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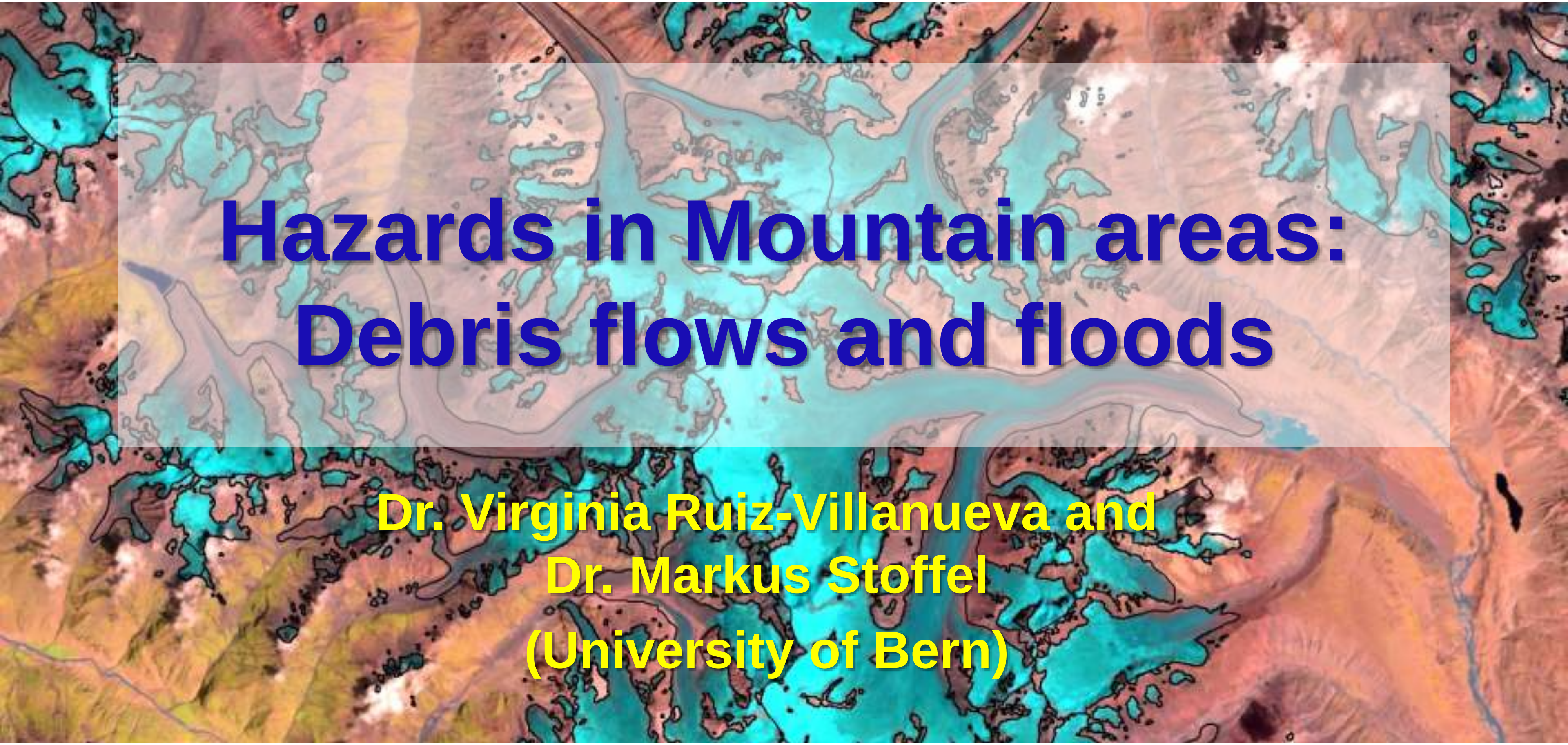


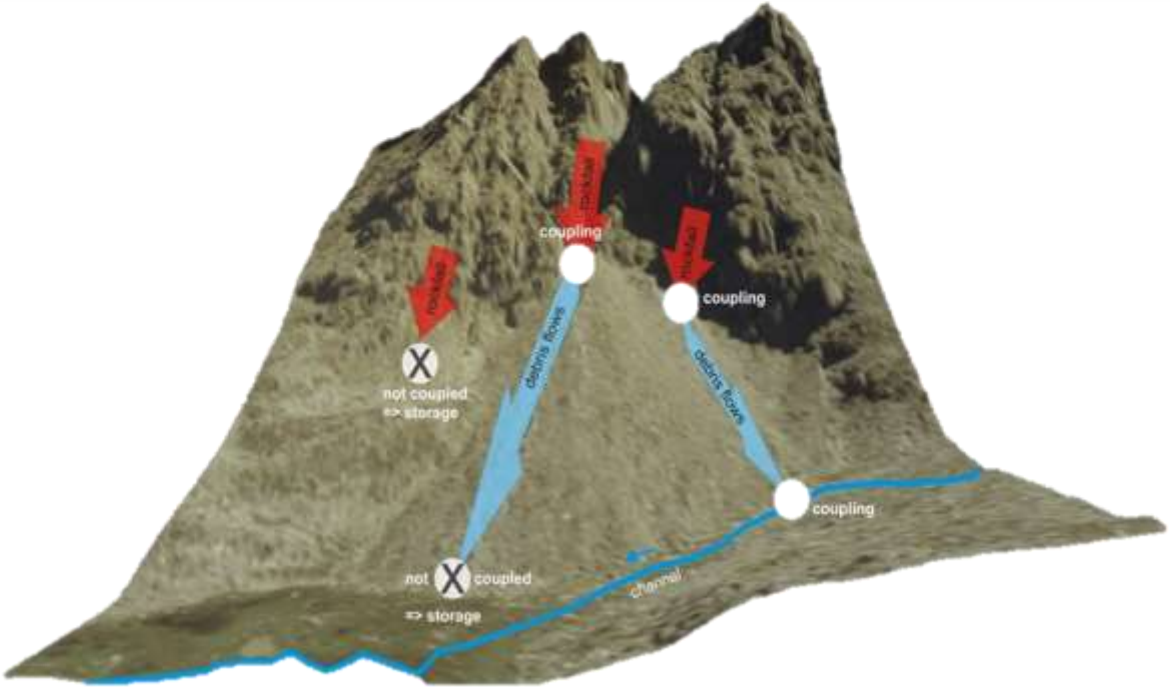
Hazards in Mountain areas: Debris flows and floods

Dr. Virginia Ruiz-Villanueva and
Dr. Markus Stoffel
(University of Bern)

IHCAP – Indian Himalayas Climate Change Adaptation Programme
Capacity building programme Level-2 (February 3, 2015)

Hazards in Mountain areas: Debris flows and floods

- Summary
  - Debris Flows
    - Properties
    - Parameters
    - Analysis
    - Modelling
  - Floods
    - Flood hydrology
    - Channel and flow types
    - Fluvial processes
    - Estimating and reconstructing floods
    - Modelling floods: exercises



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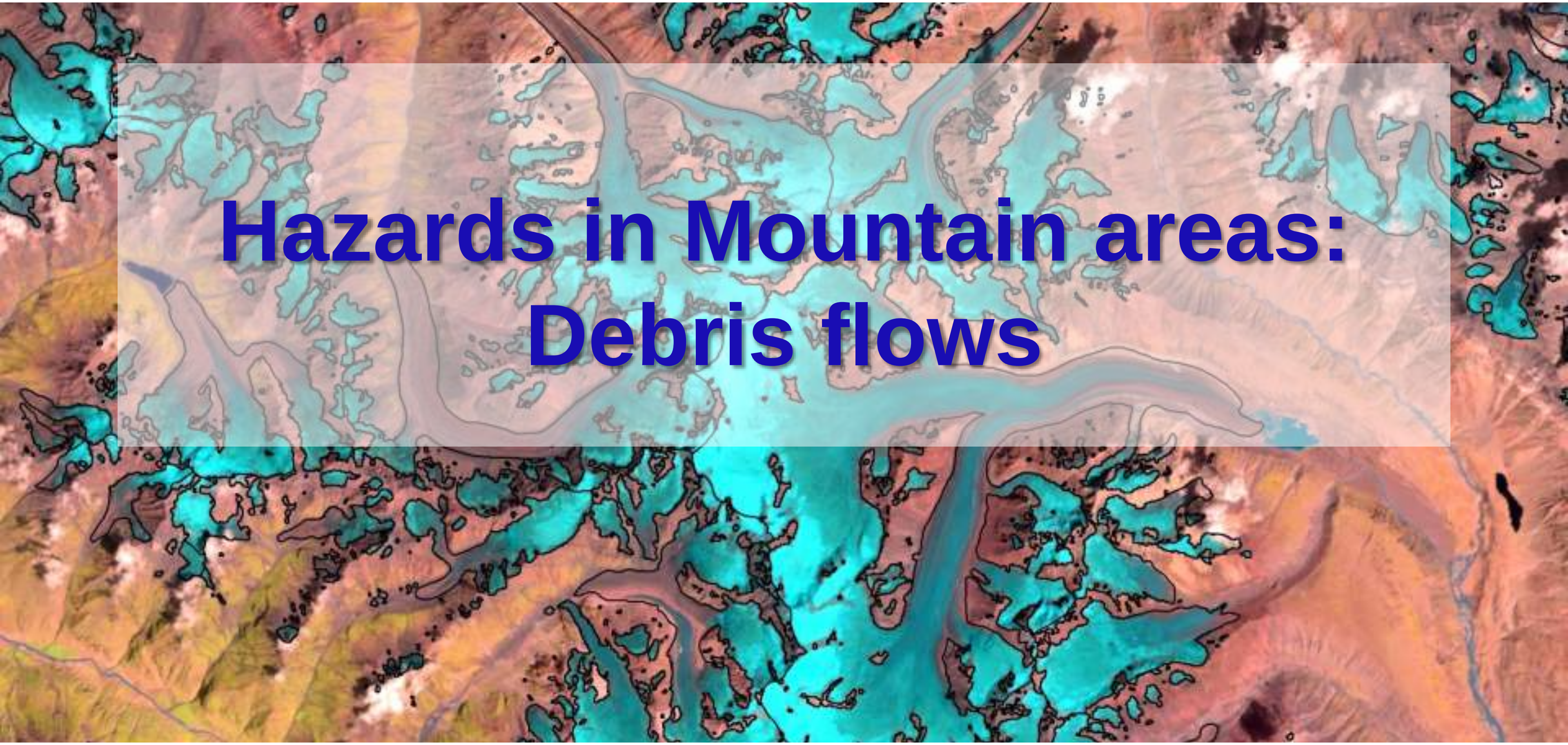

Hazards in Mountain areas: Debris flows

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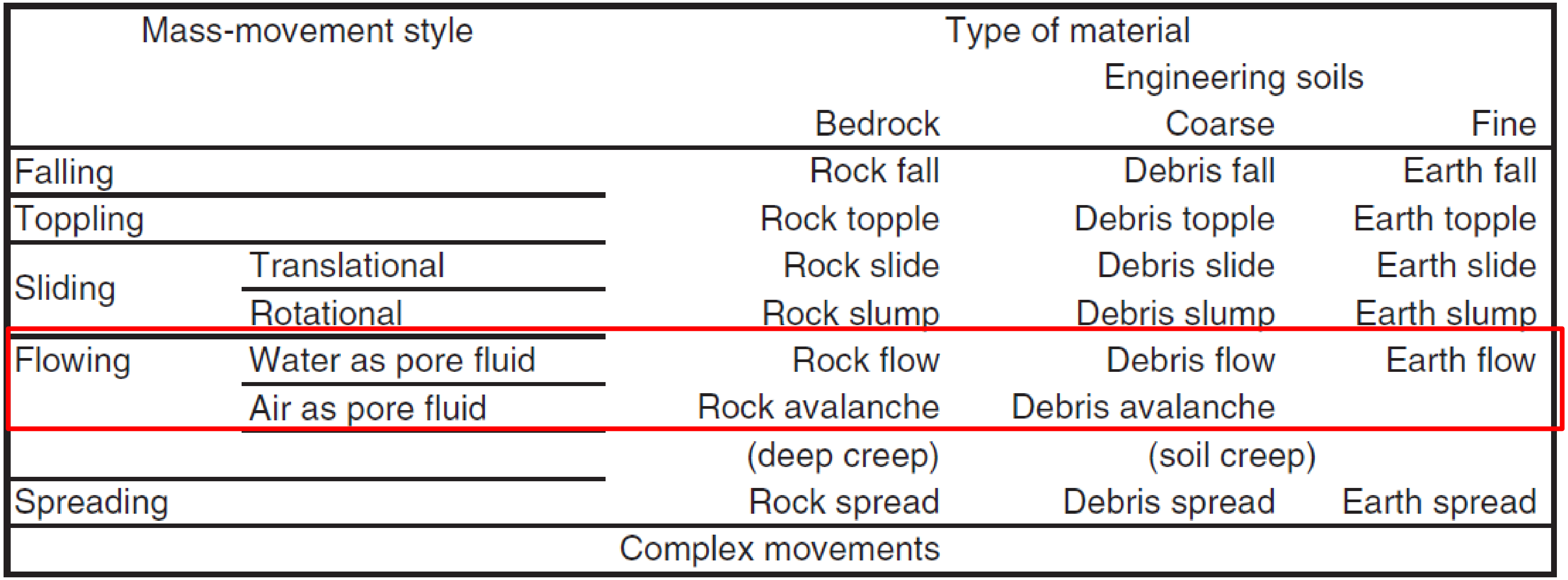
Mass movement types



Mass-movement style		Type of material		
			Engineering soils	
		Bedrock	Coarse	Fine
Falling		Rock fall	Debris fall	Earth fall
Toppling		Rock topple	Debris topple	Earth topple
Sliding	Translational	Rock slide	Debris slide	Earth slide
	Rotational	Rock slump	Debris slump	Earth slump
Flowing	Water as pore fluid	Rock flow	Debris flow	Earth flow
	Air as pore fluid	Rock avalanche	Debris avalanche	
		(deep creep)	(soil creep)	
Spreading		Rock spread	Debris spread	Earth spread
		Complex movements		

Source: Varnes, D.J., 1978. Slope movement types and processes. In: Schuster, R.L., Krizek, R.J. (Eds.), Landslides: Analysis and Control. TRB Special Report 176. Transportation Research Board, National Research Council, Washington, DC, pp. 11–33.

Debris flow

Debris flow

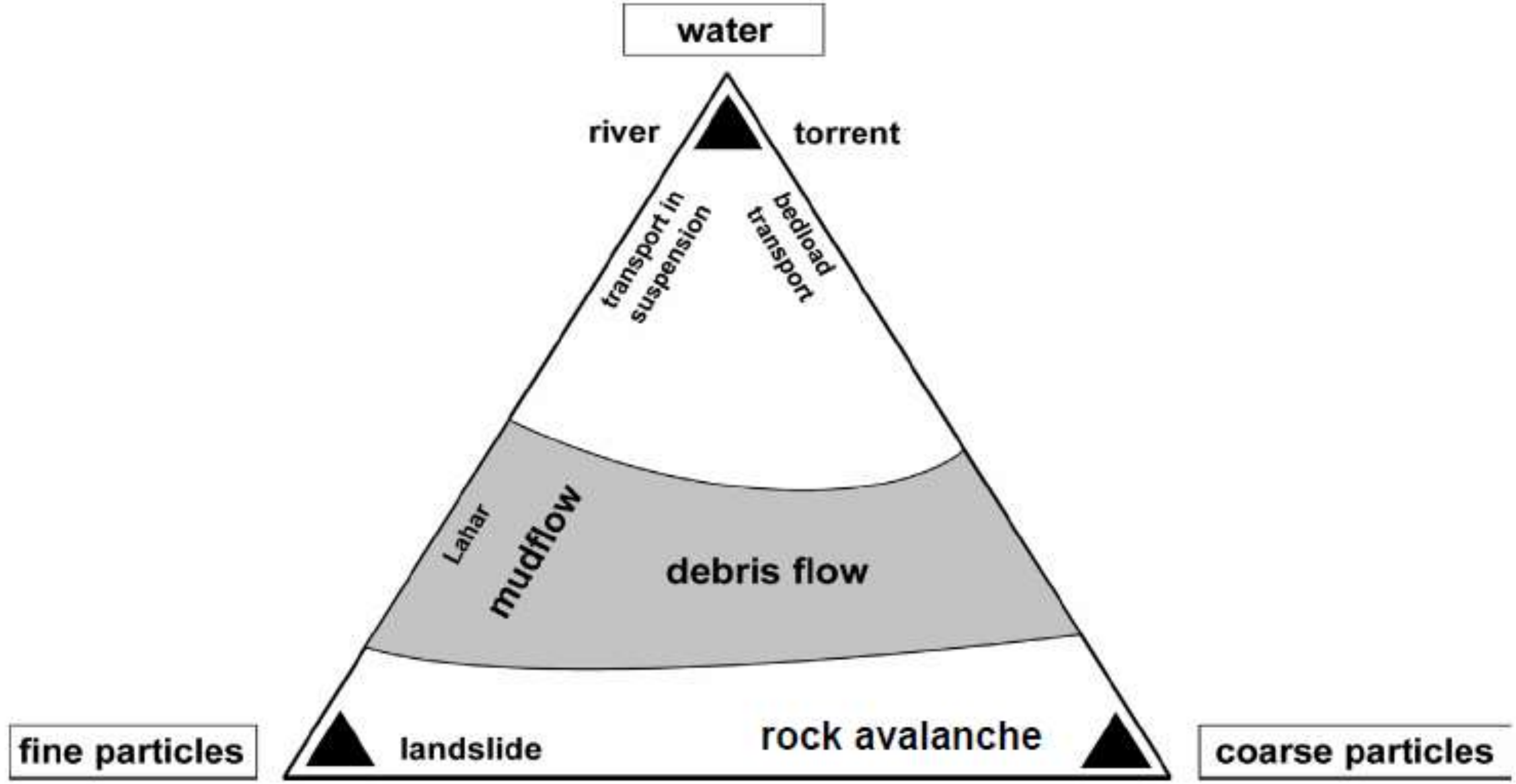
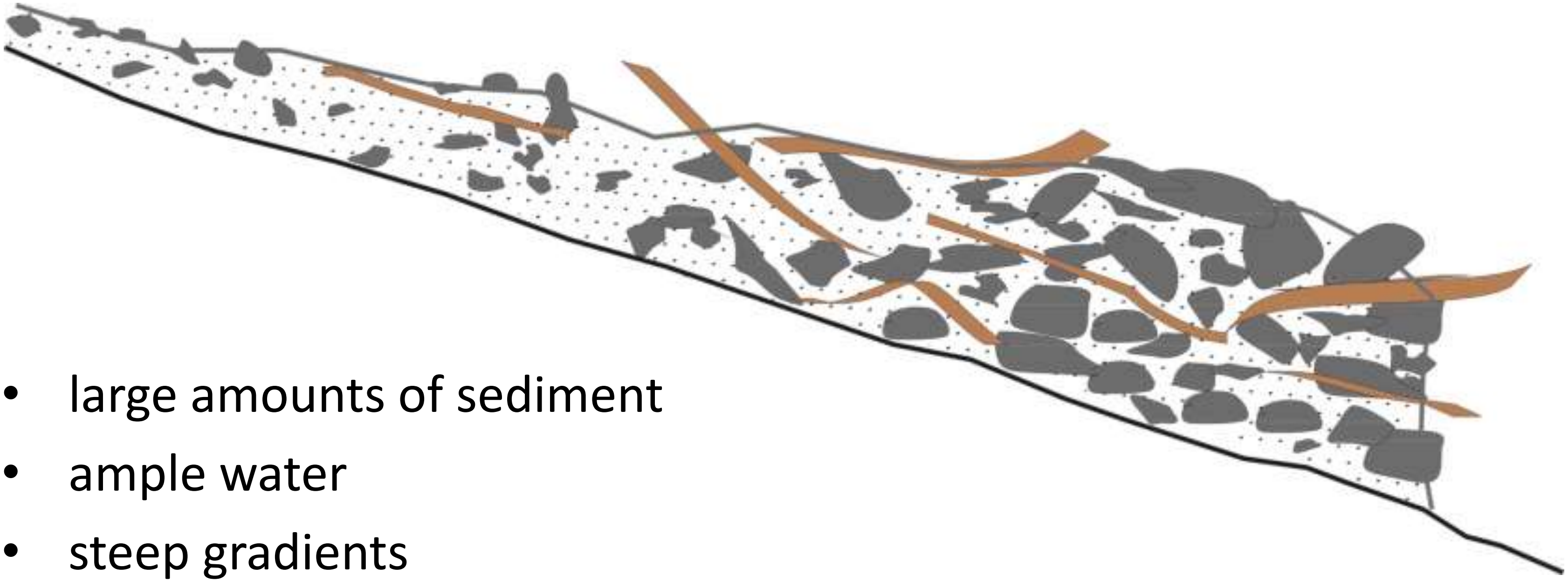


Figure 5: Ternary phase diagram of a debris flows and rapid mass movements (modified from Phillips and Davies, 1991).

Debris flow

- Debris flow = fast moving mixture of unconsolidated water and debris. Their movement is often compared to flowing lava or concrete. A debris flow behaves as Bingham plastics, it is a visco-plastic material that behaves as a rigid body at low stresses but flows as a viscous fluid at high stress (like toothpaste or ketchup…).



- large amounts of sediment
- ample water
- steep gradients

Debris flow

Table 1: Debris flows: likelihood of occurrence and risk class (from Rickenmann, 1995).

Initiation zone: channel or side-slope gradient	Characteristics of channel and debris potential F (gullies and side-slopes)	Risk class
J > 25%	channel in loose material, larger slope instabilities possible (F>10'000 m^3)	A1
	channel primarily in loose material (F=1'000 to 10'000 m^3)	A2
	channel primarily in bedrock (F<1'000 m^3)	B
15% < J < 25%	channel in slate or flysch-like rocks, slope instabilities possible (F>10'000 m^3)	A1
	other rock types, temporary flow blockage possible in channel (F>10'000 m^3)	A2
	channel without possibility for flow blockage (F=1'000 to 10'000 m^3)	B
	channel primarily in bedrock (F<1'000 m^3)	C
J < 15%	not relevant	C

Risk classes:

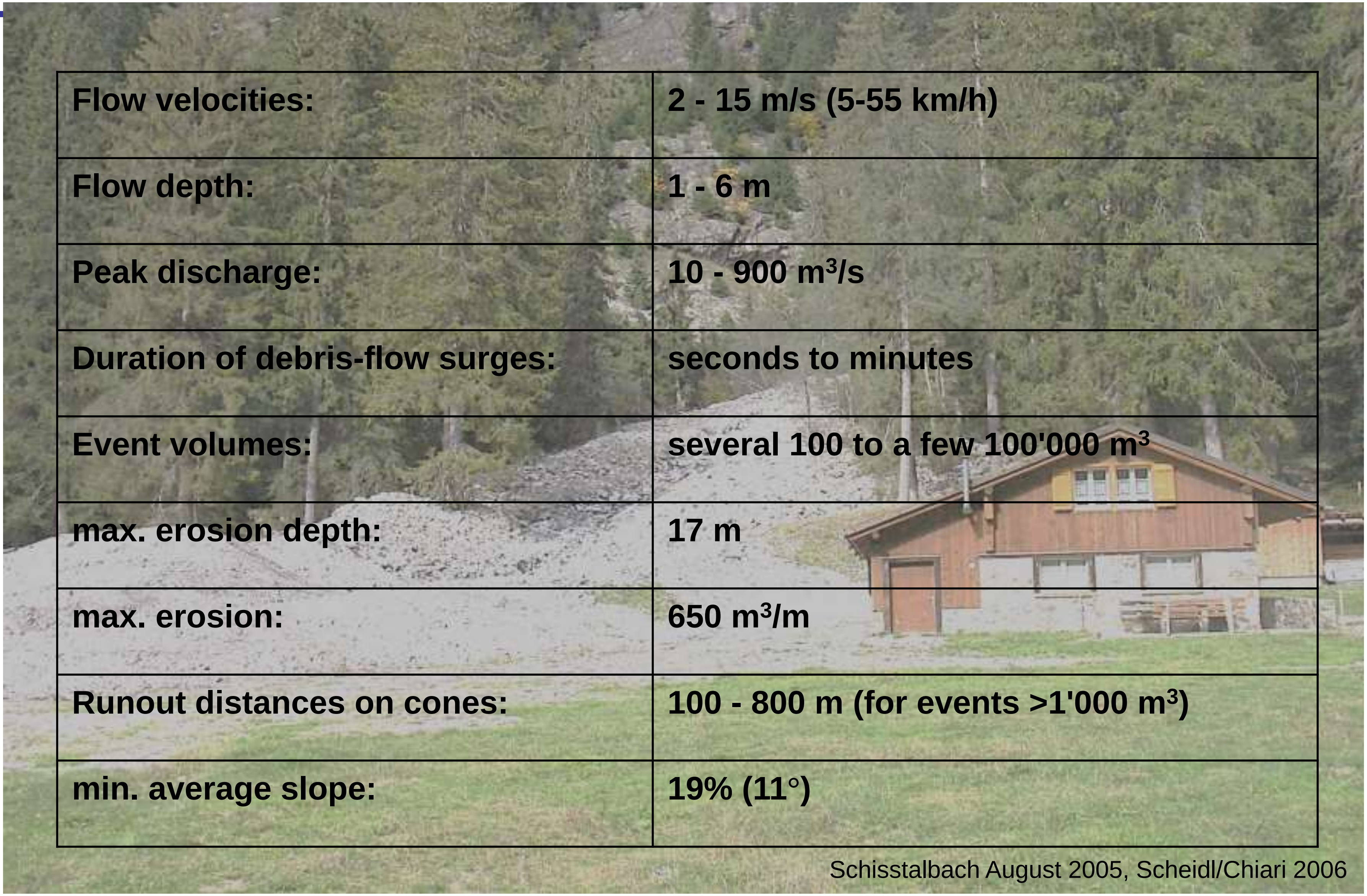
A1 - strong risk of debris flows

A2 - risk of debris flows

B - weak risk of debris flows

C - almost no risk of debris flows

Typical values of debris flows in Switzerland

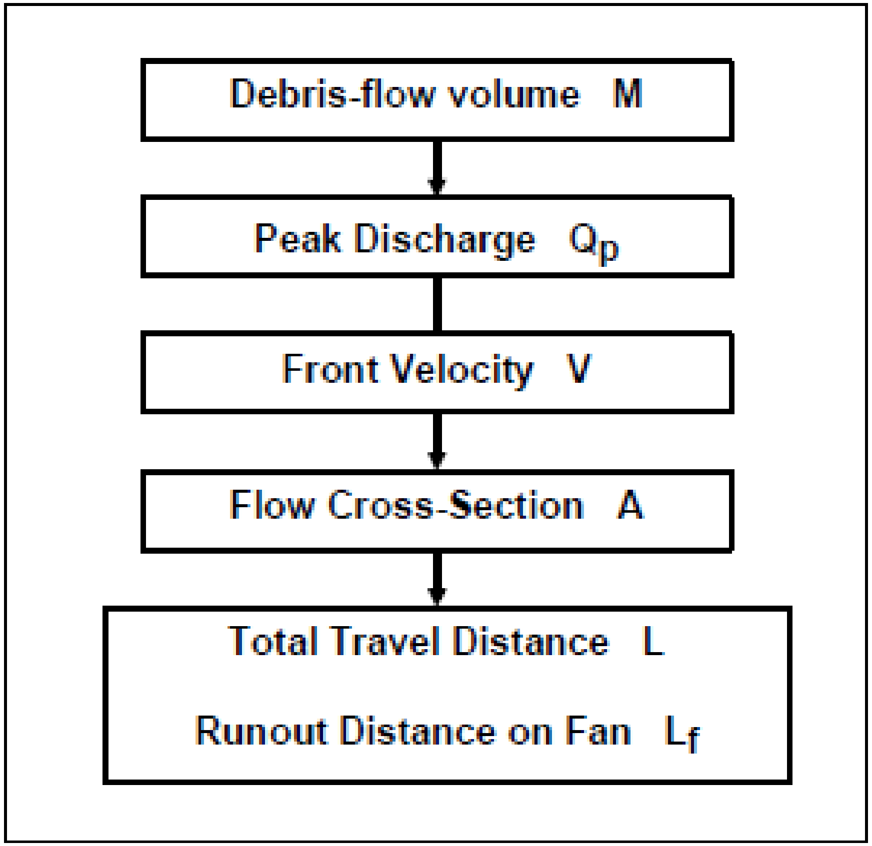


Flow velocities:	**2 - 15 m/s (5-55 km/h)**
Flow depth:	**1 - 6 m**
Peak discharge:	**10 - 900 m^3/s**
Duration of debris-flow surges:	**seconds to minutes**
Event volumes:	**several 100 to a few 100'000 m^3**
max. erosion depth:	**17 m**
max. erosion:	**650 m^3/m**
Runout distances on cones:	**100 - 800 m (for events >1'000 m^3)**
min. average slope:	**19% (11°)**

Schisstalbach August 2005, Scheidl/Chiari 2006

Debris flow

Debris flow Parameters



Debris-flow volume M

Peak Discharge Q_p

Front Velocity V

Flow Cross-Section A

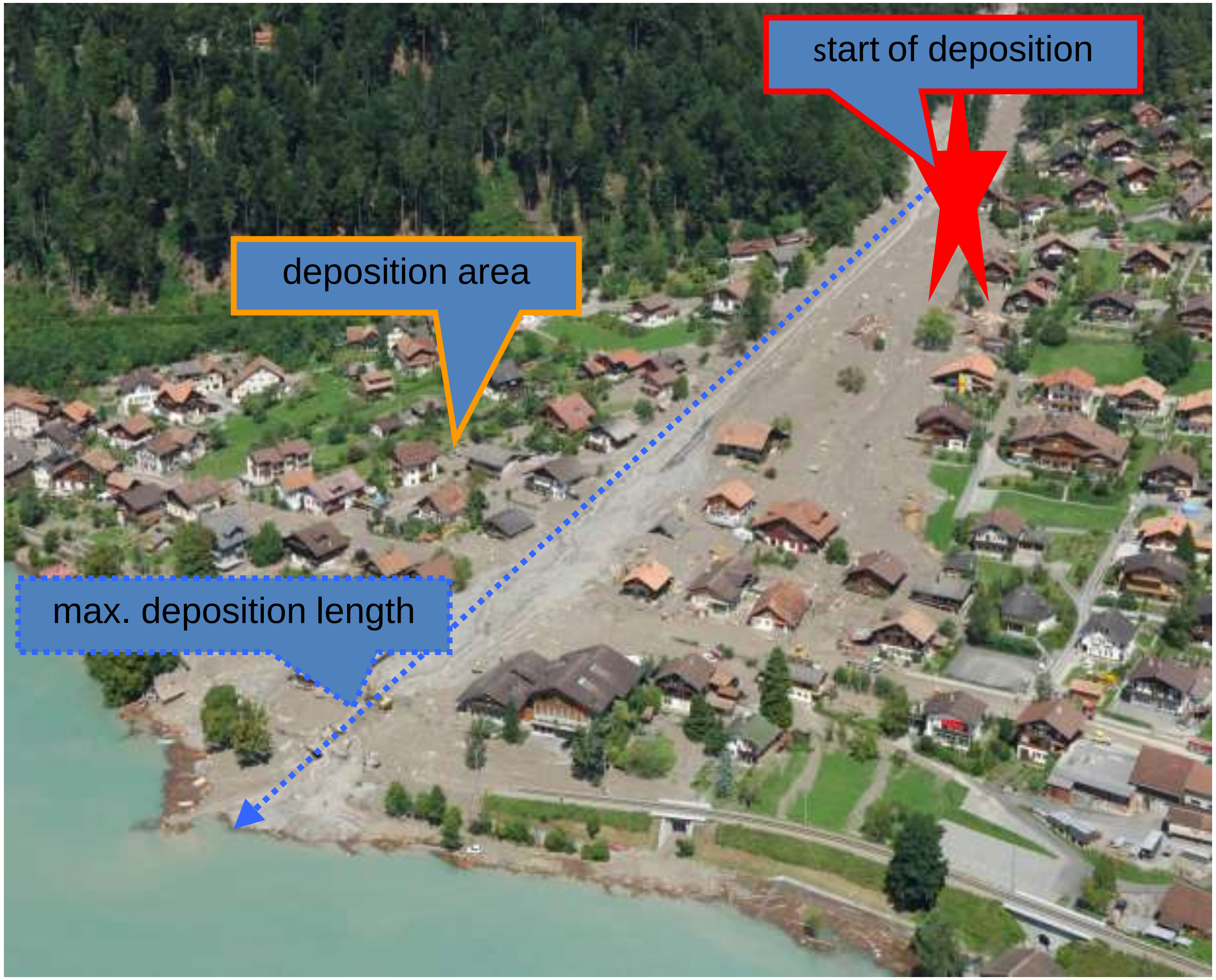
Total Travel Distance L

Runout Distance on Fan L_f

Figure 1: Sequence of estimating debris-flow parameters using empirical formulae (from Rickenmann, 1999).

