Deterministic Modelling
What, Why, How

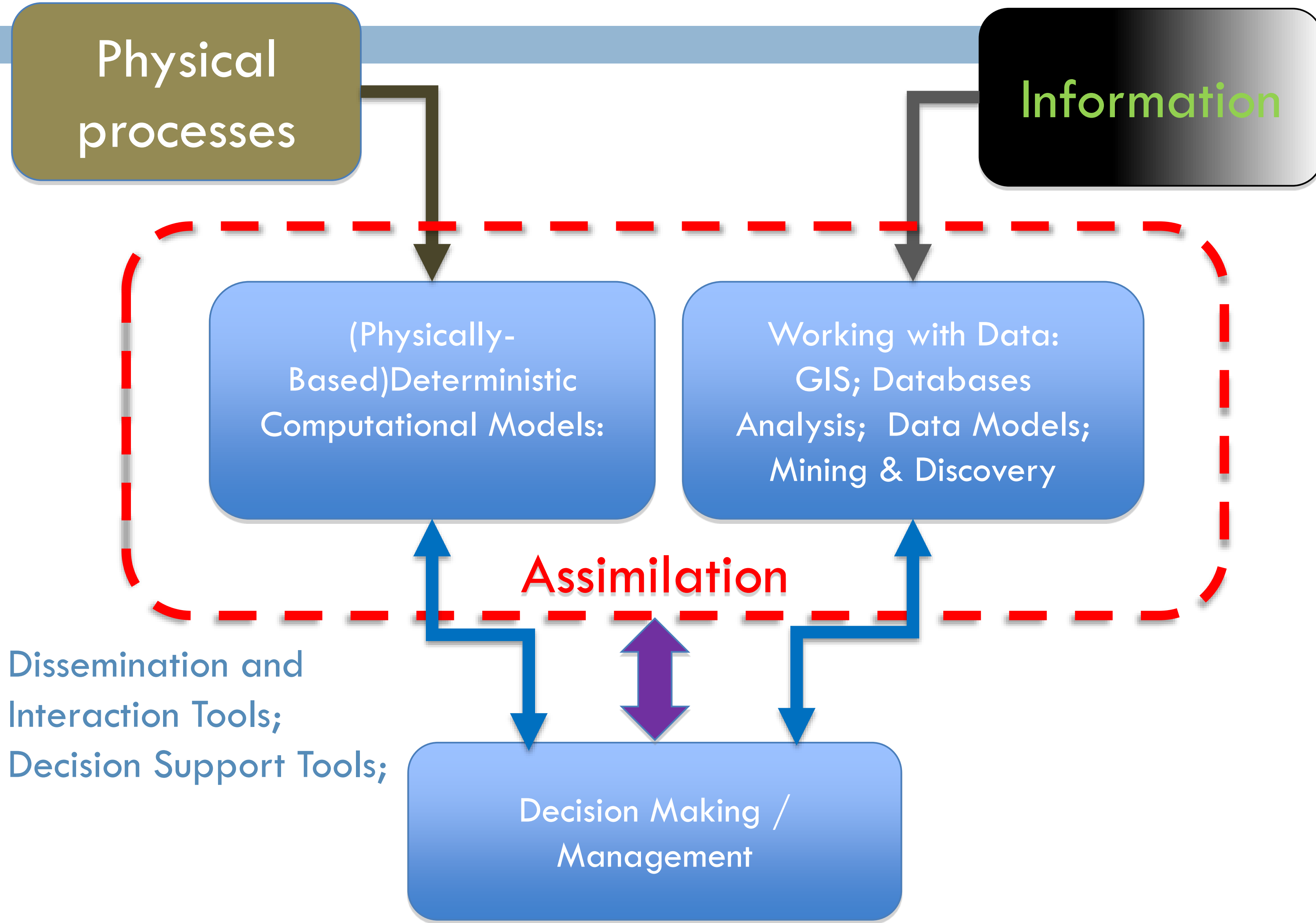
Outline

- Part 1
  - Hydroinformatics
    - What is hydroinformatics?
    - Where is deterministic modelling in hydroinformatics?
  - If you need to predict discharge how do you do it?
  - Why do we need deterministic models?
  - Main factors in designing a rainfall-runoff models (revision)
- Part 2
  - Numerical issues
- Part 3
  - A few examples… with practical issues

Hydroinformatics

- Application of ICT to address the problems of water use
- Attempts to blend technology with social application
- On the technical side focused on
  - Data
    - Databases
    - GIS
    - Data analysis methods
  - Models
    - Deterministic and
    - Data-driven

Hydroinformatics



Reality

- Sava River

Sava River Flood Mapping Workshop

back | previous | next

start: 06.09.2010. **end: 08.09.2010.**
venue:

On September 6 - 8, 2010, the Sava River Flood Mapping Workshop was held at the Hotel Laguna in Zagreb. As a result of the cooperation of the ISRBC with the US Army Corps of Engineers (USACE), with support of the Parties to the Framework Agreement on the Sava River Basin (FASRB), at the workshop, in a set of presentations, the initial hydraulic Sava River model, the experiences of the USACE expert team in development of flood maps, as well as some Slovenian experiences in the Flood Directive transposition into the national programs have been presented.
About 40 experts from the whole Sava River Basin have participated to the workshop and supported the discussion on further steps in achieving the goals of the Protocol on Flood Protection to the FASRB.
As a sign of a good cooperation, a plaque has been handed over by the ambassador of the U.S.A. in Croatia, H.E. Mr. James B. Foley, to the Chairman of the ISRBC, Mr. Branko Bačić.

All the presentations from the workshop are available for download bellow.

- Agenda
- 1.Jourdan_Sava River Flood Mapping workshop introduction.pdf
- 2.Newman_Digital Ground Surface Datasets.pdf
- 3.Richter_Data Extraction Using HEC-GeoRAS.pdf
- 4.James_General Workflow in HEC-RAS.pdf
- 5.Richter_Data Entry and Editing in HEC-RAS.pdf
- 6.James_Modeling Hydraulic Structures.pdf
- 7.Richter_Developing Flood Inundation Mapping.pdf
- 8.James_Sava Modeling Process Overview.pdf
- 9.Zeljko_Incorporating Existing Modeling along the Sava River.pdf
- 10.James_Development of the Sava River Model.pdf
- 11.James_Results of the Sava River Model.pdf
- 12.James_OFI to the Sava River Model.pdf

What do you need to know

- To predict the runoff from this catchment?

What can you use? And why

What kind of deterministic models are there?

Why Model Deterministically?

Why use Deterministic Models?

- Physics-based
- Data models need data! → (in)sufficiency
- Extrapolation →

Wilnis 2003

Physical-Scale Model (1)

physical model of the river Grensmaas (WL | Delft Hydraulics), 1:60

Physical-Scale Model (2)

- Assessing the protection of an intake

Double Barge

b) Single Barge

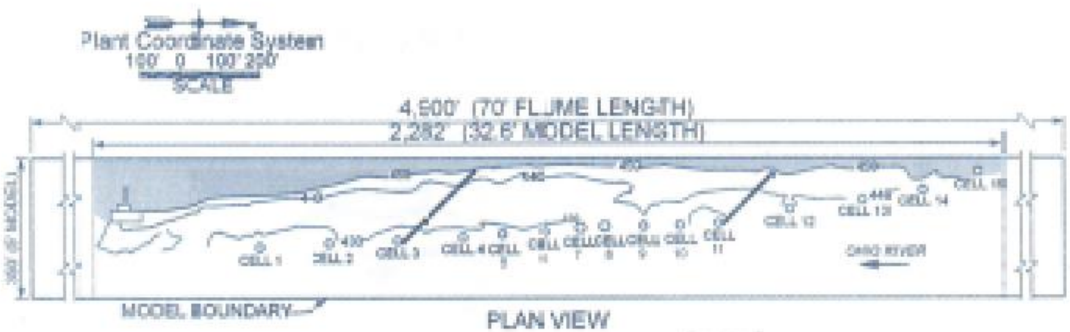


Figure 5-4: Plan View Of Model Showing Positioning Of Deflection Booms.

Both Booms Are Set At $\alpha_1 = 45°$.

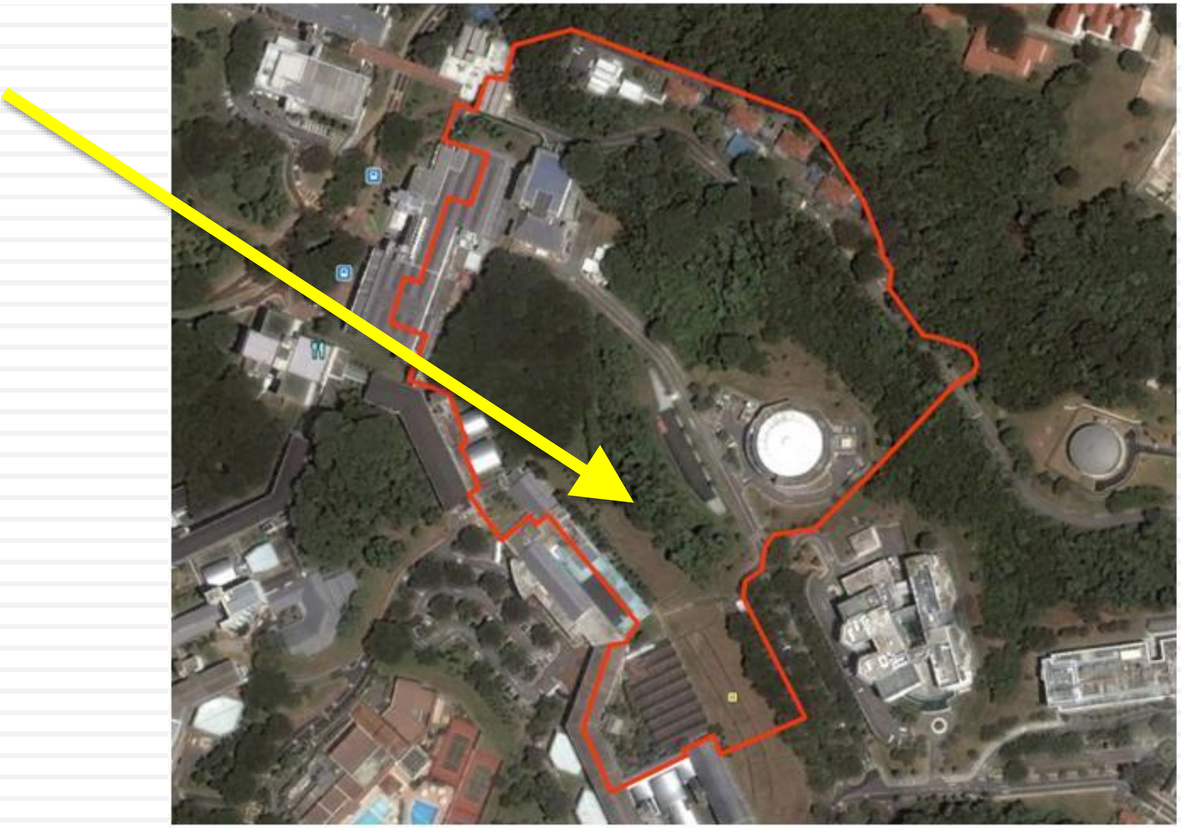
What are the predominant issues related to these choices?

