flows, Drainage, Water supply, Floods/Droughts, Climate variability

1.2 Water in AUS and the world

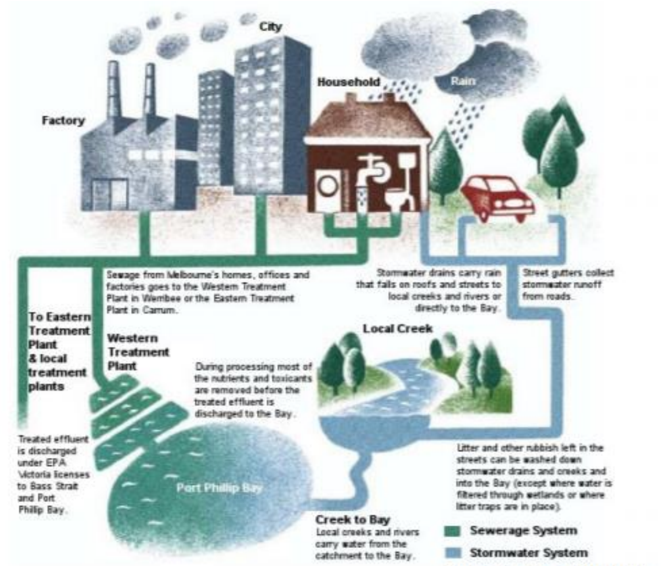
- Many regions (urban & rural) in Australia are facing water shortage problems
- Water quality & pollution control is another serious problem
  i.e less water with same amount of pollutants ∴ ↓ water quality
- AUS is a major consumers of freshwater in the developed world per capita (in particular because of mining & agriculture)
  Note: over 90% of water in VIC comes from our 13 reservoirs, is kept natural i.e is clean, fenced off & protected to enable natural runoff & is slightly treated
- Urban consumption (public supply) ~15% as opposed to Rural consumption ~50% (irrigation)

1.3 Urban Water Management

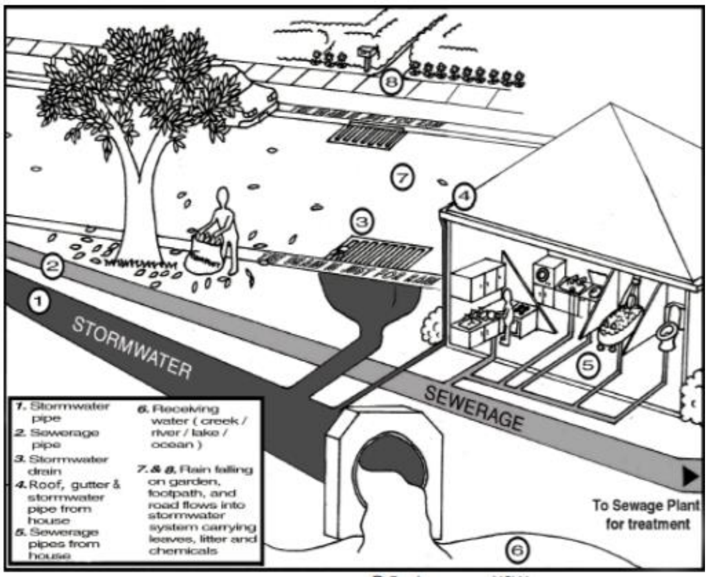
The three components of urban water mgmt.:

- Stormwater systems i.e to prevent flooding need good stormwater system
- Wastewater systems i.e want good wastewater system to clear toilets etc.
- Water supply systems

These systems are interconnected: *Water for supply is taken from the same rivers, lakes or groundwater aquifers which receives wastewater & stormwater runoff*



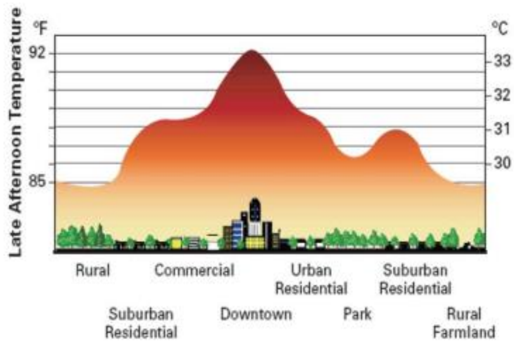
Source: Melbourne Water



- **Design of Drainage Systems**
  Gutters, pits, drains etc. convey water downstream
  i.e must manage water supply/use & its infrastructure

- **Storm water Systems**
  Problem occur when conveying system moves water too quickly ∴ less water for vegetation etc. to use around system (Use of artificial retarding basins to retain water helps improve this issue)
  In time aqueducts served as effective storm water systems
  (0.2% standard slope of aqueducts)