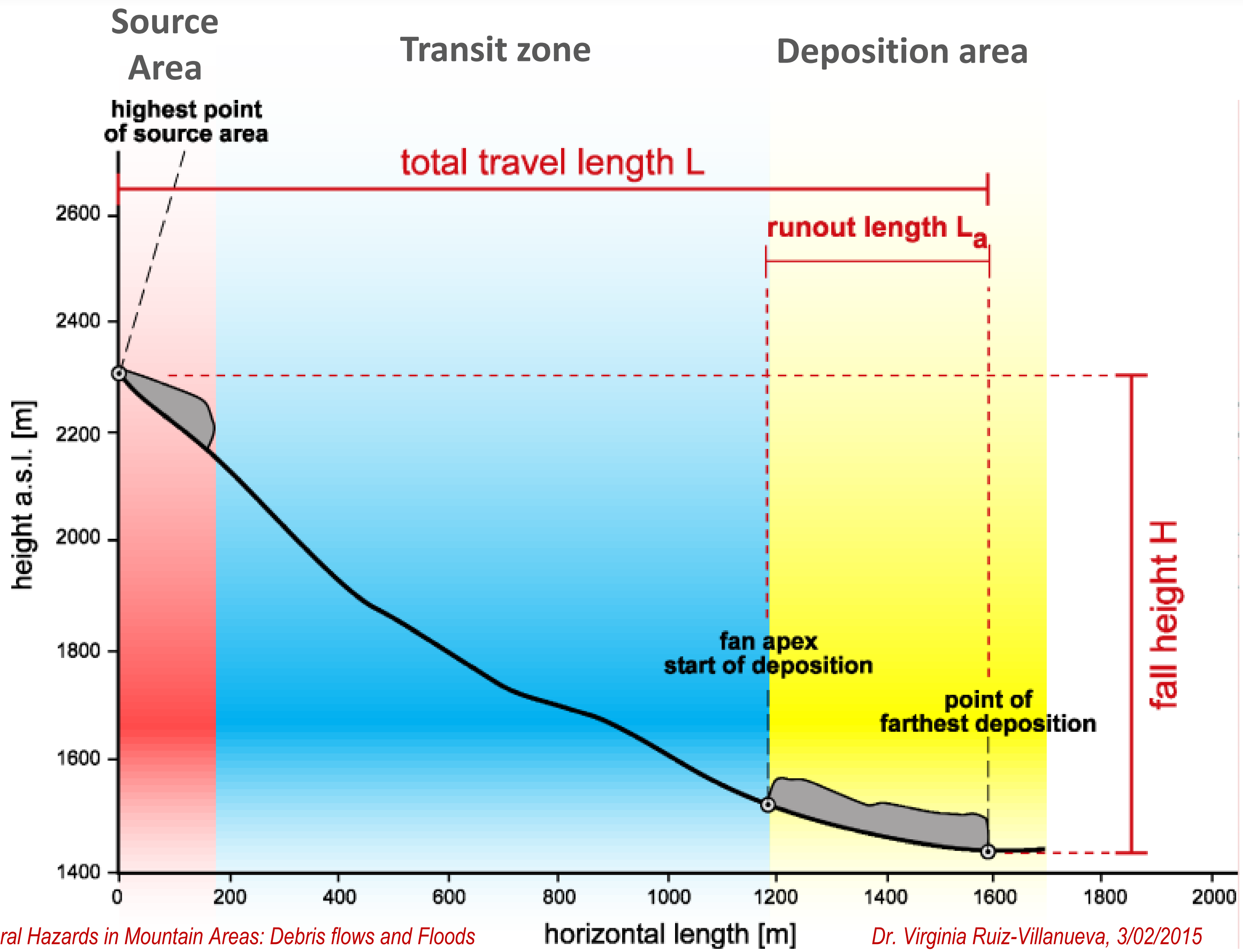
Debris flow Parameters

The term runout of debris flows refer to the length and form of the deposit area.



Event: Glyssibach August 2005,
© Schweizer Luftwaffe 2005

Geometry


Source Area
Transit zone
Deposition area
highest point of source area
total travel length L
runout length L_a
fan apex start of deposition
point of farthest deposition
fall height H
height a.s.l. [m]
2600
2400
2200
2000
1800
1600
1400
0
200
400
600
800
1000
1200
1400
1600
1800
2000
horizontal length [m]

Debris flow patterns

Runout pattern

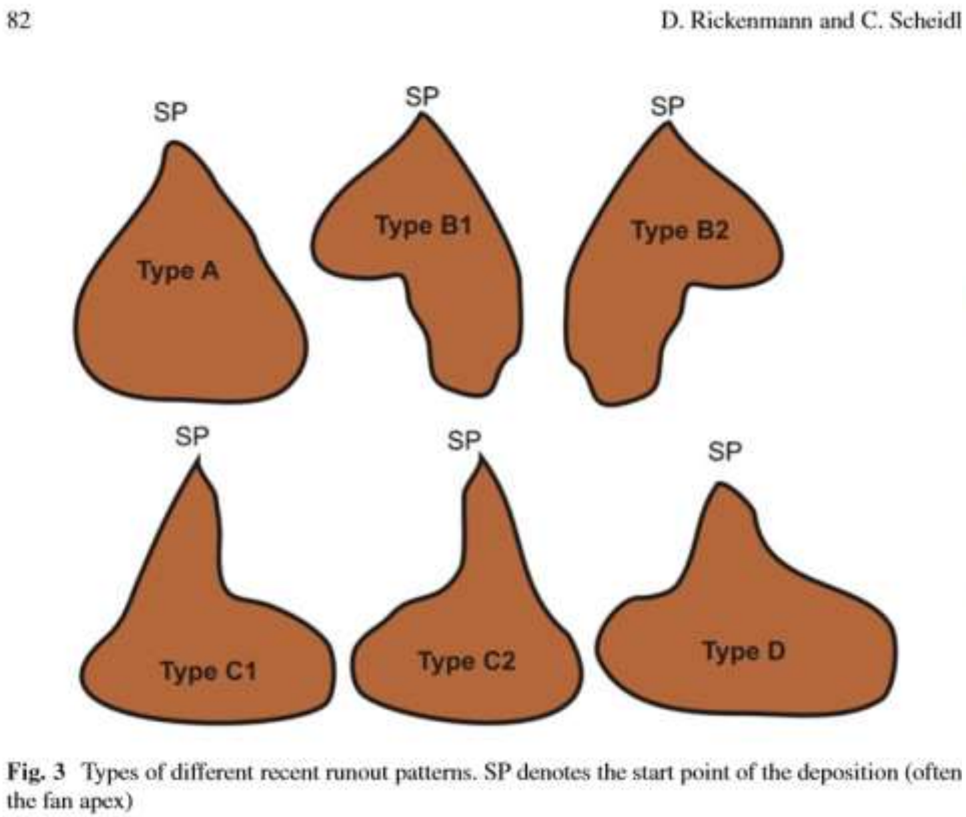


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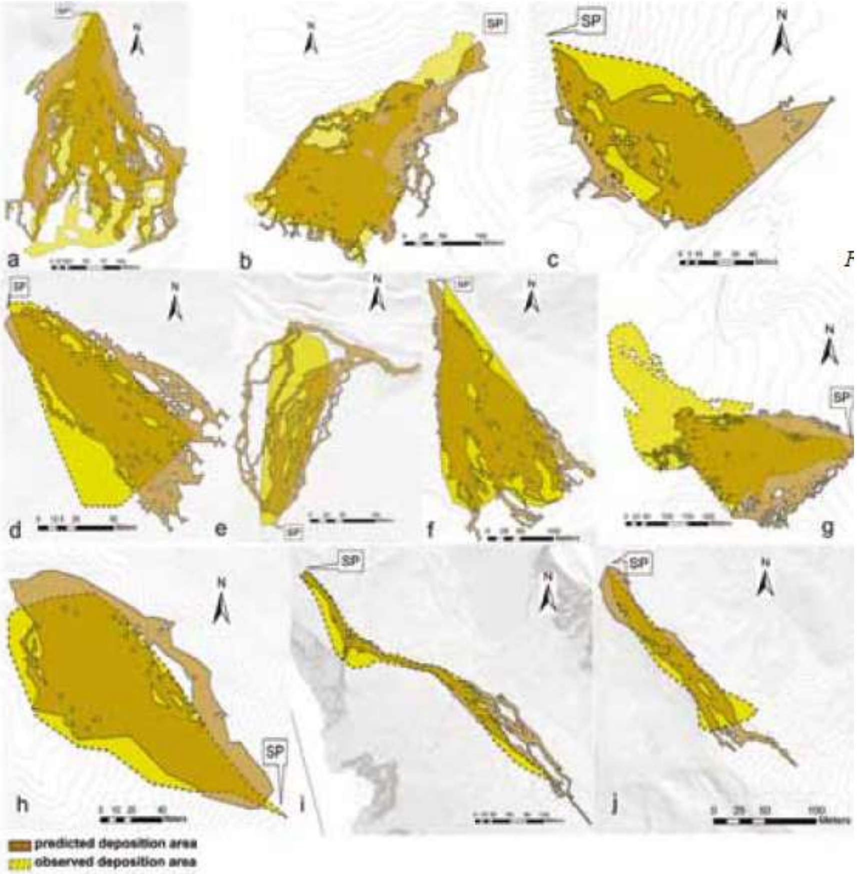
Fig. 3 Types of different recent runout patterns. SP denotes the start point of the deposition (often the fan apex)



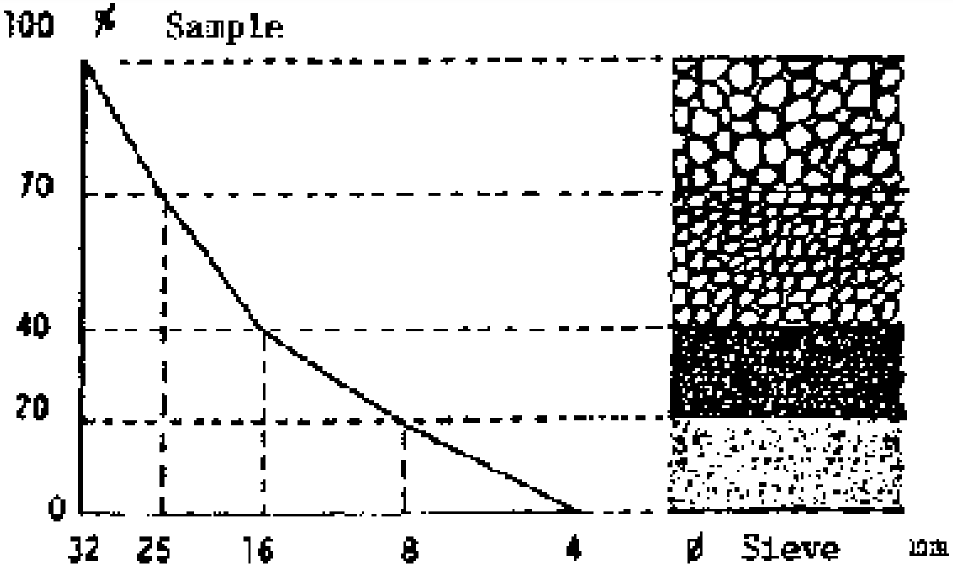
Debris flow field investigations

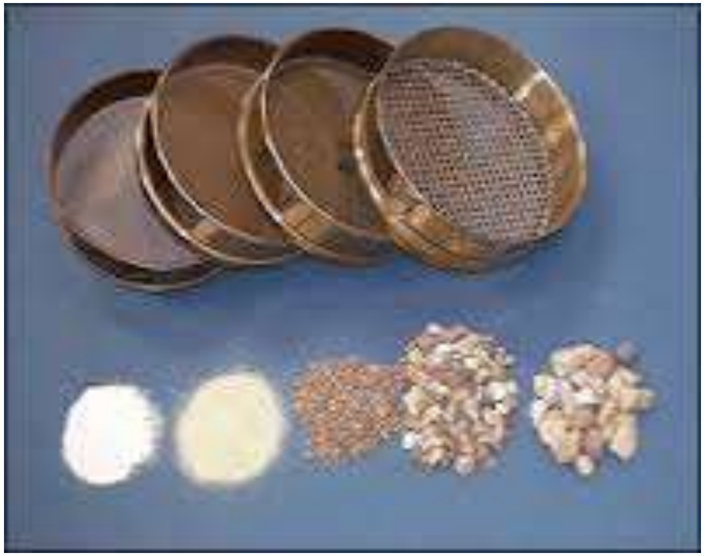
To determine the rheological parameter values characterising the behaviour of a debris flow:

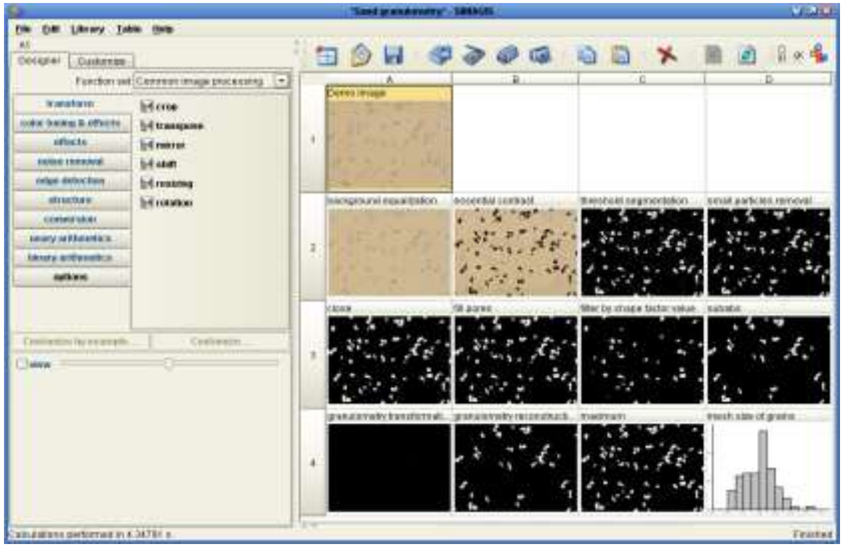
- a grain-size analysis
- rheological analysis

the choice of the sampling point is important

Debris flow field investigations: grain-size analysis



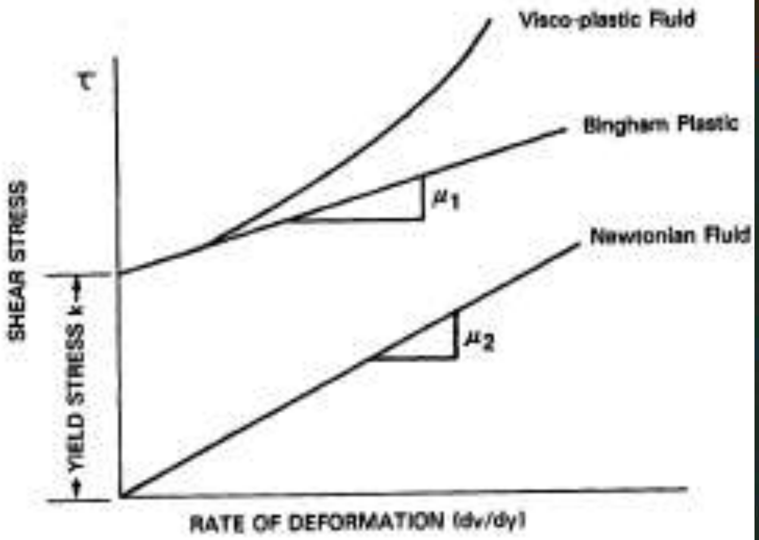


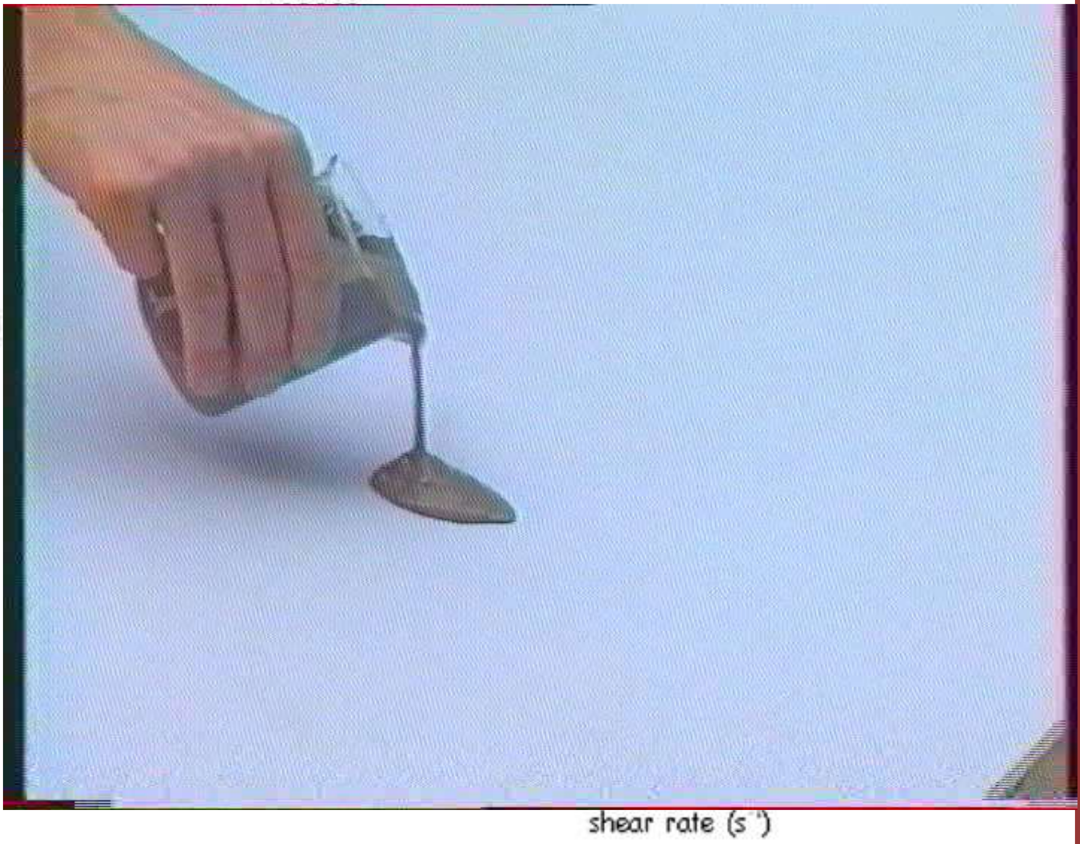


Debris flow field investigations: rheological analysis

The rheological study concerned only the fine fraction passing the 0.063 mm sieve.

The aim is to characterise the viscous behaviour of such plastic systems





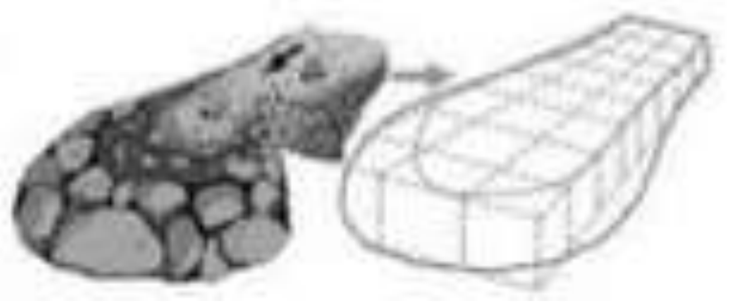
Debris flow can be related with a Bingham model

Debris flow analysis

- Empirical approach
  - Volume-loss rate method
  - Channel geometry method
  - The angle of reach method
  - Geometrical method
- Physical scale modeling
- Dynamic modeling
  - Lumped mass method
  - Distinct element method
  - Continuum method
    - Analytical solution
    - Numerical simulation

Figure 5 Summary of the run-out prediction approaches (adapted from: Chen & Lee (2004))

Debris flow analysis



numerical models can simulate the total runout distance, the velocity and flow depth at each point along the flow path

A number of models are based on a **rheological formulation for a Bingham or viscoplastic** fluid (Laigle and Coussot, 1997; Fraccarollo and Papa, 2000; Imran et al., 2001)

some of them including a friction term accounting for **channel roughness** and **turbulence** (Han and Wang, 1996; Jin and Fread, 1999).

In several model applications, the **Voellmy fluid flow rheology (friction)** was successfully used for back-calculating velocity and runout distance of debris flows (e.g. Jakob et al., 2000; Hürlimann et. al., 2003b; Revellino et al., 2004; Naef et al., 2006).

appropriate values for the rheological parameters are assumed or back-estimated from field observations

Debris flow modelling

1- Dimensional (1-D)		2-Dimensional (2-D)	
Empirical/statistical	**Dynamical**	**Empirical/statistical**	**Dynamical**
• Corominas (1996) • Rickenmann(1999) • ACS Method (Prochaska, 2008)	• Takahashi, Yoshida (1979), Hungr et al. (1984), Takahashi (1991)	• Laharz (Iverson et al. 1998) • Dflowz (Berti & Simoni, 2007) • TopRun DF (Scheidl & Rickenmann, 2009)	• FLO-2D (O'Brien et al., 1993) • RAMMS (Christen et al., 2010) • FLAT-Model (Medina et al., 2008) • TopFlow DF (Scheidl & Rickenmann, 2011)

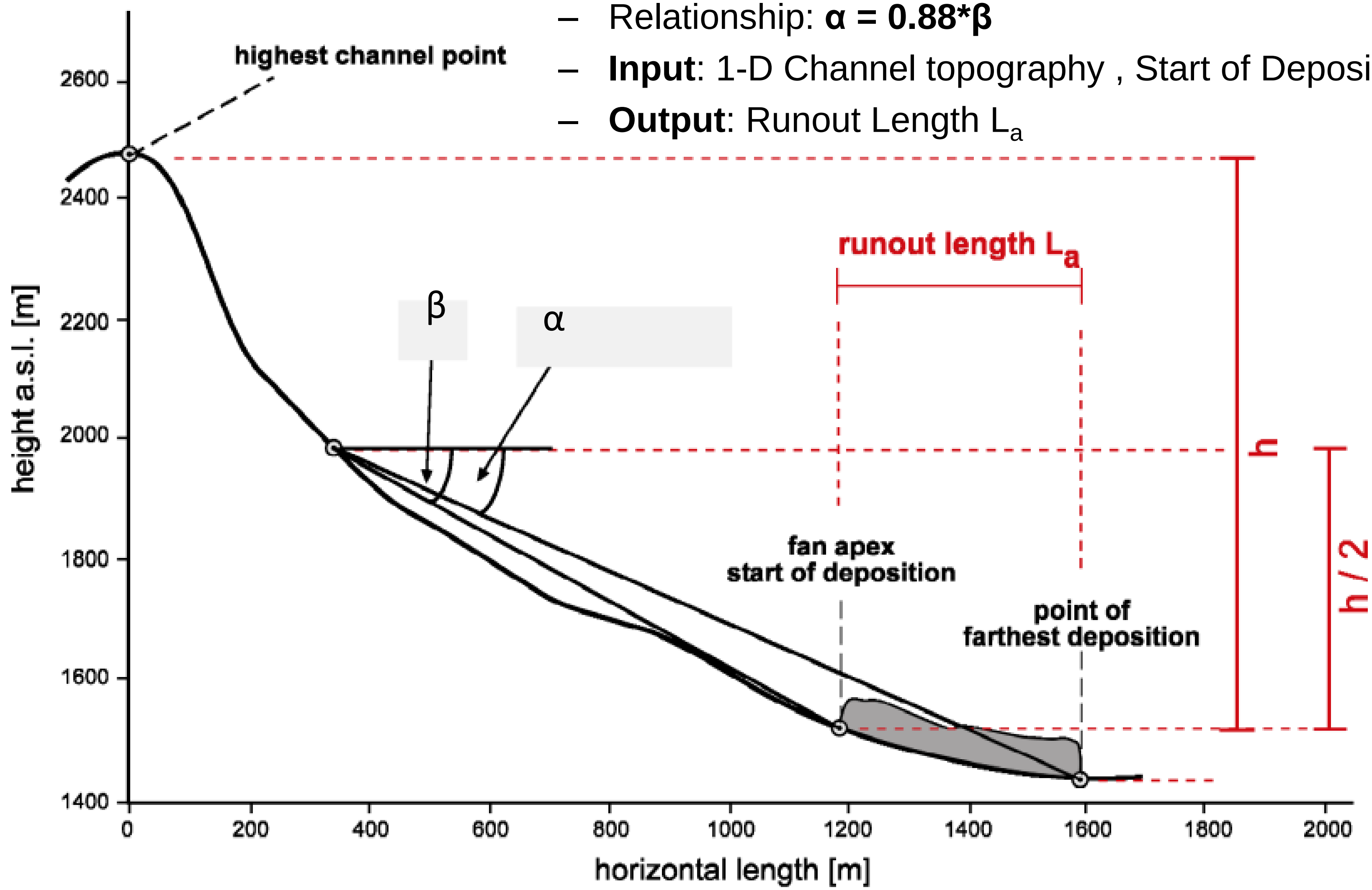
The choice of the appropriate model depends on:

- Prevailing conditions (geology, morphology, hydrology, human influence)
- **Quantity and quality of available information**
- Purpose of simulation results
- Cost-effectiveness considerations

1D: average channel slope (ACS)

Prochaska, (2008)

- Relationship: **$\alpha = 0.88 * \beta$**
- **Input**: 1-D Channel topography , Start of Deposition
- **Output**: Runout Length L_a



1D: Empiric-statistical approaches

- Corominas (1996)
  - Relationship: **$L = 1.03 * V^{0.105} * H$**
  - Input: 1-D channel topography; Debris Flow Volume, Location of release area
  - Output: Total Travel Length L

- Rickenmann (1999,2005)
  - Relationship: **$L = 1.9 * V^{0.16} * H^{0.83}$**
  - Input: 1-D channel topography; Debris Flow Volume, Location of release area
  - Output: Total Travel Length L

1D: Empiric-statistical approaches

The total travel or runout distance, *L*, of a debris flow may be important to know for a rough delineation of potentially endangered areas (as for example made in hazard index maps)

$$f_m = H_e / L$$

He is the elevation difference between the starting point and the lowest point of deposition of the mass movement

mean gradient (f_m)

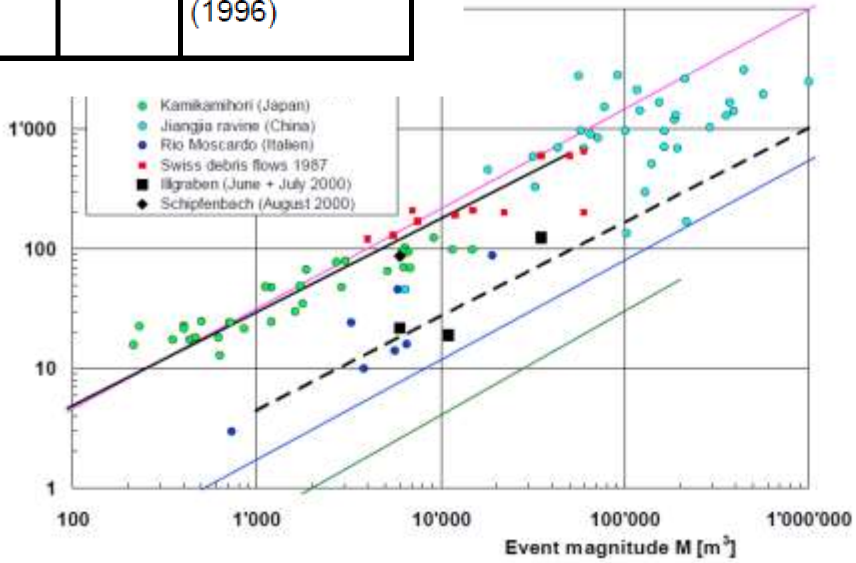
$$f_m = 0.20\, A_c^{-0.20}$$

as a function of the catchment area *Ac* [km2]

1D: Empiric-statistical approaches

Table 2: Empirical formulae relating debris-flow peak discharge and event magnitude (from Rickenmann, 1999).

Flow type	Formula	Eq.	N	r^2	Source
granular debris flows (Japan)	$Q_p = 0.135\ M^{0.780}$	(2)	~ 50	nn	Mizuyama et al. (1992)
muddy debris flows (Japan)	$Q_p = 0.0188\ M^{0.790}$	(3)	~100	nn	Mizuyama et al. (1992)
lahars, Merapi volcano (Indonesia)	$Q_p = 0.00558\ M^{0.831}$	(4)	~200	0.95	Jitousono et al. (1996)
lahars, Sakurajima volcano (Japan)	$Q_p = 0.00135\ M^{0.870}$	(5)	~100	0.81	Jitousono et al. (1996)



1D: Empiric-statistical approaches

To describe the flow velocity of debris flows

The peak or **front flow velocity V** of debris flows may be estimated using a Manning-Strickler type equation (Rickenmann, 1999):

$$V = (1/n)\, h^{0.67}\, S^{0.5}$$

where *h* is the flow depth, *S* is the channel slope, and pseudo-Manning *n* values are around 0.1 $s/m^{1/3}$.

$$V = 2.1\, Q^{0.33}\, S^{0.33}$$

where *V* is in $[m \cdot s^{-1}]$, *Q* in $[m^3 \cdot s^{-1}]$ and *S* is a fraction (sin of the bedslope angle)

Conclusion 1-D

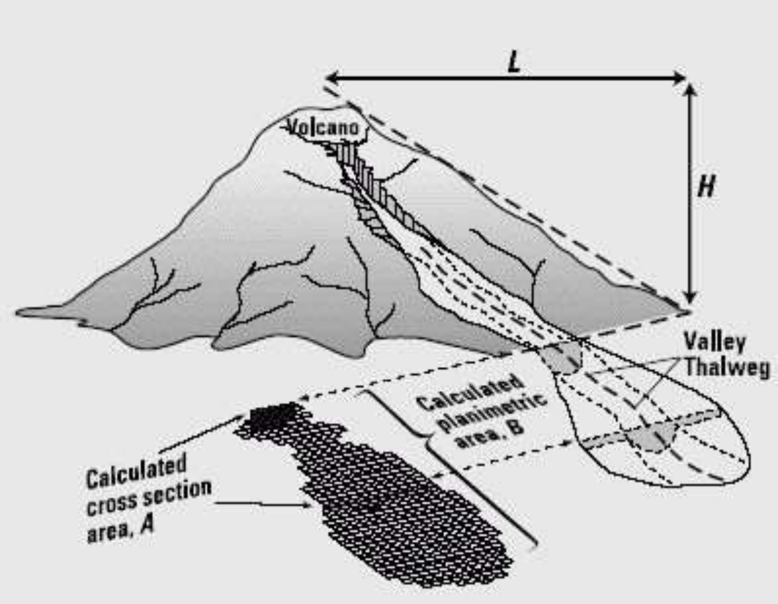
- Application under consideration:
  - Flow path known a priori
  - Sediment source area is clearly identified
  - Lateral spreading on the fan can be neglected (e.g. confined channel) or is of minor interest
  - Considerable uncertainties of predicted runout distances

- Possible Application:
  - Pre-screening of possible runout lengths on a coarser scale
  - Estimation of runout length in clearly confined channels without expected overflowing

2D: Empiric-statistical approaches

LAHARZ (USGS, Iverson et al., 1998)

Runout-prediction of volcanic mudflows (Lahars)



Delineation of lahar-inundation hazard zones (Iverson et al., 1998).

Iverson described the runout of Lahars due to 2 empirical equations:

$$A = 0.05 \cdot V^{2/3}$$

$$B = 200 \cdot V^{2/3}$$

V = Volume
A = Flow Cross Section
B = Deposition Area

2-D Dynamic models

- Flo 2D
  - based on Quadratic rheological model
  - finite difference
  - Commercial code
- RAMMS
  - Simulates 2-phase flows, based on friction relations of Voellmy-Salm
  - Prediction of areas of inundation, inundation level, flow velocity
  - Commercial code
- TopRun DF and TopFlow DF
  - semi-empircal approach with stochastic elements
  - Open-source code

2-D Dynamic models: FLO-2D

FLO-2D is a 2-dimensional flood-routing model based on a model using a quadratic rheological model that includes viscous stress, yield stress, turbulence and dispersive stress terms as a function of sediment concentration.

The model uses the full dynamic wave momentum equation and a central finite difference routing scheme with eight potential flow directions to predict the progression of a flood hydrograph over a system of square grid elements.