- Physical-Scale Model
  - Model scale;
  - Time;
  - Cost;
  - Large temporal/areal studies
- Numerical Model
  - Scale Issues;
  - Breadth of application

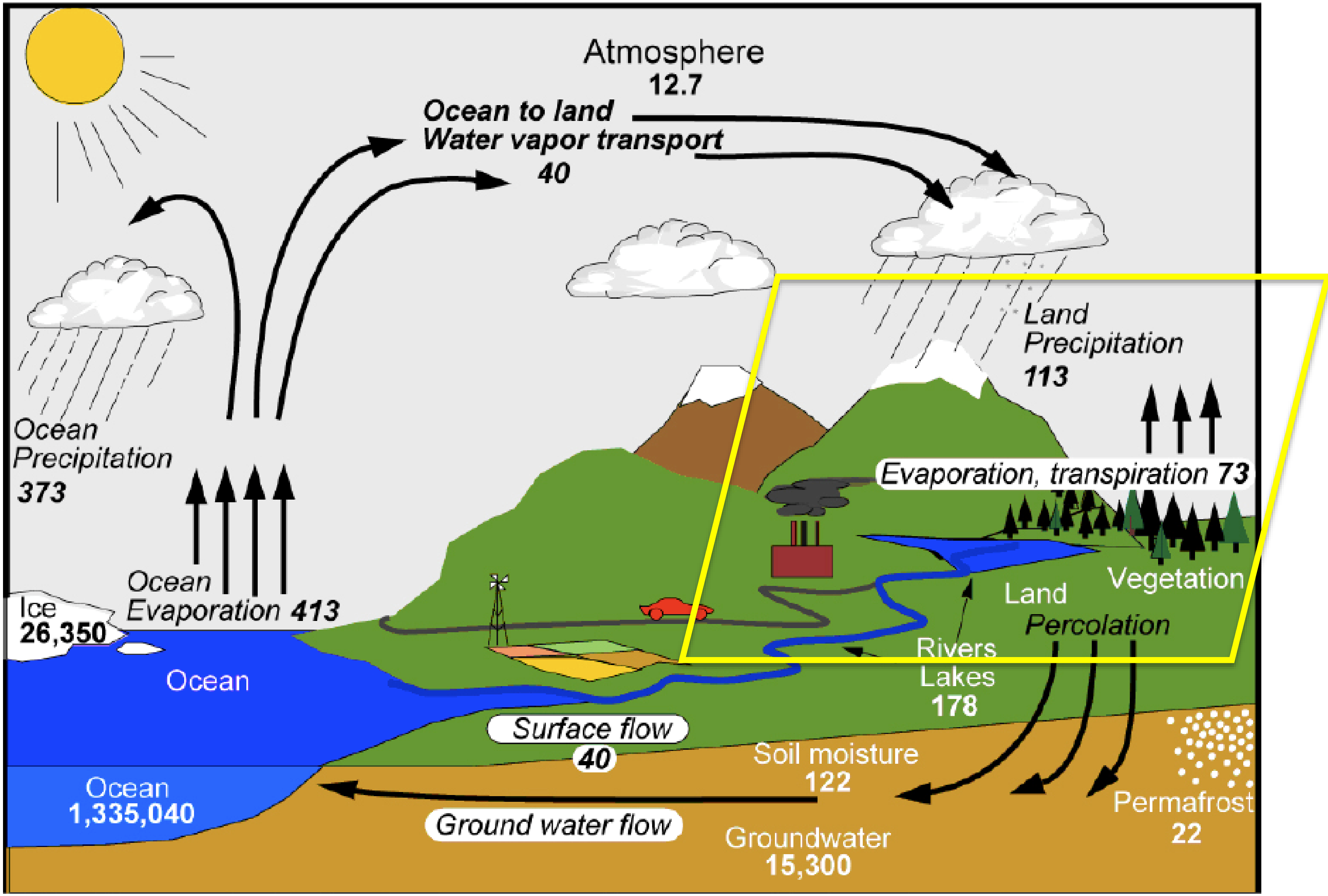
What do computer models need?

- Schemes (models)
  - Typically differential equations of conservation
- Algorithms
- Boundary and initial conditions.
- Data
- Calibration and Verification

Processes - Review



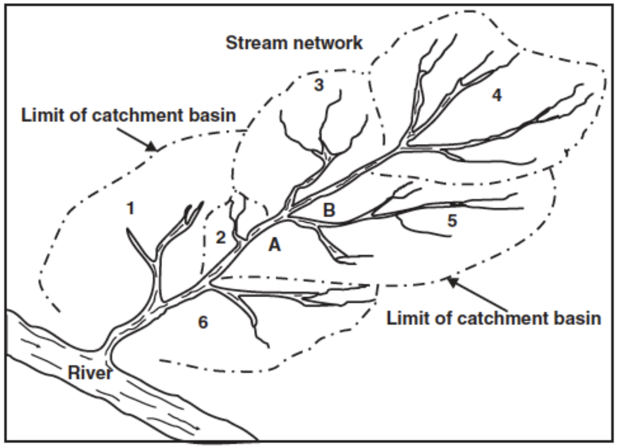
Hydrological Cycle



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

What concept do we use?

- What is a watershed?
  - Area of land surface that receives precipitation and drains or stores water
  - Typically defined by topographic data and surface stream(drain) flows
    - Ranges from hectares to km2
    - Can cross international boundaries!

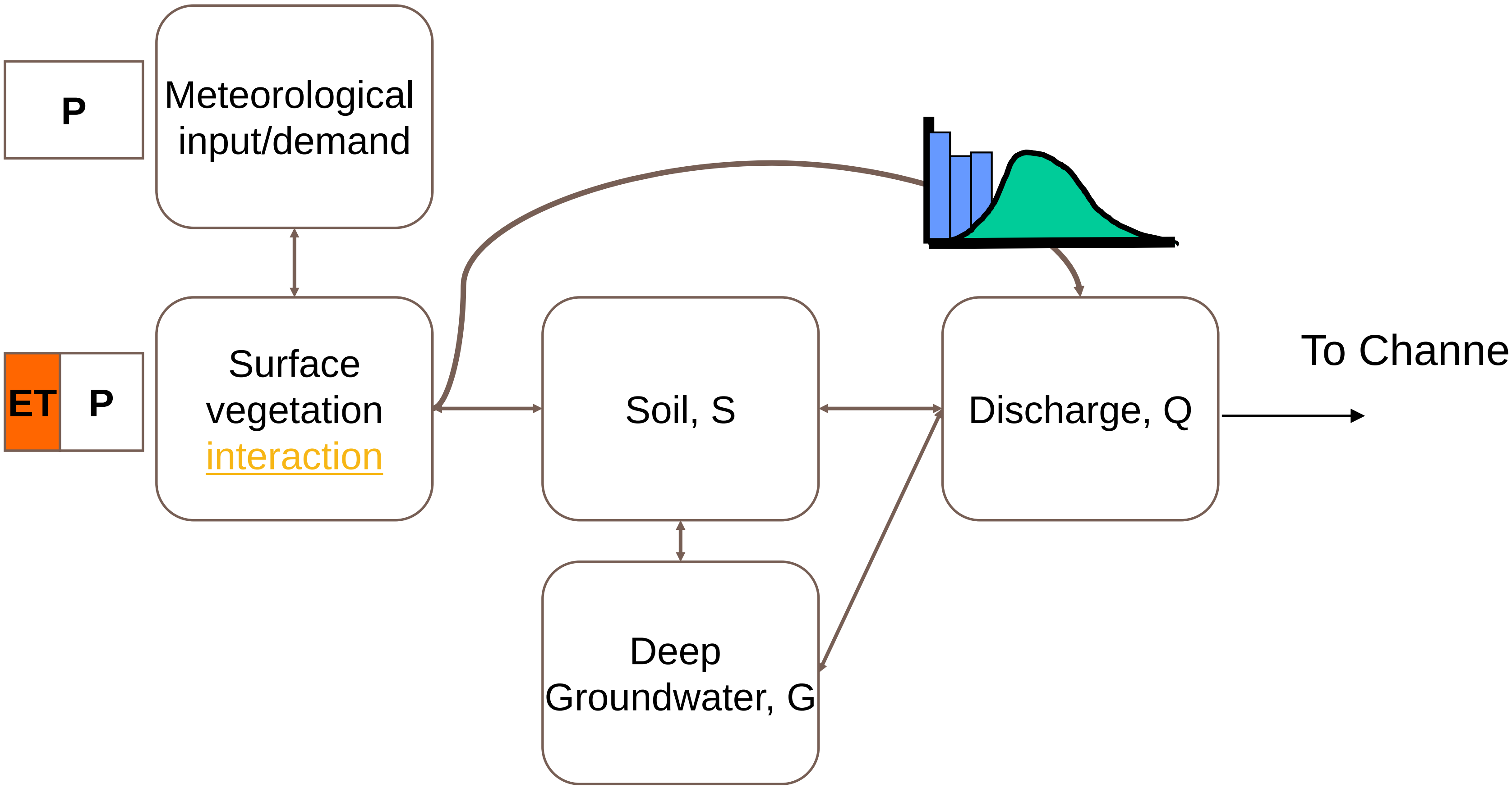


- Scale issues!
- Easily used for static mass balance estimates
- However we are more interested in the dynamics

Water balance components

$$P = ET_a + Q + \Delta S + \Delta G$$

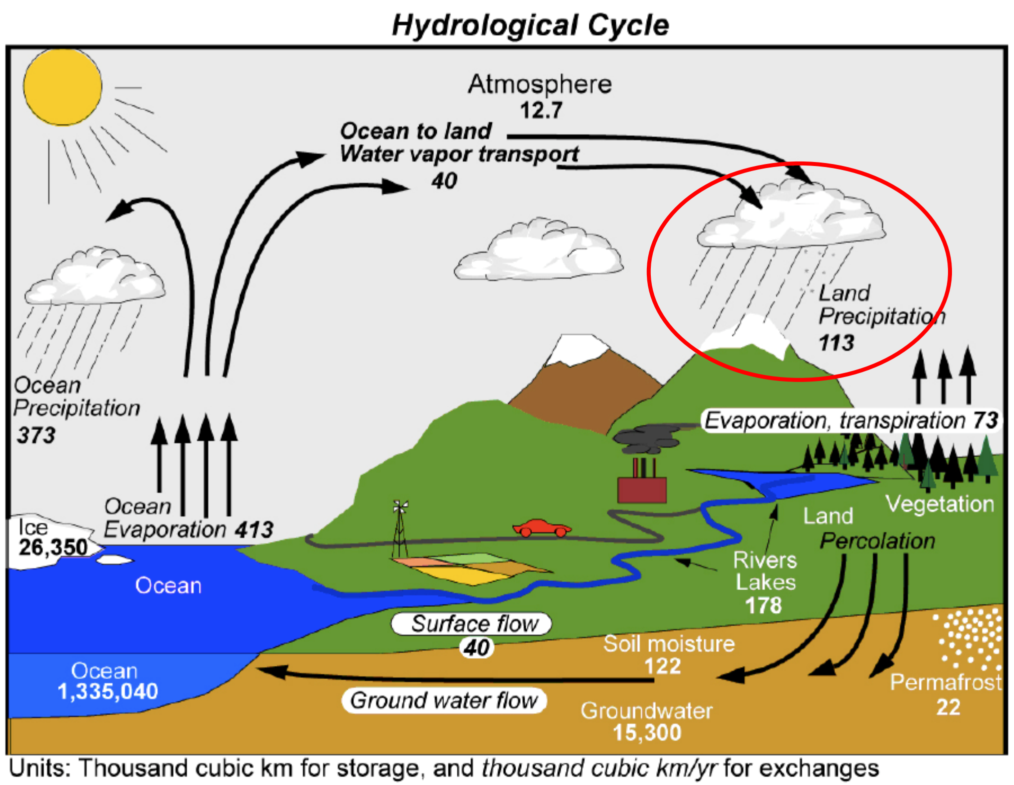
with Q= Runoff + Interflow + Baseflow



How do we translate the hydrological cycle into discrete processes?