- Water has a heat capacity, it absorbs ambient heat to ↓ temp
  - Vegetation is now planted and infiltrated to break up urban environments and help ↓ ambient temp



- **Our Biggest Problem**
  - ↑ of CO_2 & temp (Global warming) having adverse effects on climate & hydrology
  - As temp ↑ air can take up more water ∴ rain events become more extreme as there is more water to precipitate hence our urban environments must convey more water

3. Precipitation/Rainfall

3.1 Precipitation & its different forms

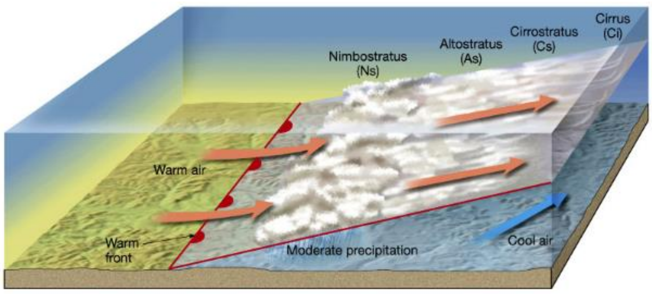
- Frozen = Snow (ice crystals), hail (balls of ice) & sleet (grains of ice/slush)
- Liquid:
  – Drizzle, mist: <1 mm/hr
  – Light rain: <2.5 mm/hr
  – Moderate rain: 2.5-7.6 mm/hr
  – Heavy rain: >7.6 mm/hr

3.2 Precipitation Formation

- Evaporation over ocean surfaces is the main source for precipitation
- Formation is also through:
  Cooling of air by lifting
  Saturation of the air
  Condensation in the presence of nuclei
  Growth of water droplets by collision & coalescence
  Precipitation after reaching critical mass

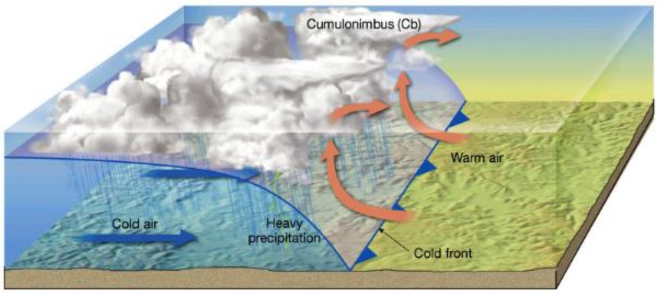
Cloud Formation

- **Warm Fronts**



- Warm front air driven to cold, warm air is lighter so goes up at gradual slope, starts to condensate (as lots of water in warm air) then starts cooling causing cloud formation and starts raining
- Typical of long rainfall events

- **Cold Fronts**



- Suddenly whole belt of cold air hitting warm, cold air is wedged under hot air, lifts it quickly causing sudden stormy events (as the air condensates & is cooled quickly)
- Typical of heavy rainfall events

3.3 Importance of Precipitation

- Water Resources Planning and Management
  - Human consumption, food production and ecosystem consumption
  - Energy production
  - Human and ecosystem (in particular water systems) health
- Engineering Designs
  – Dam design and management
  – Drainage networks, bridges, other infrastructure (includes structural design of foundation, groundwater, drainage, load)
- Floods: High water levels caused by excessive rainfall/storm surge/dam-break etc. that overtop natural or artificial banks of a stream creek, river estuary, lake or dam
- Fires: Vegetation is less flammable when wet, however, more biomass is produced w/ sufficient water

4.4 Calculation of ET (FAO 56 and Pan Factors)

- We have 3 main methods = **FAO 56**, **Pan Factors** & **Morton's method**
- ET is tricky as many contributors play a role & are interlinked
- Measurements can be undertaken (But question of representativeness remain due to uncertainties)
  Models are ∴ used (But are simplifications of real physical processes)

Evapotranspiration

- FAO56
  - Widely available
  - Reference crop, ET_o
  - need a crop coefficient
  - Good (the best) for estimating water requirements for individual crops
- Pan
  - Widely available
  - Need a crop factor
  - 'Ok' for irrigation scheduling (but not as good as FAO56)
  - 'Last resort' for hydrologic modelling and water balance studies but has been widely used for them
- Morton
  - Widely available
  - Can be used to estimate other ETs, e.g. Pan (PPET in dry areas or APET in wet areas)
  - Long term
  - Not so good for short term plant water requirements
  - Good for water balance studies on whole catchments
  - Good for hydrologic modelling

FAO56

- A standard, internationally recognized method to calc. ET from crops
- FAO56 can be used on time scales for about a day or less
- Calculate ET from a reference crop (ET_o), then multiply ET_o to a crop coefficient to get actual ET