(O'Brien and Julien, 1988; Calligaris et al., 2008)

2-D Dynamic models: RAMMS

INPUTS

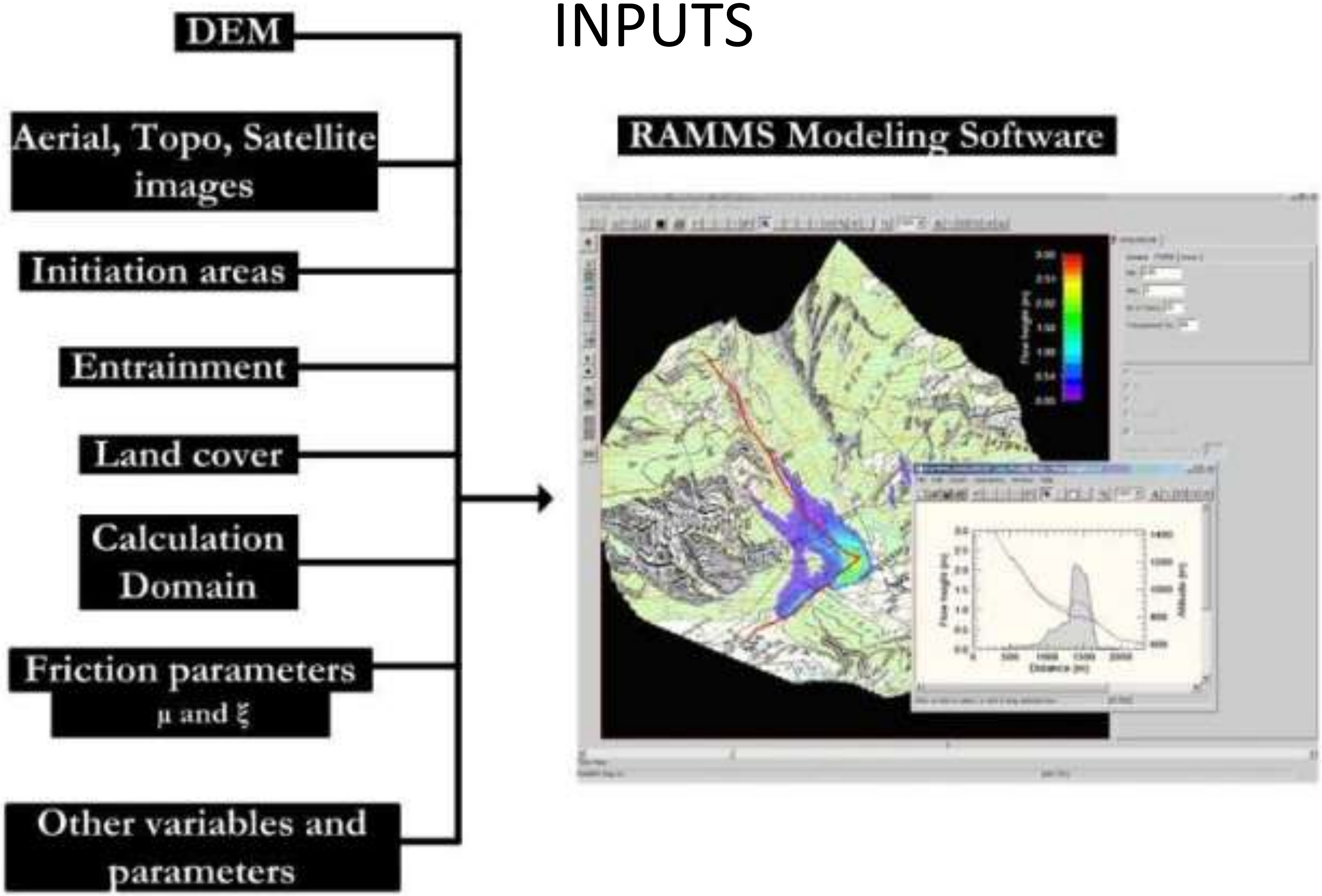
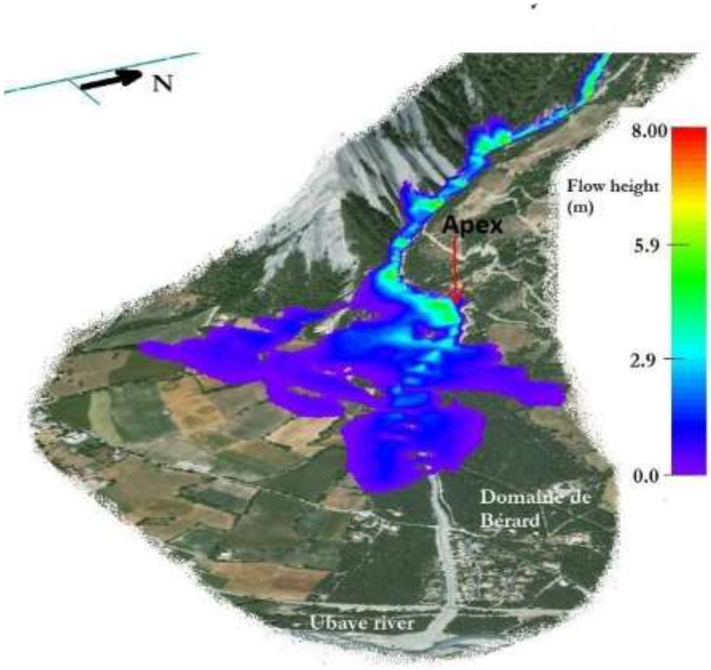


Figure 28 RAMMS inputs and the user interface

2-D Dynamic models: RAMMS

OUTPUTS

- Initiation, entrainment and deposit volumes (m3) at any moment of the flow
- The surface area of the flow (m2) at any moment
- Deposit heights (m)
- velocities (m/s)
- impact pressures (kPa)
- entrainment rates (kg/m2s) and eroded mass (kg) at any moment of the flow
- Longitudinal path profiles and cross sections of the debris flow
- Animations of the entire flow in the GIF file format



HUSSIN, 2011

2-D Dynamic models: RAMMS

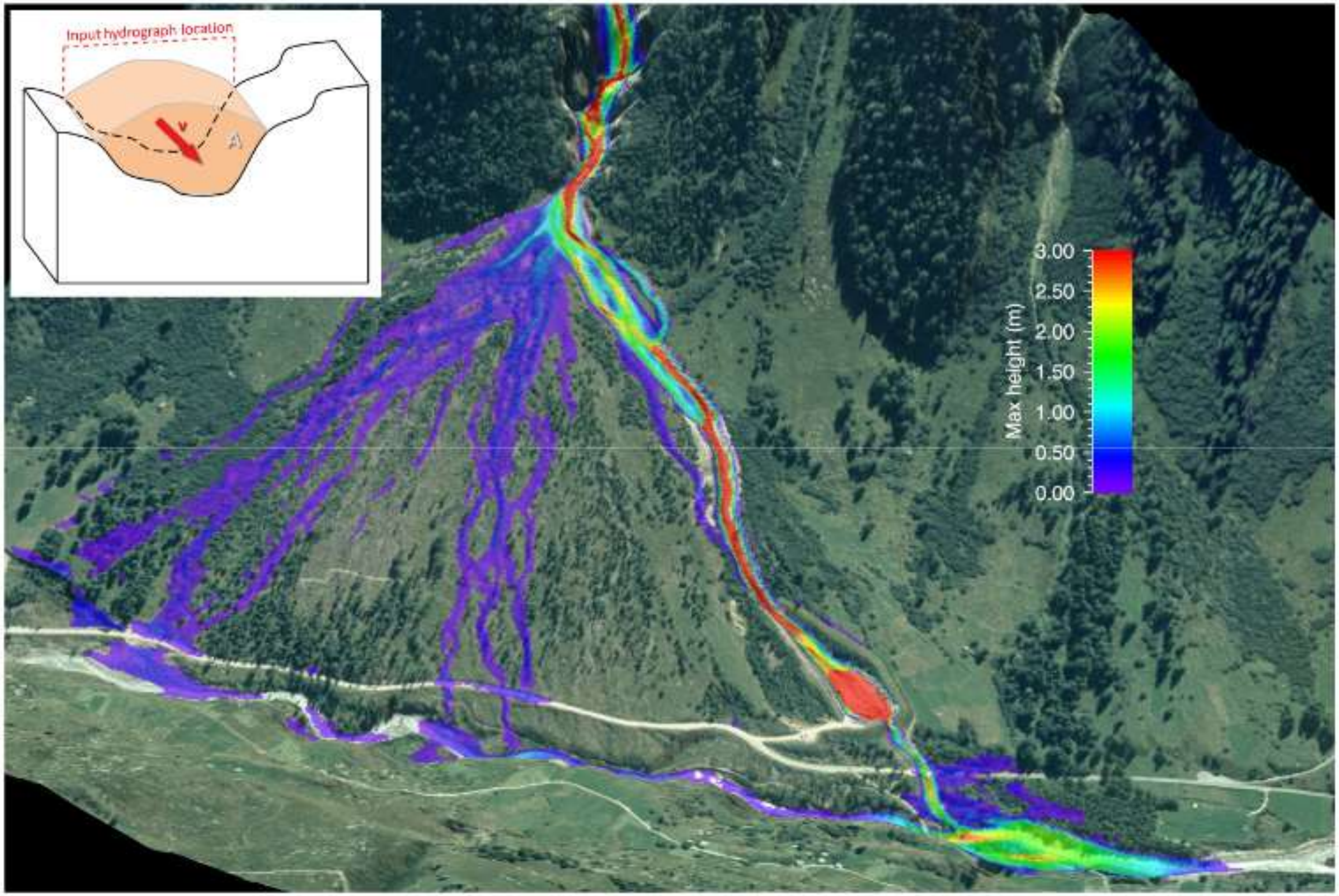


Fig. 3 RAMMS::DEBRIS FLOW simulation, Stampbach, Switzerland. Hydrograph (upper left): discharge Q = A * v (m3/s) where A (m2) is the cross-sectional area of the debris flow and v (m/s) the inflow velocity.

2-D Dynamic models: TopFlow DF

TopFlowDF combines the simple physical approach of the constant discharge model with a random based flow algorithm which is also implemented in the empirical runout prediction model TopRunDF (Sch eidl & Rickenmann, 2010).

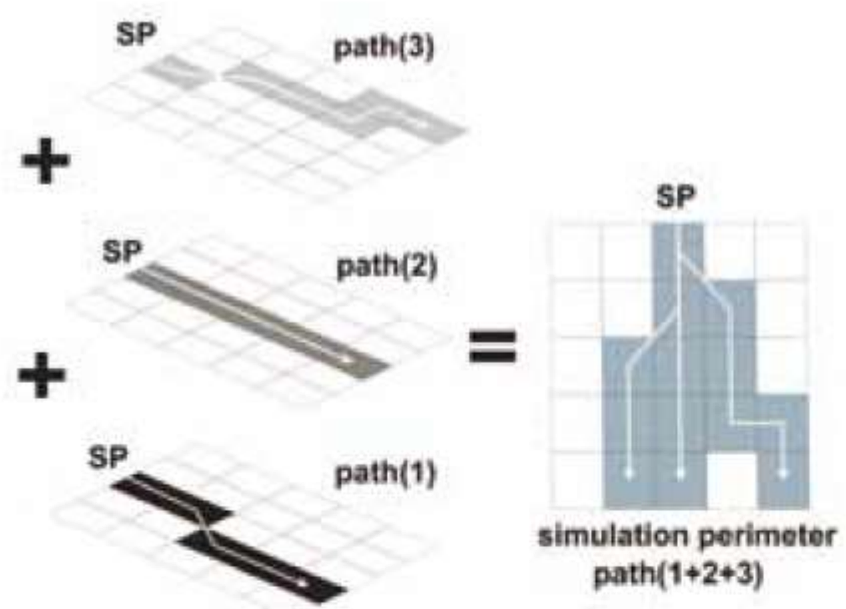


Fig. 3 - Estimation of the simulation perimeter with multiple individual flow pathways. SP denotes the user defined start point

The **input** parameters:

- debris-flow volume,
- a mobility coefficient,
- a starting point of the deposition (fan apex)
- digital terrain model of the fan area

2-D Dynamic models: TopFlow DF

C. SCHEIDL & D. RICKENMANN

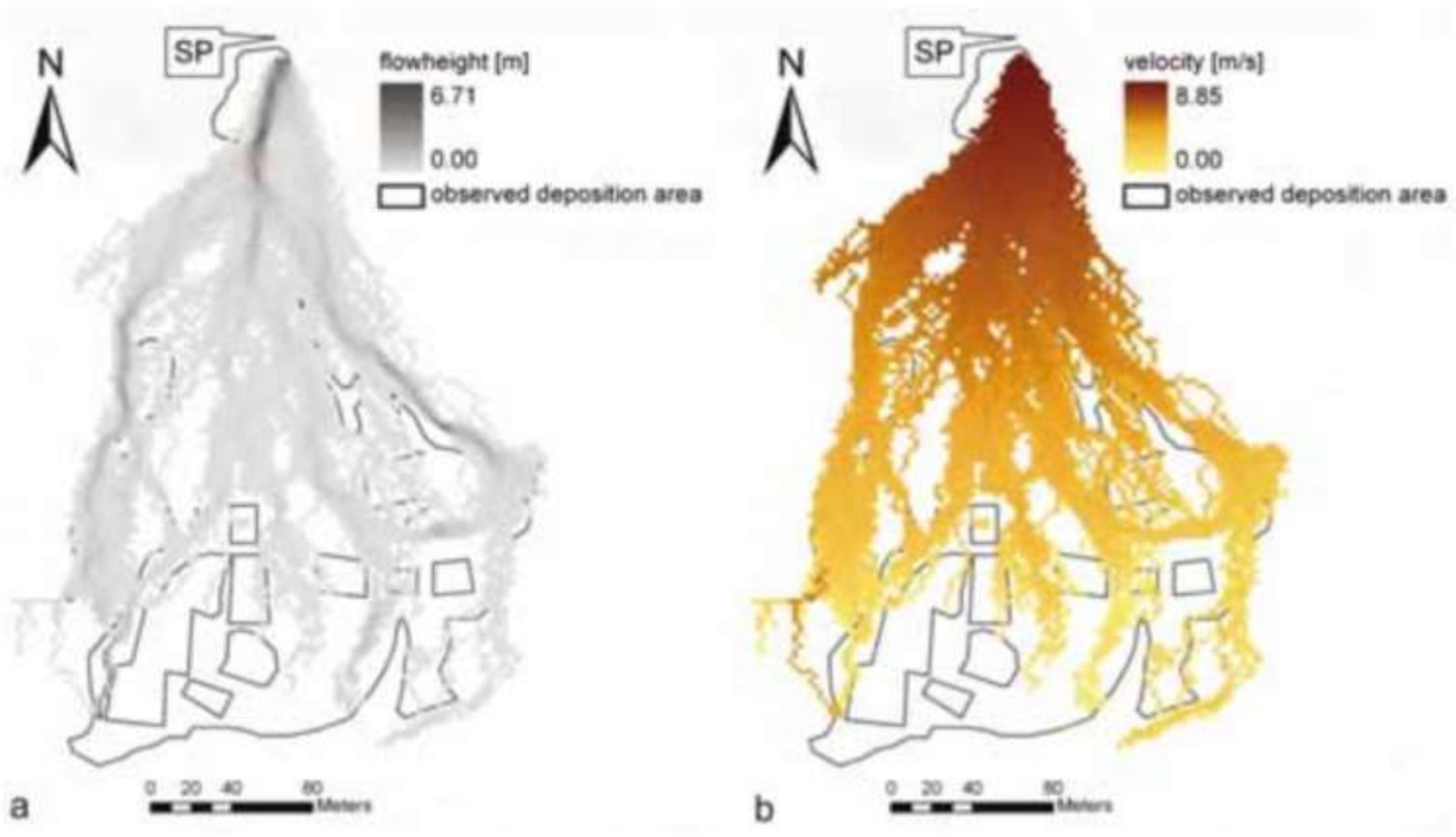
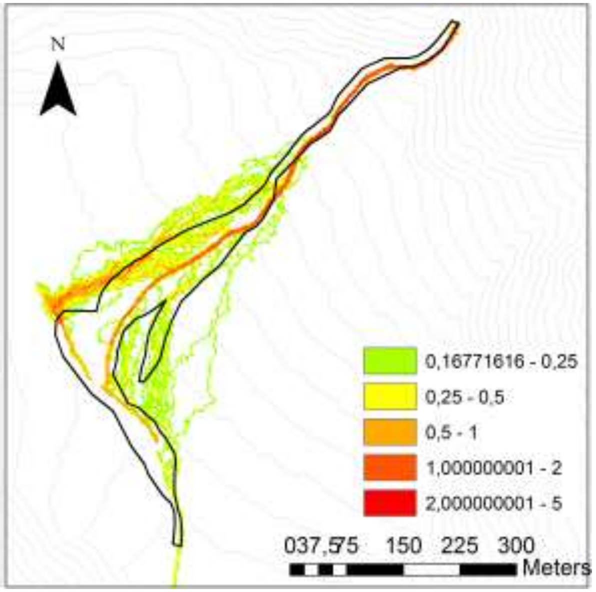


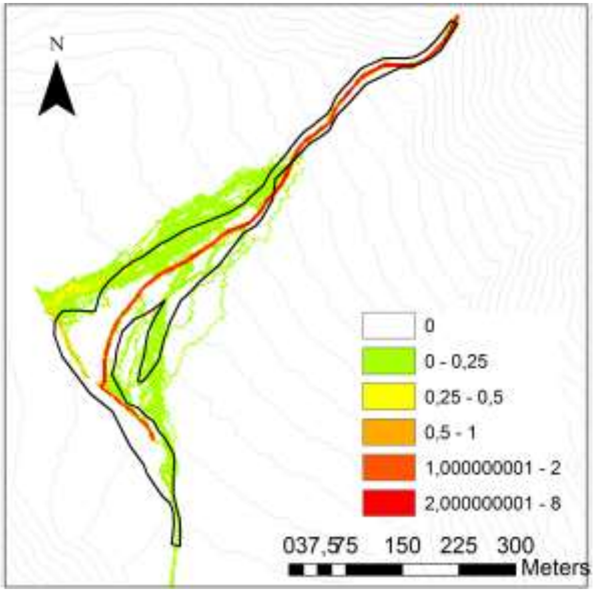
Fig. 4 - Simulation results of TopFlowDF for the Glattbach debris-flow event. a) predicted deposition zones, b) predicted velocity pattern. SP denotes the starting point of the simulation Contour interval is 1 m

2-D Dynamic models

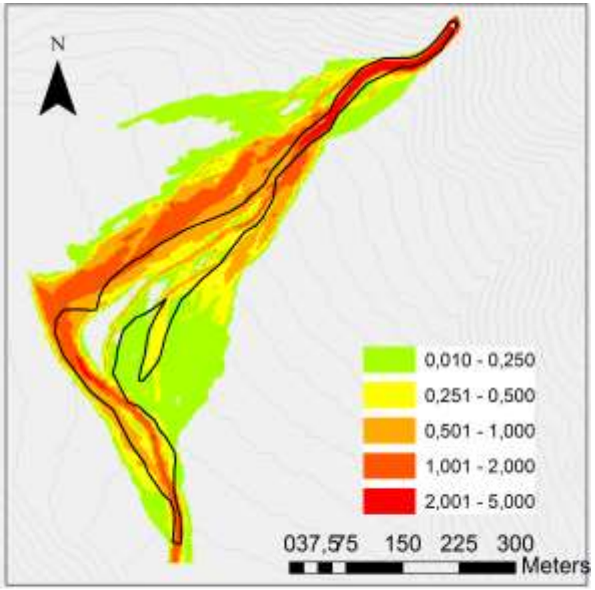
Best fit simulations for Arundakopfbach (South Tyrol):
V_{dok}=15.000 m^3, A_{dok} = 35.500m^2



topRun DF:
MCS = 50
Kb=58

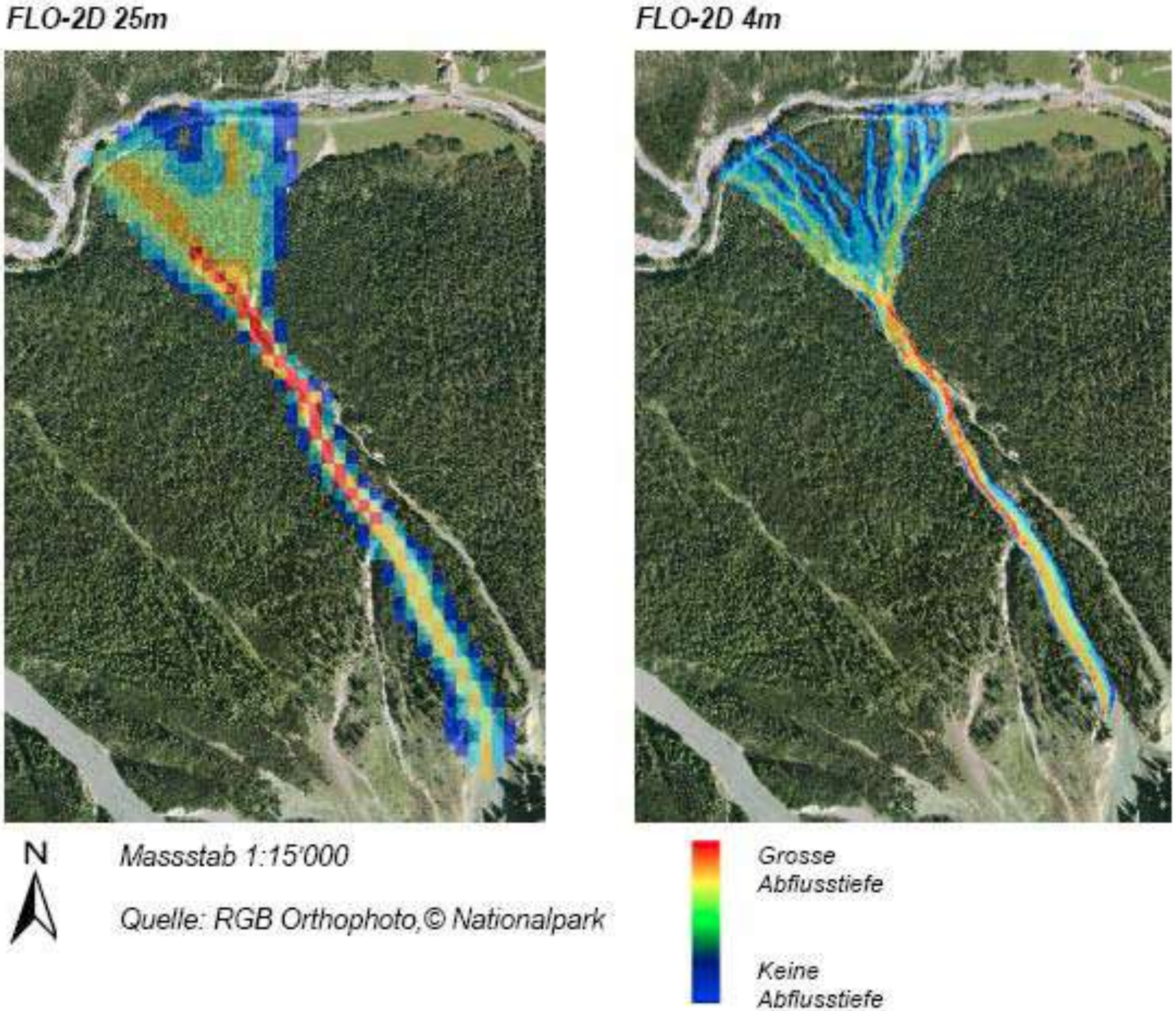


topFlow DF:
MCS = 50
Kb=58
Sfric = 1.032

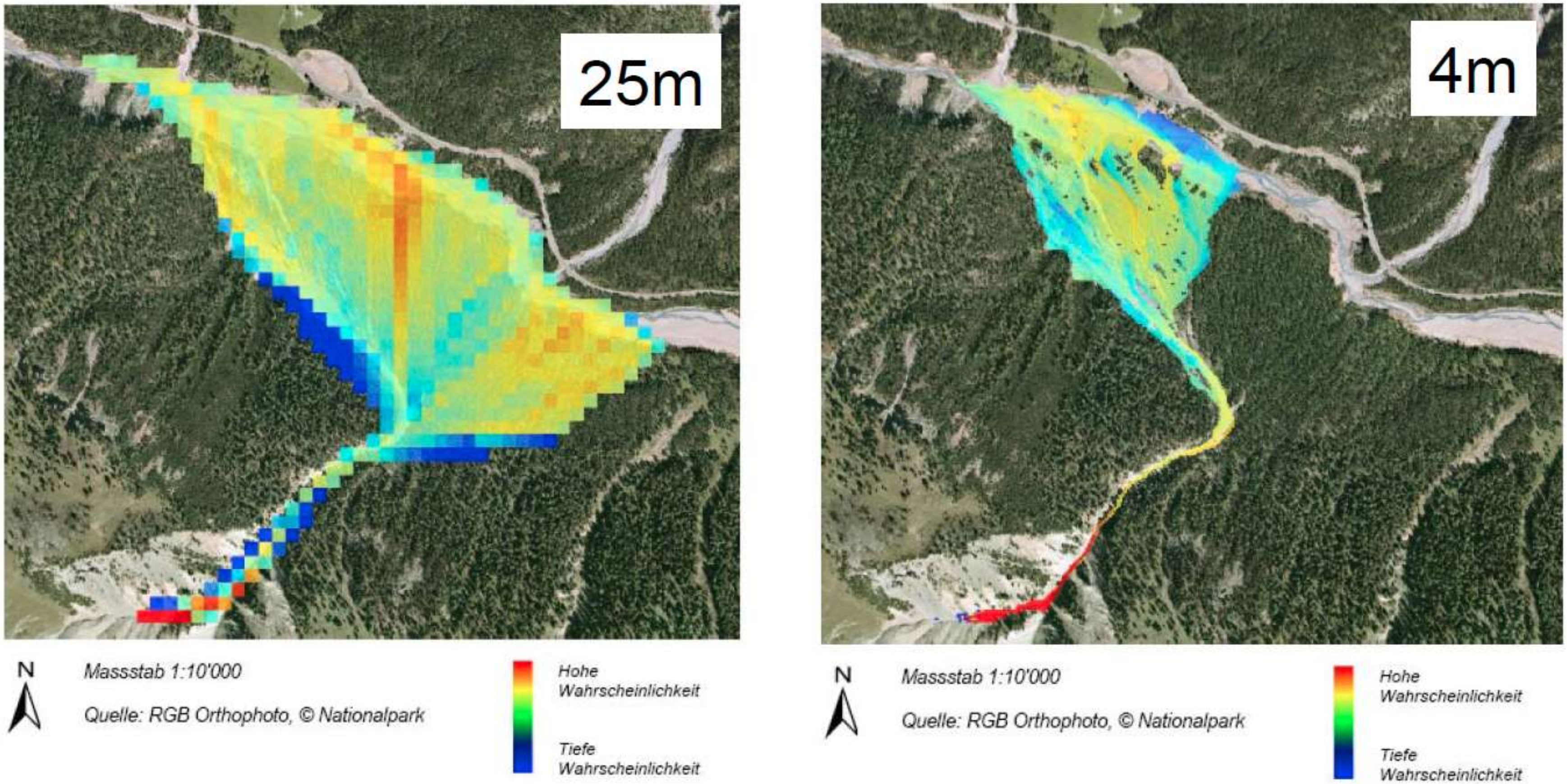


RAMMS:
μ=0.09
ξ = 250
t =

2-D Dynamic models



2-D Dynamic models



Stolz and Huggel, 2008

Debris flow modelling: calibration

The calibration of model parameters can be best developed through the back-analysis of historic events

Debris flows are **complex phenomena**, due to spatial and temporal variability in material properties (Sosio et al., 2007; Scotto Di Santolo and Evangelista, 2008), they are made up of soil, rock and water (Pirulli et al., 2008).

Their **flow characteristics** depend on the **water content, sediment size and/or sorting**, and on the dynamic **interaction between the solid and fluid phases** (Pirulli et al., 2008). In particular, the rheological properties naturally change, even **during a single debris-flow** event (Remaitre et al., 2005) or still for debris flows taking place **in the same torrent** (Arattano et al., 2006).

models outcome are very sensitive to the wide variability of input parameters (Arattano et al., 2006). This implies that, for purposes of hazard prediction and assessment on a debris fan, **different simulations** have to be performed assuming **different rheological** behaviours and exploring the related **consequences**.

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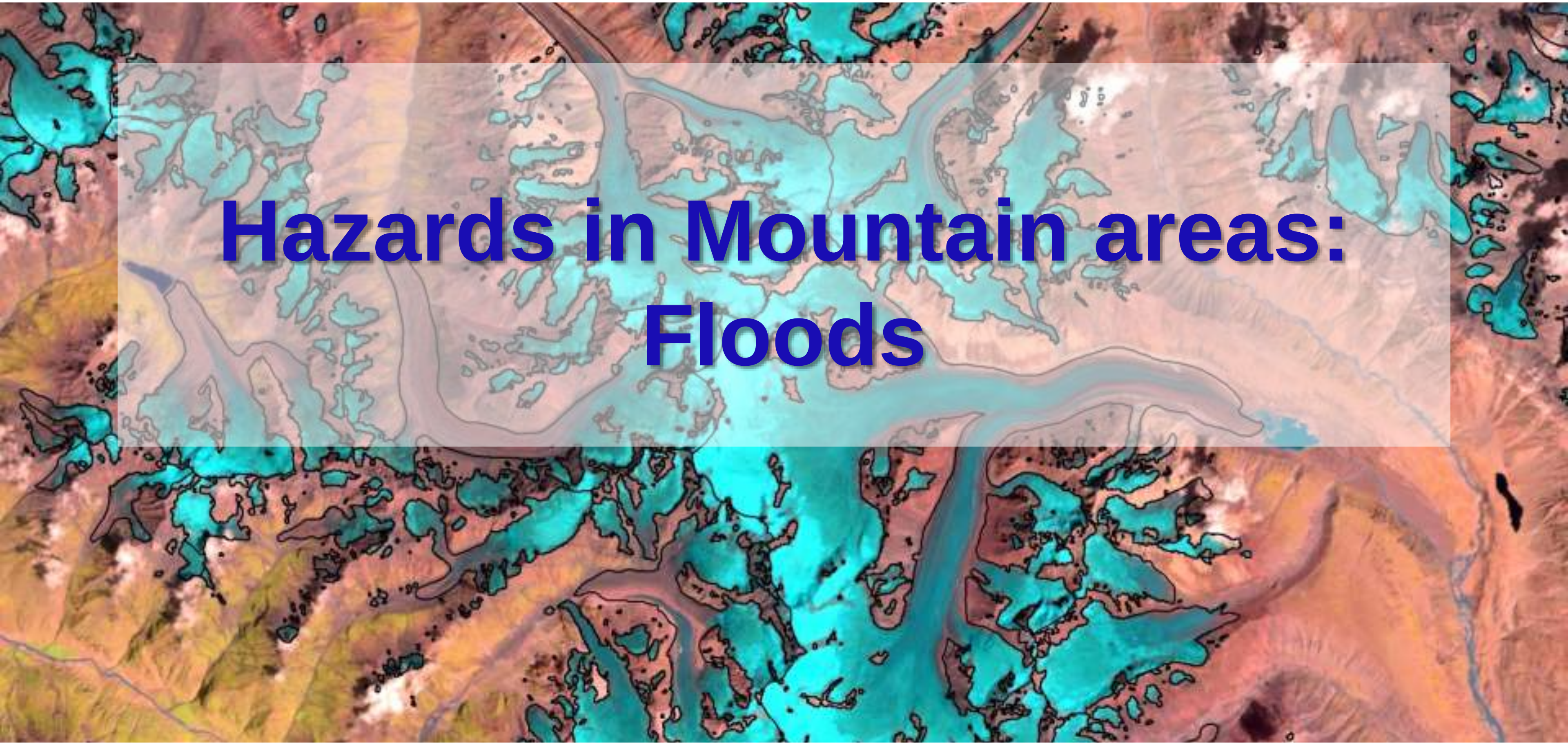

Hazards in Mountain areas: Floods

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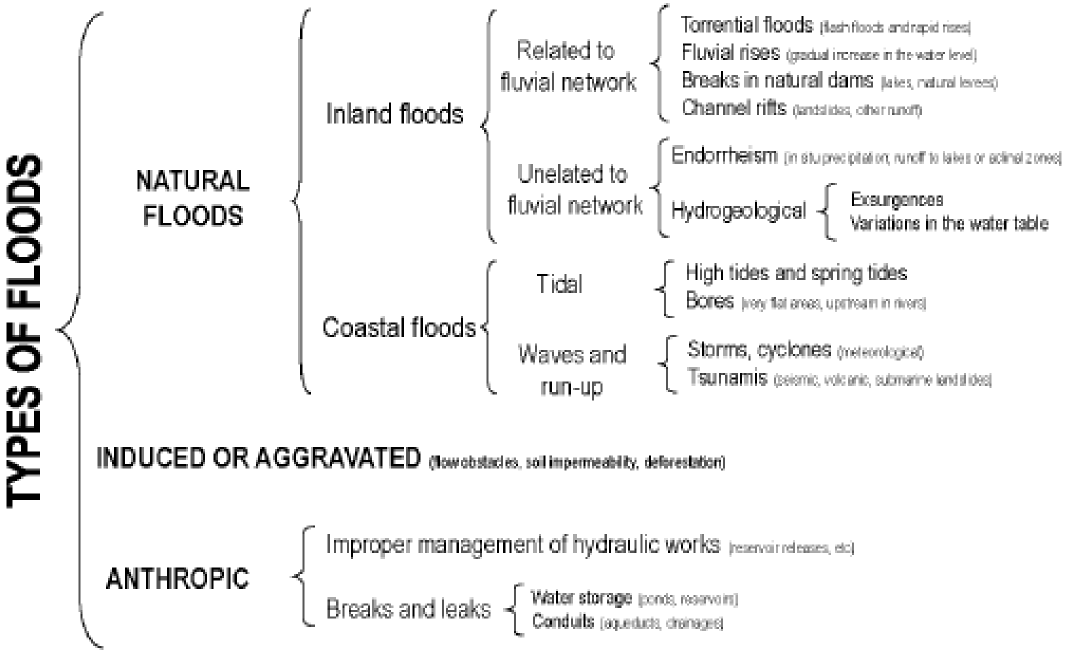
Floods: what we learnt (we already know)