- Precipitation
- Infiltration
- Evaporation / Transpiration
- Rainfall → Runoff
- Stream / Channel Flow

PRECIPITATION



Precipitation, P (1)

- How to measure?
  - Standard bulk collectors with measures
    - uncertainty due to delayed read out times
    - typically no records of short time intensities
    - evaporation
  - Automatic tipping buckets with loggers
    - frequent logging times; measurement of intensities
    - uncertainty during intense rainfall (tipping)
  - Radar imagery
    - Larger spatial coverage of rainfall information; resolution is low
    - Not sensistive to cloud formation
    - Accuracy depending on radar location, amount of ground truthing points and numerical framework used
    - Noise during heavy rainfall
  - Satellite
- Each source has their typical errors

Precipitation, P (2)

- Often point measurements are used in hydrological modeling
  - High spatio-temporal variation of rainfall especially in the tropics
  - Need for interpolation/extrapolation of point measurements within a catchment
    - Interpolation:
      - Definition of new values **within** the range of measured values/spatial distribution (the limit of the function is defined by measured values)
    - Extrapolation:
      - Definition of new values **outside** the range of measured values/spatial distribution (the function has no real limit and is defined by a trend, which is subject to great uncertainties).

Using the information

- Methods:
  - Isohyetes (contour lines of equal precipitation values)
  - Average (mean value)
  - Geostatistical methods using GIS
    - Kriging
    - Inverse distance weighting
    - Thiessen polygons (weighted mean)
- Summarise data in suitable timesteps for modeling purposes
  - Depending on time of concentration (t_c)of the catchment:
    - t_c= time it takes discharge to move from the most remote point on a watershed to the outlet of the watershed
    - Several formulas (example Kirpich: $t_c = 0.0078\ L^{0.77}\ S^{-0.385}$ unit ft)
    - Example: if $t_c = 5$ min in a small catchment then summarising rainfall to 1 hour timesteps would be not meaningful

Thiessen polygons

Equation 1: $$w_i = \frac{A_i}{A_t}$$

Equation 2: $$\overline{P} = \sum_{i=1}^{n} \frac{A_i}{At} \cdot P_i$$

W_i: weight [-]
A_i: polygon area [km²]
A_t: catchment area [km²]
P: precipitation [mm]

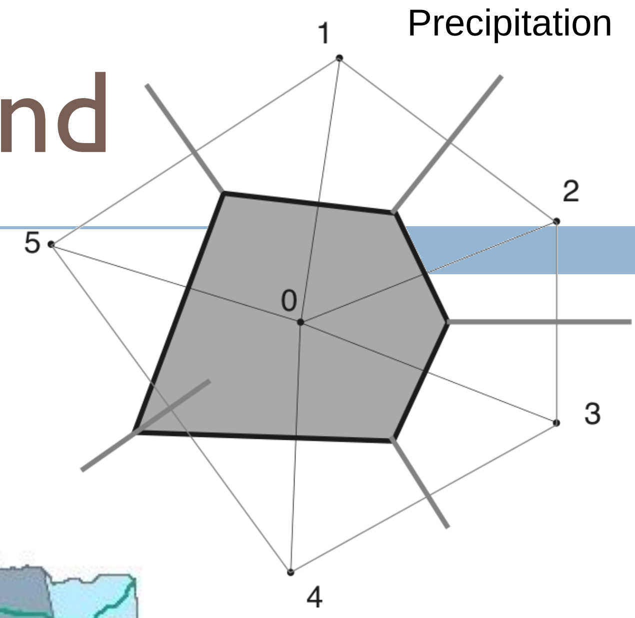
Example

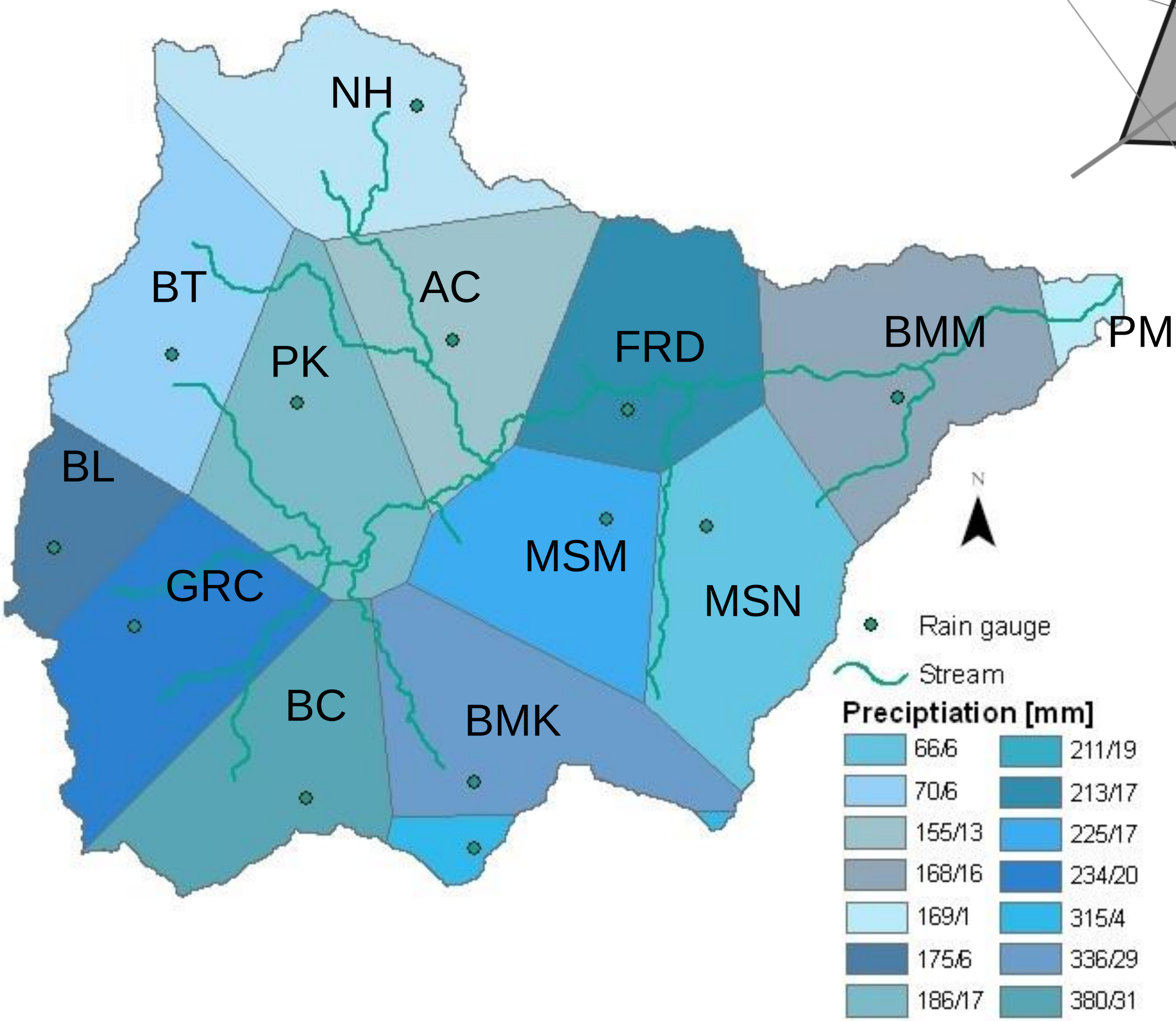
A_t: 76.4 km²
A_{i}FD: 6.18 km²
A_{i}BMK: 3.71 km²
A_{i}MSM: 4.61 km²
P_{BMK}: 32.8 mm
P_{MSM}: 20.5 mm
P_{FD}: 24.8 mm