1) **Use Penman Eqn.:**

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{(T_m + 273)} U_2 (e_s - e_d)}{\Delta + \gamma(1 + 0.34 U_2)}$$

ET_o = reference evapotranspiration for grass lands [mm/day]
R_n = net radiation at the crop surface [MJ/m²*day]
G = soil heat flux density [MJ/m²*day]
T_m = mean daily air temperature at 2 m height [°C]
U_2 = wind speed at height of 2m [m/s]
e_s = saturation vapour pressure [kPa]
e_d = actual vapour pressure [kPa]
    $e_s - e_d$ = saturation vapour pressure deficit [kPa]
Δ = slope vapour pressure curve [kPa/°C]
g = psychrometric constant [kPa/°C].

Morton's Method (Can ignore this method in CIV3285)

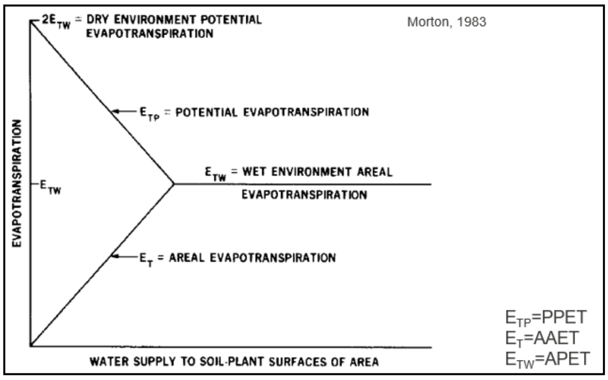
- Morton models ET for large areas over long time periods
  (Do not need to consider specific information on land use and vegetation)
  (Useful for water balance studies or when modelling hydrology of whole catchments)
  (Pan estimates are poor for this application)

- Morton gives 3 types of data:

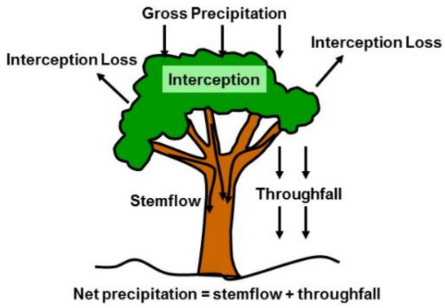
Point Potential – PPET
- ET from a small well-watered area
- Depends on Energy available & Capacity of the air

Aerial Potential – APET
- ET from a large well watered area (>1km²)
- APET < PPET because capacity of the air is reduced

Aerial Actual – AAET
- Actual ET that takes place with existing water supply



5.3 Interception



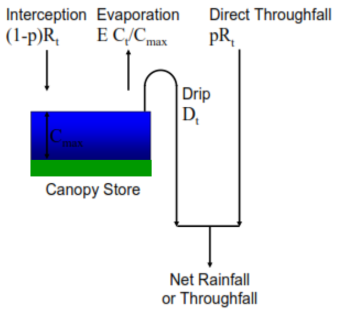
- Interception effects the water available for Surface Runoff:
  - Interception stores = branches/leaves or on floor material
  - Through-fall = Water intercepted falls off leaves
  - Stem-flow = Important for vegetation but small effect on runoff
- Interception effects are generally only seen at the start of events
  - i.e Interception stores are then filled ∴ now what comes in goes out
- Interception is not really evident in large rainfall events (including floods)
  - However, interception can be large over an entire year

- Different vegetation has different capacities to absorbs water:

Common name	Interception store [mm]
Manna gum	0.2
Snow gum	0.8
Radiata pine	1

Common name - floor	Interception store [mm]
Spotted gum	0.35
Red cedar	3.4
Red tulip oak	6.8

- <u>Rutter Model</u>



R_t = gross rainfall rate at time t
p = proportion of R_t that passes thorough canopy w/out touching it
C_t = depth of water stored on leaf surfaces at time t
C_{max} = maximum depth of water stored on leaf surfaces
D_t = canopy drip rate
E = evaporation rate from saturated canopy

5.4 Depression Storage

- **Depression storage** = Volume of water that is held in puddles or small depressions at the surface
  - (Depressions are lower than surrounded area ∴ collects water)
- During rainfall, depressions fill/overflow & contribute to surface runoff
- Emptied via evaporation & seepage into the soil system
- In urban areas, our impervious surfaces also have depression storages
  - i.e Roadway (asphalt) 1.8 mm, Concrete 0.6 mm, Metal roof 0.2 mm

