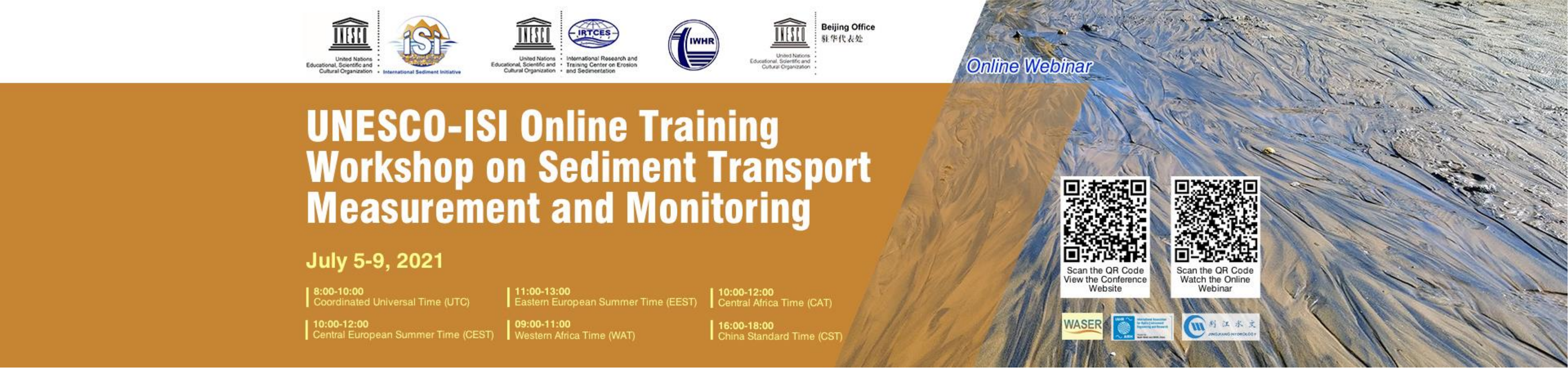

Collecting sediment data for studying sediment-based ecological problems

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Tsinghua University

Content

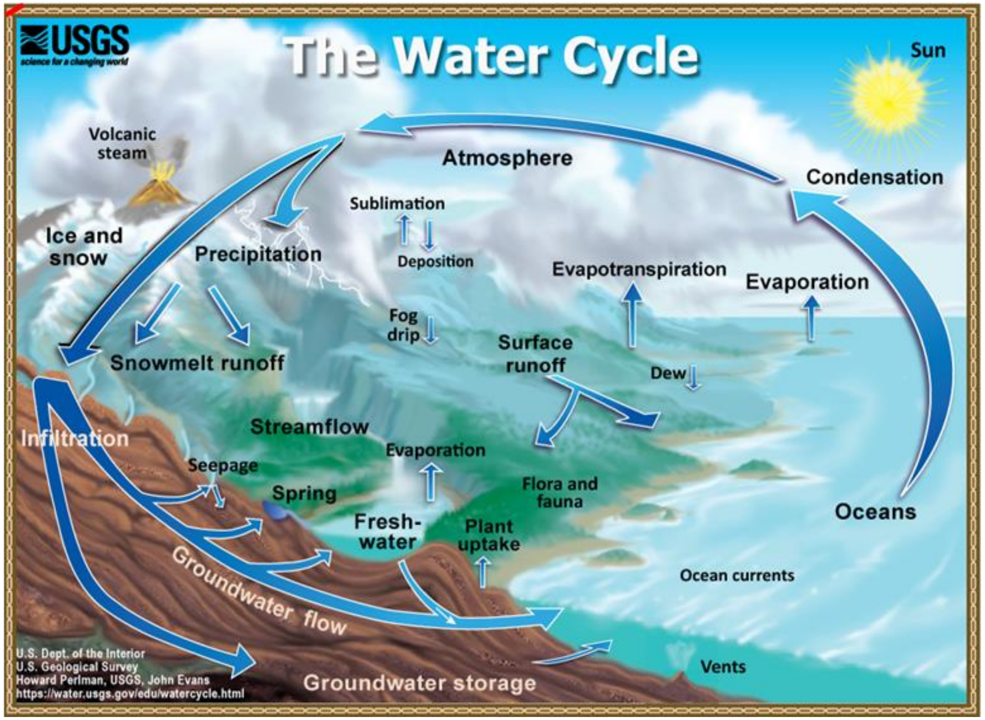
1. Basic concepts
2. Data collecting
3. Environmental impacts of massive sediment movement
4. Water-sediment-ecology integrated management