W_{FD} : 6.18/76.4 = **0.08**
W_{BMK} : 3.71/76.4 = 0.05
W_{MSM} : 4.61/76.4 = 0.06

P = (0.08*24.8)+(0.05*32.8)+(0.06*20.5)
P = 4.8 mm

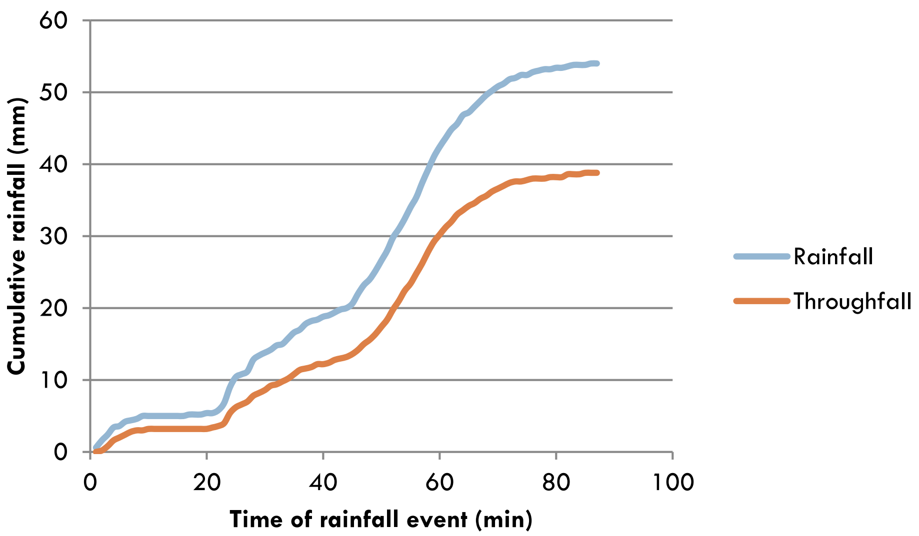
Example from Thailand

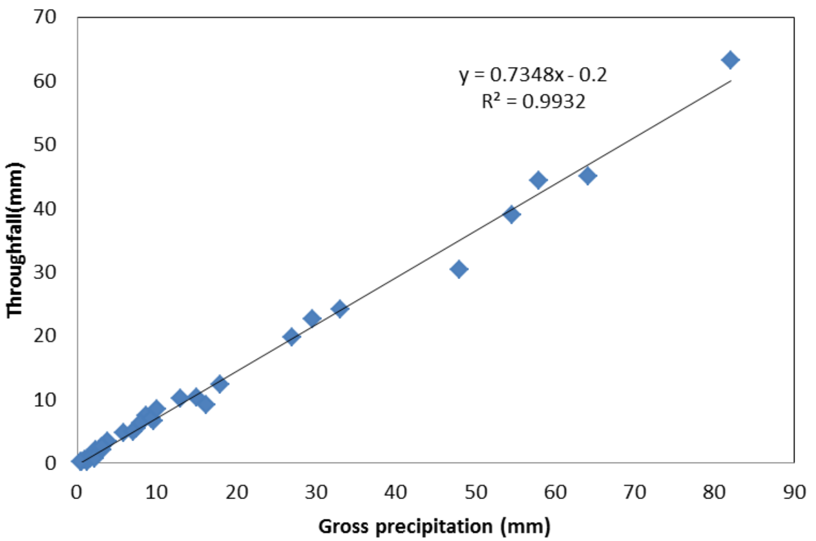




Rainfall: throughfall

- Interception of rainfall = f(vegetation)





- As such effective rainfall that will create surface runoff or infiltrate in the soil is smaller then the overall measured rainfall
- Adjust the rainfall time series within the model based on rainfall vegetation interception from literature or field measurements

Modelling interception losses

- In the (Rutter et al., 1971) model the change in amounts of water stored on the canopy is determined by the proportion of the rain that hits the canopy, the drainage from the canopy and evaporation of intercepted water:

$$dD/dt = (1 - p - p_t)R - E_w - D \qquad when \quad C \geq S$$

$$dD/dt = (1 - p - p_t)R - (C/S)E_w - D \qquad when \quad C < S$$

- An exponential function is used to calculate drainage from the canopy:

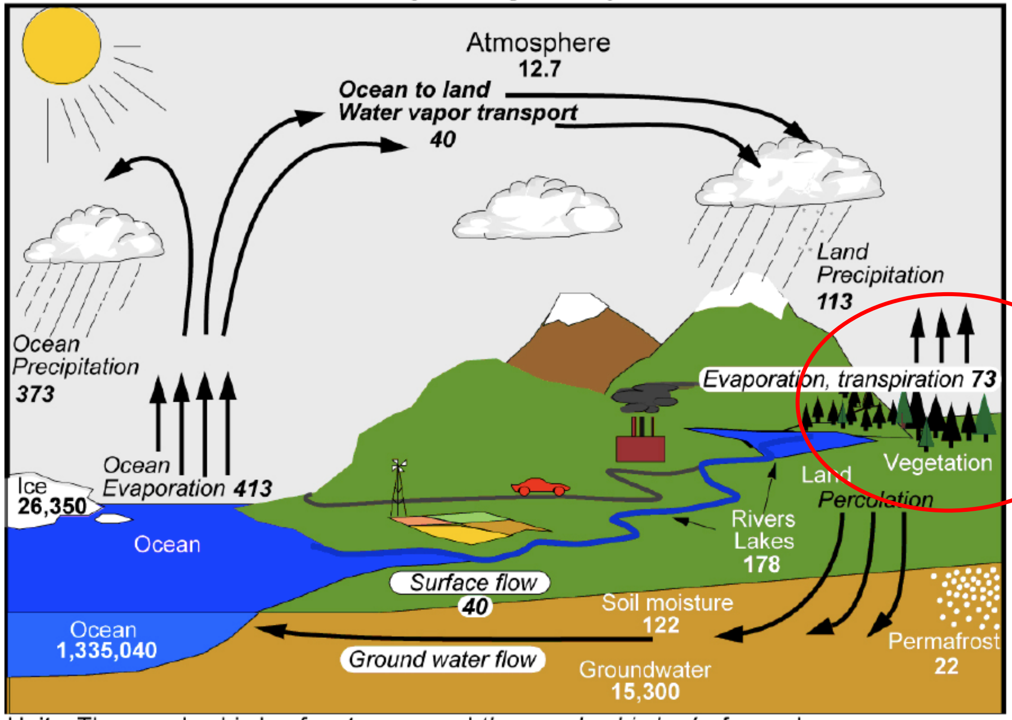
$$D = D_0 e^{b(C-S)}$$

When the canopy is calculated as being only partially wet (C<S), the estimated evaporation rate is reduced such that:

$$E_{reduced} = (C/S)E_w$$

EVAPOTRANSPIRATION

Hydrological Cycle



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Evapotranspiration (ET)

- Evapotranspiration determined by atmospheric demand and local parameters (vegetation, soil, water content of soil etc)
  - Rainfall interception (Ei)
  - Transpiration by vegetation (Et)
  - Soil-surface evaporation (Es)
  - Evaporation from open water surfaces (E_w)
- Difficult to distinguish between evaporation of the surface and transpiration by plants => combined in evapotranspiration
- Potential (ET_0) and actual evapotranspiration (ET_a)
  - ET_0= "the amount of water transpired in a unit time by a short green crop (grass), completely shading the ground, of uniform height and never short of water" (Penman-Monteith)
  - Et_a = the amount or rate of ET occurring from a place of interest by correcting ET_0 with the crop coefficient of the crop in the place of interest

- Potential (ET_0) evapotranspiration
  - Measured using a pan

  - Estimated by Penman-Monteith using climate data if not available:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

With R_n = net radiation, G = soil heat flux, ϒ psychrometric constant, u_2 windspeed, e_s-e_a water vapour deficit, Δ slope of the saturation vapor pressure-temperature curve, λ latent heat vaporization and T temperature

- Actual (ET_a) evapotranspiration
  - Calculated from ET_0 by using the crop coefficient characteristic for the vegetation
  - $ET_a = k_c \, ET_0$
    - K_c is dependent on vegetation and development stage of the plant (young plants vs. mature plants, trees,…)
  - Detailed overview for ET_0 calculation can be found in FAO irrigation paper number 56
- What about ET in urban cities:
  - Evaporation from paved open surfaces (E) and ET in green patches (parks, green infrastructure,...)
- ET within models is important for simulations covering a period (season, yearly) for example in defining irrigation practices
- They **are normally neglected** in event based urban modeling (design storms for urban drainage calculations)

INFILTRATION!

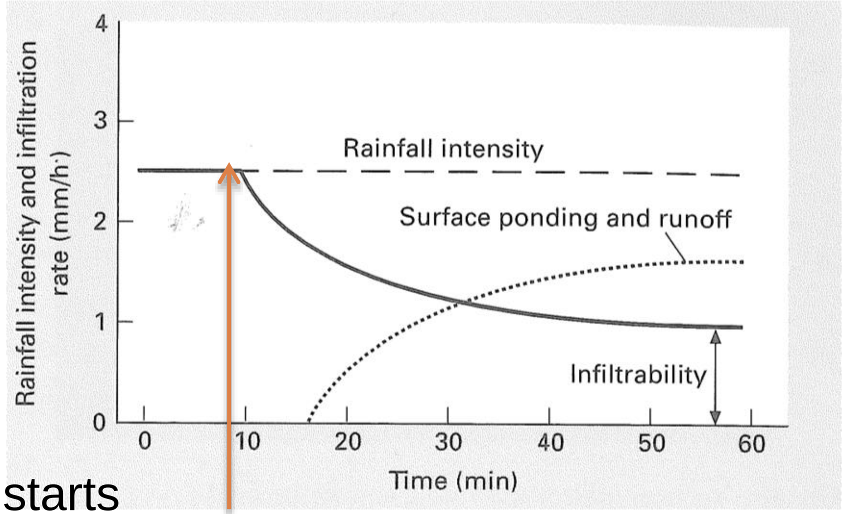
Changes in soil water content: infiltration

- Measure for the rate that rainfall on the ground surface will enter the soil
- If rainfall > infiltration rate => runoff will occur
- Infiltration is affected by:
  - Soil texture (sand, silt, clay) and structure (arrangement of particles, organic matter,...)
  - Vegetation (rootzone)

  ⇒Both have an influence on the space where water can flow through (porosity of the soil)
  - Water content of the soil
  - Soil temperature
  - Rainfall intensity
- Infiltration capacity = is the maximum rate of water that can enter a soil in a given condition

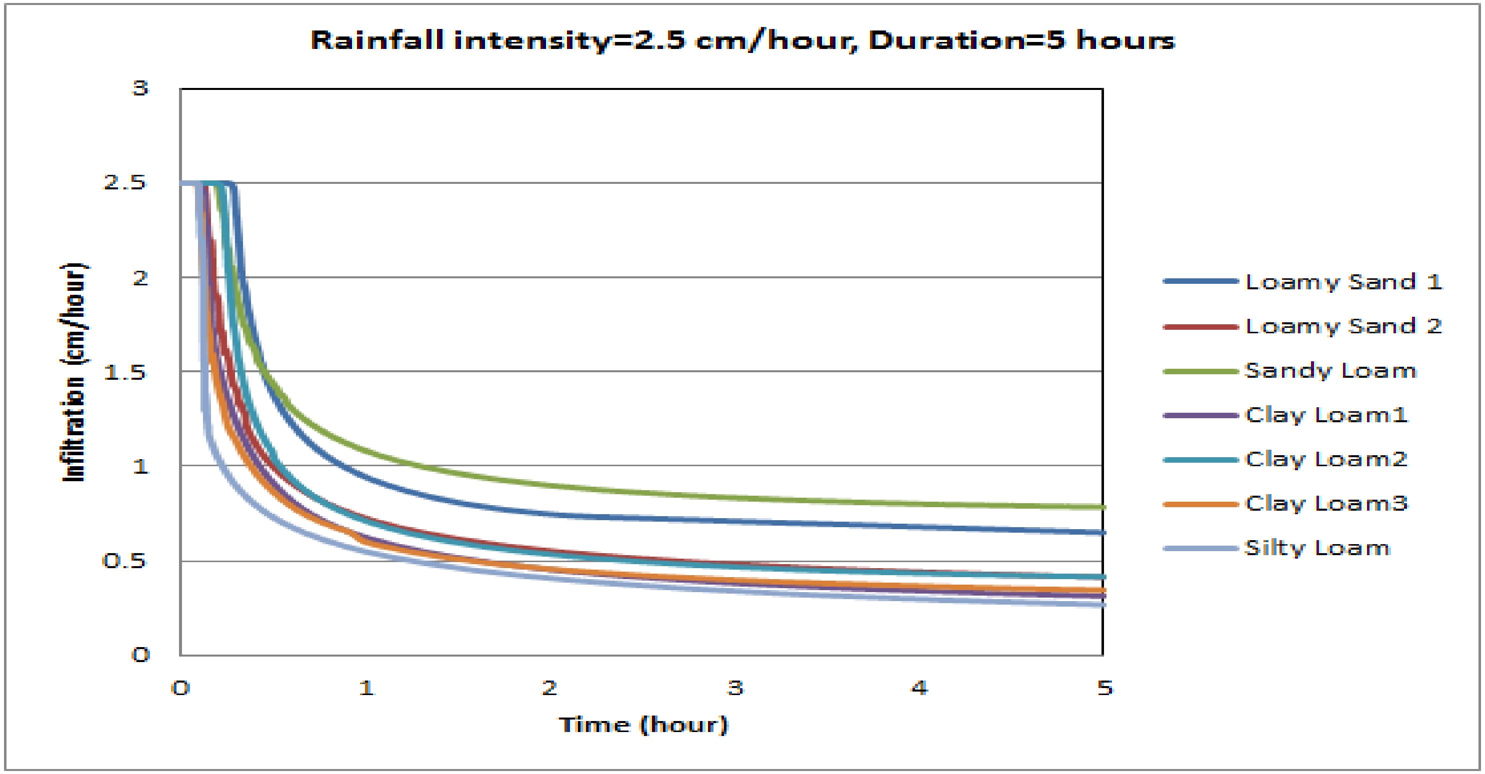
- Estimating infiltration rates (f):
  - Horton equation (Sobek Urban concept): empirical solution
    - $f = f_c + (f_0 - f_c)\, e^{-\beta t}$