5.5 Runoff Mechanisms & Infiltration (infiltration excess & saturation excess)

- Infiltration is the movement of water into/through soils
- The infiltration rate depends on:
  1) Soil characteristics (i.e. size of particles, level of compactness, level of saturation); these determine the maximum rate of infiltration **(infiltration capacity)**
  2) Rate at which water is supplied to the system

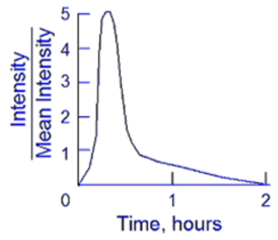
Infiltration & Surface Runoff		
○ If rainfall rate < infiltration capacity All rainfall infiltrates into soil Rate of infiltration = rate of rainfall Rate of surface runoff = 0	○ If rainfall rate > infiltration capacity Soil can't cope w/ rainfall intensity, so some water will begin to pond on the surface & then become runoff Rate of infiltration = infiltration capacity Rate of surface runoff = effective rainfall rate – infiltration rate Runoff produced from this is called ***infiltration excess (Hortonian)***	○ If soil is saturated (i.e. its pores are filled with water) All rainfall (independent of rate) will contribute to surface runoff Rate of infiltration = 0 Rate of surface runoff = effective rainfall rate Runoff produced from this is called ***saturation excess (Dunne)***

7.5 Temporal & Areal Pattern of Rainfall (Hydrograph)

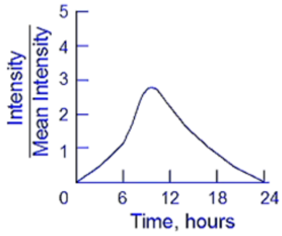
- Temporal patterns & Areal patterns of rainfall both affect our hydrograph

▪ <u>Temporal Pattern of Storm Rainfall</u>
  - Two theoretical types of storms:
    1) Thunderstorms (Cold front)
    2) Frontal Storms (Warm front)

  - **This matters** bcas it could be the difference between catchments flooding or our streets getting wet

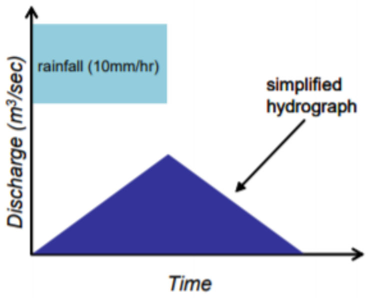


Thunderstorms



Frontal Storms

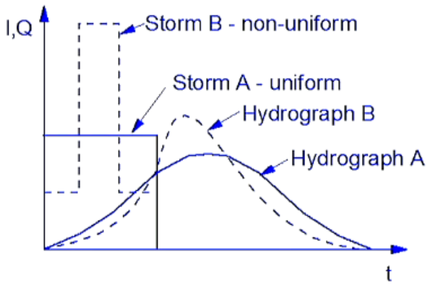
➢ **Rainfall to Runoff: The Hydrograph**
  - Consider: Rain falls for 10 minutes at a constant rate, greater than the infiltration capacity of soil, what will the resulting hydrograph look like?



If exceed infiltration capacity of soil; the extra rainfall becomes runoff (rainfall excess)

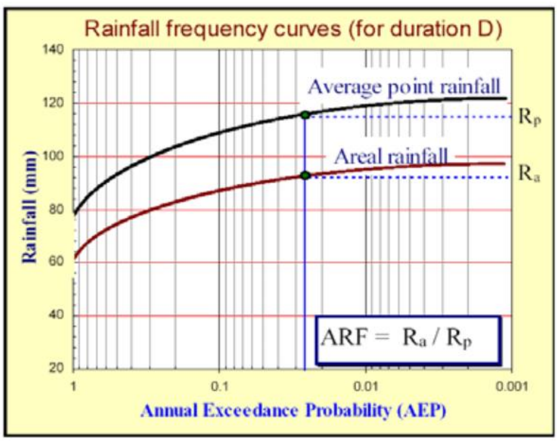
As time ↑ more of the rain in the catchment area can reach the outlet ∴ the recession lin shows that water takes time to move through the catchment to outlet

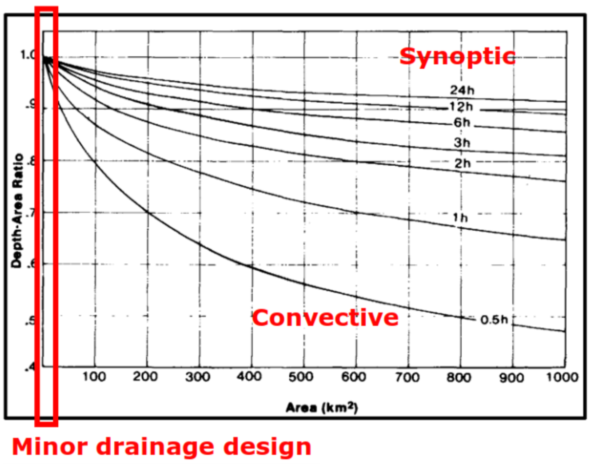
- Hydrograph is flow over time
- The more non-uniform the rainfall, the higher the peak discharge*