1. Flood types
2. Flood parameters
3. Flood triggering
4. Flood characteristics
5. Flood analysis
6. Flood mapping



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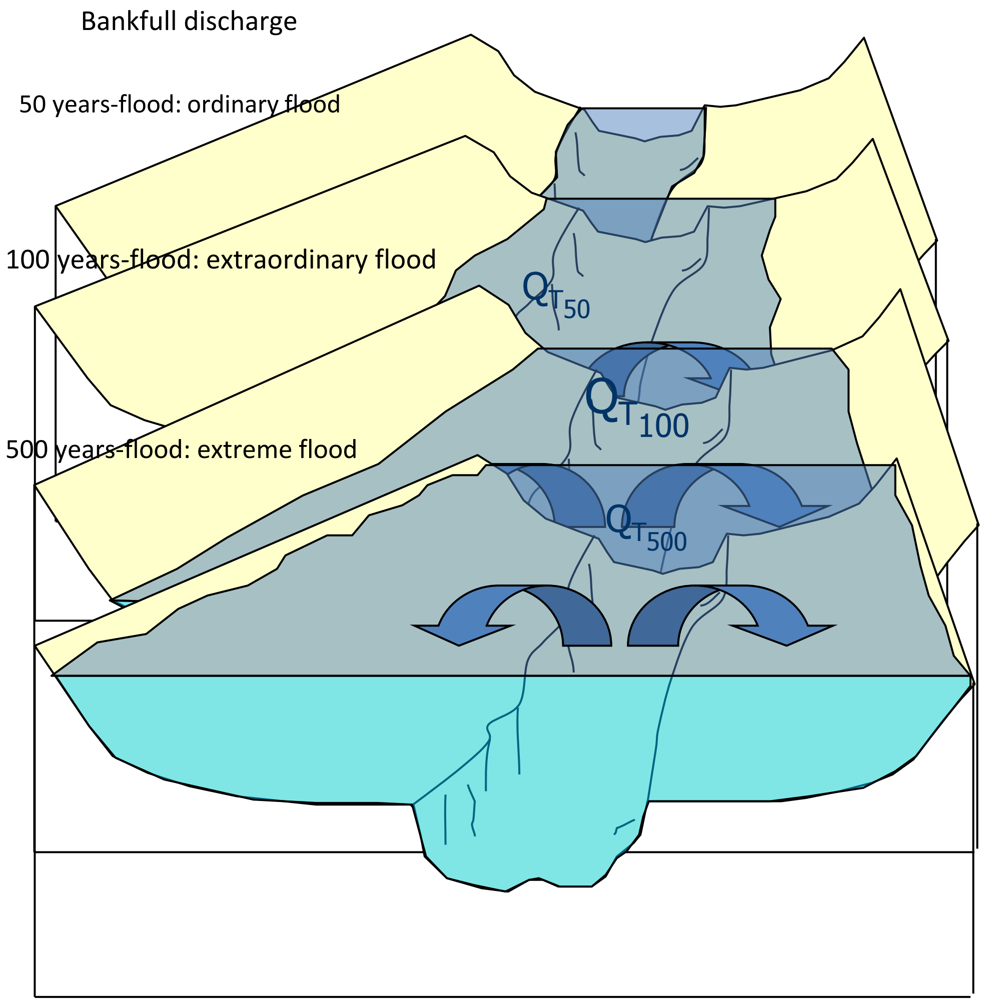
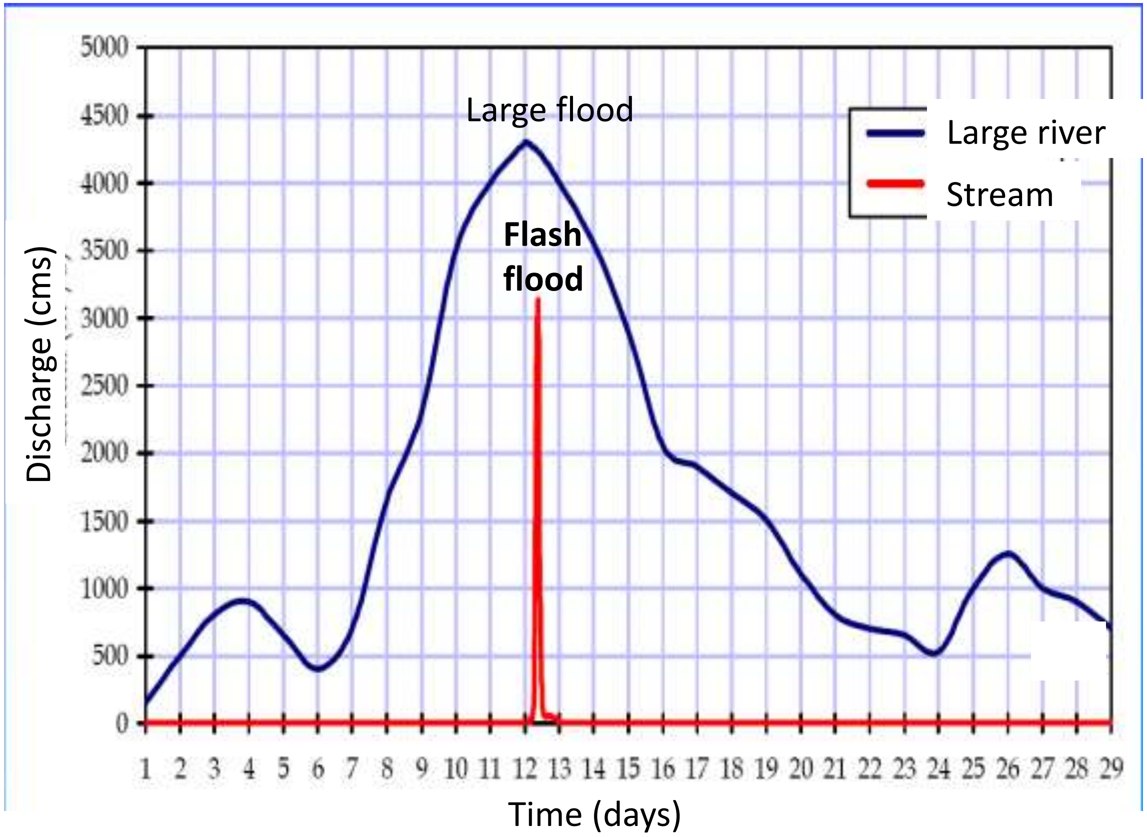
5. Flood analysis
6. Flood mapping



Floods: what we learnt (we already know)

1. Flood types
2. Flood parameters
3. Flood triggering
4. Flood characteristics
5. Flood analysis
6. Flood mapping



Floods: what we learnt (we already know)

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3. Flood triggering
4. Flood characteristics
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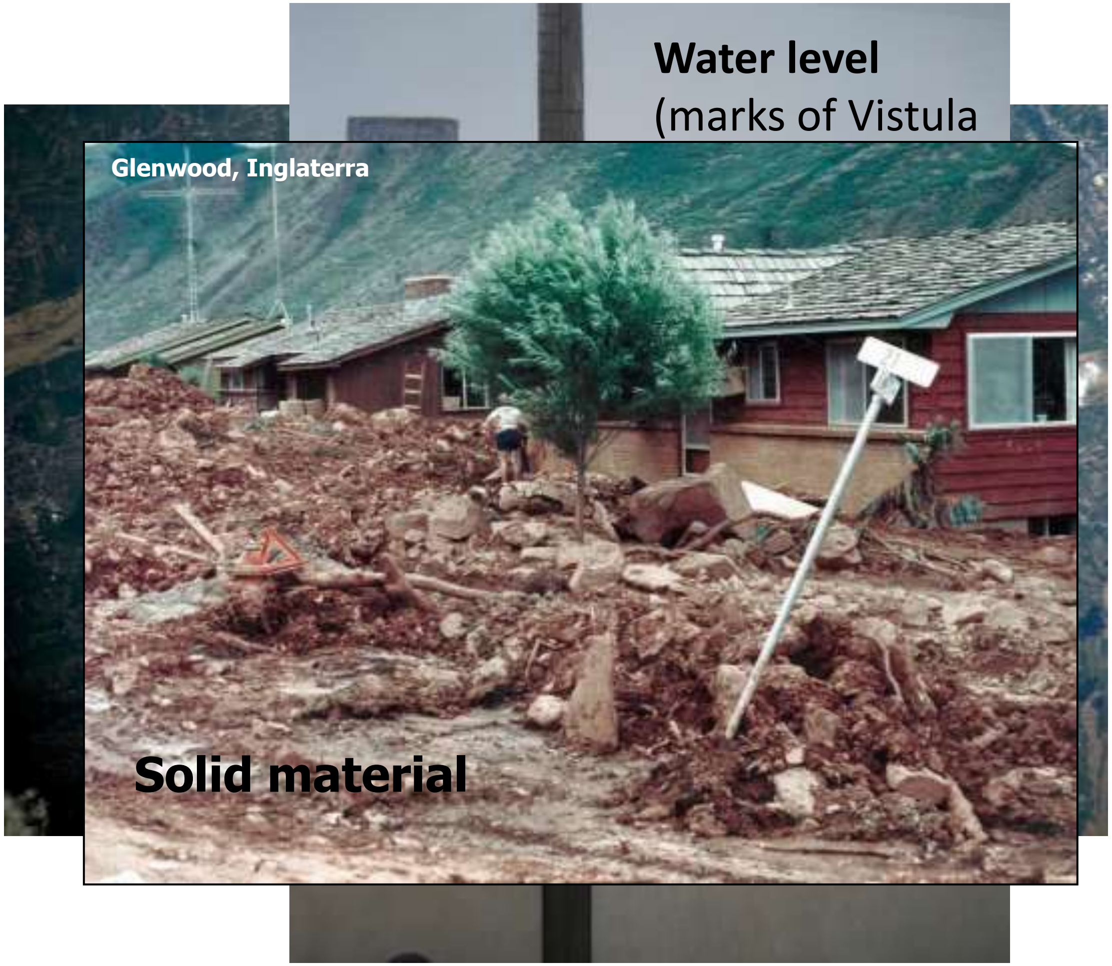


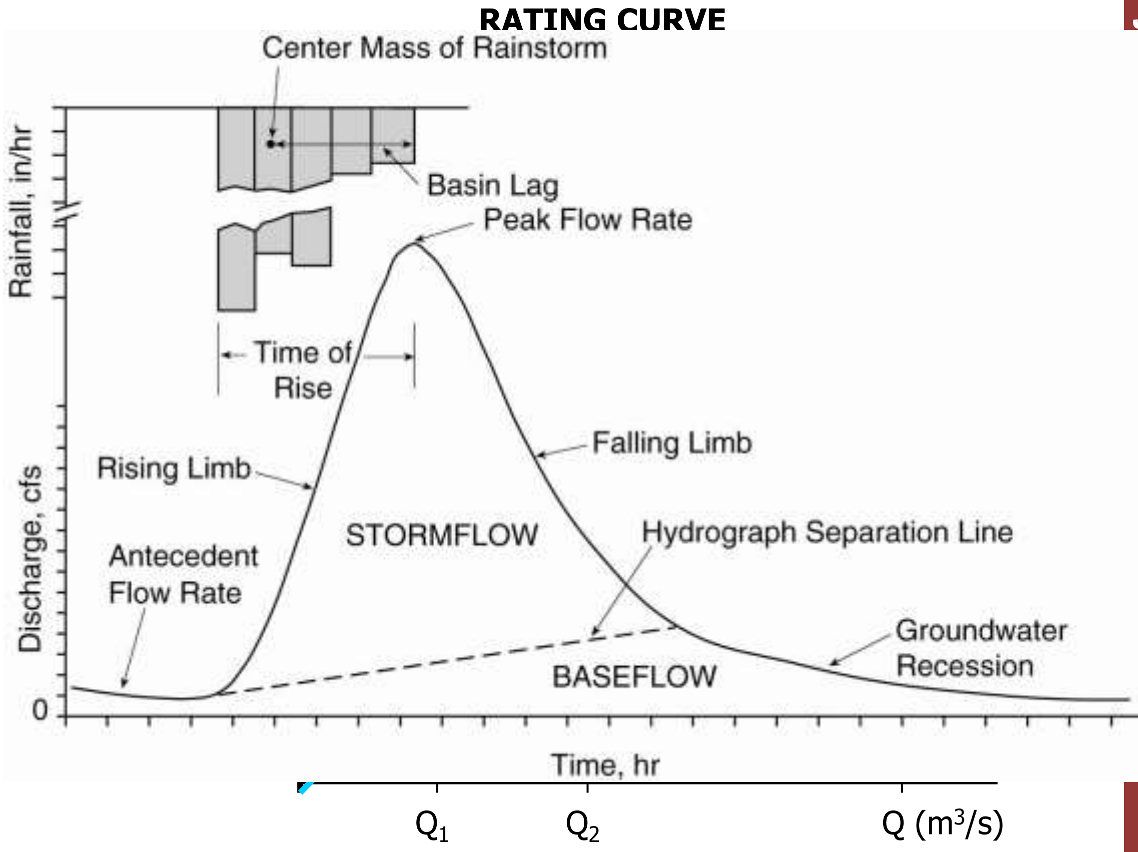
Floods: what we learnt (we already know)

1. Flood types
2. Flood parameters
3. **Flood triggering factors**
4. Flood characteristics
5. Flood analysis
6. Flood mapping


glacial lake outburst flood

Floods: what we learnt (we already know)

1. Flood types
2. Flood parameters
3. Flood triggering
4. Flood characteristics
5. Flood analysis
6. Flood mapping



Floods: what we learnt (we already know)

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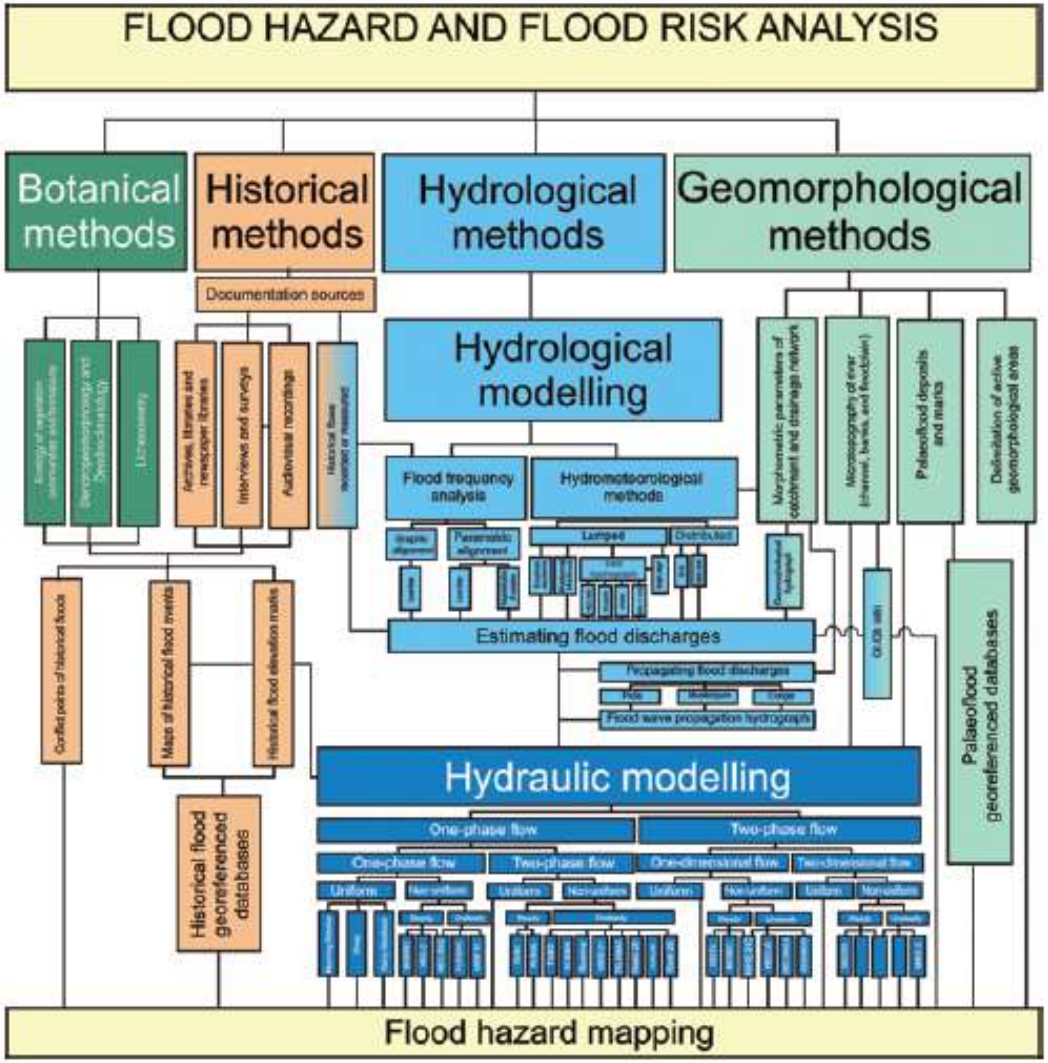

Floods: what we learnt (we already know)

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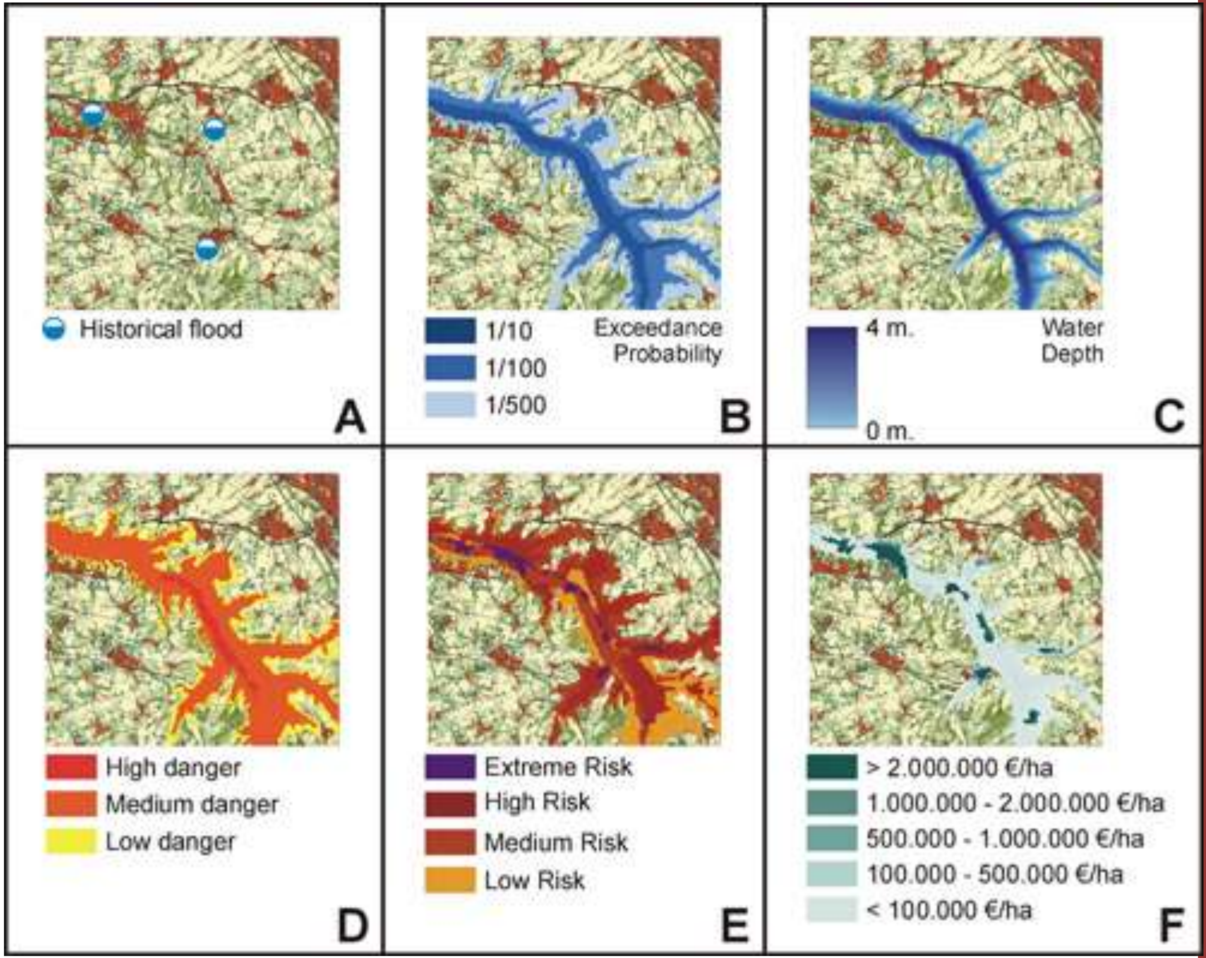
6. Flood mapping



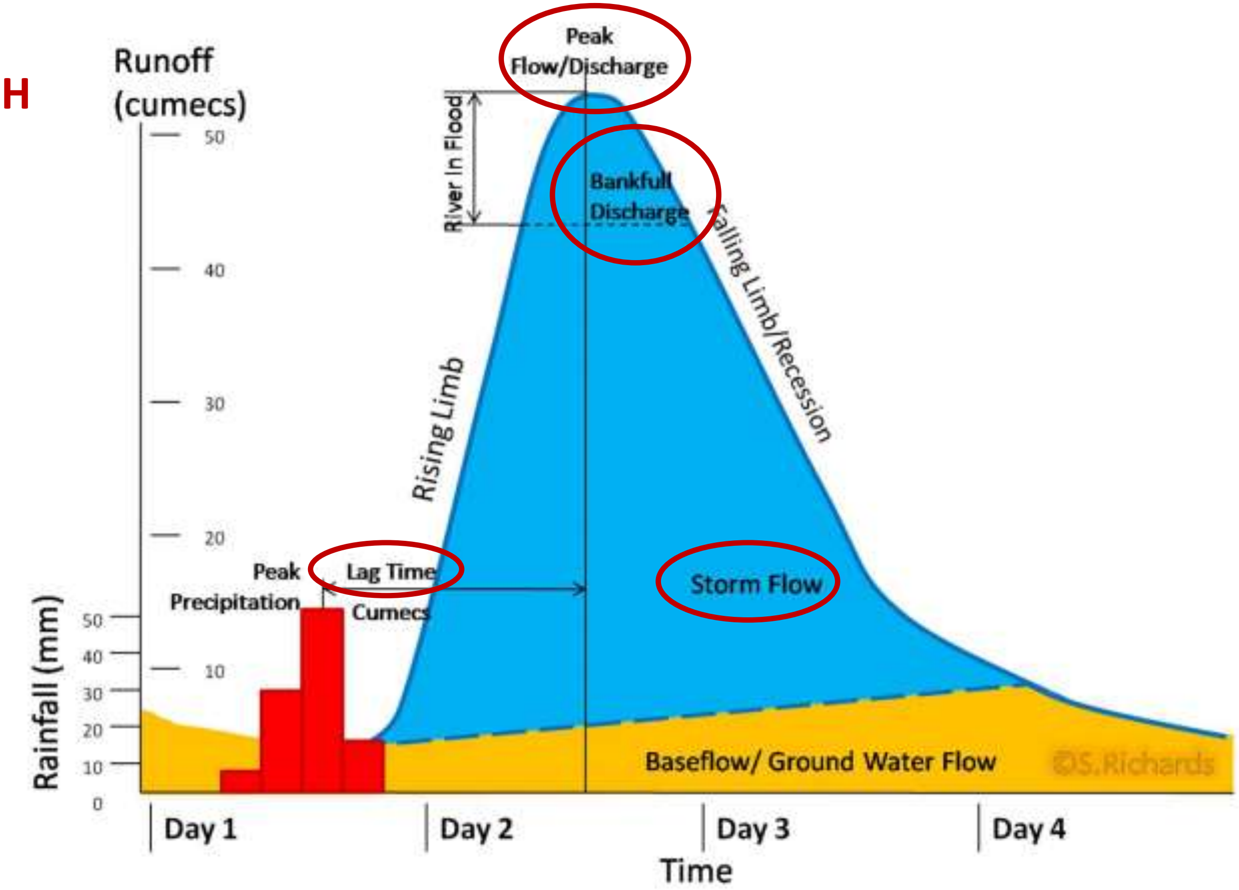
Floods: what we will learn

1. Flood hydrology
2. Channel and flow types
3. Estimating and reconstructing floods
4. Modelling floods

1. Flood hydrology

THE FLOOD HYDROGRAPH

- Basin characteristics
- Time of concentration
- Channel processes
- Antecedent conditions
- Storm intensity and duration



1. Flood hydrology

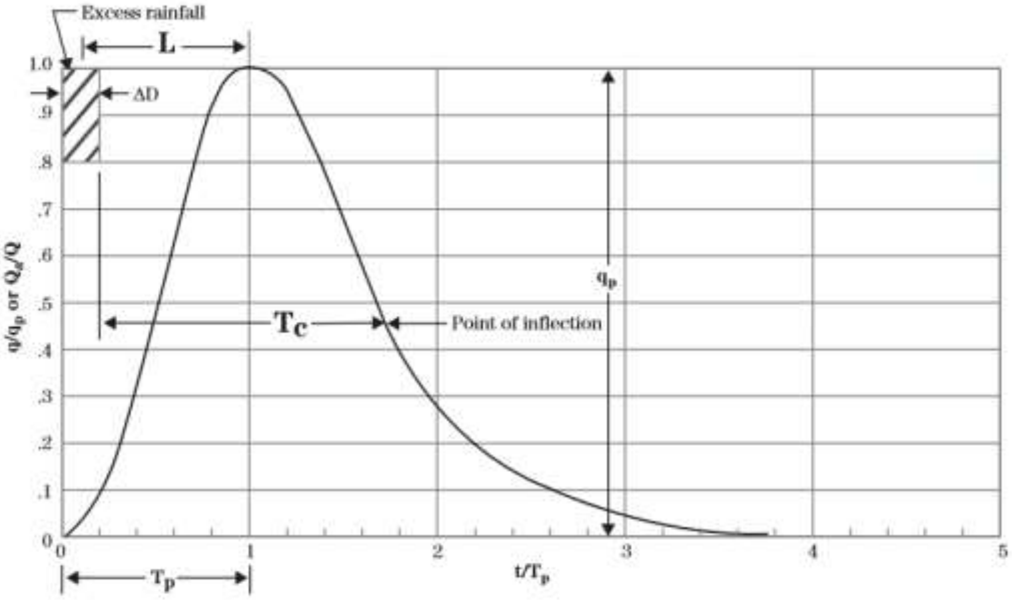
Time of concentration (Tc) is the time required for runoff to travel from the hydraulically most distant
point in the watershed to the outlet

$$t_c = 0.3\left(\frac{L}{(J)^{0.25}}\right)^{0.76}$$

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H}}$$

$$t_c = 0.1272(AL/H)^{½}$$

The drainage characteristics of **length (L)** and **slope (J)**, relief (H) together with the hydraulic characteristics of the flow paths, determine the time of concentration.



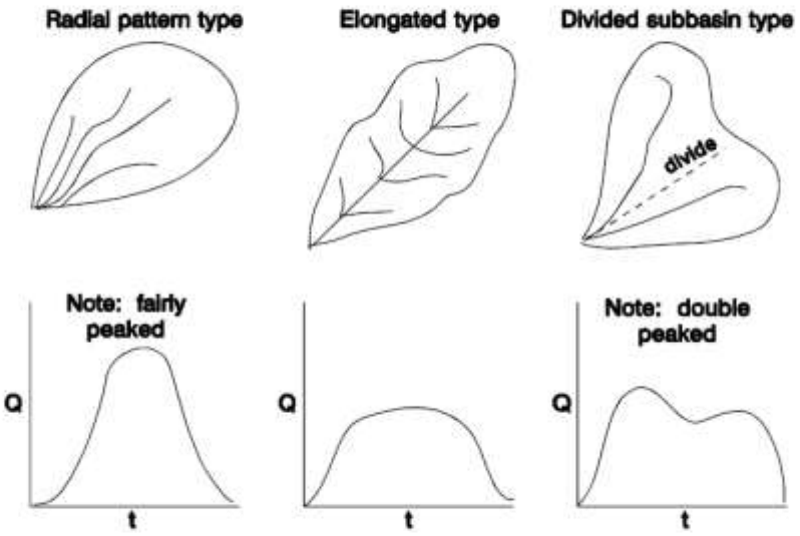
Lag time (L) is the delay between the time runoff begins until runoff reaches its maximum peak.

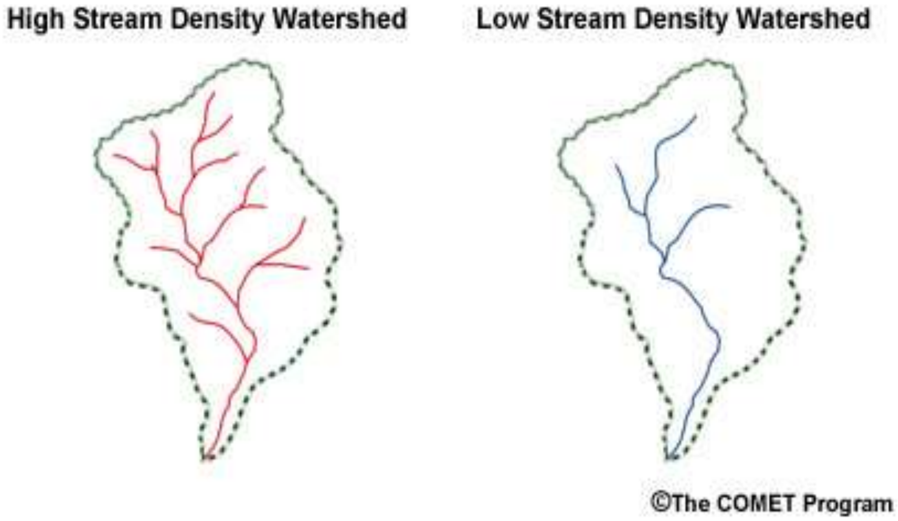
lag time is not unique watershed characteristic and varies from storm to storm depending on: amount, duration and intensity of rainfall; vegetative growth stage and available temporary storage

1.Flood hydrology

Basin morphometry

Identical flood generating mechanisms, may result in very different floods (from catchment to catchment or within a catchment form time to time)





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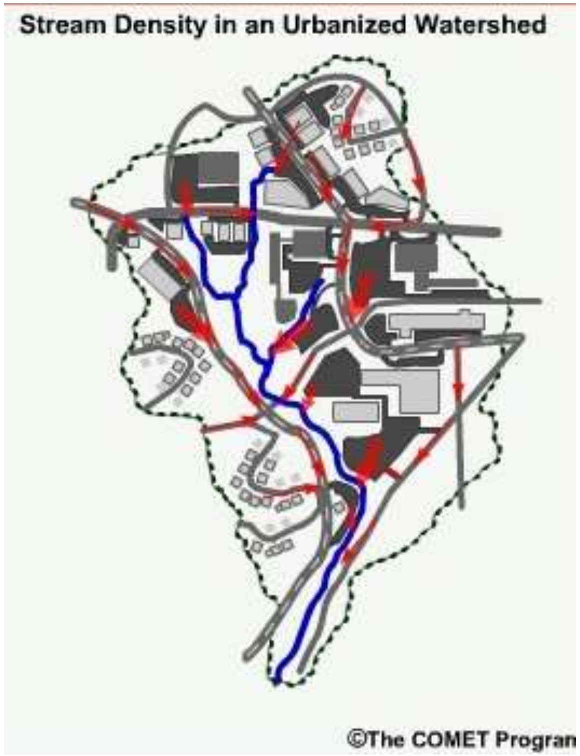
Elongated or Concentrated Shape: Affects Timing and Peak Flow

Basins with **high stream density** have **quicker** runoff response than those with low stream density

1.Flood hydrology

In **urban watersheds** the road grid, drainage ditches, and storm sewer systems act as tributaries and artificially increase stream density



Stream Density in an Urbanized Watershed

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Urban areas grow

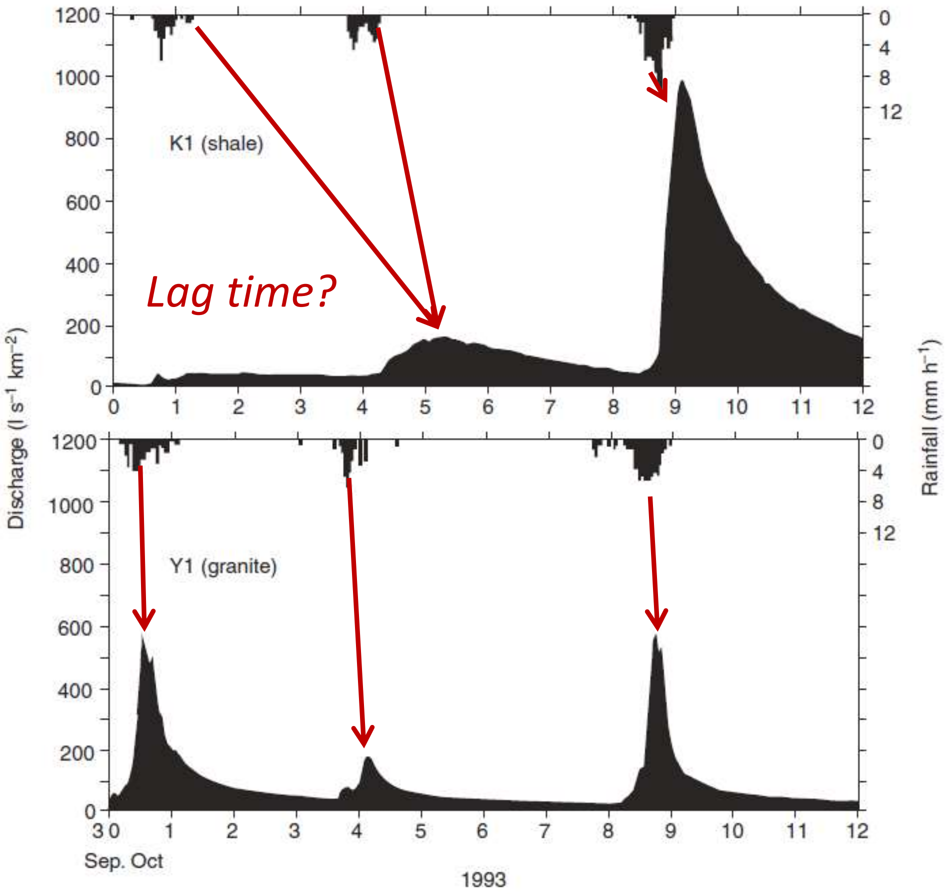
Photo by Lynn Betts, USDA / NRCS

Photo by Dave Saville / FEMA News Photo

Flood risk increases!