    With f = the infiltration at time t, f_0 initial infiltration rate (t =0), f_c the final constant infiltration capacity of the soil and β the best-fit empirical parameter (=0 if saturated!)
    - Often used in storm watershed models as infiltration represents only a small fraction within the catchment (e.g. parks)



Point where infiltration starts

Infiltration experiment for various soil types



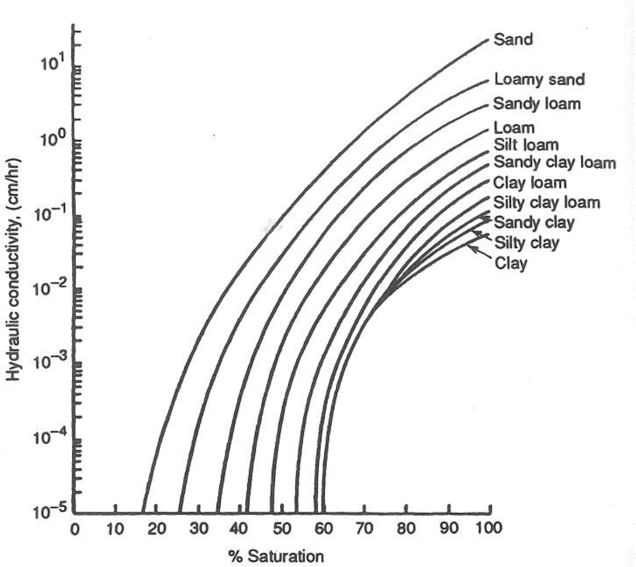
More complex calculation for modelling infiltration and transport in the vadose (unsaturated zone) :

- Physically based infiltration method
- Darcy's law:
  - If a soil is saturated or nearly saturated it is approximately in **steady state**
  - Water flux into a given volume = water flux going out
  - If laminar flow through a homogeneous soil is assumed then the rate of flow is proportional to the hydraulic gradient
  - q= -K dψ/dz

    with q= flux of volume,

    K =hydraulic conductivity

    ψ/dz=hydraulic gradient
  - K = function of soil water content



- Richards' equation:
  - **Unsaturated non uniform flow (rootzone)** due to surface evaporation, plant uptake and rainfall

  $\Rightarrow$ fluctuation of soil water content

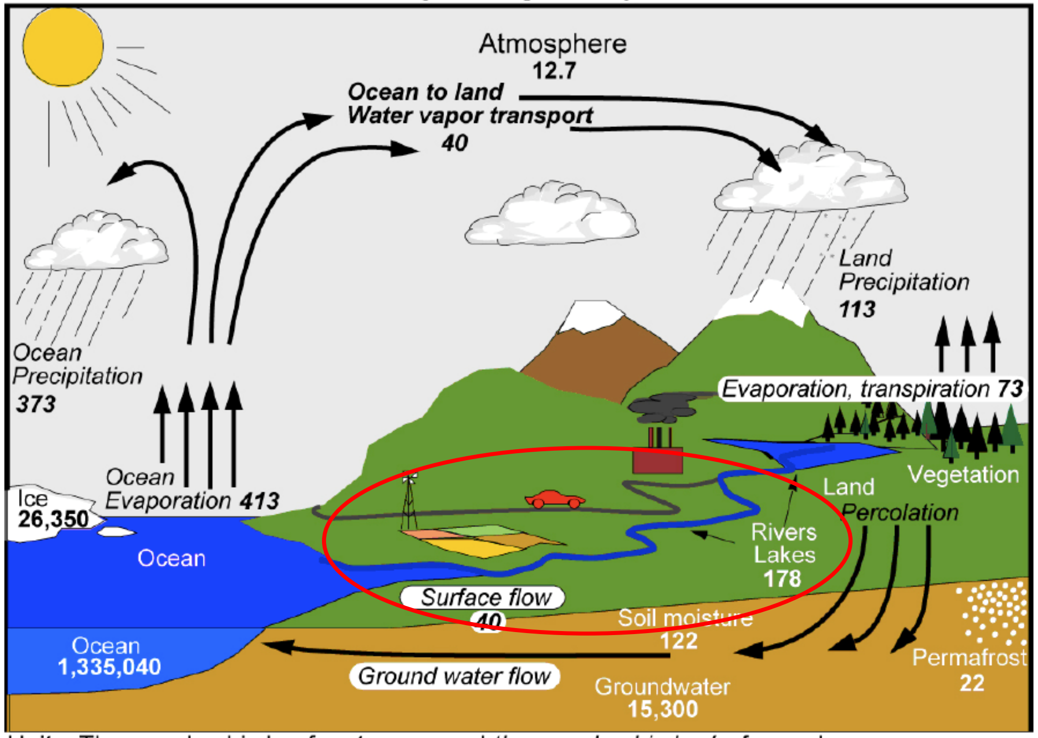
  $\Rightarrow$ resistance to flow increases => K decreases
  - Combination of Darcy's law and the principle of mass conservation

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h)$$

  - Simulation of hydraulic conductivity based on soil physical characteristics: several soil functions exist (i.e. pedotransfer functions: van Genuchten)
  - Solving Richards equation take a relative long time due to non-linearity of these functions
- **The amount that does not infiltrate will be drained from the catchment as runoff**