- If storm isn't uniform in time, this affects the runoff:
  In B the intensity at start is less so the rising lin is less bcas the rainfall contributing earlier is less intense
  The peak rainfall comes earlier so the hydrograph peaks earlier & ∴ floods earlier

▪ <u>Areal Pattern of Rainfall Storm</u>
  - Need to check representativeness of rain gauge (due to variations in rainfall away from the rain gauge)
  - Rainfall IFD curves (from AR&R or AusIFD) are applicable to a point (suitable for up to 4km^2)
  - Over larger catchments average over the area will be lower (**apply Areal Reduction Factor**, ARF):
    Note: The ARF is ignored for most minor drainage (small urban catchments)





- Determining T_c (to find Intensity)
  - A range of techniques are available
  - Need to choose appropriate technique for given circumstances
  - Think about the physical process!
  - In general, we have two categories of methods for the two types of catchments:
    1) Rural Catchments
    2) Urban Catchments

Rural catchments

- There are three formulas provided in AR&R (Book 4):

(1) Rural Flow Formula:

Note: Doesn't reflect conditions of catchment i.e no slope or flow length in calculation

$$T_c = 0.76A^{0.38}$$

A = Catchment Area (km²)
Tc in [hour]

(2) Bransby Williams formula (BW):

$$T_c = 58L/(A^{0.1}S_e^{0.2})$$

L = stream length [km]
A = catchment area [km²]
Se = average stream slope [m/km]
Tc in [min]

> Comparing the 3 methods:
> - KWE is considered best for design as It considers flow length, roughness & slope ∴ has ↑ accuracy
> - BW considers area & slope
> - Rural is quick estimate just using Area

(3) Kinematic wave equation (KWE):

Note: Tc depends on I & I depends on Tc ∴ iterate guesses using IFD curve

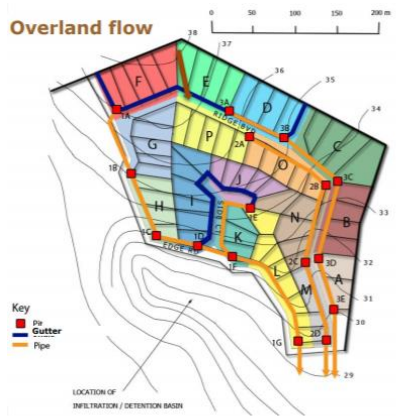
$$Tc = \frac{6.94(L.n^*)^{0.6}}{I^{0.4}S^{0.3}}$$

Tc = Tc for overland flow time [min]
L = Longest flow length [m]
n* = Surface roughness coefficient
I = Rainfall intensity [mm/hr]
S = slope [m/m]

Overland flow surface type	Roughness coefficient n*
Concrete, asphalt	0.010-0.013
Bare sand	0.010-0.016
Gravel	0.012-0.030
Bare clay-loam soil (eroded)	0.012-0.033
Sparse vegetation	0.053-0.130
Short grassland	0.100-0.200
Lawn	0.170-0.480

Urban catchments

- Important to remember: In an urban environment, flow consists (generally) of three components = Surface + Gutter/Swale + Pipe



(1) "Full" method:

Here Tc = (overland + gutter + pipe flow times) for the furthest point (in travel time) from catchment outlet

$$\therefore T_c = \frac{x}{V}$$

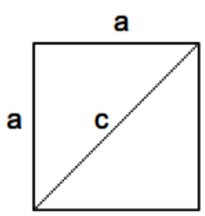
x = Travel distance
V = Velocity (Using Manning's Equation below)

$$V = (R^{2/3}S^{1/2})/n$$

V = velocity [m/s]
R = hydraulic radius (area/wetted perimeter) [m]
S = slope (rise/run)
n = roughness coefficient

(2) "Simple" (& conservative) method:

Assume catchment is square
∴ longest path = sqrt(A) (A = Catchment Area)



Square catchment
Longest flow path = c
$c = \sqrt{2a^2}$ hence:
$c = 1.41a$ or $\sqrt{(2A)}$
T_c (seconds) = c/v
Assume: v = 1m/s
Hence
$T_c = \frac{\sqrt{(2A)}}{60}$ (in minutes)

CIV3285 – Engineering Hydrology (Part 2 - Urban Hydrology & Water Quality)