1.Flood hydrology

Soil type, geology



Lag time?

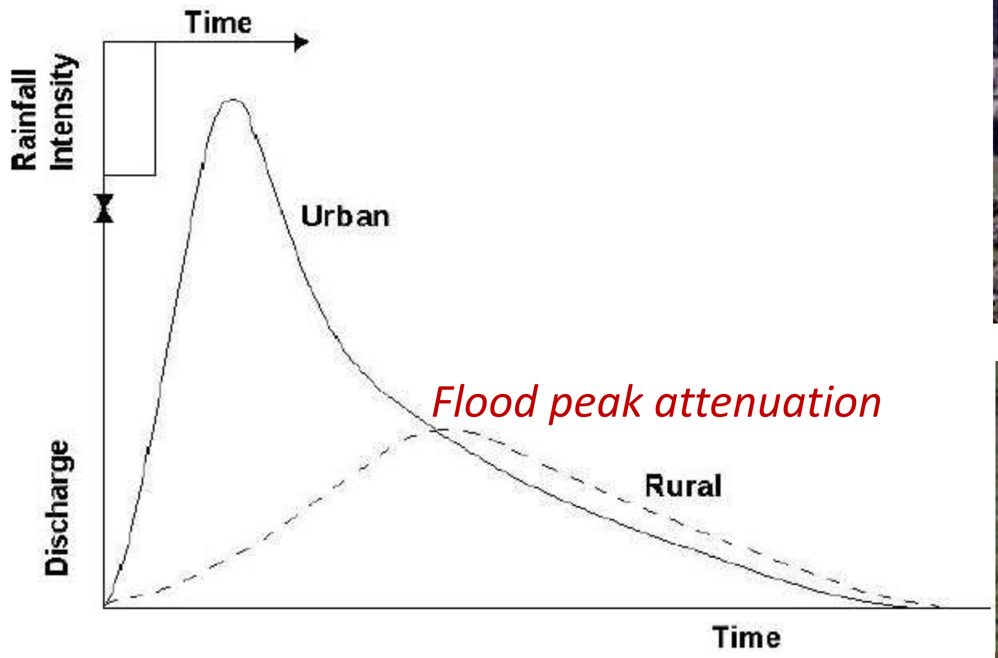
Figure 7 Sequence of storm event hydrographs from 30 September to 12 October 1993 for two forested watersheds in central Japan with different bedrock substrates. Reproduced from Onda, Y., Tsujimura, M., Fujihara, J., Ito, J., 2006. Runoff generation mechanisms in high-relief mountainous watersheds with different underlying geology. Journal of Hydrology 331, 659–673.

FLOOD ALERT

FLOODING IS POSSIBLE. BE PREPARED.

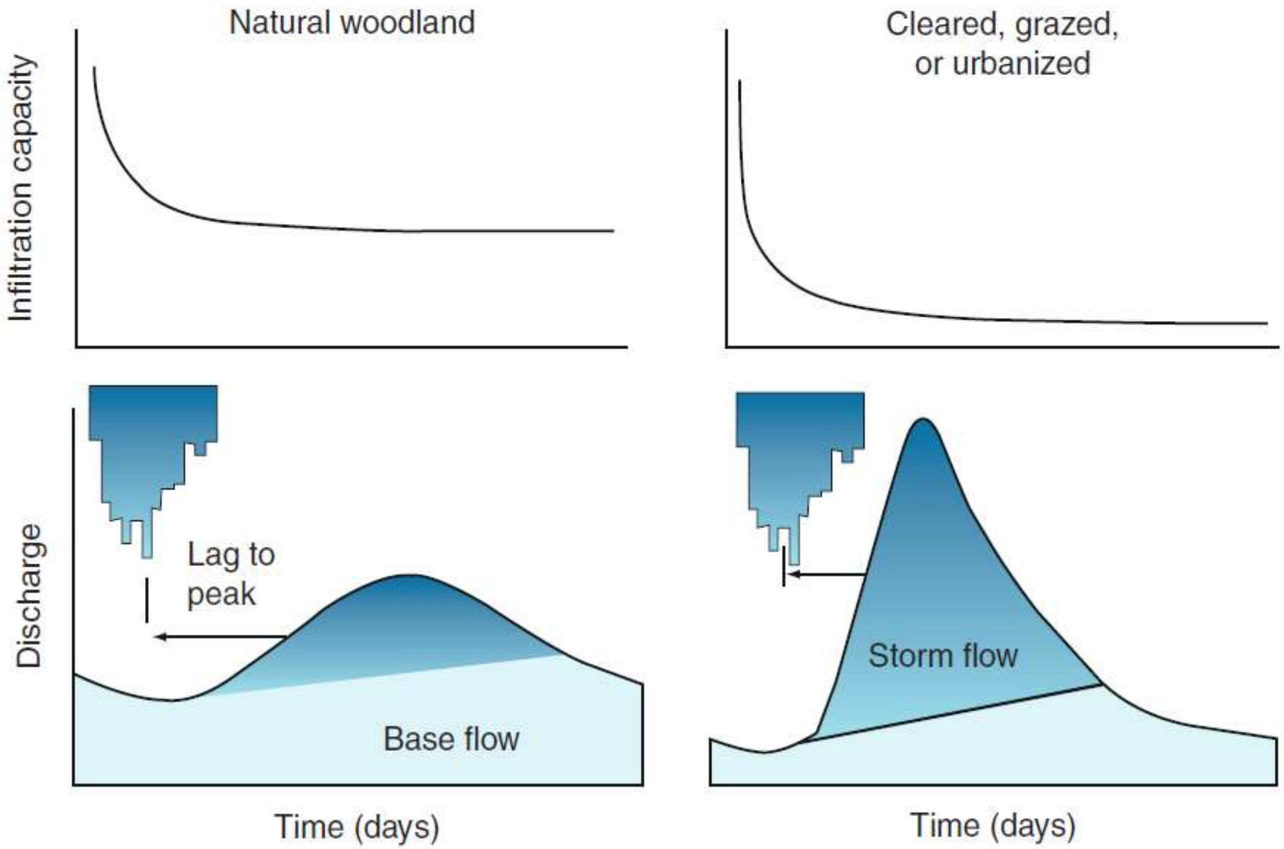
1. Flood hydrology

Vegetation, land use



Flood peak attenuation

1.Flood hydrology

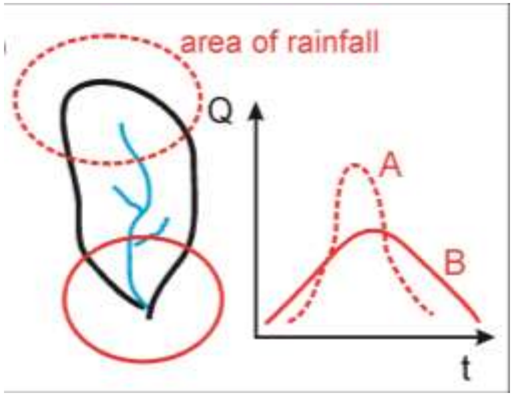


High infiltration rates
Low peak discharge
Long lag time
High base flow

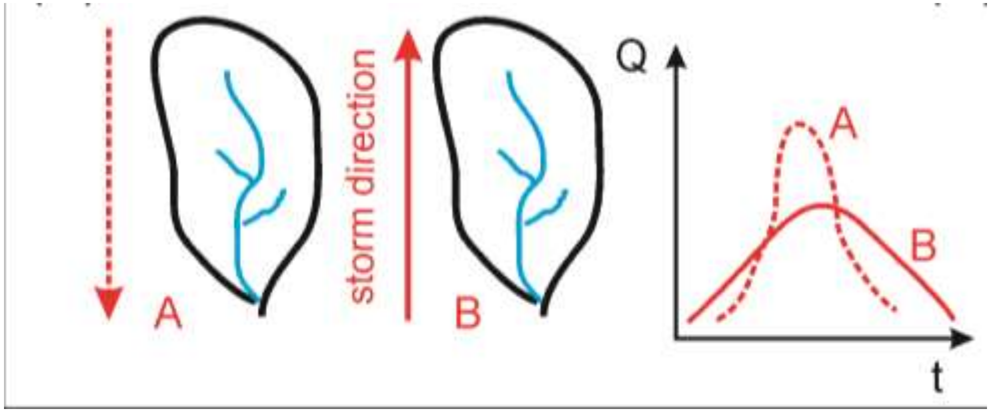
Low infiltration rates
high peak discharge
Short lag time
Low base flow

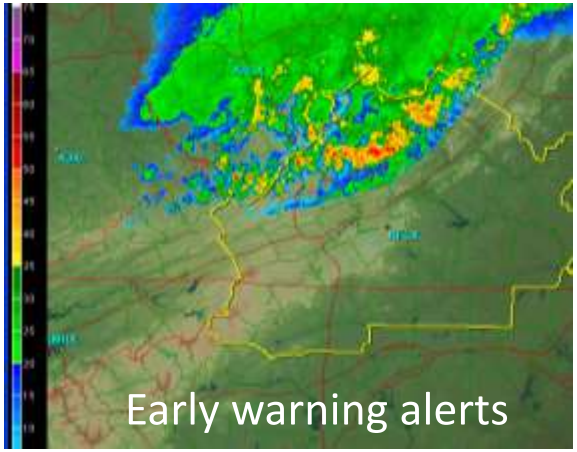
1.Flood hydrology

Flood triggered storm



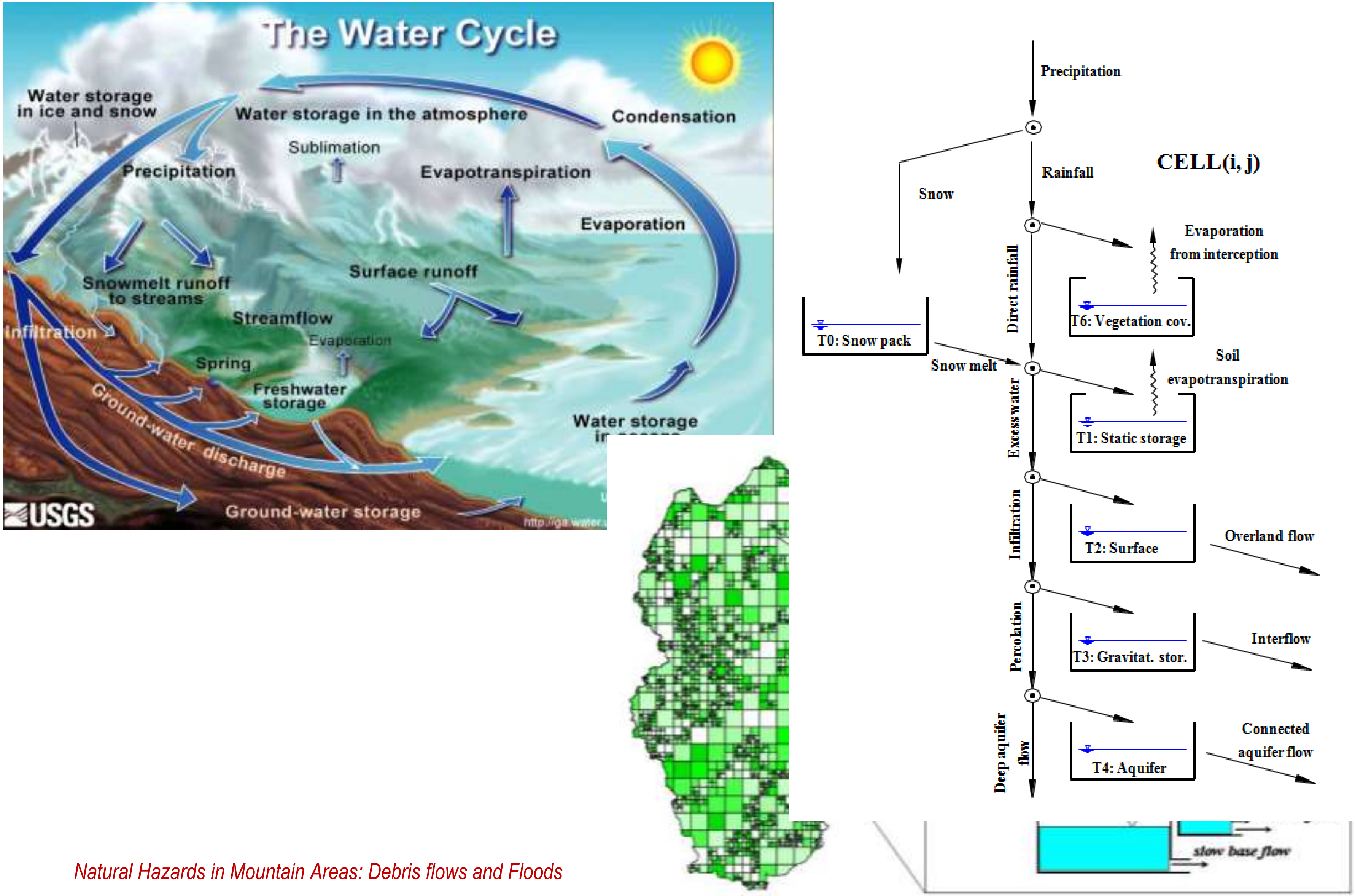
The storm velocity may rise to a stronger flood peak than that of an equivalent **stationary storm** characterized by the same temporal rainfall distribution and by the same time period





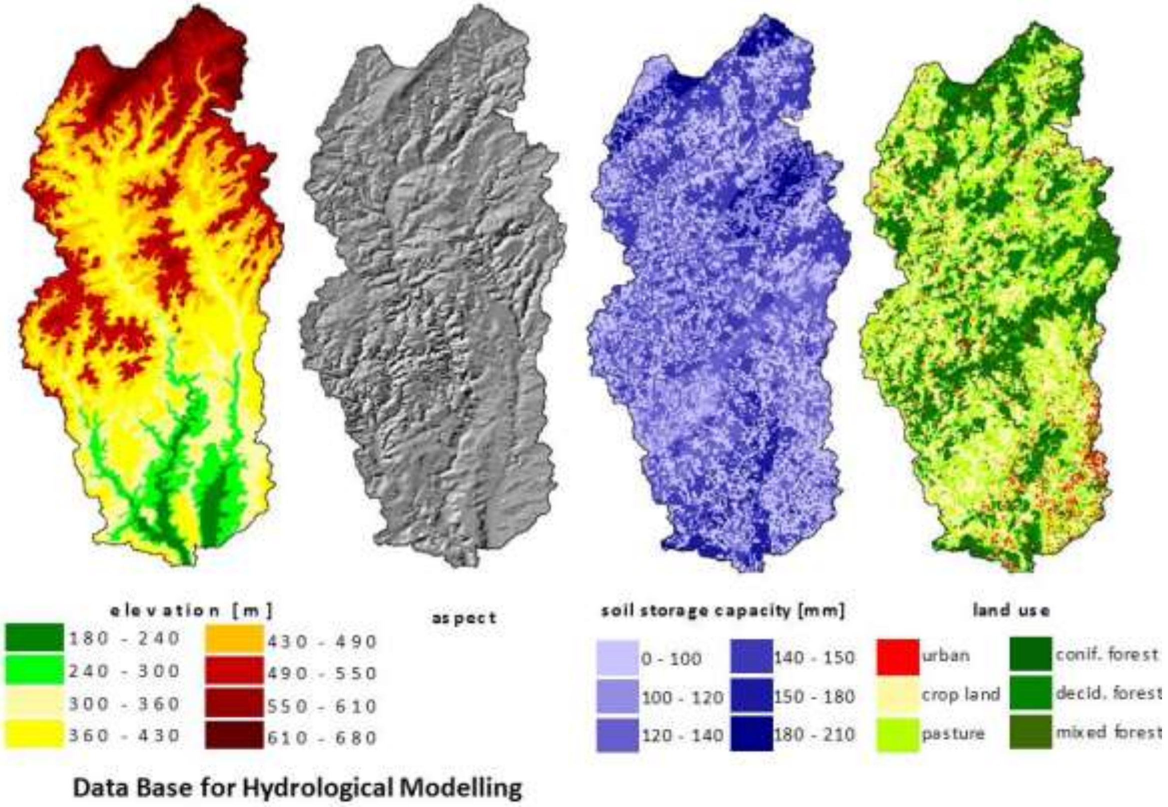
http://www.erh.noaa.gov/rnk/events/2012/Jun29_derecho/summary.php

1. Flood hydrology: modelling

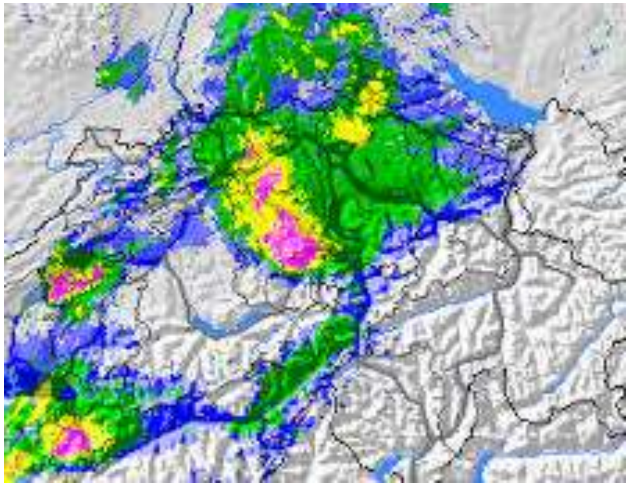


1. Flood hydrology: modelling

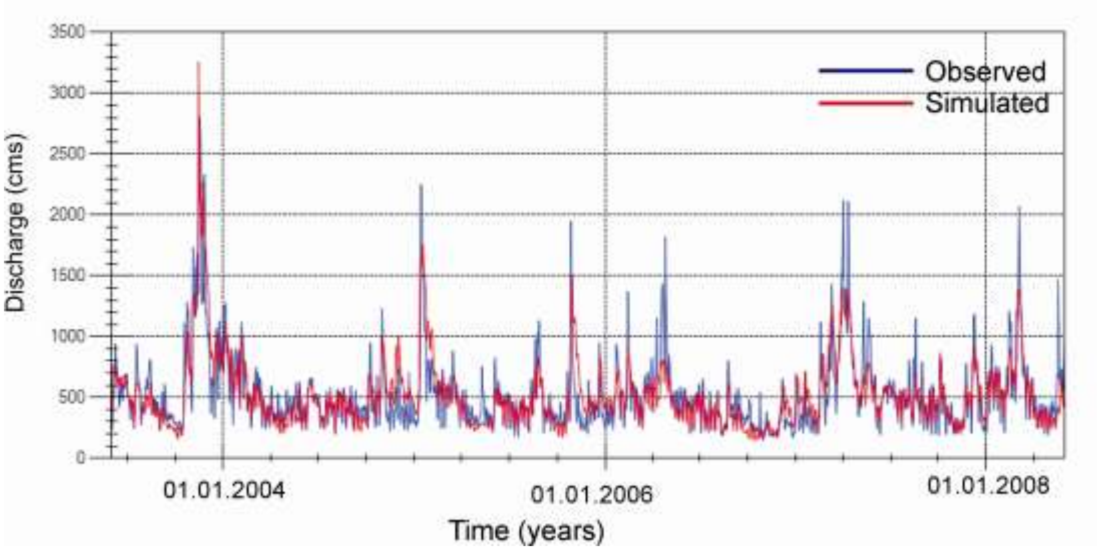
Input parameters

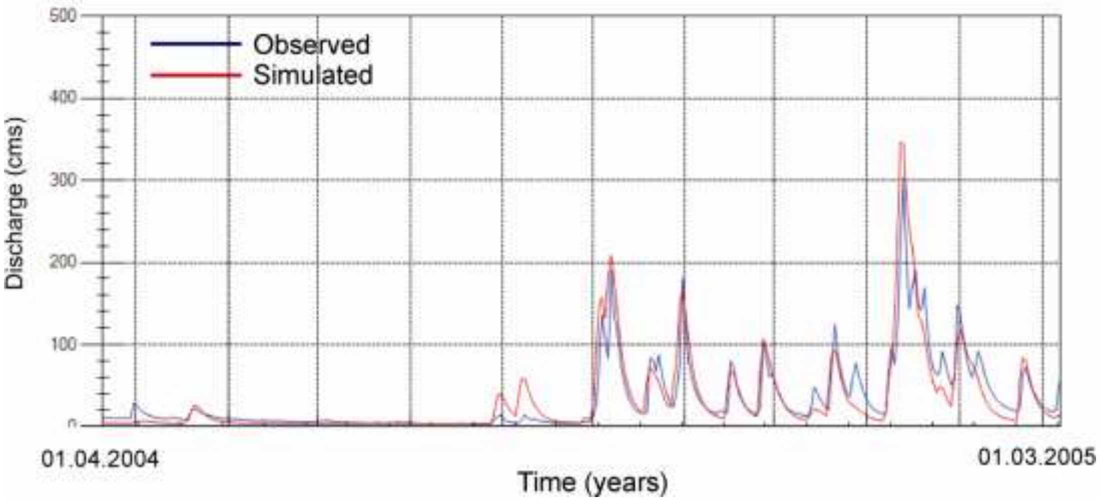


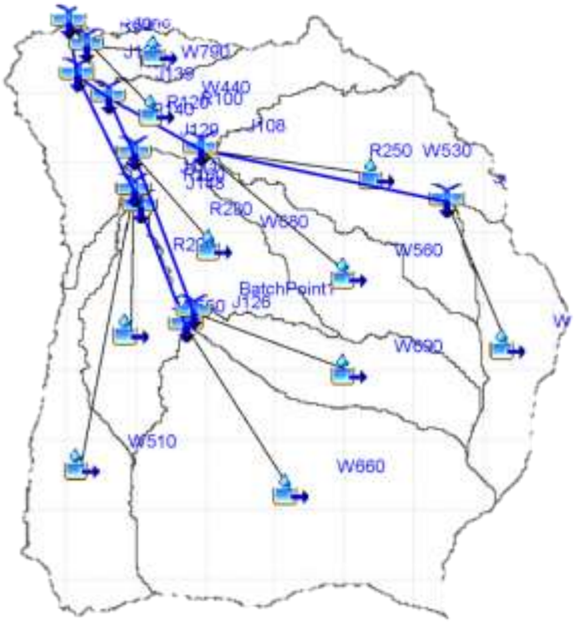
Data Base for Hydrological Modelling



1. Flood hydrology: modelling







1.Flood hydrology: empirical approaches

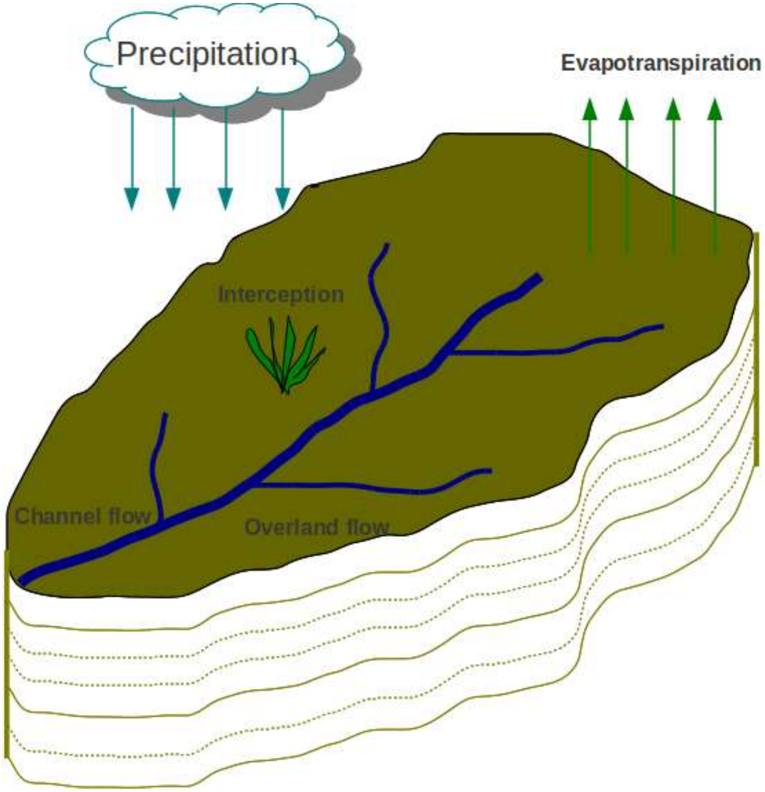
Rational Method Equation

The Rational equation is the simplest method to determine peak discharge from drainage basin runoff.

$$Q=c\cdot i\cdot A$$

Q = Peak discharge

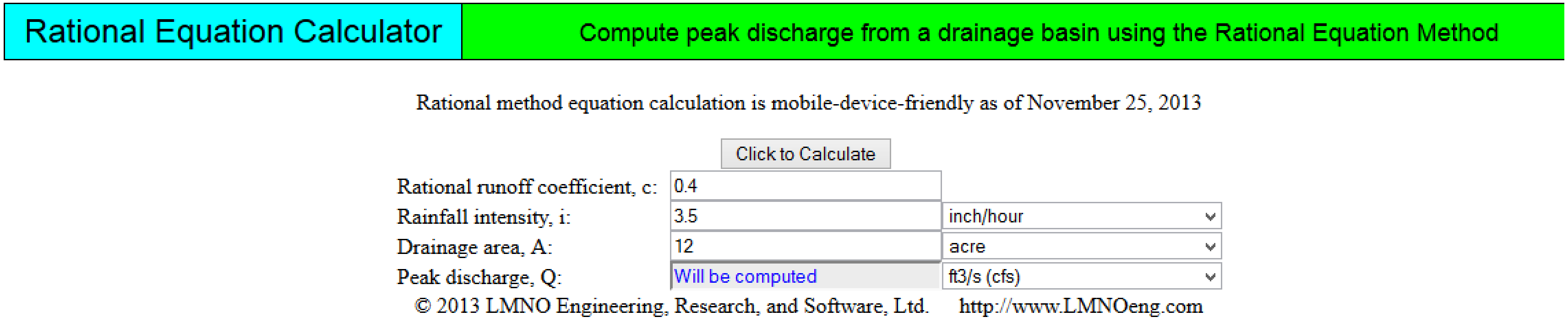
inputs:
c = runoff coefficient
i = Rainfall intensity
A = Drainage area



1.Flood hydrology: empirical approaches

Rational Method Equation

http://www.lmnoeng.com/Hydrology/rational.php



Rational Equation Calculator

Compute peak discharge from a drainage basin using the Rational Equation Method

Rational method equation calculation is mobile-device-friendly as of November 25, 2013

Rational runoff coefficient, c: 0.4

Rainfall intensity, i: 3.5 inch/hour

Drainage area, A: 12 acre

Peak discharge, Q: Will be computed ft3/s (cfs)

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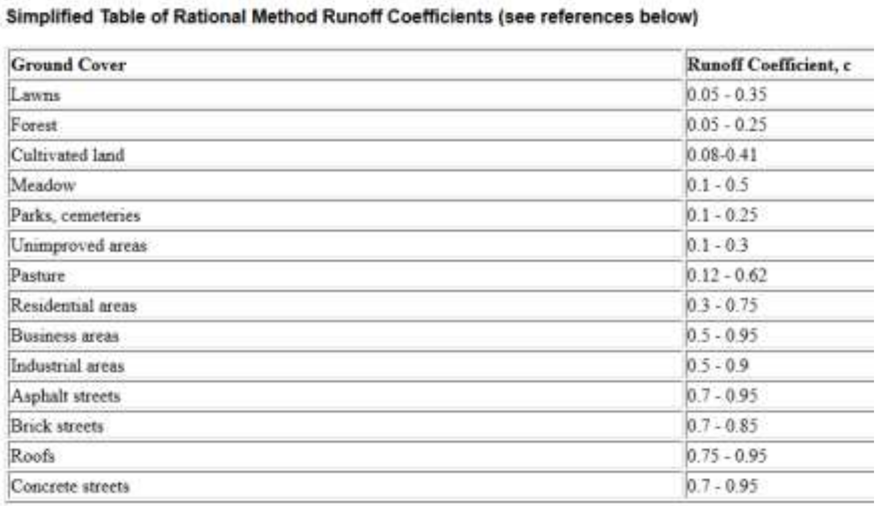


Simplified Table of Rational Method Runoff Coefficients (see references below)

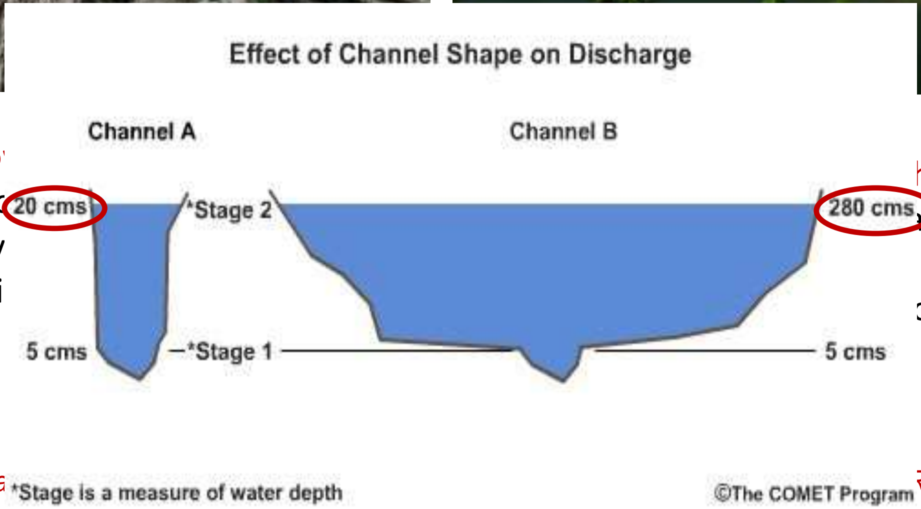
Ground Cover	Runoff Coefficient, c
Lawns	0.05 - 0.35
Forest	0.05 - 0.25
Cultivated land	0.08-0.41
Meadow	0.1 - 0.5
Parks, cemeteries	0.1 - 0.25
Unimproved areas	0.1 - 0.3
Pasture	0.12 - 0.62
Residential areas	0.3 - 0.75
Business areas	0.5 - 0.95
Industrial areas	0.5 - 0.9
Asphalt streets	0.7 - 0.95
Brick streets	0.7 - 0.85
Roofs	0.75 - 0.95
Concrete streets	0.7 - 0.95