Runoff and Discharge

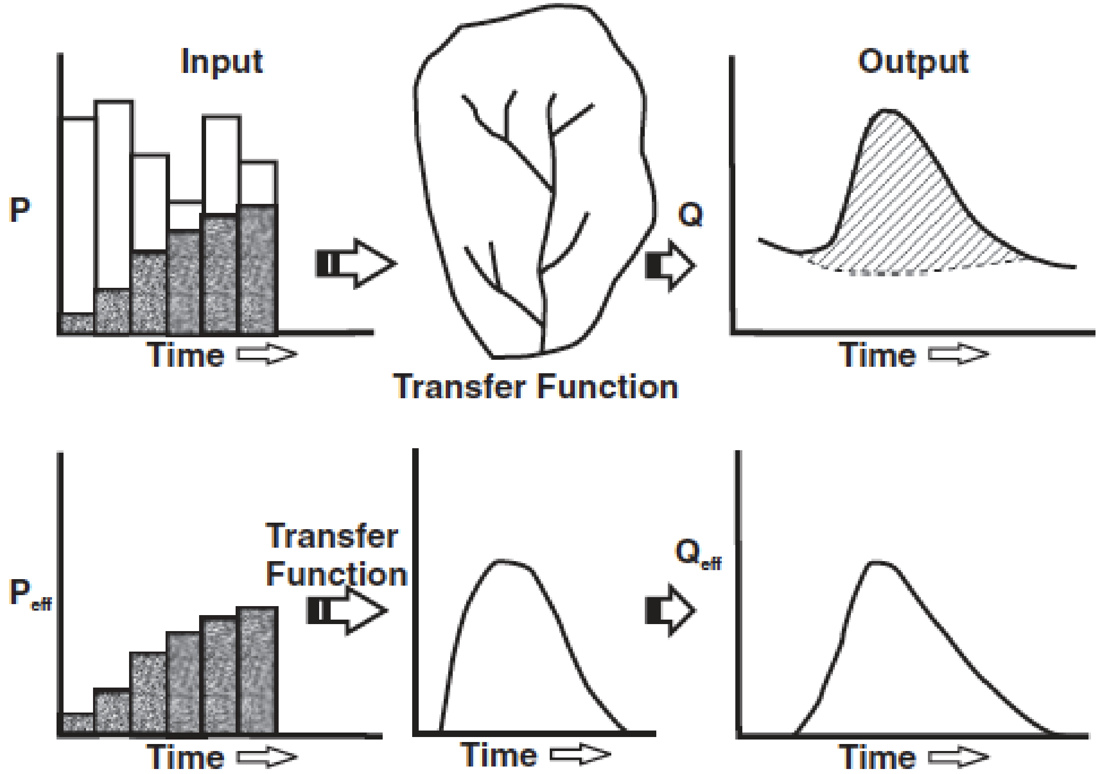
Hydrological Cycle



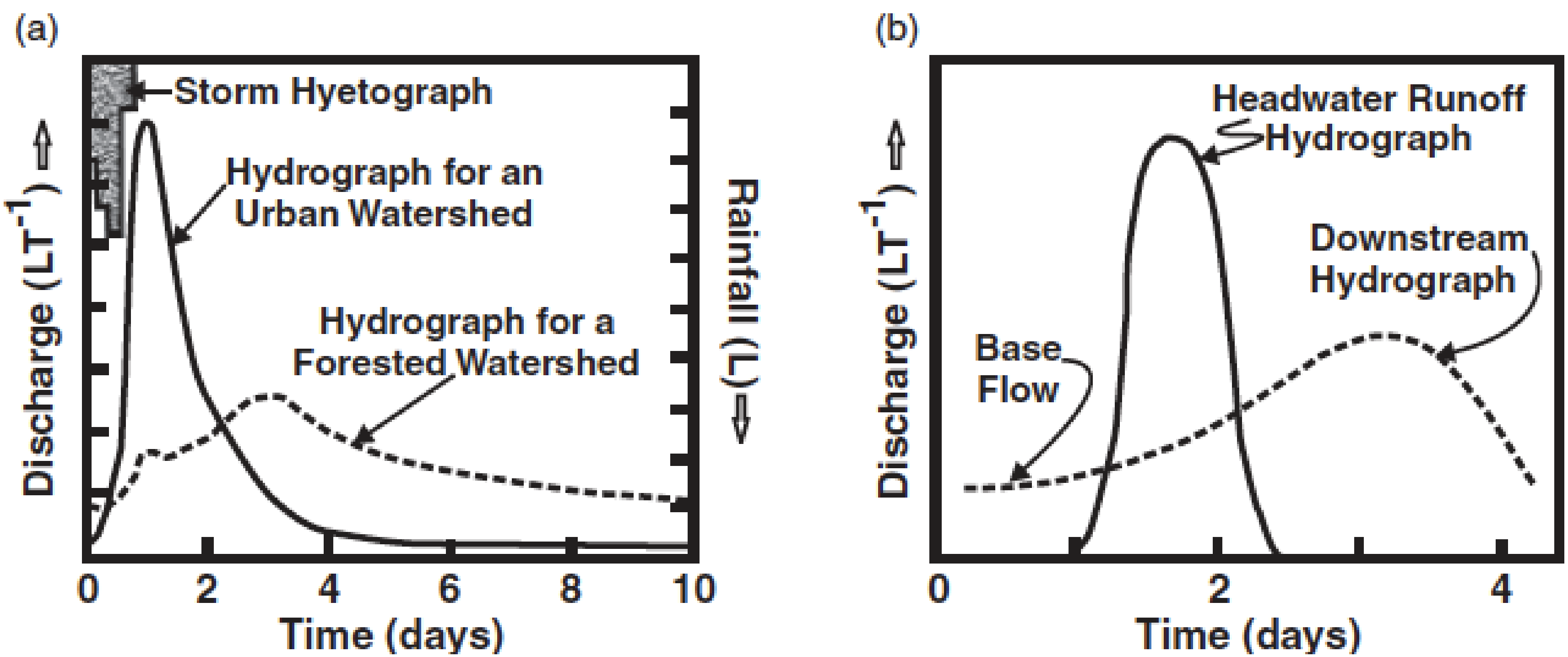
Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

How do we put them together to model and analyze? (I)

- Essentially a watershed becomes a …..



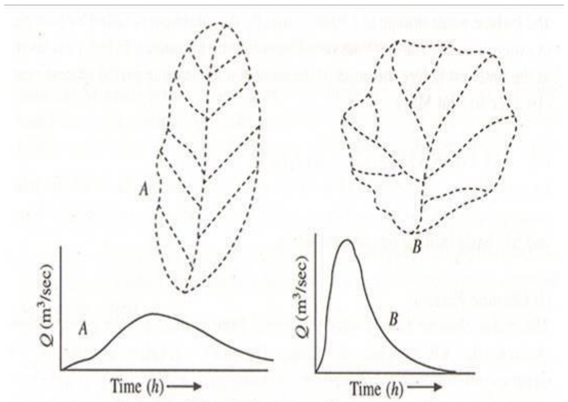
How do we put them together to model and analyse? (2)



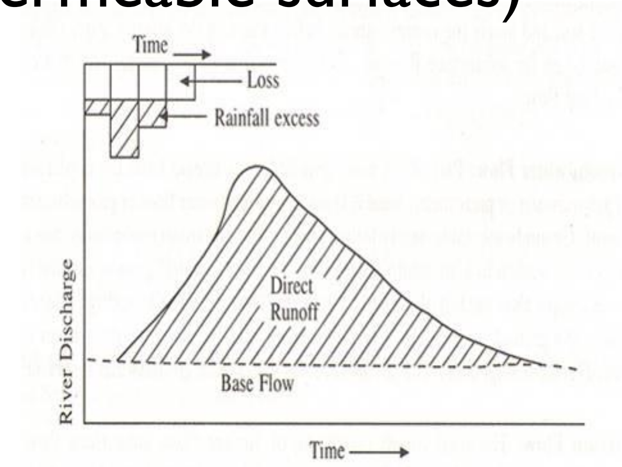
Prediction of peak runoff rates

Magnitude of runoff is a function of:

- Topography i.e. steepness of the terrain: the steeper the slope the less
- Catchment shape
- Rainfall characteristics (i.e. Rainfall intensity, duration,...)
- Soil (influence on infiltration) and land use characteristics (incease runoff with increased impermeable surfaces)



Effect of Catchment Shape on Runoff



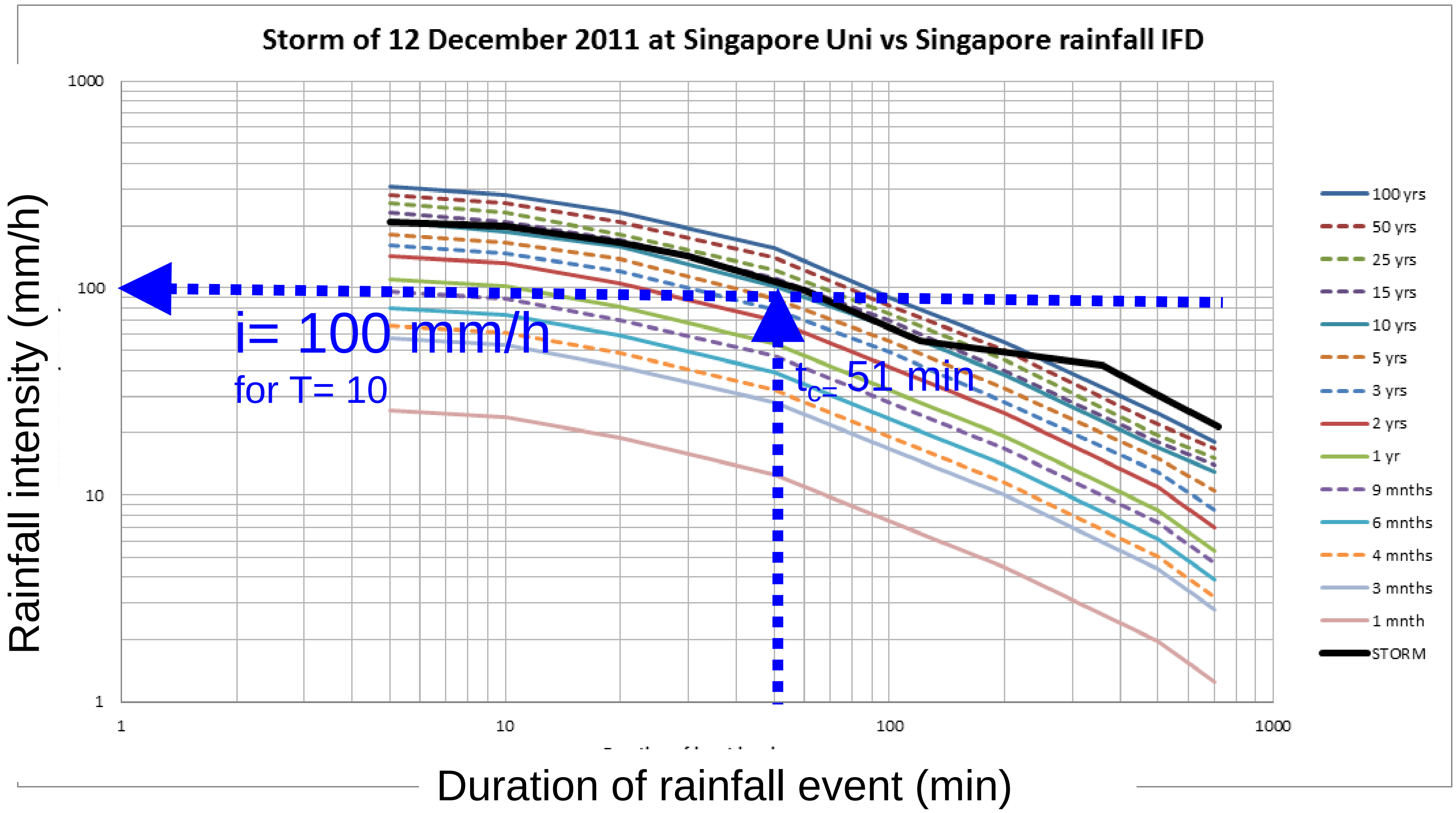
Hydrograph

- Various means of constructing a hydrograph:
  - 1D RF-RO Models
  - SCS-CN
  - Unit hydrograph
  - SCS Unit Hydrograph
  - Rational method: $Q\ (m^3/s) = C\ i\ (mm/hr)\ A\ (m^2)$
    - Designed for ungauged sites
    - Assumptions:
      - RF Duration and Intensity is uniform over basin
      - Storm Duration $\geq$ Time of Concentration of the Watershed
      - C is dependent upon watershed physical characteristics

Rational Method

- $Q\ (m^3/s) = C\ i\ (mm/hr)\ A\ (m^2)$
  - Designed for ungauged sites
  - Assumptions:
    - RF Duration and Intensity is uniform over basin
    - Storm Duration ≥ Time of Concentration (Tc) of the Watershed
    - C is dependent upon watershed physical characteristics
    - Various ways to calculate Tc. (Typically Tc = T0 + Tt)

IDF curves for the rational method (design)