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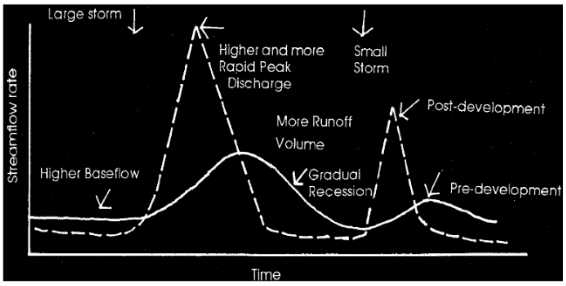
2. Effects of Urbanisation

- Effects & Impacts of Urbanisation

1) Hydrology changes due to ↑ Imperviousness

> ↑ imperviousness causes a translation of peak & change of magnitude (bigger/flashier floods)
bcas impervious surfaces provide less resistance to flow
i.e surface roughness from plants, vegetation etc. slows down the progression of floods

> W/ ↑ imperviousness, certain sized events become more frequent (ARI ↓)



> Main driver of surface hydrology in urban environment are impervious surfaces
Urban environment area is sealed (w/ upto 70% of impervious surfaces are transport infrastructure)
Natural environments have no sealed surfaces to restrict water falling on soil
In metro Melb., large concentration of sealed surfaces surrounds CBD, this impacts streams/creeks in the area

2) Stormwater quality

> Urbanisation ↑ pollutant generation
bcas of ↑ ability of surface to wash pollutant into system

> Urbanisation ↑ delivery efficiency
Strong events can cause erosion (river banks, structures etc.)

> ↑ Nutrient Load
Allows algae to strive and take over water system. Algae prevents light & oxygen mixing into water system
This can lead to fish/organisms dying affecting the food chain

3) Ecosystem Health

> Drainage connections connect parts of the catchment that weren't previously communicating
This ↑ connectivity of catchments

4) Impact on Receiving Waters

> Implications for receiving waters
↑ flow velocity & volume (Habitats scour and erode ∴ ↓ habitat diversity, i.e Scour removes good soil from system, plants have nowhere to grow, fish habitats ↓ & river system dies)
Sediment mobilisation & deposition (Sediment can smother habitat ↓ habitat diversity)
Mobilises pollutants & urban system transports them downstream

> Direct Habitat Modification
Streams channelized to ↑ hydraulic efficiency
This ↑ pollutant transport, scour land & ↓ habitat diversity

> **Note:** Legislative requirement to protect receiving water systems & Environmental performance of waterway/drainage is increasingly assessed on ecosystem health outcomes (not just flow or water quality)
Push for water sensitive urban design

3.2.2 Determine Design Discharge (Q) at Pit Inlet (& TAM overview)

- Apply the **Rational Method** (also see section 9.2 of Physical Hydrology):