2. Channels and flow types

One important factor in determining how streamflow varies along a stream is the **geometry of the channel and floodplain**

en.wikipedia.org

Photo by Andrea Booher/FEMA Photo



Effect of Channel Shape on Discharge

*Stage is a measure of water depth

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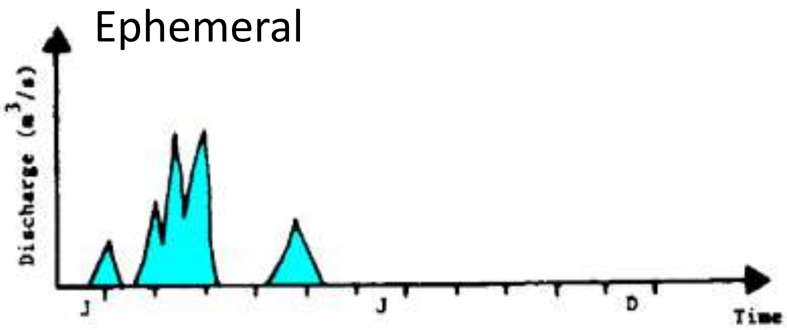
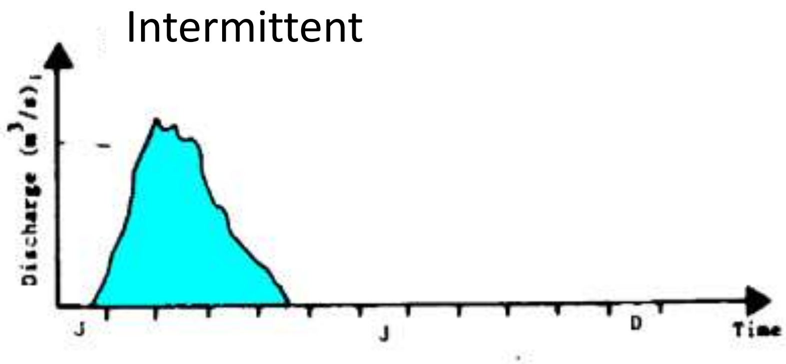
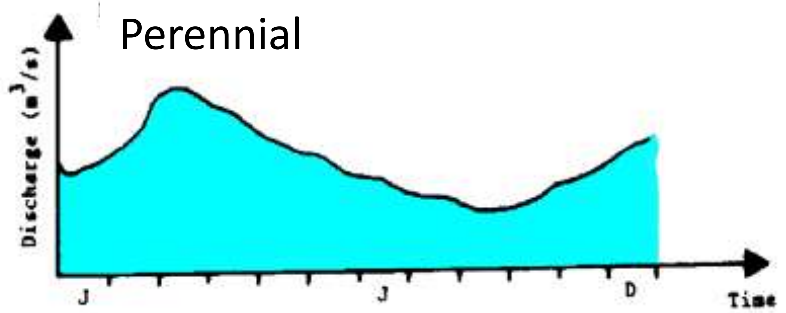
If a channel is narro
like with almost no fl
rise in stage may only
increase in di

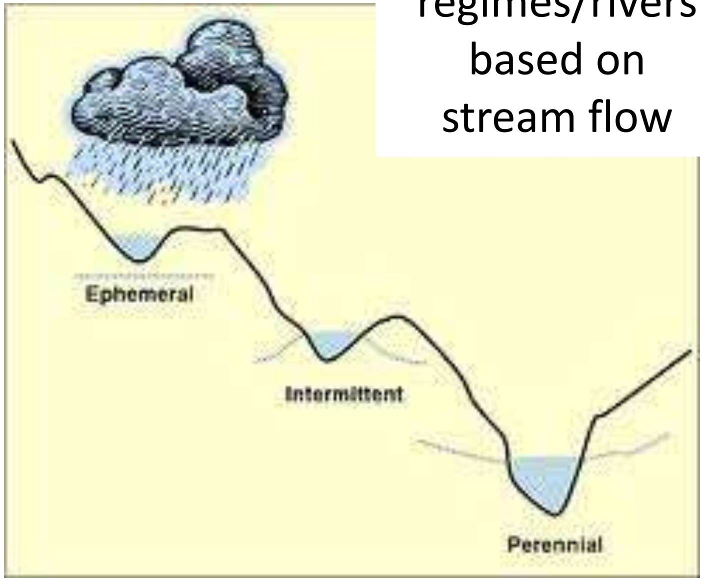
hannel with a very broad
ge increase could result
in the discharge as the
oss the flood plain

2. Channels and flow types


Ephemeral


Intermittent


Perennial


Type of regimes/rivers based on stream flow

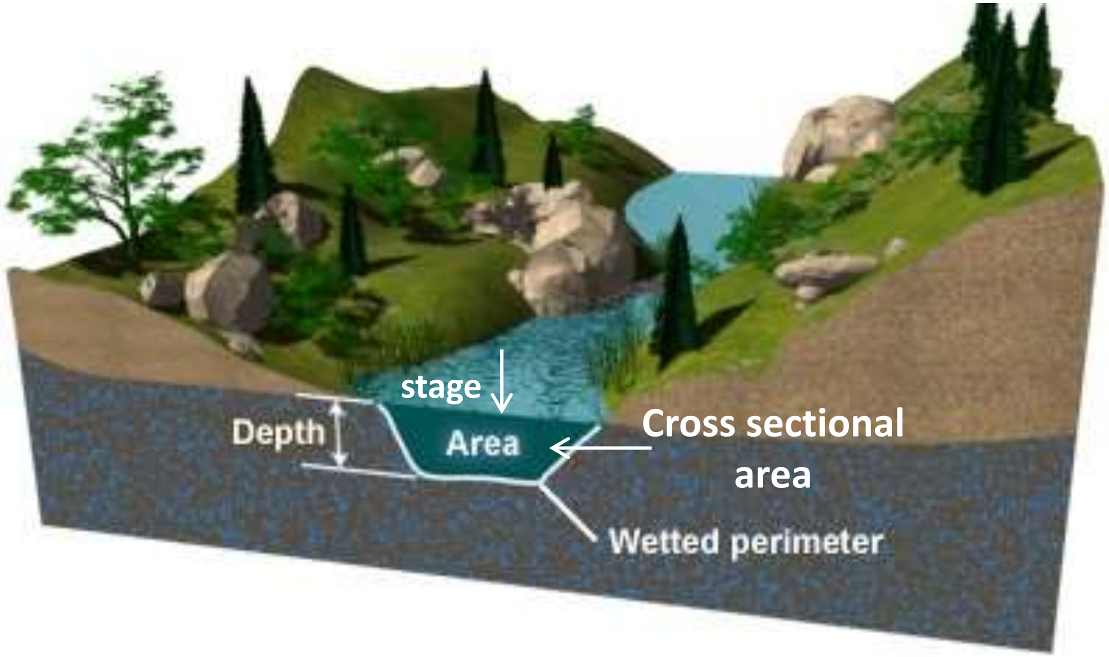
Ephemeral: flows only during and immediately after precipitation

Intermittent: only flows for part of the year

Perennial: flows continuously

2. Channels and flow types

Various parameters are used to describe the hydrologic characteristics of **a stream or river**



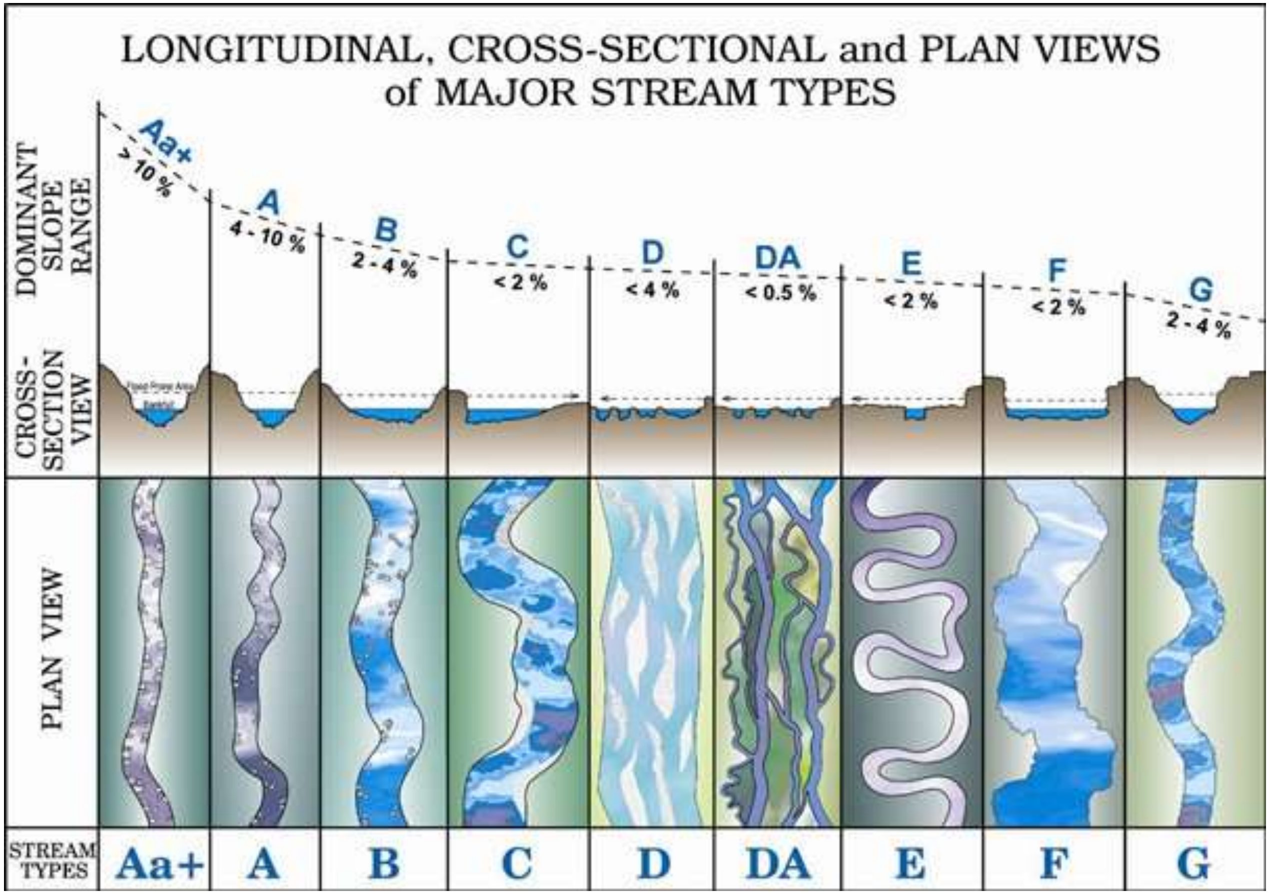
R = Area / Wetted perimeter

The **wetted perimeter** is the length of the wetted edge of a channel cross section containing flowing water.

The **hydraulic radius** is the **cross–sectional area** of the channel divided by the wetted perimeter.

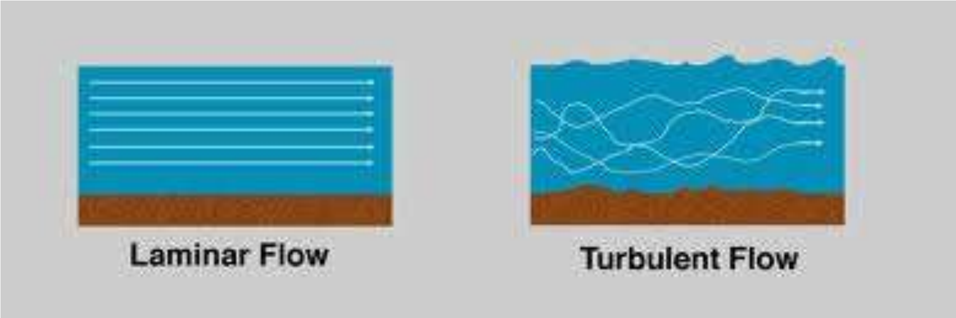
2. Channels and flow types

Streams can be classified in many ways, different stream types will show broad differences resulting in contrasting **flow types**



(Rosgen, 1996)

2. Channels and flow types



Reynolds number:

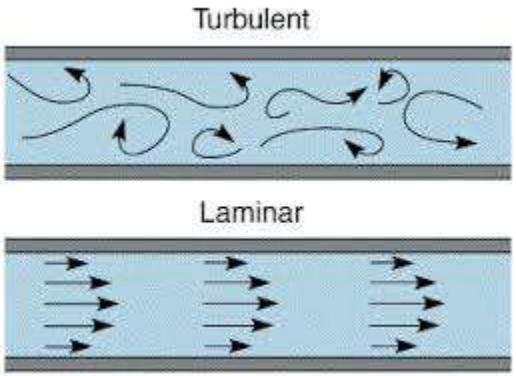
$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \mathbf{v} L}{\mu} = \frac{\mathbf{v} L}{\nu}$$

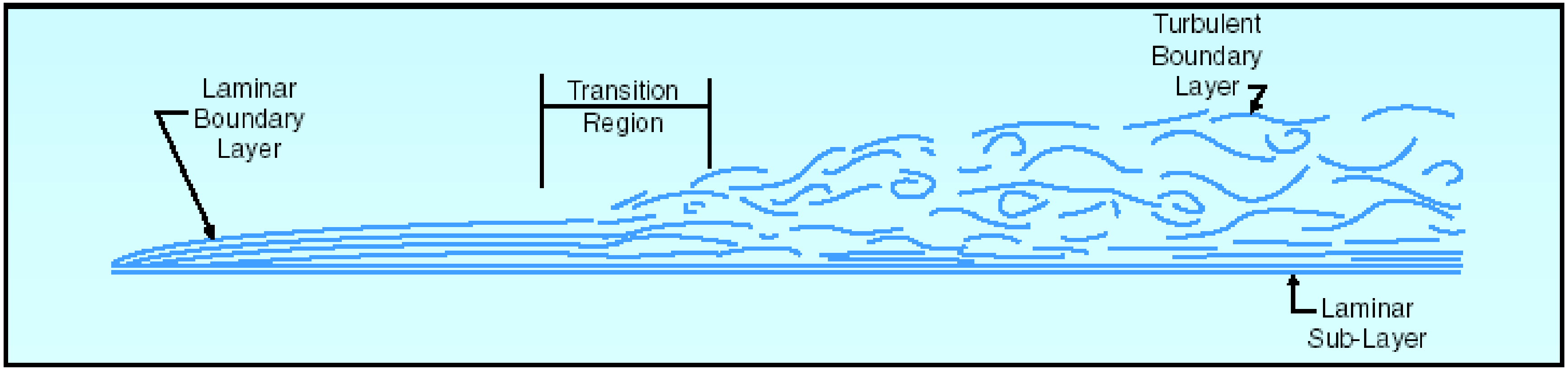
laminar when Re < 2300
transient when 2300 < Re < 4000
turbulent when 4000 < Re

Laminar flow: fluid flows in parallel layers, with no disruption

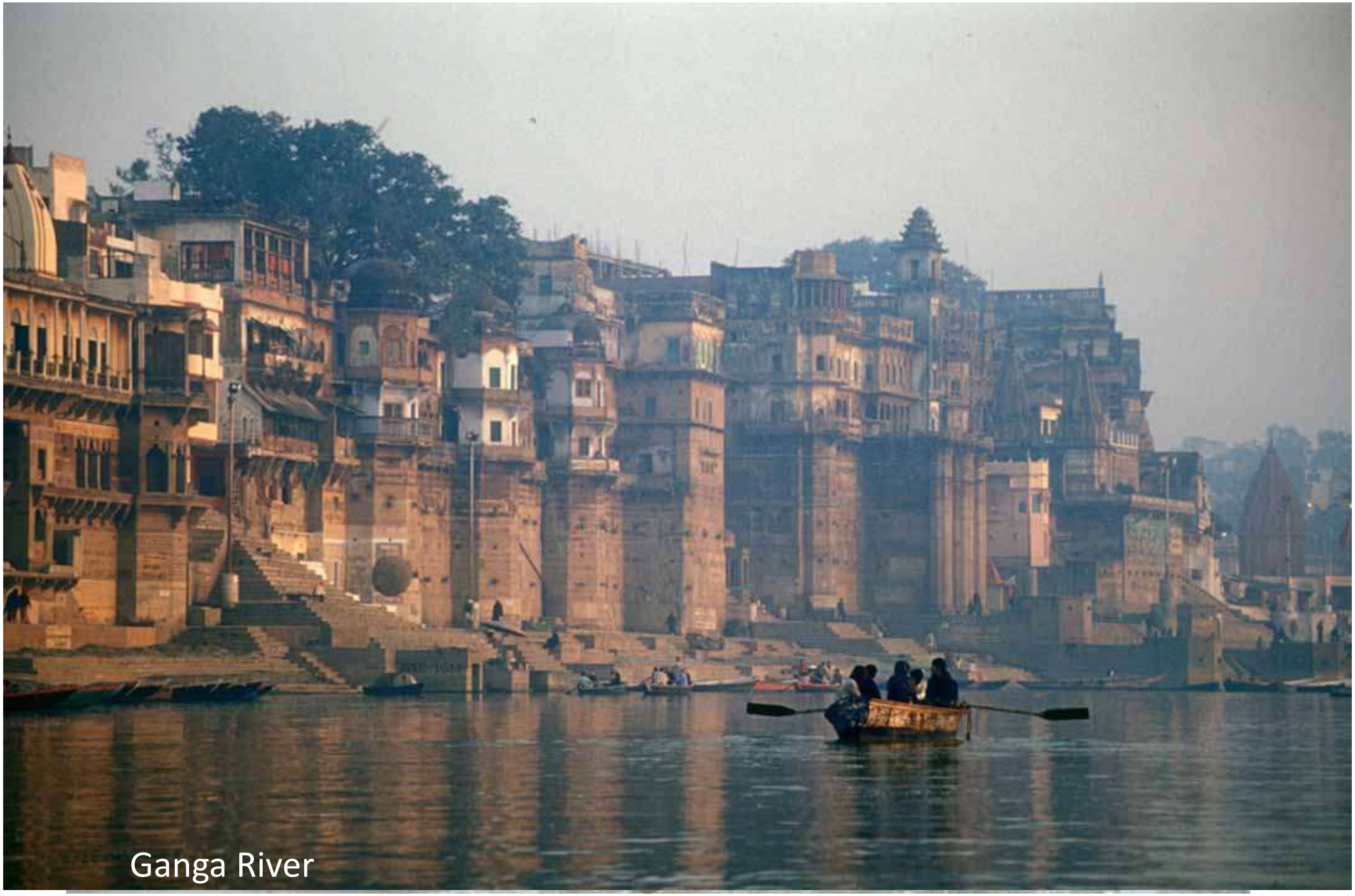
2. Channels and flow types

Turbulence or **turbulent flow** is a flow regime characterized by chaotic and stochastic property changes.





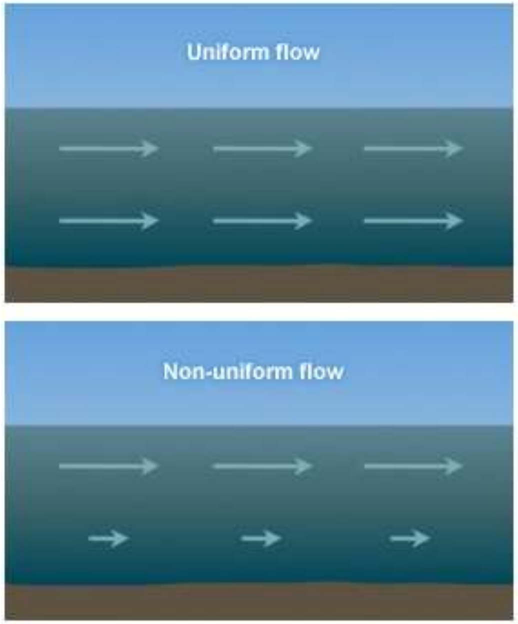
2. Channels and flow types



Ganga River

2. Channels and flow types

We examine two flow conditions: the uniformity of the flow within the stream and the steadiness of the flow over time.



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Uniform : flow velocity is assumed to have the same <u>speed</u> and <u>direction</u> at every point within the fluid

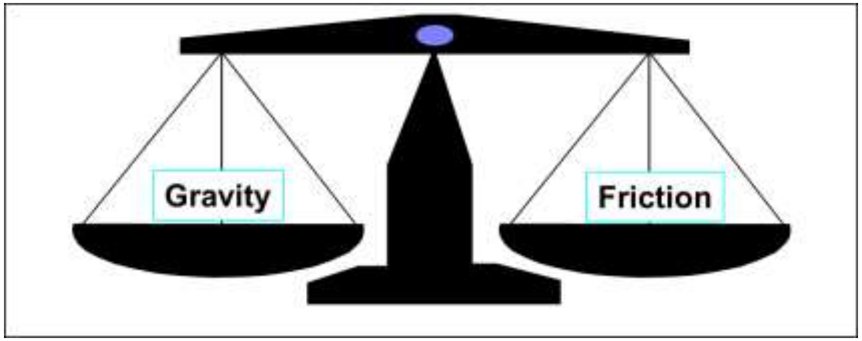
<u>Uniform in space</u>

<u>Uniform Flow</u>: $\frac{\partial(U \cdot A)}{\partial x} = 0$

<u>Nonuniform Flow</u>: $\frac{\partial(U \cdot A)}{\partial x} \neq 0$

2. Channels and flow types

Uniform flow occurs when the gravitational forces are exactly offset by the resistance forces

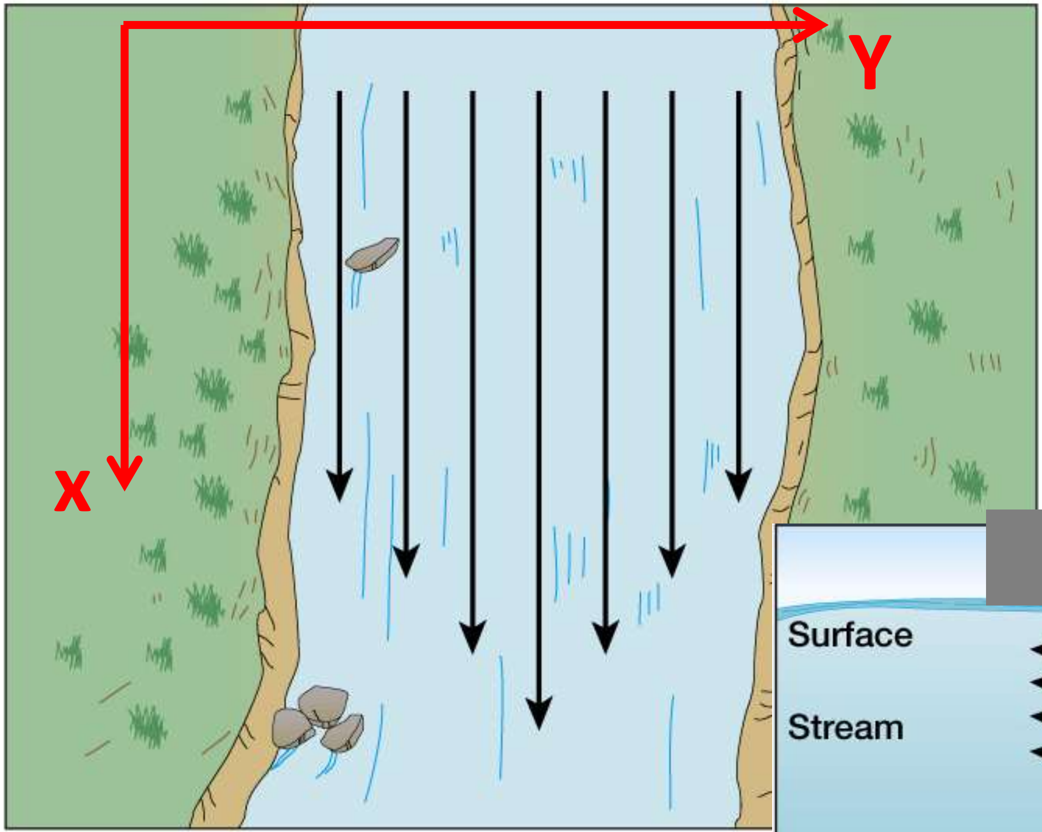


- Mean velocity is constant from section to section
- Depth of flow is constant from section to section
- Area of flow is constant from section to section

Therefore: It can only occur in very long, straight, prismatic channels

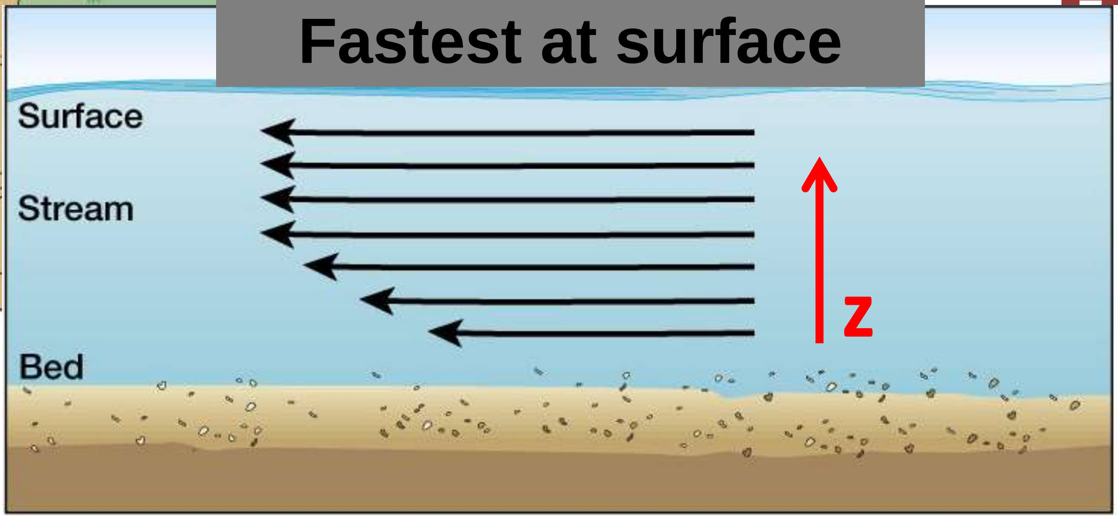
2. Channels and flow types

Faster at middle & surface

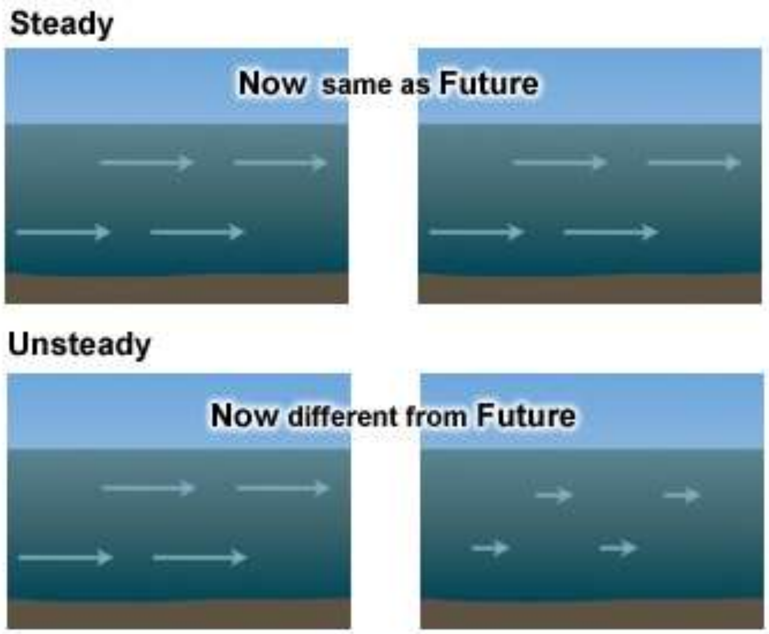


Uniform in space??

Fastest at surface



2. Channels and flow types



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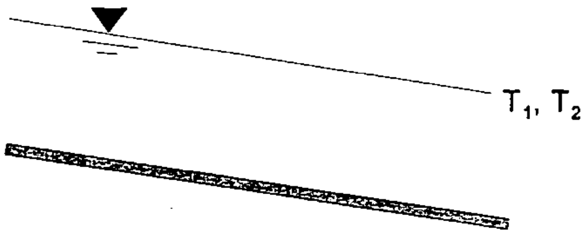
Steady flow: the conditions of velocity and/or depth, may differ from point to point but do not change with time.

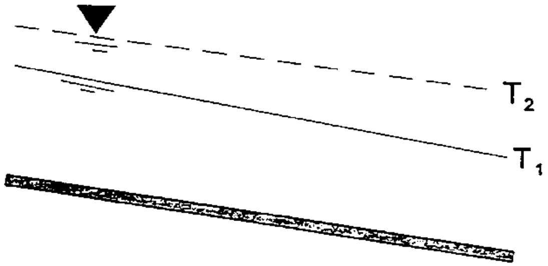
Natural streams are always unsteady

In practice there are always slight variations in velocity and pressure, **but** if the average values are constant, the flow is considered steady.



Steady Flow

Depth and velocity at a given location do not vary with time.



Unsteady Flow

Depth and velocity vary with time at a given location.

Steady in time

$$\text{Steady Flow}: \frac{\partial(U \cdot A)}{\partial t} = 0$$

$$\text{Unsteady Flow}: \frac{\partial(U \cdot A)}{\partial t} \neq 0$$

2. Channels and flow types

2. Channels and flow types

Conditions do not eam or with time.

Conditions chang ream but do not

At a given instant ir point are the same,

Every condition of t t to point and with

2. Channels and flow types

Classify the types of flow according to the uniformity within the stream and the steadiness of the flow over time

Unsteady non-uniform

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2. Channels and flow types

Non-uniform (varied) flow and boundary conditions

$$Fr = \frac{V}{\sqrt{gD}}$$

Inertial (velocity)

Gravitational (celerity)

Where:
V = Water velocity
D = Hydraulic depth
g = Gravity

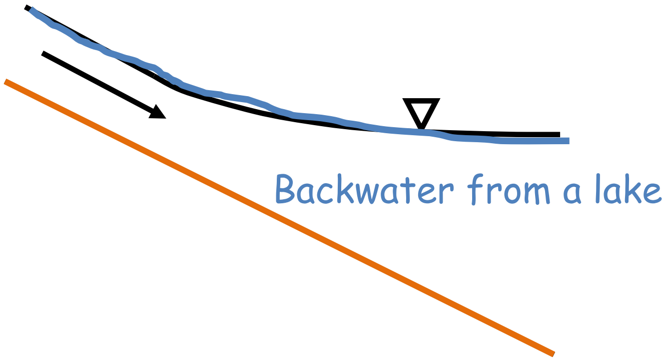
- At **critical** flow celerity equals flow velocity: any disturbance to the surface will remain stationary. $Fr \approx 1$
- In **subcritical** flow the flow is controlled from a downstream point and information is transmitted **upstream**. This condition leads to backwater effects. $Fr < 1$
- The **supercritical** flow is controlled upstream and disturbances are transmitted **downstream**. $Fr > 1$

2. Channels and flow types

Supercritical flow does occur in very steep mountain streams. In the case of a supercritical flow the effect of a disturbance propagates **downstream**

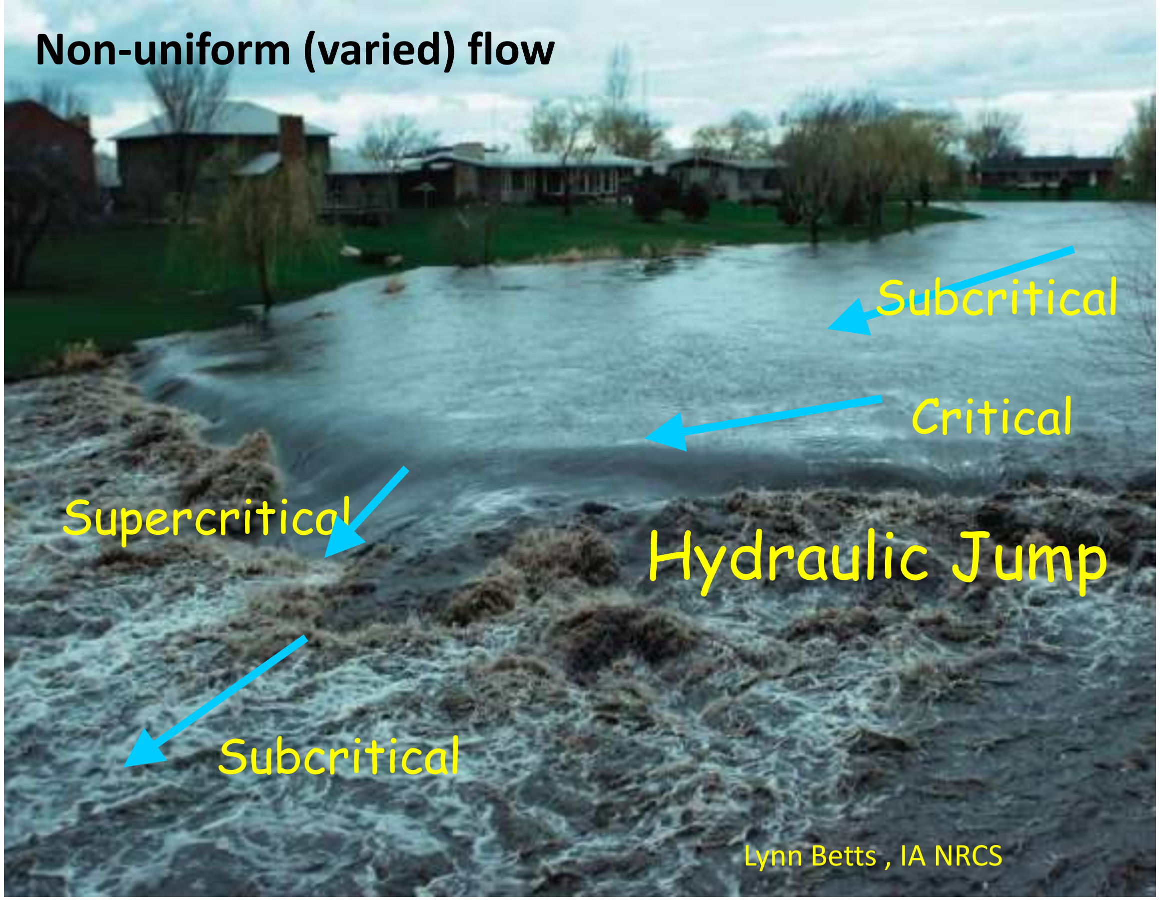
Non-uniform (varied) flow

If (most) alluvial streams are disturbed at a point, the effect of that disturbance tends to propagate **upstream**.