1. Basic concepts

Hydrological cycle

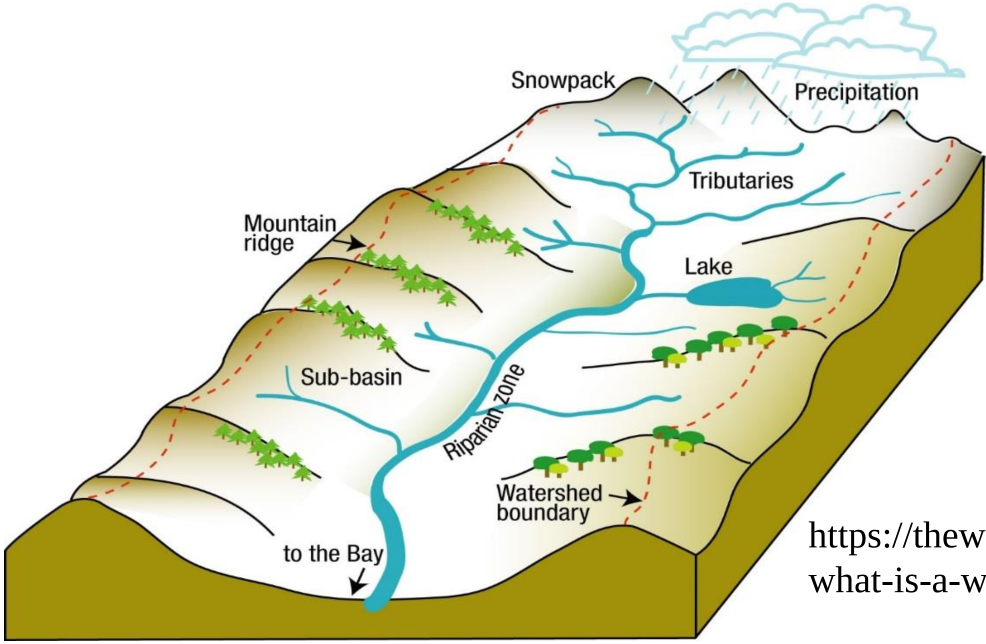
Hydrological cycle includes

- ✓ Evaporation
- ✓ Transpiration
- ✓ Condensation
- ✓ Precipitation
- ✓ Runoff
- ✓ Infiltration



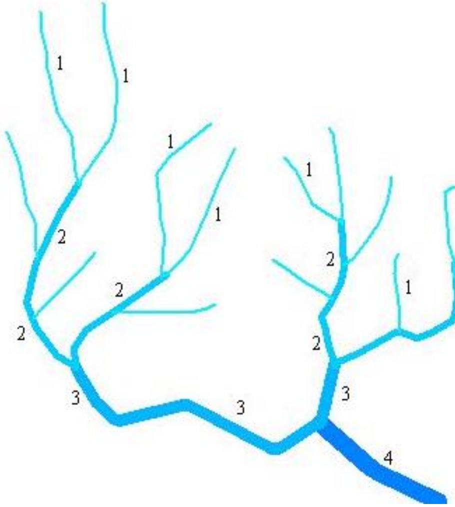
https://water.usgs.gov/edu/watercycle.html