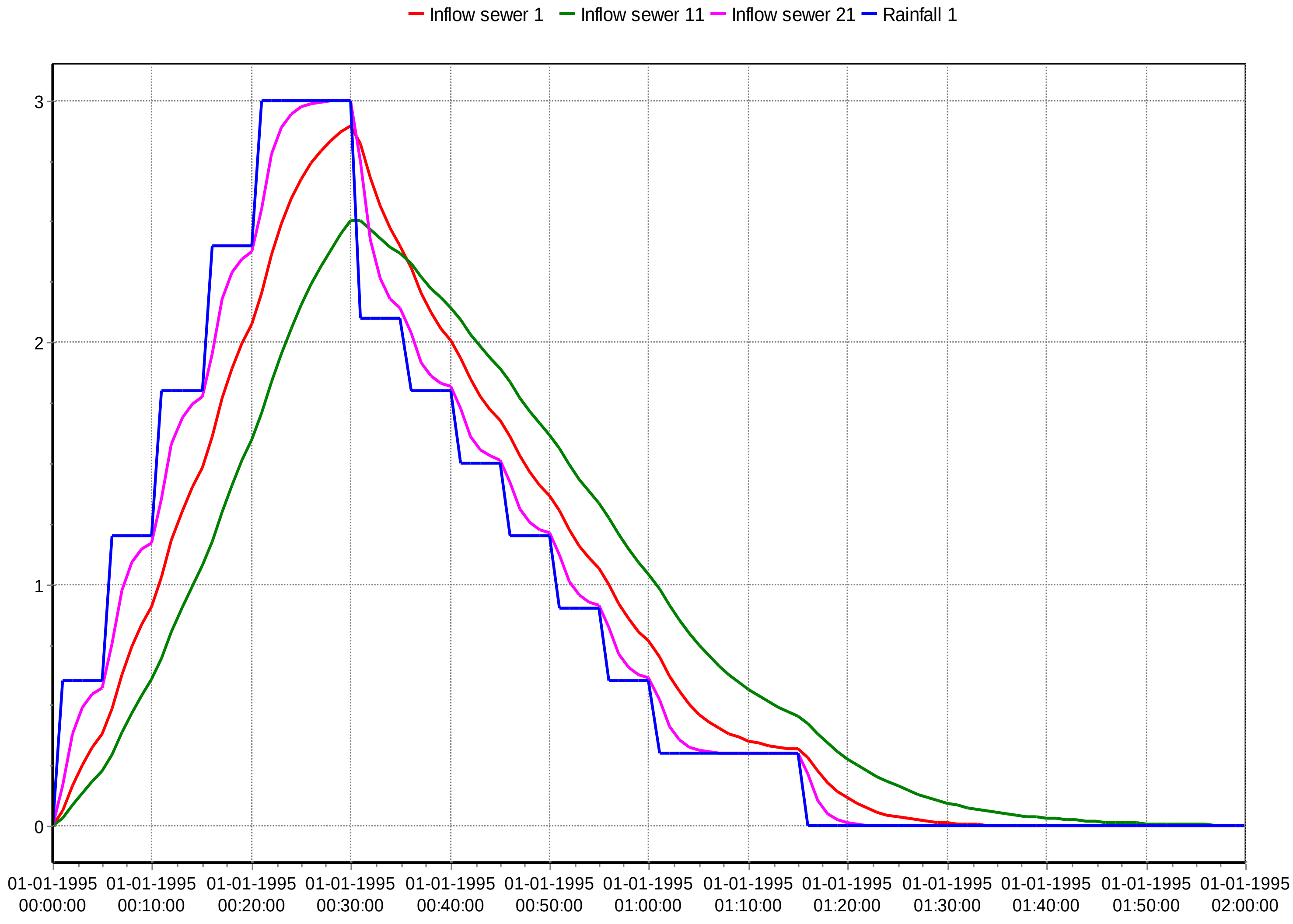
Runoff coefficients (C_i):

Land Use	C
Business:	
Downtown areas	0.70 - 0.95
Neighborhood areas	0.50 - 0.70
Residential:	
Single-family areas	0.30 - 0.50
Multi units, detached	0.40 - 0.60
Munti units, attached	0.60 - 0.75
Suburban	0.25 - 0.40
Industrial:	
Light areas	0.50 - 0.80
Heavy areas	0.60 - 0.90
Parks, cemeteries	0.10 - 0.25
Playgrounds	0.20 - 0.35
Railroad yard areas	0.20 - 0.40

Land Use	C
Lawns:	
Sandy soil, flat, 2%	0.05 - 0.10
Sandy soil, avg., 2-7%	0.10 - 0.15
Sandy soil, steep, 7%	0.15 - 0.20
Heavy soil, flat, 2%	0.13 - 0.17
Heavy soil, avg., 2-7%	0.18 - 0.22
Heavy soil, steep, 7%	0.25 - 0.35
Agricultural land:	
Bare packed soil	
*Smooth	
*Rough	
Cultivated rows	0.30 - 0.60
*Heavy soil, no crop	0.20 - 0.50 0.30 - 0.60
*Heavy soil, with crop	0.20 - 0.50
*Sandy soil, no crop	0.20 - 0.40
*Sandy soil, with crop	0.10 - 0.25
Pasture	0.15 - 0.45
*Heavy soil	0.05 - 0.25
*Sandy soil	0.05 - 0.25
Woodlands	
Streets:	
Asphaltic	0.70 - 0.95
Concrete	0.80 - 0.95
Brick	0.70 - 0.85
Unimproved areas	0.10 - 0.30
Drives and walks	0.75 - 0.85
Roofs	0.75 - 0.95

http://water.me.vccs.edu/courses/CIV246/table2b.htm

Influence of runoff coefficient



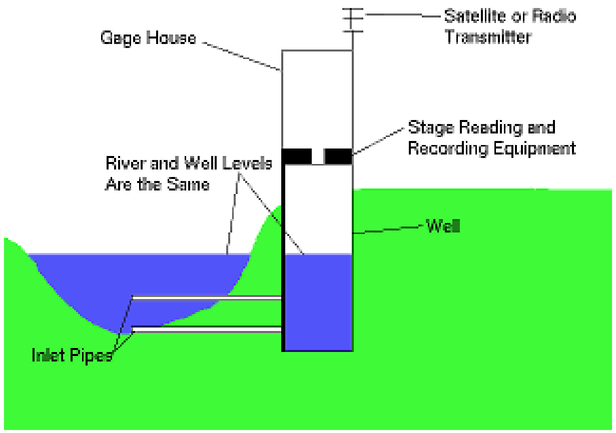
Discharge within a catchment

- Discharge is the water volume which flows through a defined cross section. It is normally presented in [l/s] or [m^3/s].
- Due to the definition of the cross section the discharge can be related to a specific area (catchment).
- Consists of :
  - Surface runoff = Rainfall does not infiltrate and exceeds the ponding capacity of the surface will flow downhill and directly enter the stream (fast)
  - Interflow = lateral flow of infiltrated water through the unsaturated zone in the soil compartement entering the stream (intermediate)
  - Baseflow = lateral deeper subsurface flow throught the saturated zone (groundwater) entering the stream (slow)

=> In urban areas; predominant interest is in SURFACE RUNOFF ! WHY?

How to measure discharge?

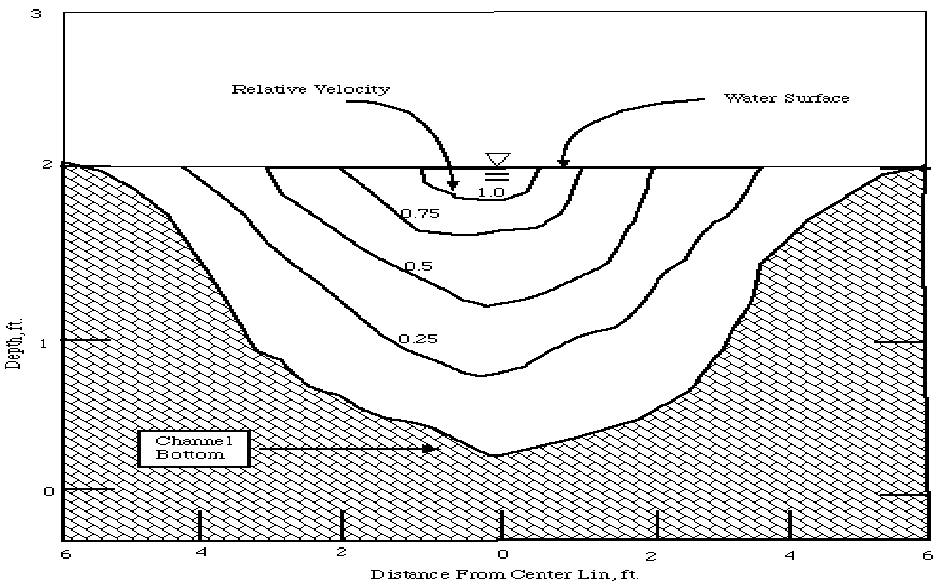
- Continuous measurement of **water level (stage, h)**
  - Non automated stations:
    - Staff Gauges
  - Automated stations:
    - Floater system
    - Pressure sensor
    - Acoustic pressure sensor

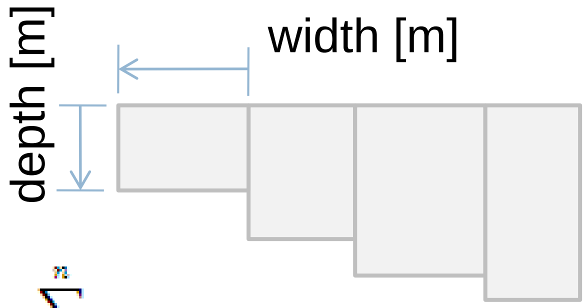


- Stage-discharge curve **(h-Q) = rating curve**
  - Velocity-area: measure velocity and cross-section area (float method: quick idea; current meter: precise)
  - Dilution method (tracer injection)
  - Hydraulic structures (e.g. Parshall Flume; V-notch): well-known and precise relation discharge-stage

Velocity area method

If hydraulic structures are not possible (mainly in natural streams)





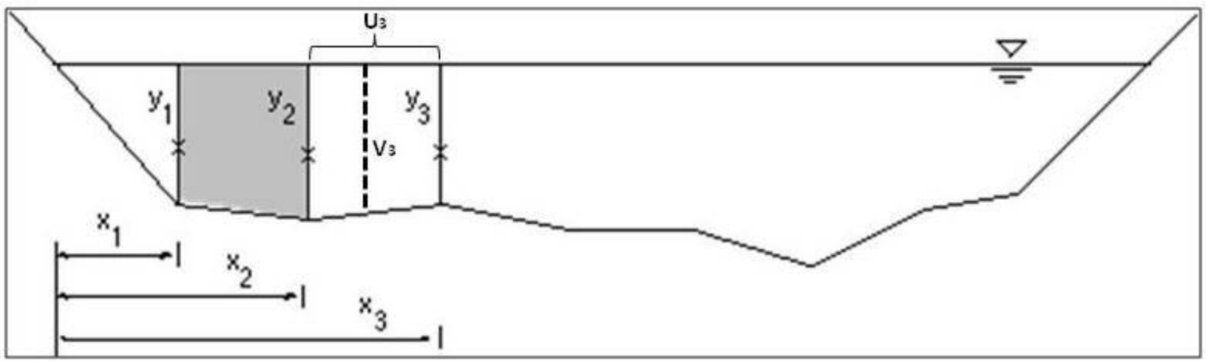
$$Q = \sum_{i=1}^{n} a_i \, \bar{v}_i$$

Q: Discharge of cross section [m³/s]