Backwater effect in a waterfall

2. Channels and flow types



Lynn Betts , IA NRCS

Critical flow is unstable and often sets up standing waves between super and subcritical flow

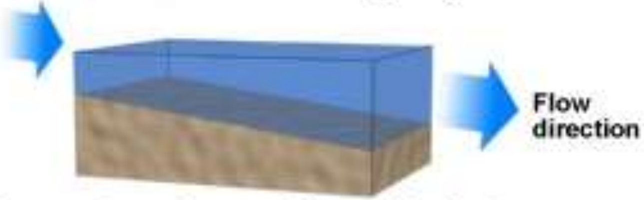
2. Channels and flow types

Water surface slope and channel slope surface

Slope and Stage Relationship

Water surface slope ≈ Channel bed slope
Flow condition = Baseflow

Water surface slope > Channel bed slope
Flow condition = Rising stage



Water surface slope < Channel bed slope
Flow condition = Falling stage

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- Under baseflow conditions, the **water surface slope** is about <u>the same</u> as the **channel bed slope**. This is typical of flow conditions between runoff events.
- Under rising stage conditions, the water surface slope is <u>greater</u> than the channel bed slope. This occurs when a flood wave is approaching.
- When the stage is falling, the water surface slope is <u>less</u> than the channel bed slope. This occurs after a flood wave has passed a location.

3. Fluvial processes: Erosion and Transport

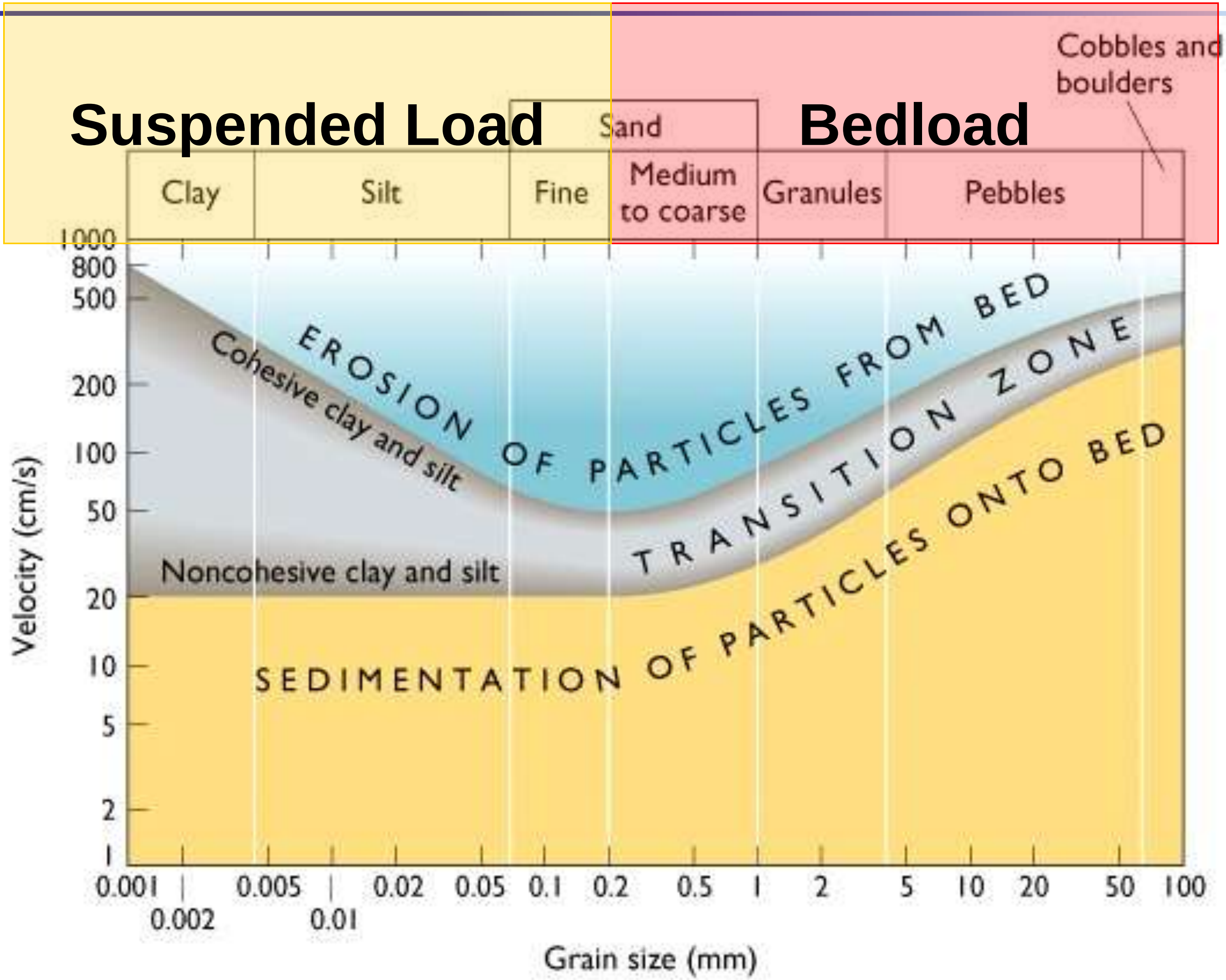
Aggradation occurs when **deposition** is greater than erosion.

3. Fluvial processes: Erosion and Transport

Incision occurs when **erosion** is greater than deposition.

Broadstreet Hollow Stream, NY

3. Fluvial processes: Erosion and Transport

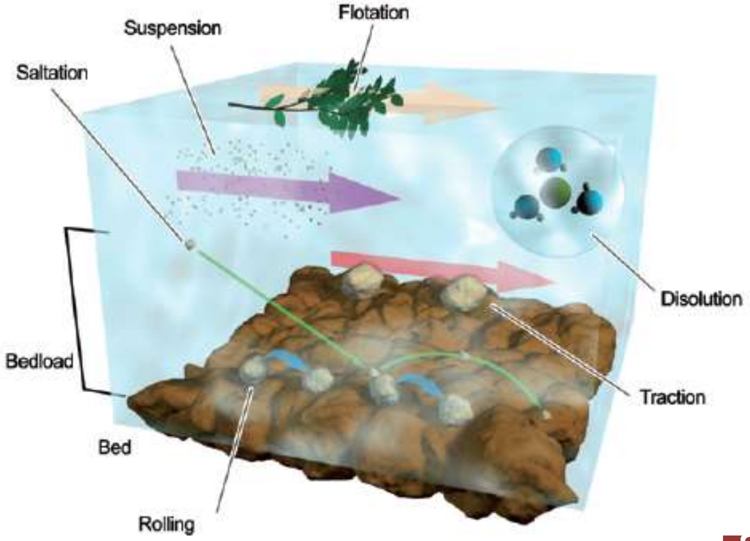


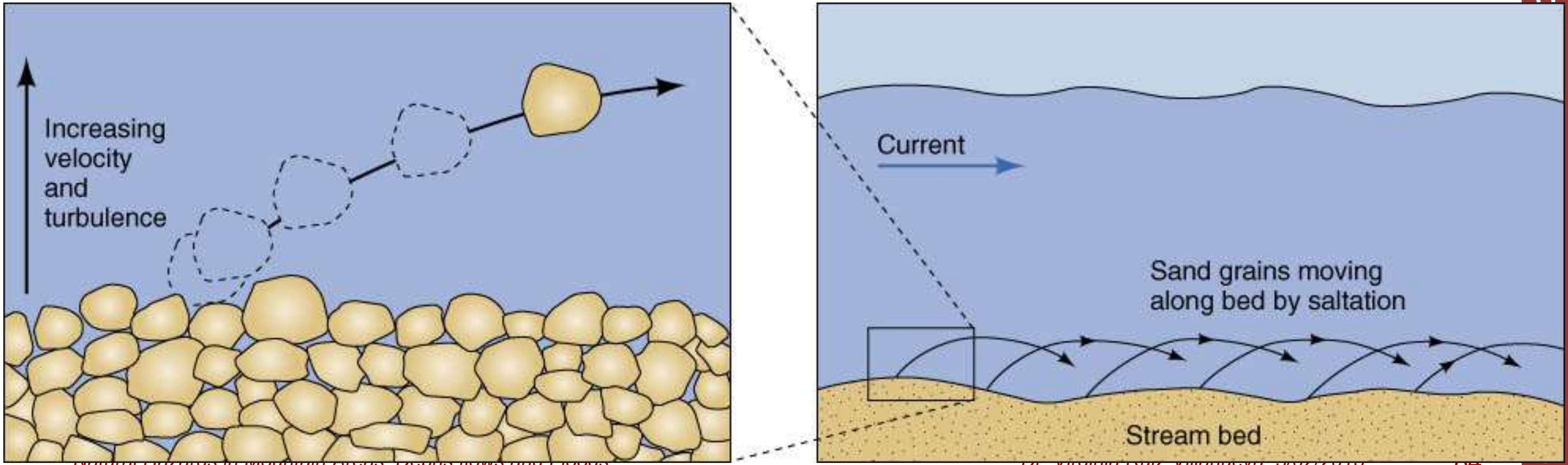
Suspended Load

Bedload

3. Fluvial processes: Erosion and Transport

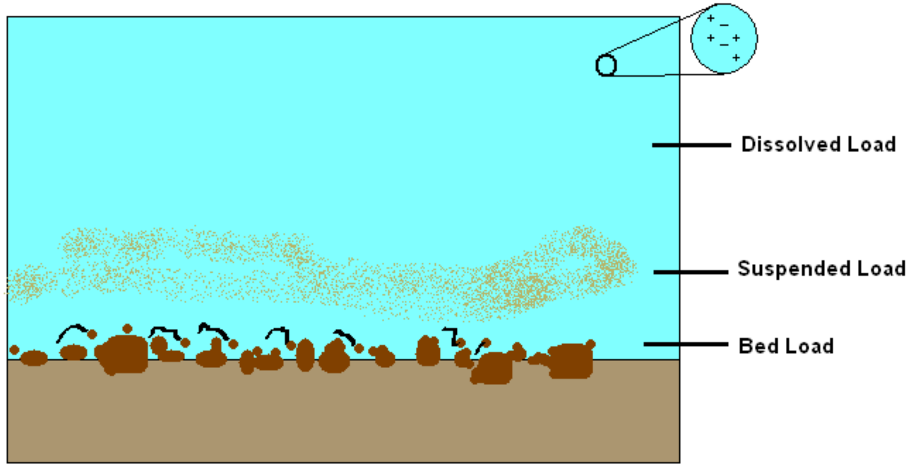
- The **bed load** generally constitutes between 5 and 20 % of the total load of a stream.
- Particles move discontinuously by rolling or sliding at a slower velocity than the stream water.
- The bed load may move short distances by saltation (series of short intermittent jumps).





3. Fluvial processes: Erosion and Transport

suspended load

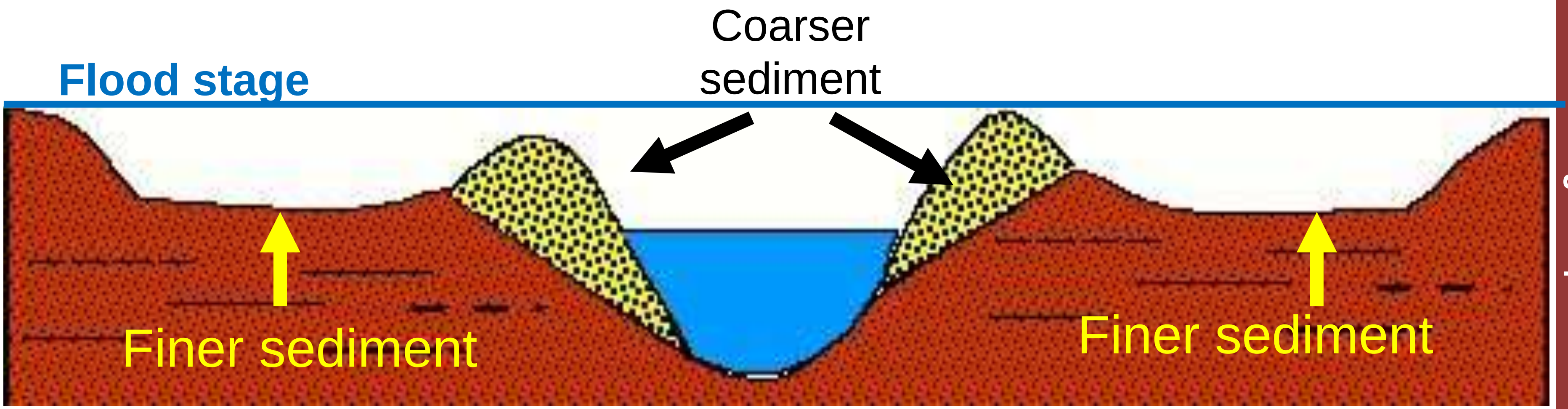


3. Fluvial processes: Erosion and Transport

Tributaries can have different sediment loads

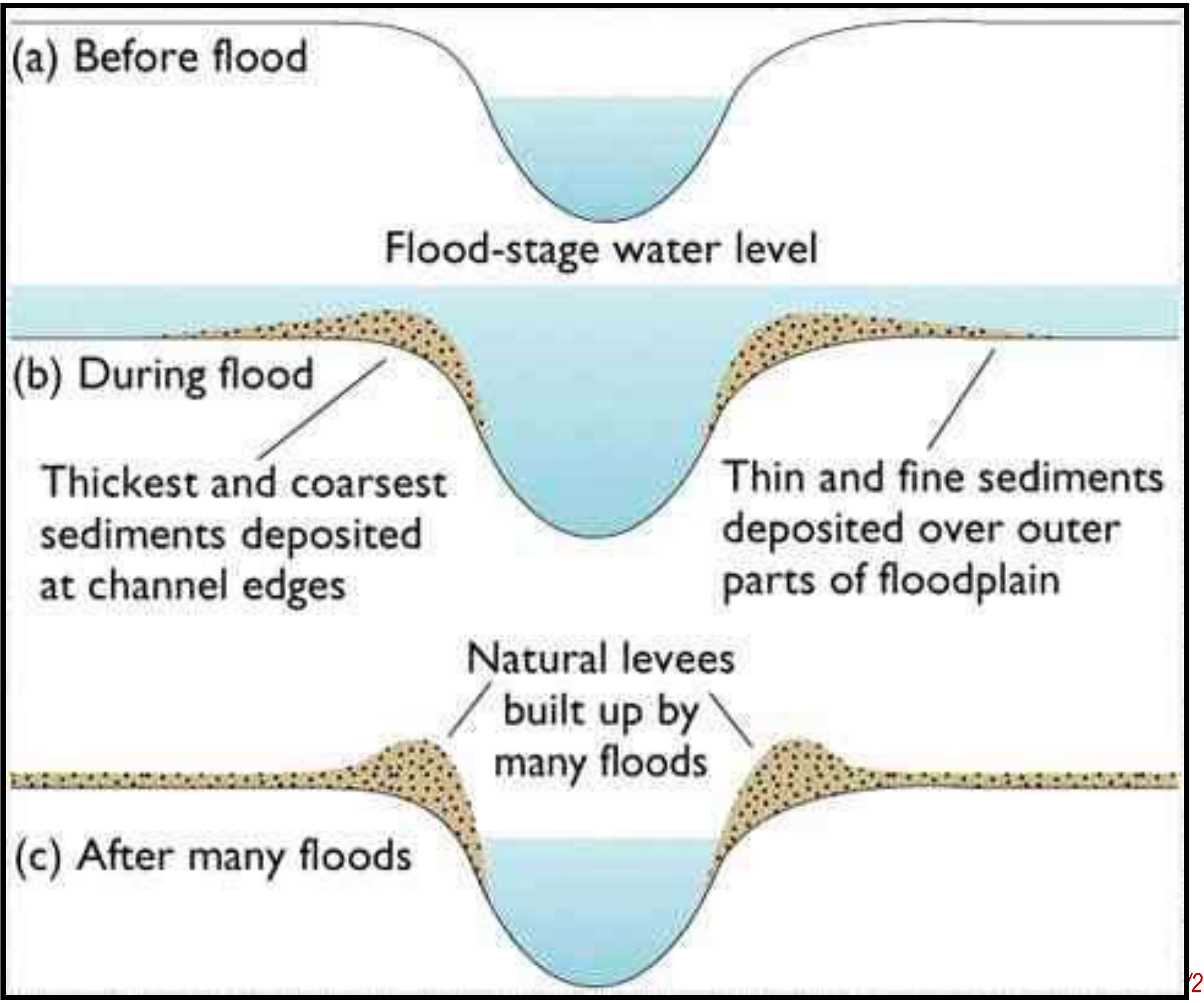
3. Fluvial processes: Erosion and Transport

Levee Deposits



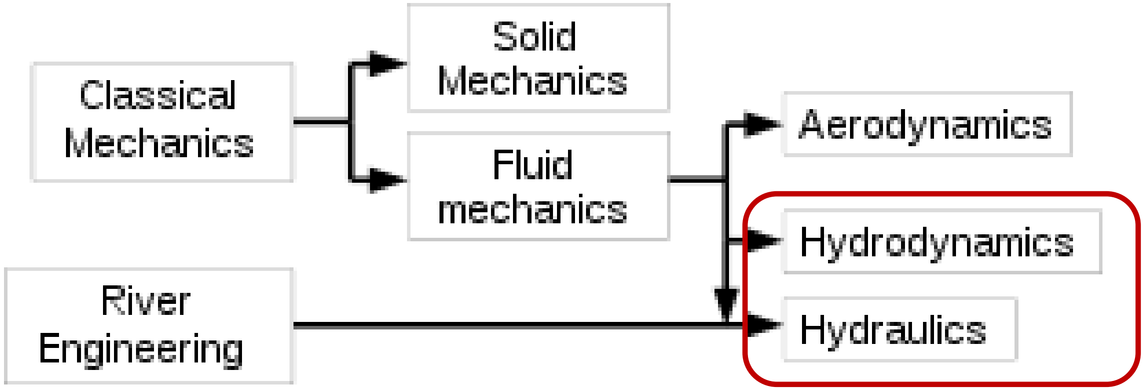
3. Fluvial processes: Erosion and Transport

Floodplain Formation by Suspended Load Deposition



4. Estimating and reconstructing floods

Hydraulics is an applied science and engineering dealing with the mechanical properties of liquids.


Classical Mechanics

Solid Mechanics

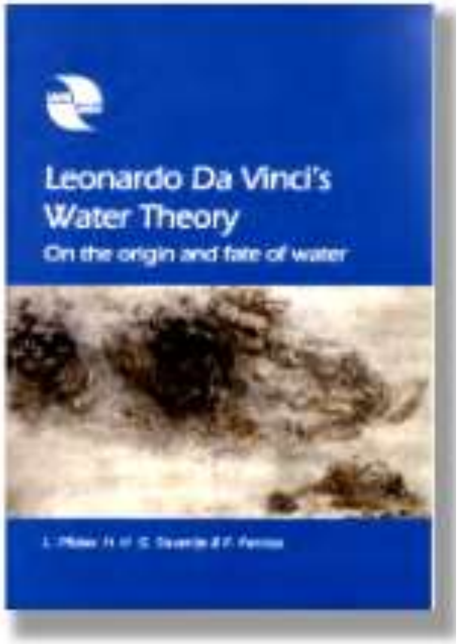
Fluid mechanics

Aerodynamics

Hydrodynamics

Hydraulics

River Engineering


Leonardo Da Vinci's Water Theory

On the origin and fate of water

Free surface hydraulics and hydrodynamics are the branches of hydraulics dealing with free surface flow, such as occurring in rivers.

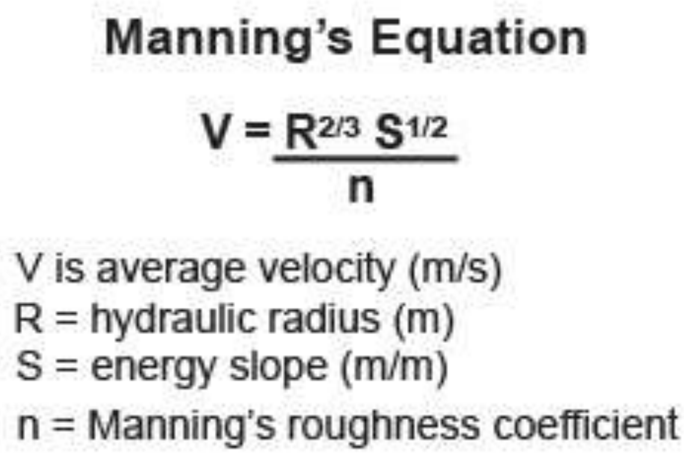
4. Estimating and reconstructing floods

1. **Steady** flow equations
2. **Non steady** (varied) flow equations:
    1. 1D modelling (standard step method)
    2. 2D modelling

4. Estimating and reconstructing floods

Steady Flow Equations: MANNING

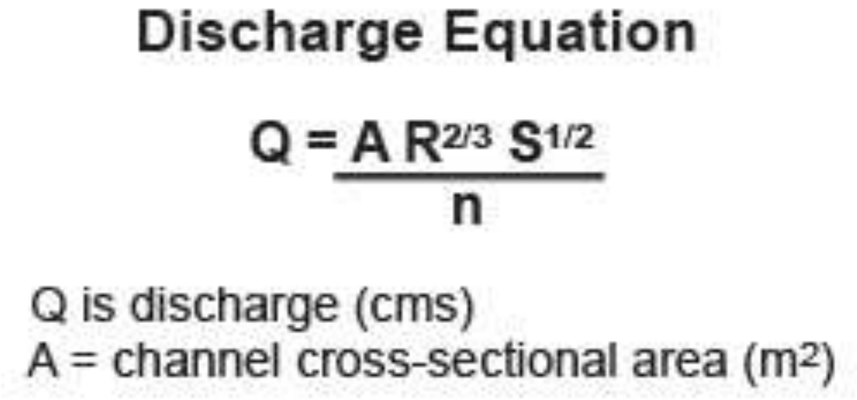
Continuity Equation: $Q = VA$



Manning's Equation

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

V is average velocity (m/s)
R = hydraulic radius (m)
S = energy slope (m/m)
n = Manning's roughness coefficient



Discharge Equation

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

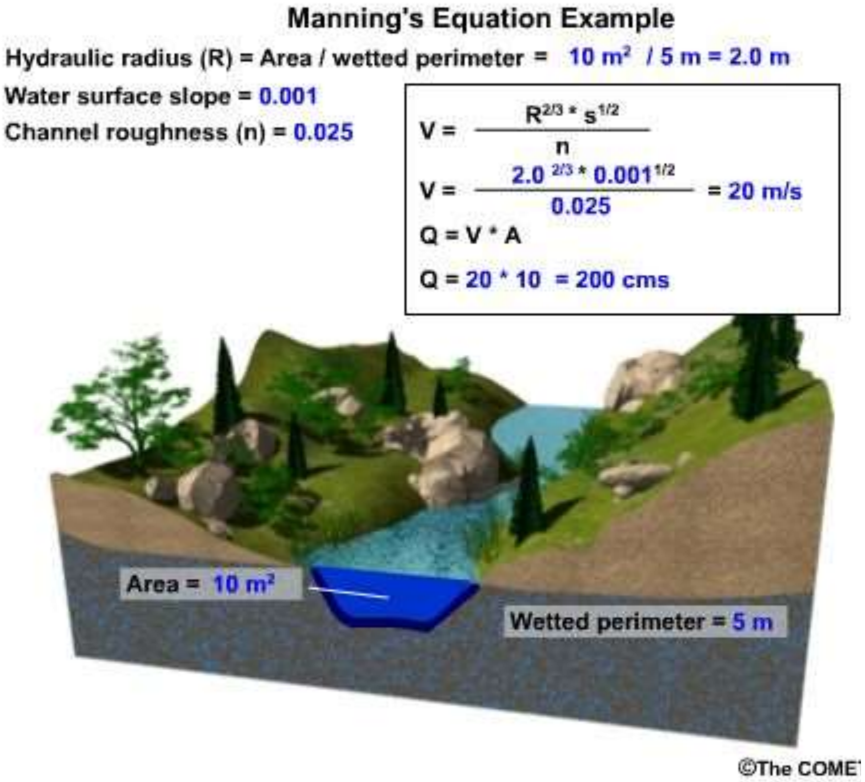
Q is discharge (cms)
A = channel cross-sectional area (m^2)

R = Area / Wetted perimeter

Manning assumes uniform flow

4. Estimating and reconstructing floods

Steady Flow Equations: MANNING



Manning's Equation Example

Hydraulic radius (R) = Area / wetted perimeter = 10 m² / 5 m = 2.0 m

Water surface slope = 0.001

Channel roughness (n) = 0.025

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

$$V = \frac{2.0^{2/3} * 0.001^{1/2}}{0.025} = 20 \text{ m/s}$$

$$Q = V * A$$

$$Q = 20 * 10 = 200 \text{ cms}$$

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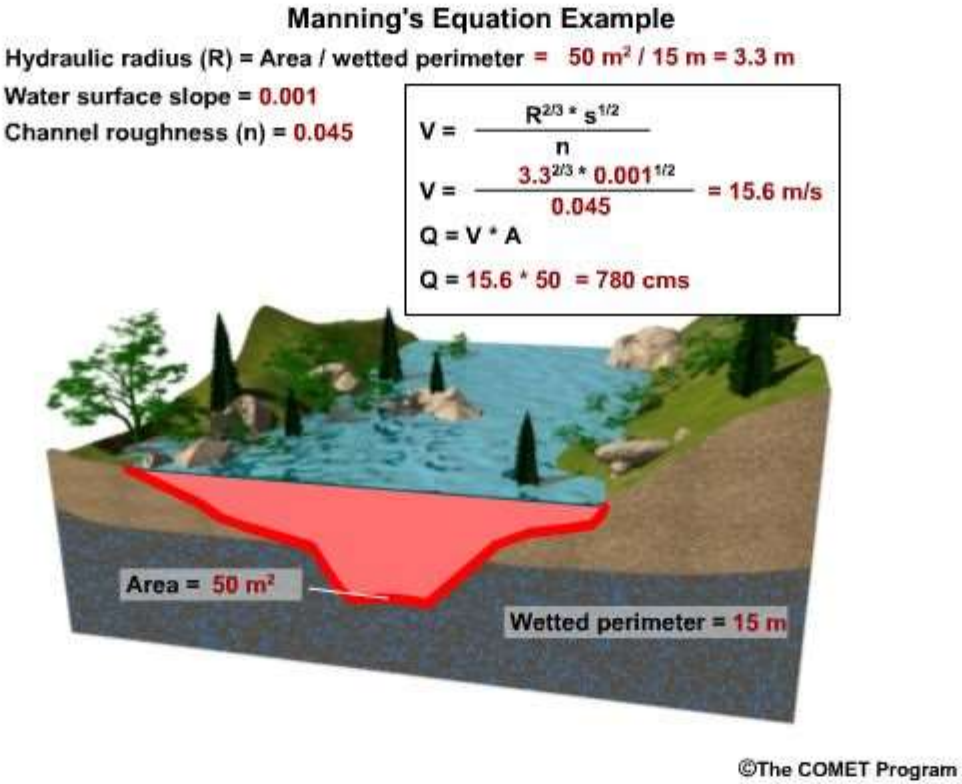

Manning's Equation Example

Hydraulic radius (R) = Area / wetted perimeter = 50 m² / 15 m = 3.3 m

Water surface slope = 0.001

Channel roughness (n) = 0.045

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

$$V = \frac{3.3^{2/3} * 0.001^{1/2}}{0.045} = 15.6 \text{ m/s}$$

$$Q = V * A$$

$$Q = 15.6 * 50 = 780 \text{ cms}$$

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4. Estimating and reconstructing floods

Non steady (varied) flow: Differential equations

Conservation of mass states that no water is created or destroyed

$$\frac{\partial U_x}{\partial x}+\frac{\partial U_y}{\partial y}+\frac{\partial U_z}{\partial z}=0$$

dM/dt=0

U denotes **flow velocity** and **x, y, z** denote the **three Cartesian dimensions**

Conservation of momentum states that the flowing water adheres to Newton's second law of motion, i.e., any change in the flow velocity is the result of the forces acting upon the flow (pressure, shear and friction, gravity, Coriolis):

Momentum equations

$$\boxed{\rho}\left(\frac{\partial U_x}{\partial t}+U_x\frac{\partial U_x}{\partial x}+U_y\frac{\partial U_x}{\partial y}+U_z\frac{\partial U_x}{\partial z}\right)=-\boxed{\frac{\partial p}{\partial x}}+\boxed{\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}}+\boxed{F_x}$$

$$\rho\left(\frac{\partial U_y}{\partial t}+U_x\frac{\partial U_y}{\partial x}+U_y\frac{\partial U_y}{\partial y}+U_z\frac{\partial U_y}{\partial z}\right)=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}+F_y$$

$$\rho\left(\frac{\partial U_z}{\partial t}+U_x\frac{\partial U_z}{\partial x}+U_y\frac{\partial U_z}{\partial y}+U_z\frac{\partial U_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}-\boxed{\rho g}+F_z$$

$\boxed{\rho}$, $\boxed{\tau}$, $\boxed{p}$, and $\boxed{g}$ denote fluid density, shear stress, pressure, gravity, $\boxed{F}$ is any additional external forces

4. Estimating and reconstructing floods

In their 3D form, these equations are known as the Navier–Stokes equations

X-Momentum

$$\rho\left(\xcancel{\frac{\partial U_x}{\partial t}} + U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_x}{\partial y} + U_z\frac{\partial U_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x$$

Y-Momentum

$$\rho\left(\xcancel{\frac{\partial U_y}{\partial t}} + U_x\frac{\partial U_y}{\partial x} + U_y\frac{\partial U_y}{\partial y} + U_z\frac{\partial U_y}{\partial z}\right) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y$$

Z-Momentum

$$\xcancel{\rho\left(\xcancel{\frac{\partial U_z}{\partial t}} + U_x\frac{\partial U_z}{\partial x} + U_y\frac{\partial U_z}{\partial y} + U_z\frac{\partial U_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} - \rho g + F_z}$$

$$\mathrm{u} = \overline{u} + u'$$

Time averaged

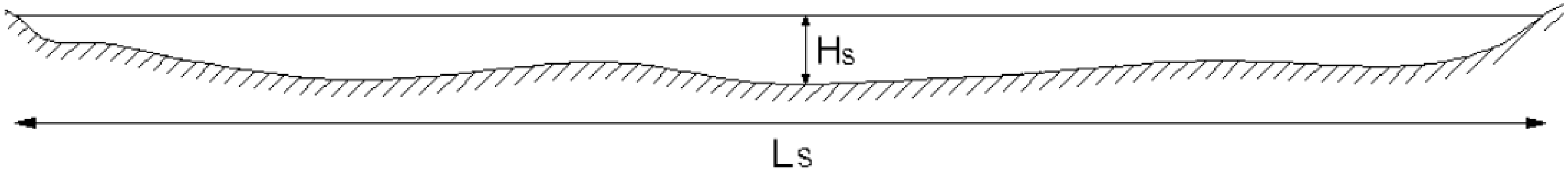
$$\overline{u} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \boxed{u\,dt}$$