Watershed & drainage network

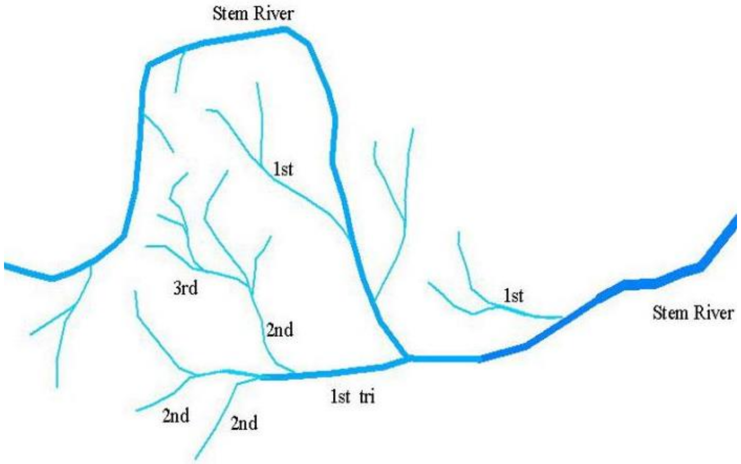


https://thewatershedproject.org/what-is-a-watershed/

a. Horton-Strahler's stream ordering system



b. Engineering stream ordering system



Morphological model

Grain size

Slope

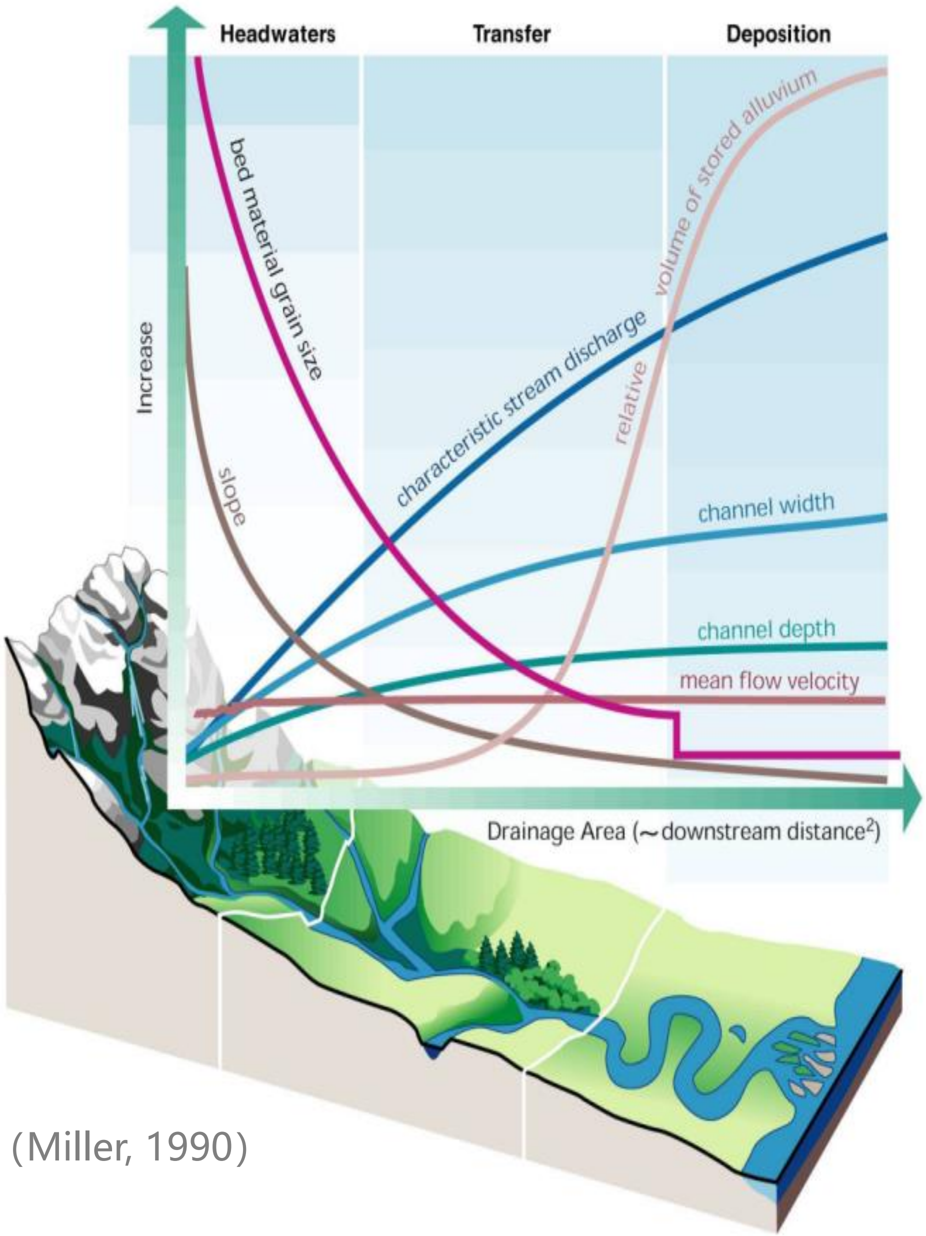
Discharge

Channel width

Channel depth

Flow velocity

……



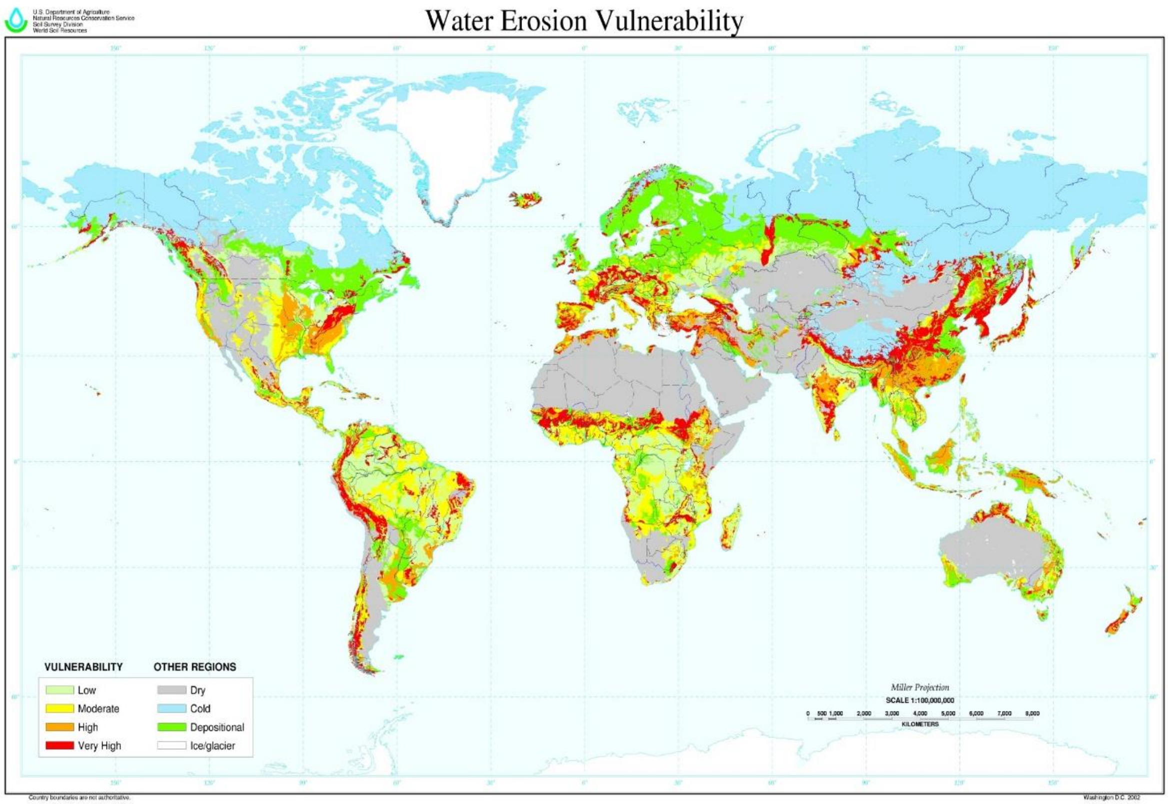
(Miller, 1990)

Soil erosion

- **Soil erosion is the displacement of the upper layer of soil; it is a form of soil degradation.**
- **This natural process is caused by the dynamic activity of erosive agents, that is, water, ice (glaciers), snow, air (wind), plants, animals, and humans.**

Water erosion

- **The four principal factors** in water erosion are **climate, soil characteristics, topography,** and **ground cover**. Also, tectonics and land development