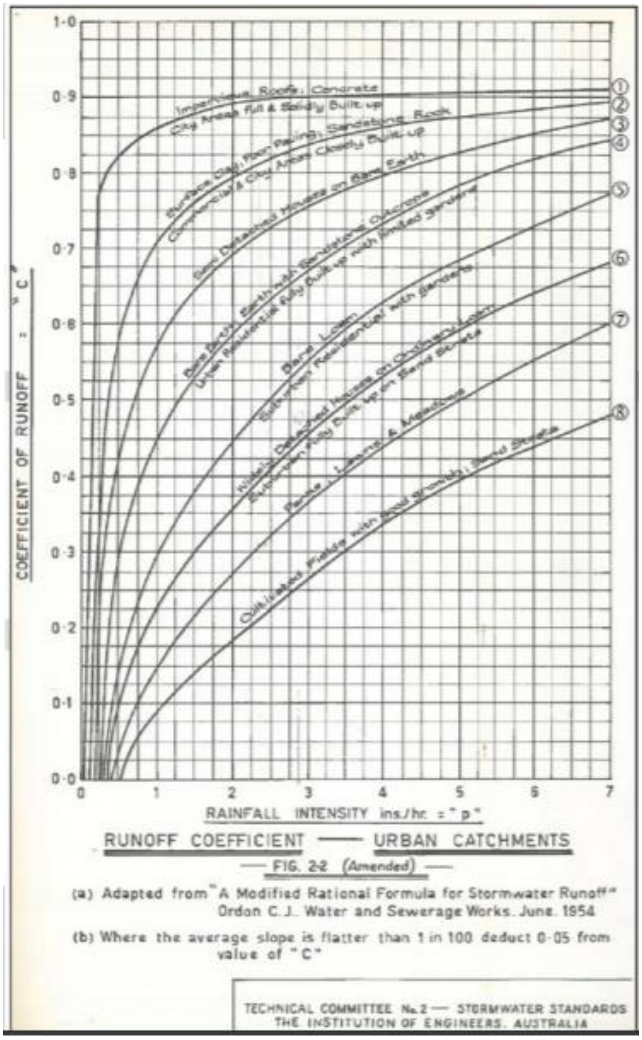
$$Q_p = f\,CIA$$

Q_p = Peak flow [m^3/sec] = peak flow rate 1 in Y years (AEP)
C = Cy = Runoff coefficient for Y year AEP (Relate Y year AEP Rainfall Intensity to the Y year AEP flood) (see below)
    $Cy = C_{10}*F_Y$
I = Iy = Rainfall intensity for Y year AEP [mm/hr]
    Based on duration t_c then find intensity from IFD curve (see section 9.3)
    Note: ARI != AEP (i.e 20 year AEP = ARI of 5 year)
A = Contributing Area [ha]
f = Unit conversion = (1/360 = 0.00278) to get m^3/sec from ha and mm/hr

- **To find Q_p** (3 steps):

  - **Step 1 = Contributing Areas**
    > Contributing Areas (A) are all areas contributing overland flow to the pit
    > Use geometry to solve for A **(Pits drain their own sub catchment)**

  - **Step 2 = Find Runoff Coefficient (C)**
    > Use graph or equation to solve for C
    > Runoff Coefficient defines a fraction of precipitation that is converted to runoff
      (the more impervious an area, the higher C)
    > In general, Runoff Coefficient (C) = $\frac{runoff}{rainfall} = \frac{Rainfall{-}Excess\ or\ Runoff\ (R)}{Rainfall\ Intensity\ (I)}$



- Plot to find runoff coefficient for different types of surfaces as a fnc of rainfall intensity

- Assumes 10% is lost (interception storage, retention basins etc.) i.e we will always have some losses

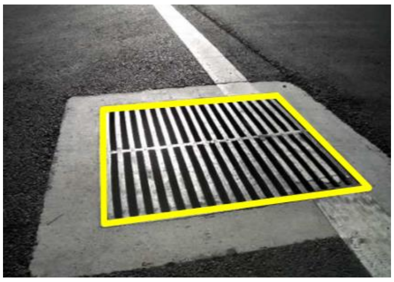
3.2.3 Select Pit Type & Size

- <u>Selecting the pit type and size</u>
  - Capacity should match the design discharge of sub-area
  - Try to avoid bypass flows (not always possible)
  - Remember that pit capacity will ↓ as gutter slope ↑

- <u>Methods for sizing pit inlet include:</u>
  1) Formulae
  2) Lookup graph
  3) Catalogue

1) Formulae

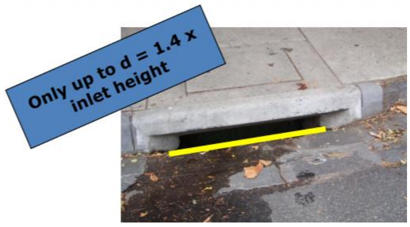
- Grated pit



$$Q_{in} = 1.66Pd^{1.5}$$

Qin = Inflow (m3/sec)
d = Average ponding depth [m]
P = Perimeter of grate [m]
(excludes kerb-side)

- Side-entry pit

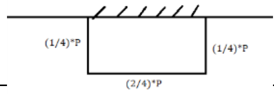


$$Q_{in} = 1.66Ld^{1.5}$$

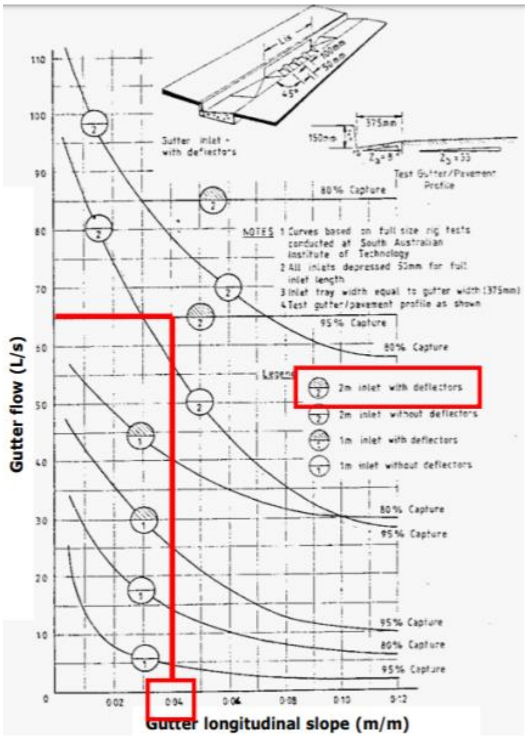
Qin = Inflow (m3/sec)
d = Average ponding depth [m]
d_{max} = 1.4*inlet height
L = Inlet length [m]
(excludes kerb-side)