Reynolds equations

Depth averaged

$$u = \frac{1}{h}\int_{z_0}^{z_0+h} \overline{u}\,\boxed{dz}$$

Saint Venant 2D or Shallow water equations



4. Estimating and reconstructing floods

Saint Venant 1D or 1D Shallow water equations

$$\frac{\partial U_x}{\partial x} + \cancel{\frac{\partial U_y}{\partial y}} + \cancel{\frac{\partial U_z}{\partial z}} = 0$$

1D Continuity Equation

$$\rho\left(\frac{\partial U_x}{\partial t} + U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_x}{\partial y} + U_z\frac{\partial U_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x$$

$$\xcancel{\rho\left(\frac{\partial U_y}{\partial t} + U_x\frac{\partial U_y}{\partial x} + U_y\frac{\partial U_y}{\partial y} + U_z\frac{\partial U_y}{\partial z}\right) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y}$$

$$\xcancel{\rho\left(\frac{\partial U_z}{\partial t} + U_x\frac{\partial U_z}{\partial x} + U_y\frac{\partial U_z}{\partial y} + U_z\frac{\partial U_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} - \rho g + F_z}$$

Momentum Equation X

4. Estimating and reconstructing floods

Saint Venant 2D or 2D Shallow water equations

$$\frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \xcancel{\frac{\partial U_z}{\partial z}} = 0$$

2D Continuity Equation

$$\rho\left(\frac{\partial U_x}{\partial t} + U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_x}{\partial y} + U_z\frac{\partial U_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x$$

Momentum Equation X

$$\rho\left(\frac{\partial U_y}{\partial t} + U_x\frac{\partial U_y}{\partial x} + U_y\frac{\partial U_y}{\partial y} + U_z\frac{\partial U_y}{\partial z}\right) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y$$

Momentum Equation Y

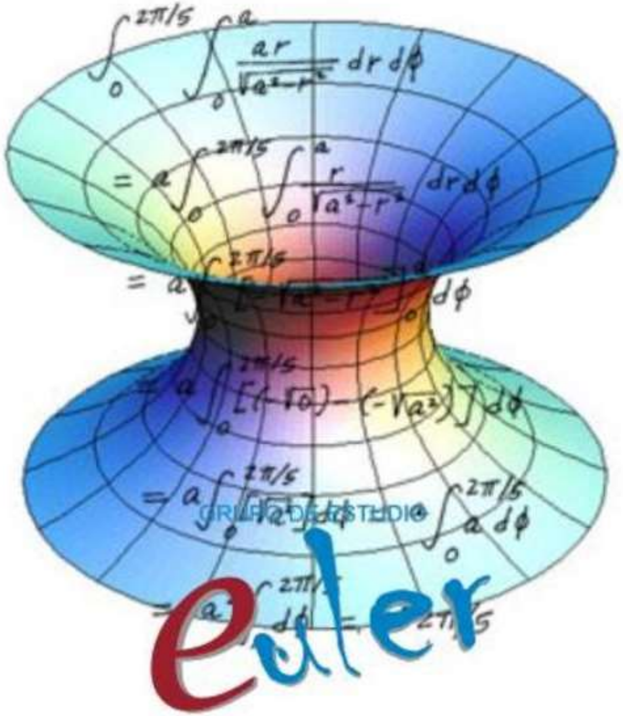
$$\xcancel{\rho\left(\frac{\partial U_z}{\partial t} + U_x\frac{\partial U_z}{\partial x} + U_y\frac{\partial U_z}{\partial y} + U_z\frac{\partial U_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} - \rho g + F_z}$$

4. Estimating and reconstructing floods

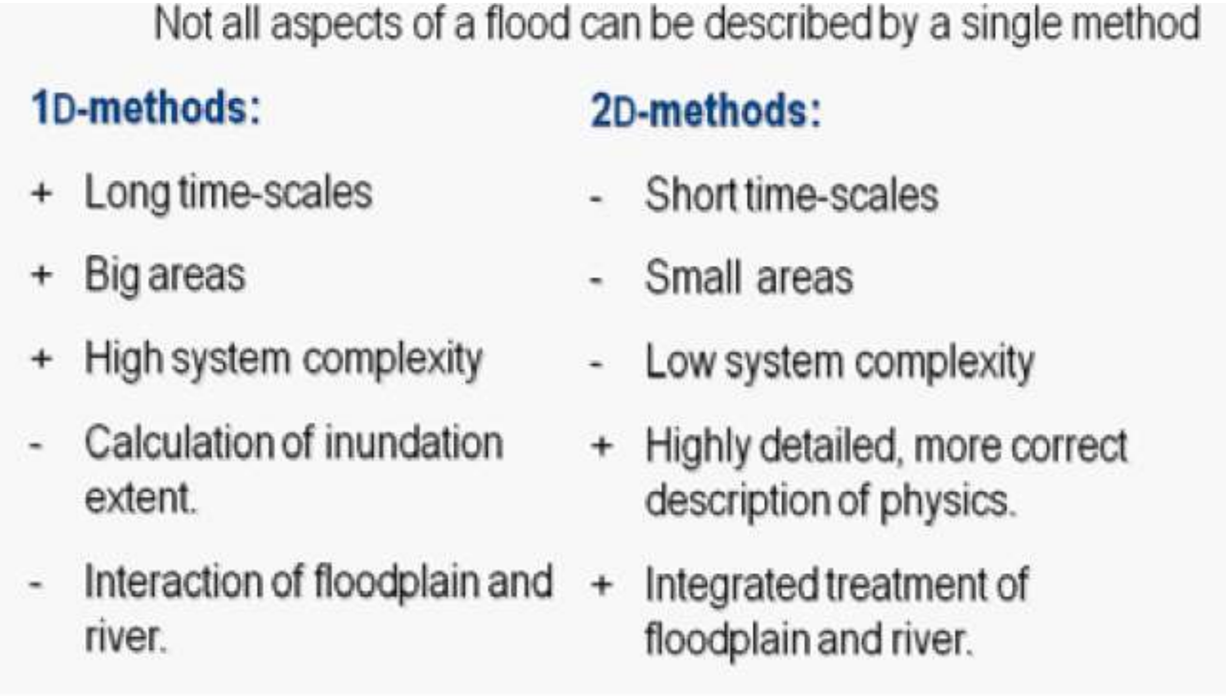
Differential equations do not have explicit solution, they need numerical methods to be solved

Methods of Solution

- Finite Difference Method
- Finite element method
- Finite volume method
- **Solution:**
- Implicit
- Explicit
- CFL condition

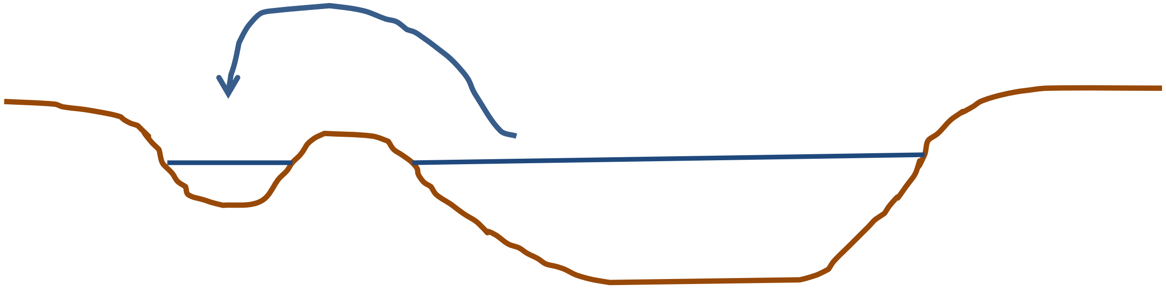


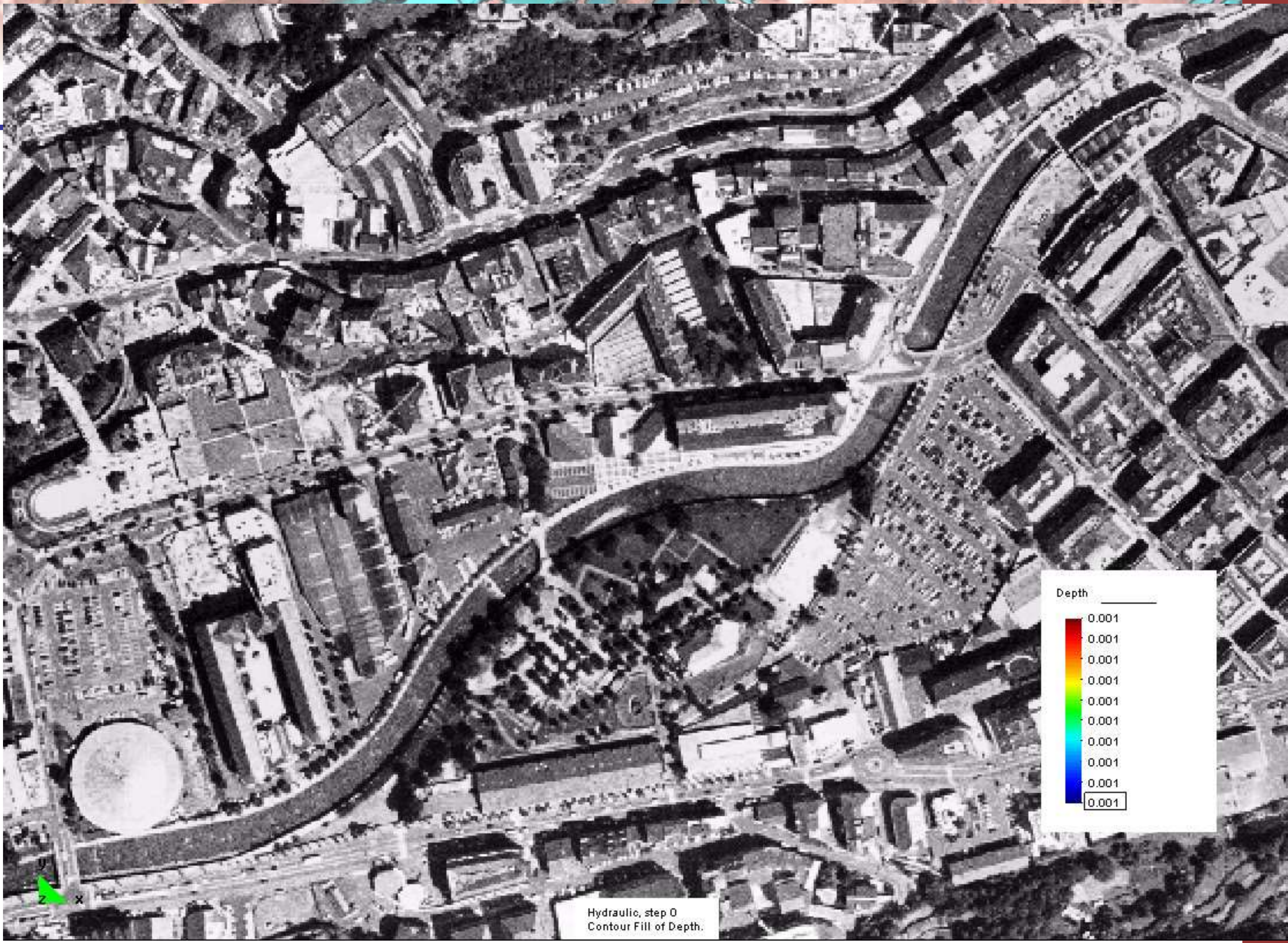
4. Estimating and reconstructing floods



Not all aspects of a flood can be described by a single method

1D-methods:	**2D-methods:**
+ Long time-scales	- Short time-scales
+ Big areas	- Small areas
+ High system complexity	- Low system complexity
- Calculation of inundation extent.	+ Highly detailed, more correct description of physics.
- Interaction of floodplain and river.	+ Integrated treatment of floodplain and river.

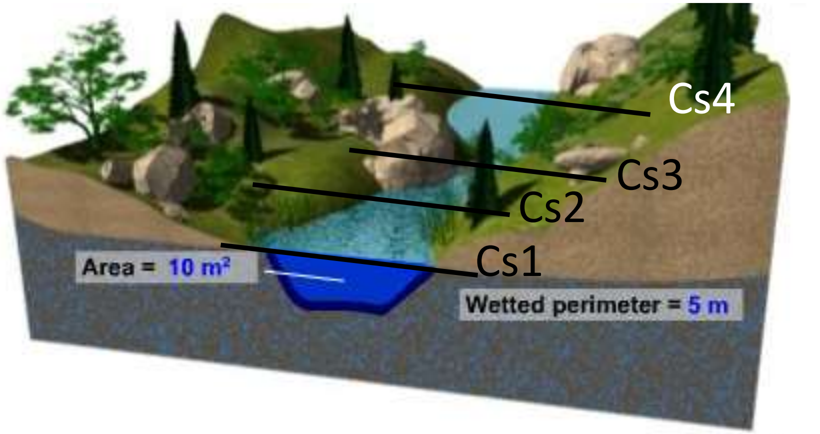




Hydraulic, step 0
Contour Fill of Depth.

4. Estimating and reconstructing floods

Slope conveyance



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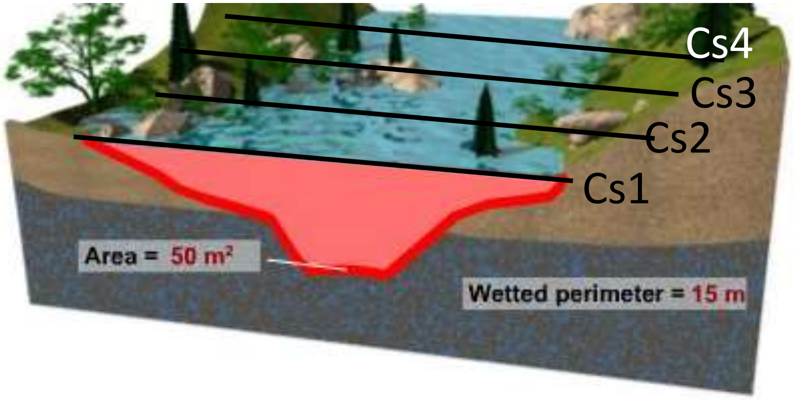

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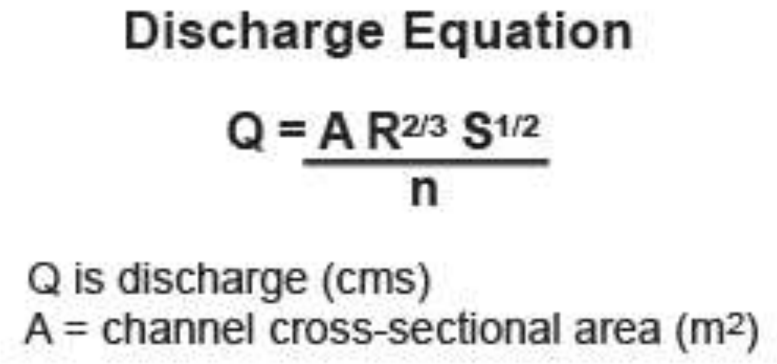


Discharge Equation

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

Q is discharge (cms)
A = channel cross-sectional area (m²)

4. Estimating and reconstructing floods

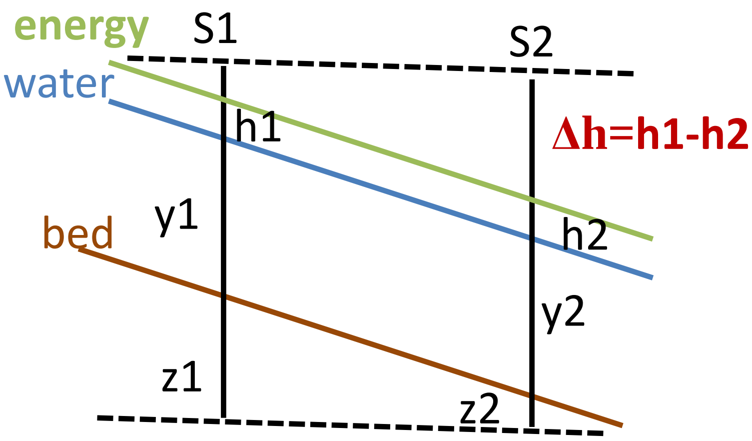
1D: STANDARD STEP METHOD

The Standard Step Method (STM) is a computational technique utilized to estimate one dimensional surface water profiles in open channels with **non uniform (varied)** flow under **steady** state conditions. It uses a combination of the energy, momentum, and continuity.

$$y_2 + z_2 + \frac{\alpha_2 \bar{v}_2^{\,2}}{2g} = y_1 + z_1 + \frac{\alpha_1 \bar{v}_1^{\,2}}{2g} + h_t$$

Supercritical= S1 is upstream

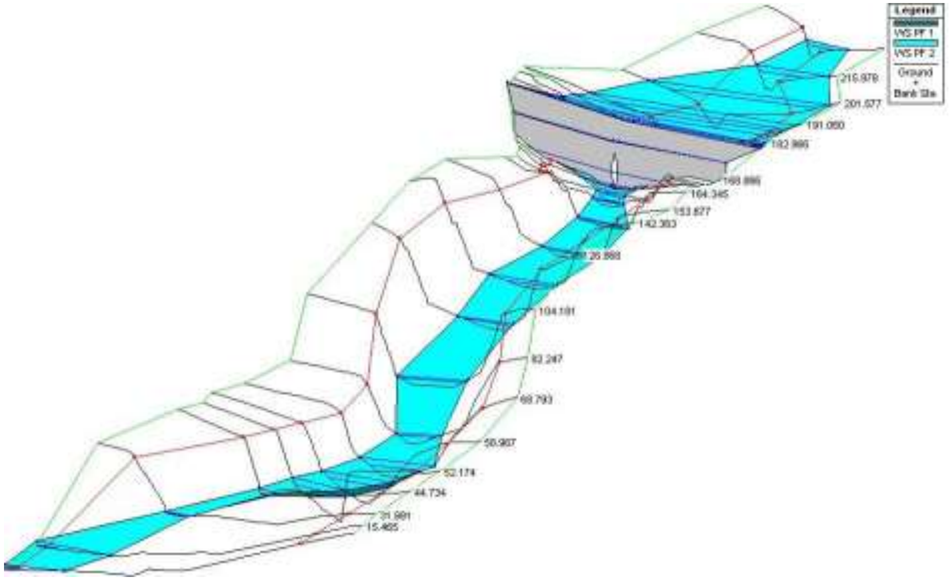
Subcritical=S1 is downstream

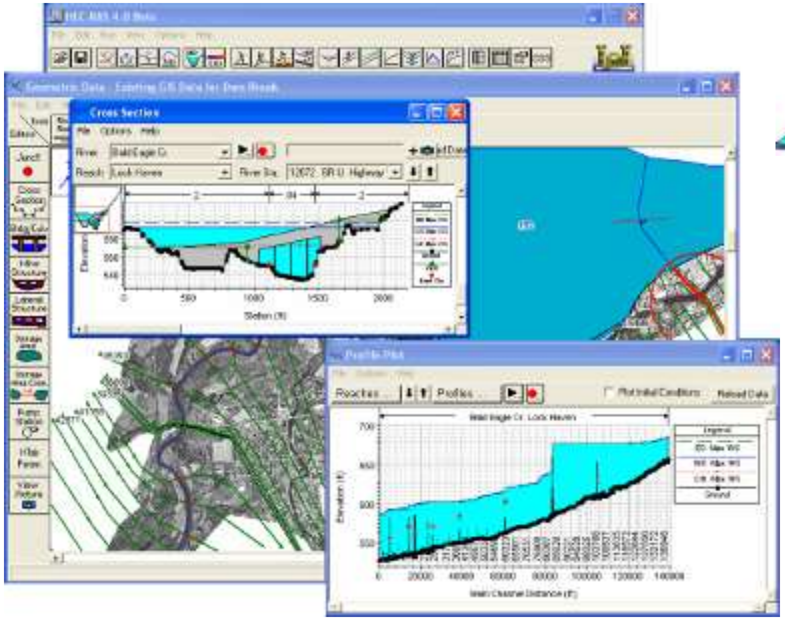


4. Estimating and reconstructing floods

HEC RAS:

1. Cross sections
2. Discharge/hydrograph
3. Boundary conditions
4. Manning roughness

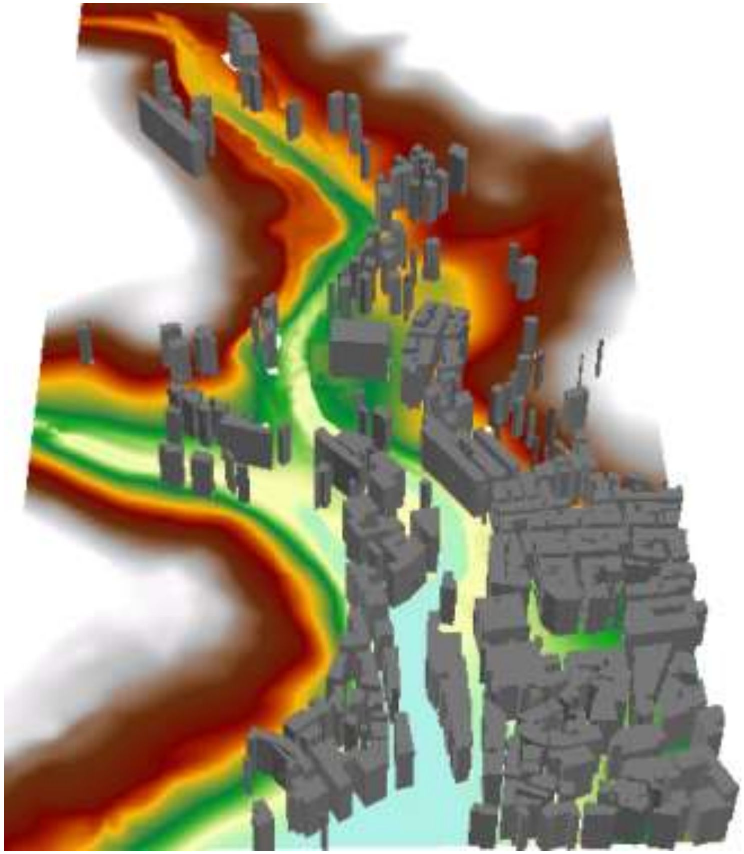


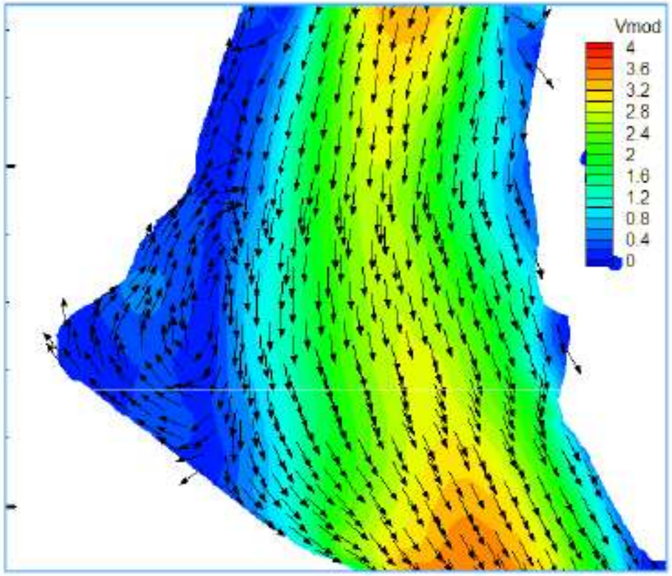


4. Estimating and reconstructing floods

2D SAINT VENANT EQ.: IBER model

1. DEM
2. Calculation mesh
3. Initial conditions
4. Boundary conditions (inlet and outlet)
5. Discharge/hydrograph
6. Manning roughness (spatially distributed)





3. Estimating and reconstructing floods

A **roughness coefficient** is used to describe the channel friction that acts to slow down the streamflow.

Roughness coefficients represent the resistance to flood flows in channels and flood plains

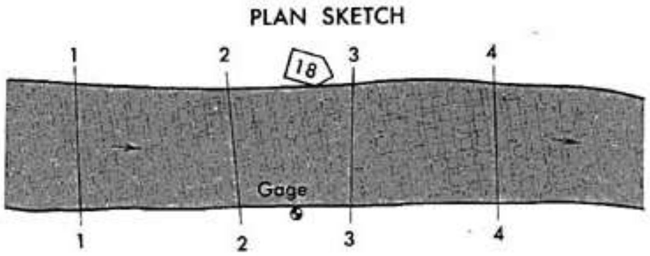
Trees and boulders would have a higher coefficient than the concrete lining of an engineered drainage channel.

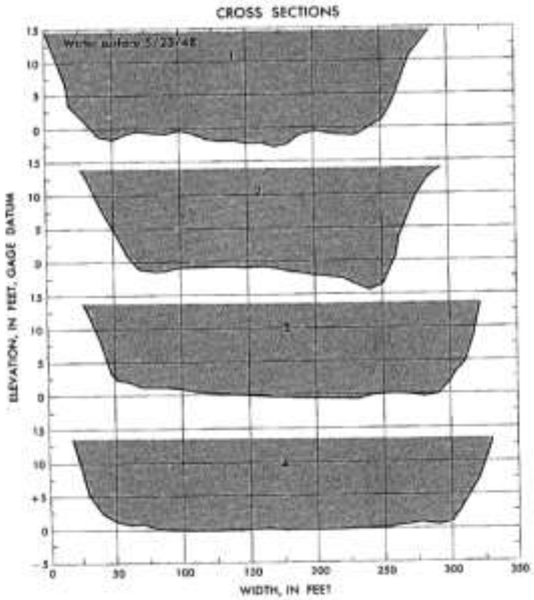
Values of the roughness coefficient, may be assigned for conditions that exist at the time of a specific flow event, for average conditions over a range in stage, or for anticipated conditions at the time of a future event.

Irregularity (n1):
Variation in **Channel Cross Section** (n2): shape and size of cross sections
Obstruction (n3)
Vegetation (n4)

$$n=n1+n2+n3+n4$$

3. Estimating and reconstructing floods



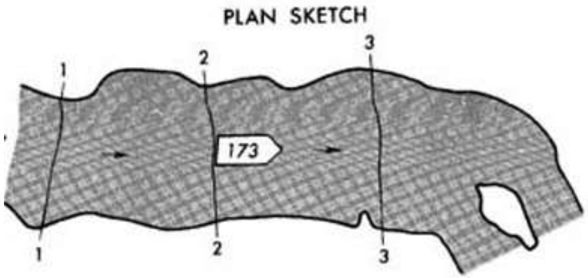


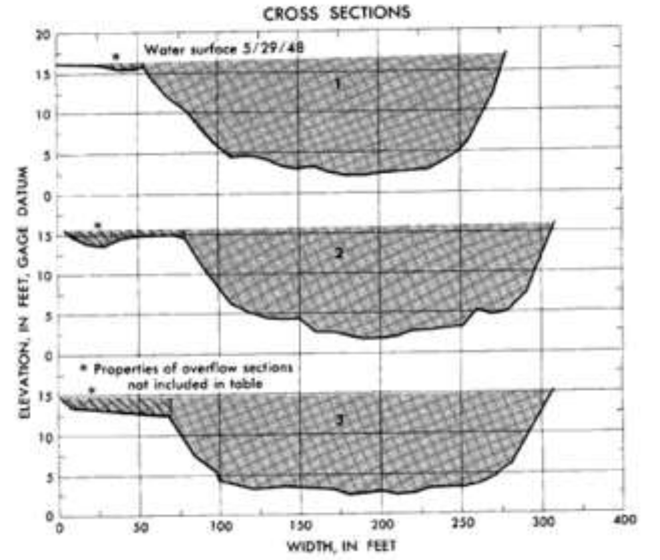
Manning *n* = 0.030

Clark Fork at Missoula, Montana

(http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/index.htm

3. Estimating and reconstructing floods



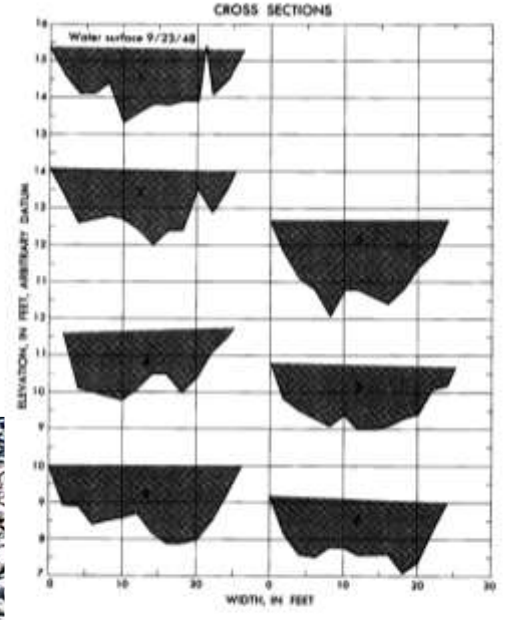


Manning $n = 0.037$

Wenatchee River at Plain, Washington

(http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/index.htm)

3. Estimating and reconstructing floods

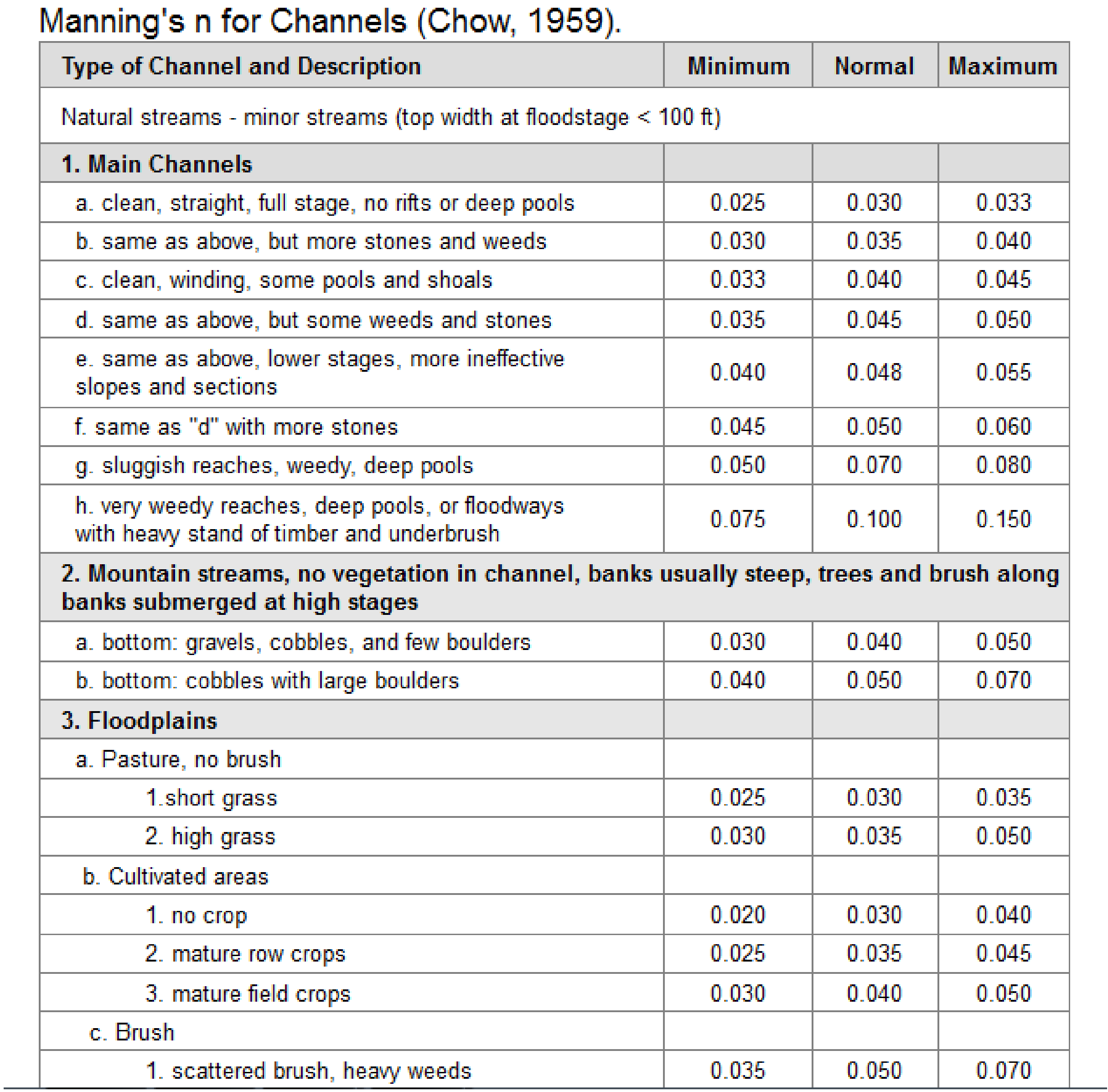


Manning *n* = 0.060

Rock Creek Canal near Darby, Montana

(http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/index.htm)

3. Estimating and reconstructing floods



Manning's n for Channels (Chow, 1959).

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070

…to be continued…

Modelling floods: exercises