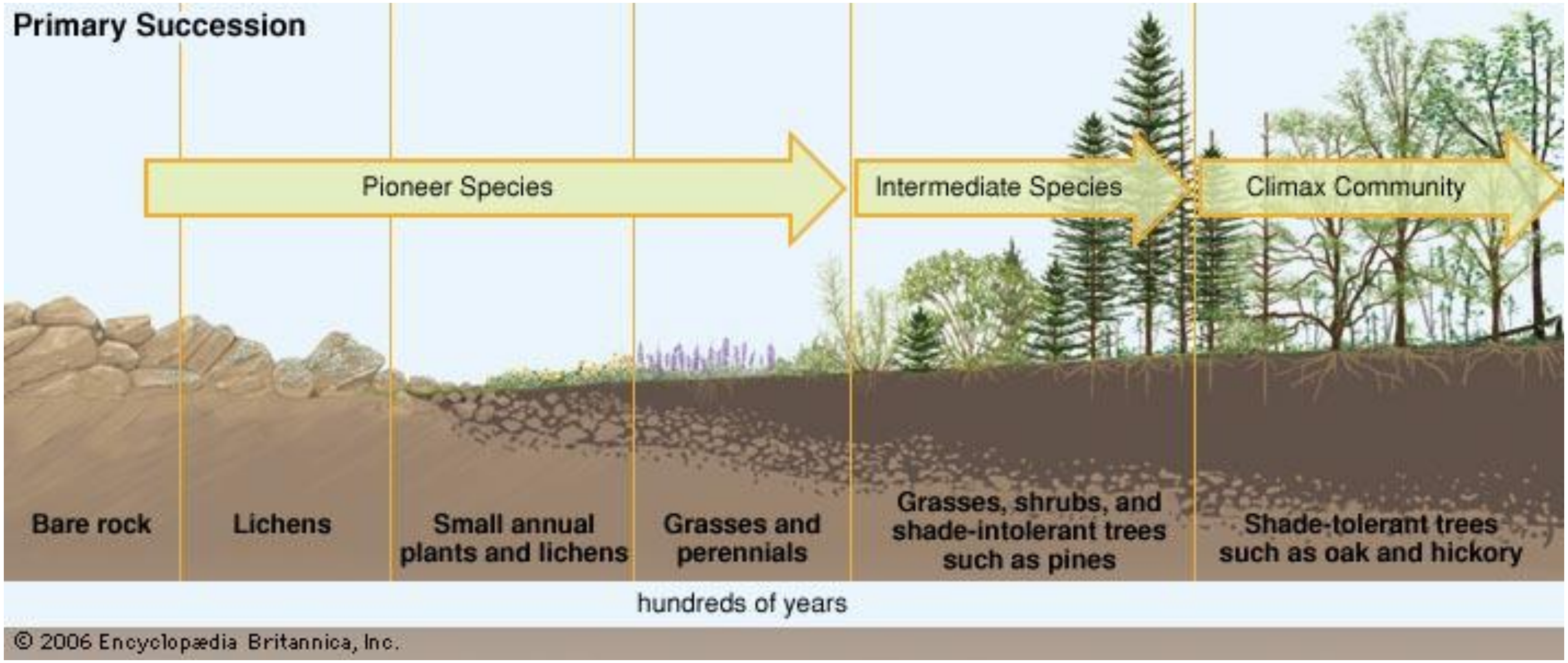


World map indicating areas that are vulnerable to high rates of water erosion

https://upload.wikimedia.org/wikipedia/commons/e/e0/Water_erosion_map.jpg

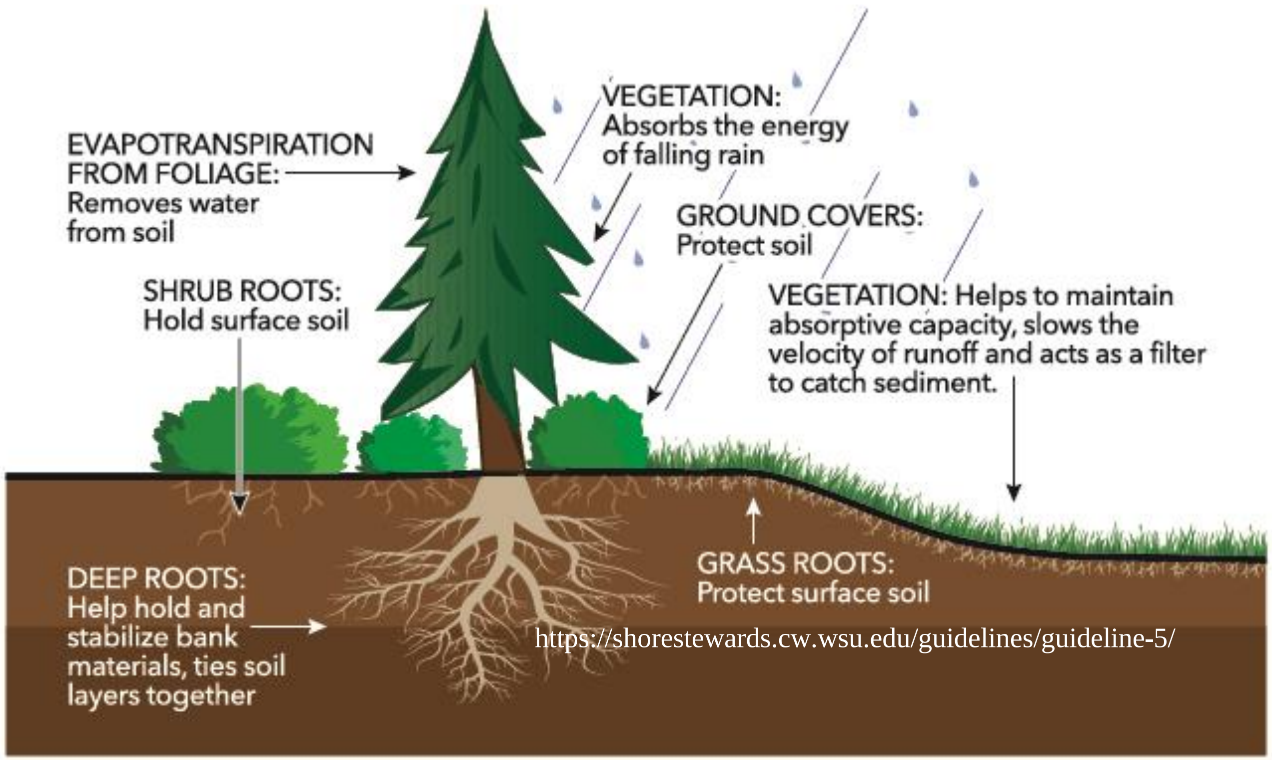
Vegetation succession

- **Vegetation succession is defined as the process of an initial pioneer suite of plants established in the early stage of colonization of a bare land, which consist mainly of herbaceous species and require high amounts of light, being replaced gradually by a suite of plants, which consist of woods, shrubs and grasses and tolerate low light or closed canopy situations.**



Vegetation-erosion dynamics

- **Vegetation reduces erosion by adsorbing impact of raindrops, reducing velocity and scouring power of runoff, reducing runoff volume by increasing percolation into soil, binding soil with roots and protecting soil from wind erosion**



Role of vegetation in reducing erosion and stabilizing slopes

Vegetation-erosion dynamics

- **The dynamics of the vegetation under the action of various ecological stresses follows the differential equation:**