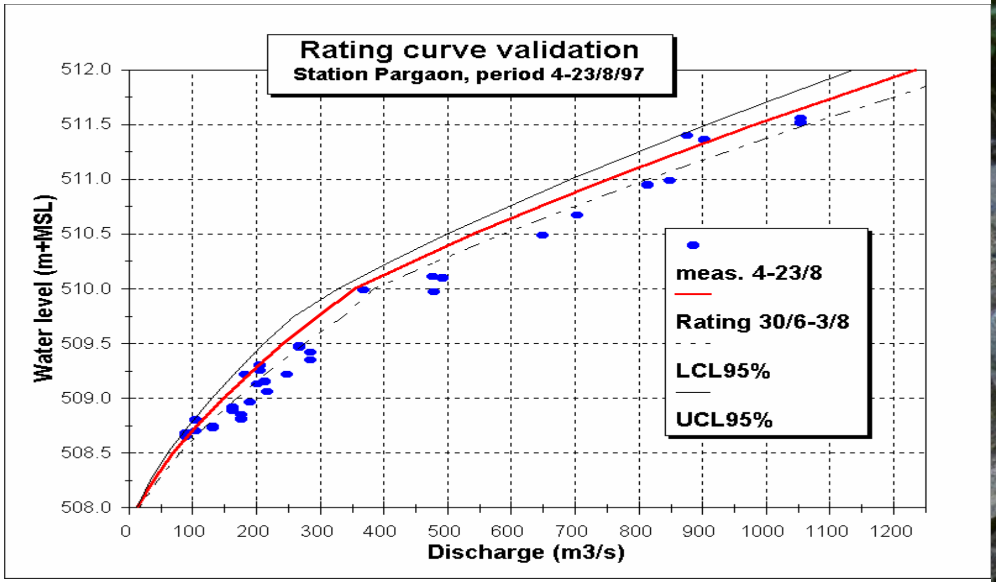
i-n: number of verticals

a: area of each vertial [m²]

v: average velocity of area [m/s]



Establishment of rating curve



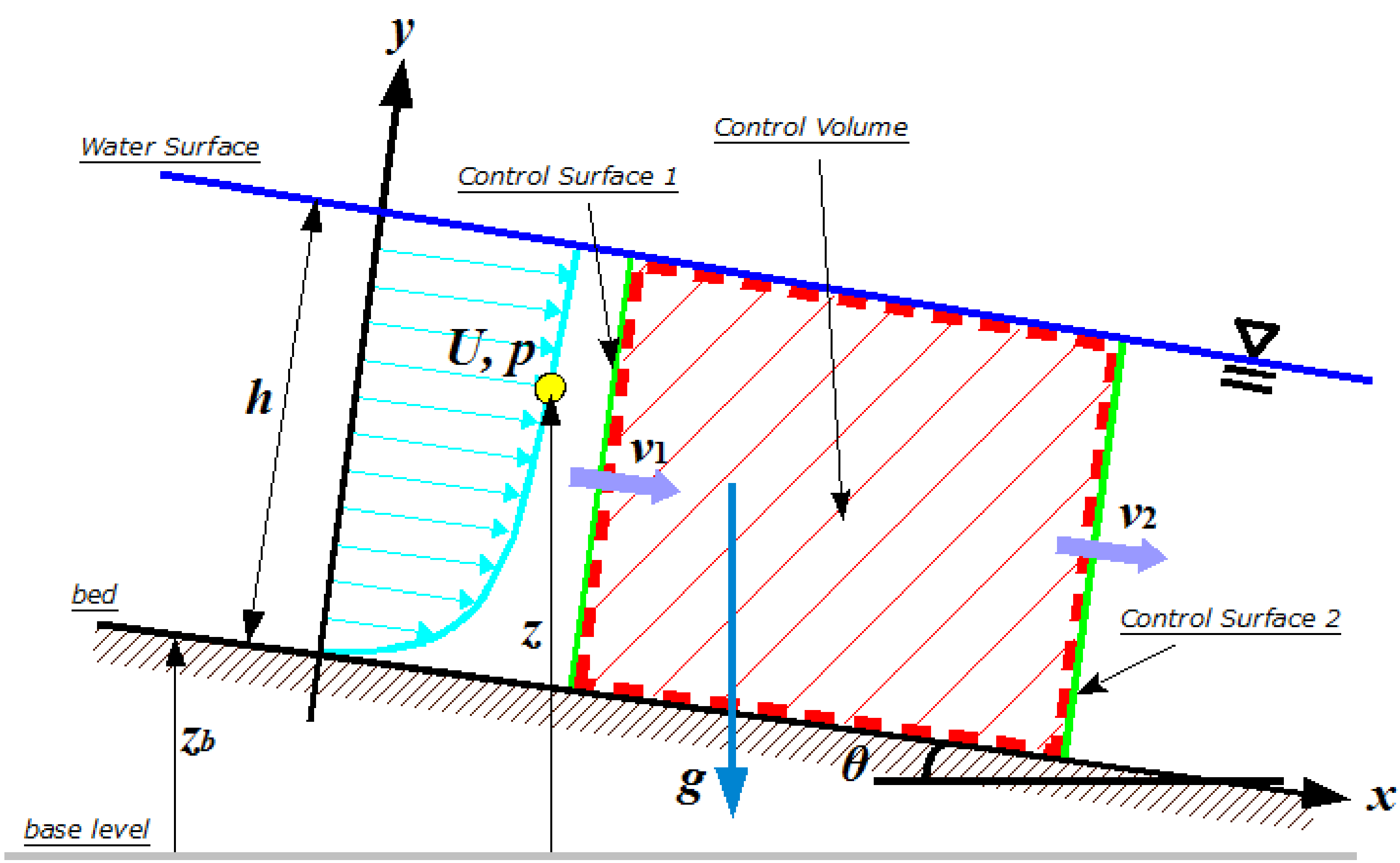
Guideline for rating curves:
Isco Open Channel flow measurement Handbook

Choice of section

- Critical depth stabilizes the relation between discharge and level
  - However low levels & high kinetic energy=> very difficult for accurate and sensitive measurements
- Downstream of critical flow:
  - good control (i.e. hydraulic structure) with good relation discharge and level and easy to measure large levels with low kinetic energy

    (Fr <0.5 lower kinetic energy)

Channel Routing



How do we route the flow?

- Simply put Conservation Equations
  - Energy / Momentum

$$z_1 + D_1 + \frac{(V_1)^2}{2g} = z_2 + D_2 + \frac{(V_2)^2}{2g} + h_L$$

  - Mass

$$v = \frac{1}{n} R^{2/3} S^{1/2} \qquad Q = A v = \frac{1}{n} A R^{2/3} S^{1/2}$$

BUT what did we assume

- What type of flow???
  -
  -
  -
- But is that true? What assumption do we make with uniform flow?

Wait… Will that cope with issues such as ?

- Flow over sharp crested weirs or changing cross section (venturi flumes and broad crested weirs),
- Hydraulic Jumps?
- If not how did we cope with this previously?

Specific energy (typical concept for open channel flow): Rapid varied flow

- Flow over sharp crested weirs or changing cross section (venturi flumes and broad crested weirs), change from super-critical to sub-critical flow
- Specific energy (= energy relative to bottom)

$$\Rightarrow \quad E_s = D + \frac{(V)^2}{2g}$$

- Open channels: for a given discharge several combinations of D and V are possible
- For a given discharge there is a minimal specific energy: the critical depth or also the critical flow

Critical flow and Froude number

- Froude number:
  - Open channel flow is
    - Supercritical or «shooting » Fr>1
    - Critical Fr =1
    - Subcritical Fr<1
  - Froude number expresses the proportion of kinetic energy/ water depth in a dimensionless number.
  - Measurement at Fr >0.5 is difficult (lots of kinetic energy and a relatively low level)

$$Fr = \frac{V}{\sqrt{g\ D_h}}$$

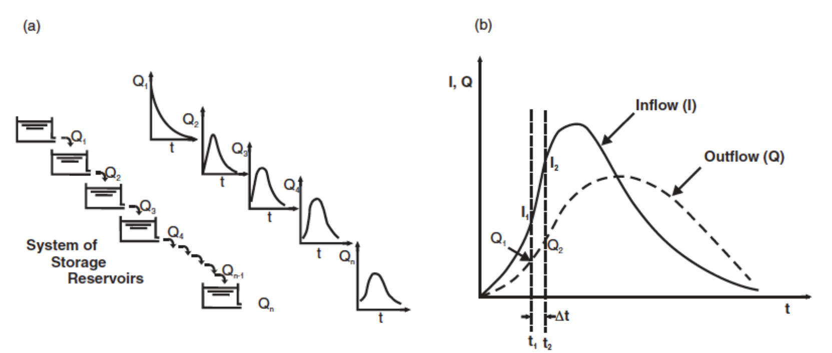
$$D_h = A / P$$

- Critical flow:

$$V_c = \sqrt{g\ D_C}$$

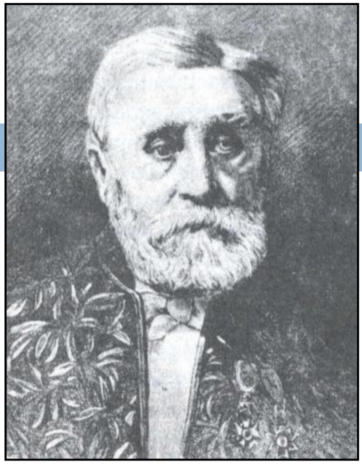
With V_c the critical flow velocity and D_c the critical water
level depth (m)

Given all that, how should we route the runoff then?



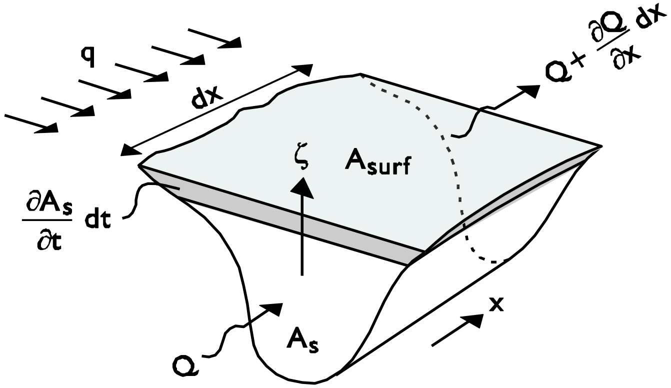
- Two Methods:
  - Hydrologic
    - Lumped (Time only)
    - Distributed-Flow (Space-Time) e.g. Muskingum, Muskingum-Cunge
  - Hydraulic
    - Method of Characteristics
    - St. Venant Equations
- Which is best?

The Saint-Venant Equations



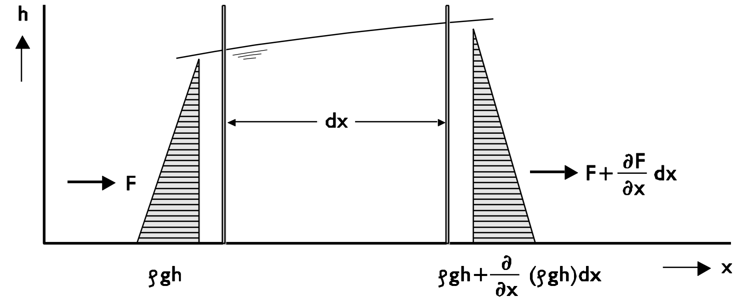
Continuity:

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$



Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha_B \frac{Q^2}{A_f}\right) + gA_f \frac{\partial h}{\partial x} + \frac{Q|Q|}{C^2 R A_f} = 0$$



REFRESHER COMPLETE