- Combination pit

- Use combination of formula for grated and side-entry pits
- For kerb-side pits use grated pit formula & exclude kerb-side for perimeter



2) Lookup Graph



1. Choose size (1 or 2m) & type (w/ or w/out deflectors)
2. Lookup slope
3. Lookup gutter flow

E.g. 2m inlet w/ deflectors (grooves to push water into pit):
- Want 95% capture capacity of pit
- Steeper pits have more bypass
- read off max capacity of pit
- if our capacity exceeds pit max, we need different size pit or consider the amount of bypass

➢ **Deflectors** aim to ↓ bypass by redirected flow into kerb & pits
Only effective if deflector depth > flow depth
Orientation must be into pit
As flow V ↑, we get smaller ponding depths

3) Catalogue

PIT SPECIFICATIONS

PRODUCT No.	PIT SIZE (mm)	PIT TYPE
PCP66	600x600	FI
PCP96	900x600	FI
PCP9383	930x835	GP
PCP99	900x900	MH
PCP105105	1050x1050	MH
PCP1059	1050x900	MH
PCP1212	1200x1200	MH
PCP129	1200x900	MH
PCP1515	1500x1500	MH
PCP159	1500x900	MH
PCP1818	1800x1800	MH
PCP189	1800x900	MH
PCP216	2100x600	FI-D

Commonly in practice you just select a pit from a catalogue provided by pit manufacturers
(these are 'standard sizes' made)

5.3 Effects & Origins of Impurities

Key Contaminants Affecting Urban Waterways			
Contaminant	**Effects**	**Sources**	**E.g.**
Oxygen demanding material	- Drop in dissolved oxygen, which aquatic life needs to survive	- Branches & organic matter from throughout the catchment - Sewer spills (see video on next slide)	- Leaf litter - Sewage - anything that decomposes in water, & uses up O^2 in the process
Suspended sediments/solids	- Smothering of aquatic habitats -> loss of biodiversity - ↓ light penetration -> reduced respiration of aquatic plants & algae - Contaminants can be associated with suspended solids	- Construction activities - Industrial and domestic wastewater - Soil erosion	- Soil - Litter
	Note: Storm events erode soil and bring debris from the surrounding landscape, i.e Sediment-laden water smothers aquatic life (↑ turbidity) ∴ should control soil erosion by planting ground cover and stabilizing erosion-prone areas		
Nutrients	- Changes in ecosystem structure - Algal blooms (both toxic & non-toxic) - Low DO levels due to the decomposition of dead algae	- Domestic waste - Animal waste - Fertilisers - Food waste - Phosphorus based detergents	- Nitrogen (ammonia, nitrate) - Phosphorus
	Note: Nutrients, such as nitrogen and phosphorus, are essential for plant & animal growth/nourishment, but the overabundance of certain nutrients in water can cause several adverse health & ecological effects		
Heavy metals (Toxic Compound)	- Toxic effects to humans and aquatic life - Lead -> neurological problems (changed behaviour, changed cognition), hearing loss, disruption to growth of children and fetuses, heart problems, nerve problems, kidney problems (e.g., Flint Water Crisis 2014) - Mercury -> psychosis, loss of consciousness, death (e.g., Minamata Disaster)	- Industrial wastewater - Accidental spills - Leaching street furniture and roofs - Vehicle emissions	- Lead - Zinc - Copper
Pesticides & herbicides (Toxic Compound)	- Toxic effects on humans and aquatic life (carcinogenic)	- Household lawns - Road runoff - Boats and ships	- Pesticides and herbicides (imidaclorpid, diuron, atrazine) - Hydrocarbons (benzene)
	Note: Pesticides are sprayed on farmland to control pests. When storms hit, the runoff carries pesticides into local streams, where they may harm aquatic life and enter drinking-water supply intakes		
PPCPs	- Minimal human health effects (maybe?) - Effects on fish & wildlife - Bacterial resistance	- Wastewater discharge	- Pharmaceuticals (e.g., antibiotics, hormones) - Personal care products (e.g., disinfectants, UV filters)
Microorganisms/ Pathogens	- Health effects on humans (gastrointestinal disease, infections of skin/eyes)	- Domestic wastewater (faecal matter) via sewage inflows - Animal waste via urban runoff	- Bacteria (Campylobacter, Salmonella) - Viruses (Norovirus, Rotavirus) - Protozoa (Cryptosporidium, Giardia)
	Note: Waterborne pathogens are transmitted to people when they consume untreated or inadequately treated water which can be life-threatening or cause digestive problems		

Notes:

1. Need to know types of contaminants & their effect on urban waterways