$$\frac{dV}{dt} = a\underset{\text{Vegetation cover}}{V} - c\underset{\text{Erosion}}{E} - K_{inst}\underset{\text{Instant stress}}{\delta(t_0)} + \underset{\text{Reforestation}}{V_R}$$

- E is the rate of erosion with dimension [mass/area.time] and unit (ton/km^2 yr);
- a, K_{inst} are coefficients of dimension [time^{-1}] and unit (yr^{-1});
- c is a coefficient of dimension [area/mass] and unit (km^2/ton); and V_R is the rate of the reforestation of unit (yr^{-1})
- $\delta(t_0)$ is instant stress

Vegetation-erosion dynamics

- **For determining of instant ecological stresses $\delta(t_0)$ step function and impulse function are applied:**

$$\Delta(t_0)=\begin{cases}0.if.t\le t_0\\1.if.t>t_0\end{cases}\quad \delta(t_0)=\frac{d\Delta(t_0)}{dt}=\begin{cases}0.for.t\ne t_0\\1.for.t=t_0\end{cases}$$

- **Instant ecological stresses can be mathematically expressed as:**

$$f_\tau=K_{inst}\delta(t_0)$$

in which K_{inst} is a coefficient representing the reduction of vegetation due to the instant stress occurring at time t_0.

Vegetation-erosion dynamics

- **St. Helens volcano, erupted in 1980. St. Helens volcano exerted an extremely high but instant stress on the forest. The forest cover (V=0.8) was totally destroyed. This process is described by the equation:**

$$\frac{dV}{dt} = -K_{inst}\delta(1980) \qquad V(t) = 0.8 - K_{inst}\Delta(1980) = \begin{cases} 0.8 & before \quad 1980 \\ 0.0 & after \quad 1980 \end{cases}$$

Vegetation-erosion dynamics

- **Long term ecological stress, e.g. air pollution is given as follows:**

$$A_\tau = a_1 Po_1 + a_2 Po_2 + a_3 Po_3 + \ldots$$

Po_1, Po_2, Po_3 are the concentrations of the pollutant 1, pollutant 2 and pollutant 3, a_1 , a_2 , a_3 are impact factors of the pollutants on the vegetation.

$$\frac{dV}{dt} = aV - cE - kA_\tau - K_{inst}\delta(t_0) + V_R$$

Long-term stress

- **Short-term ecological stress, e.g. drought is given as follows:**

$$P_\tau = \frac{P - P_e}{P_e}$$

***P*: the precipitation of the year, P_e: the vegetation water demand. If the $P > P_e$, the stress is positive and the vegetation will be promoted. If drought occurs, the stress is negative and the vegetation will suffer.**

$$\frac{dV}{dt} = aV - cE - pP_\tau - K_{inst}\delta(t_0) + V_R$$

Short-term stress

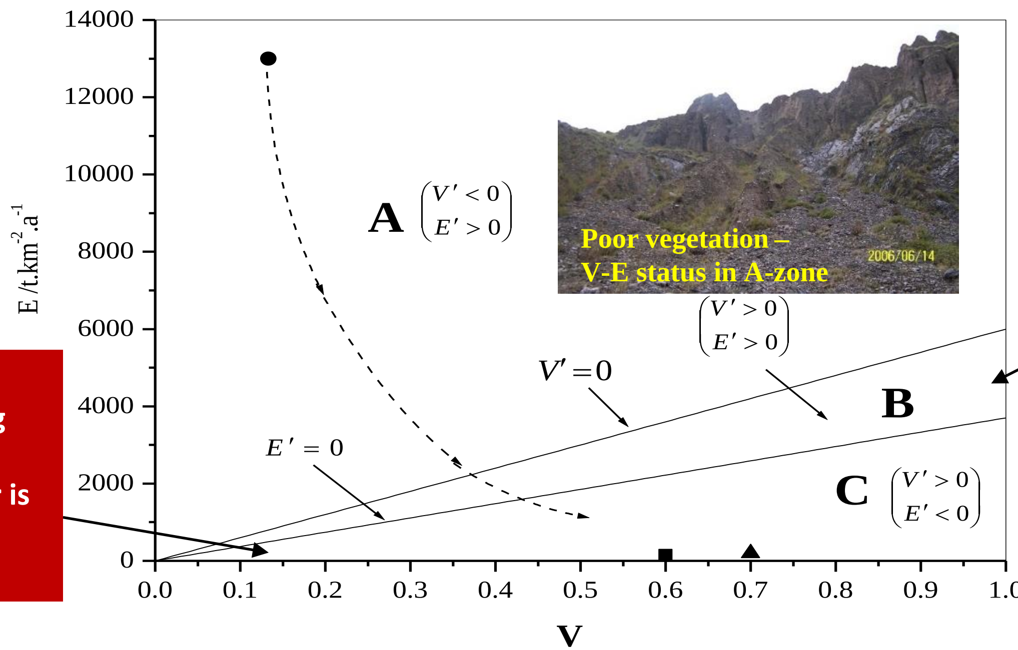
Vegetation-erosion dynamics

- **Vegetation-erosion chart for the Xiaojiang Watershed and its sub-watersheds:**

●: Xiaojiang Watershed in the 1990s; ▲: Heishuihe Watershed in the 1998;

■: Shengou Watershed in the 1996

Xiaojiang



C: *dV/dt>0, dE/dt<0,* vegetation developing and the erosion decreasing. The larger is the value of *f/d*, the bigger is the C zone.

Transitional zone:
B: *dV/dt>0, dE/dt >0.*
D: *dV/dt<0, dE/dt <0.*

Wang et al. (2014)

Sediment transport & geomorphology

- Three primary geomorphic processes affect rivers, i.e.,
  1) erosion, the detachment of soil particles;
  2) sediment transport, the movement of eroded soil particles in flowing water;
  3) sediment deposition, settling of eroded soil particles to the bottom of a water body.
- **Sediment** is defined as the solid particles found in a deposit after transportation by flowing water, wind, wave, glacier, and gravitational action.
- **Sediment discharge** is defined as the mass or volume of sediment passing a stream cross section in a unit of time. The typical unit for sediment discharge is tons per second or per day.

The confluence of Taohe and the Yellow River appeared clear yellow, green two color division

Gansu Yongjing County

Sediment transport & geomorphology

- 70% of ecosystem restoration efforts are linked to sediment and geomorphology
- Problems with too much sediment

  - raised flood profiles

  - reduced underwater light

  - decreased capacity of hydraulic structures
- Problems with too little sediment

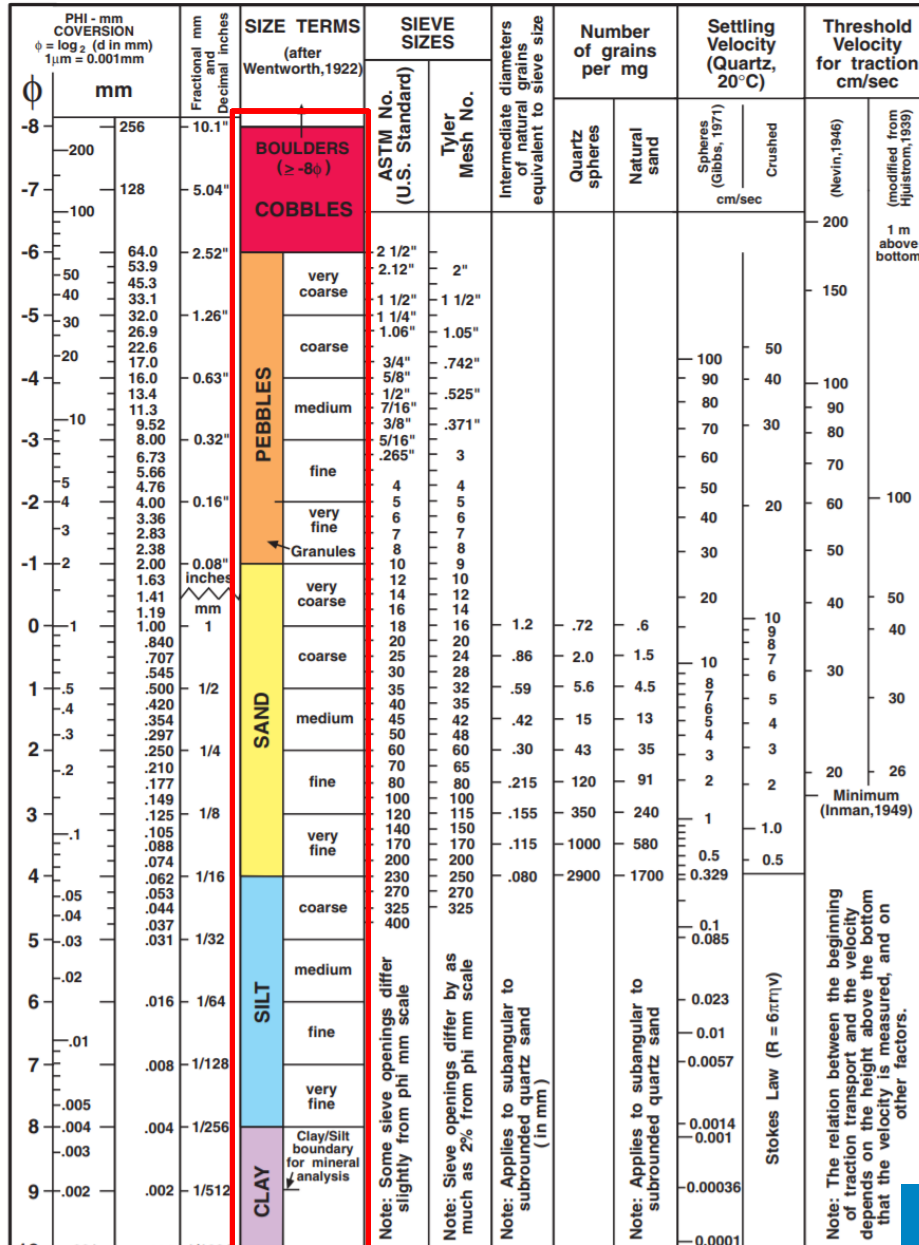
  - incision (channel lowering)

  - delta loss

  - scour at hydraulic structures

Sediment classification

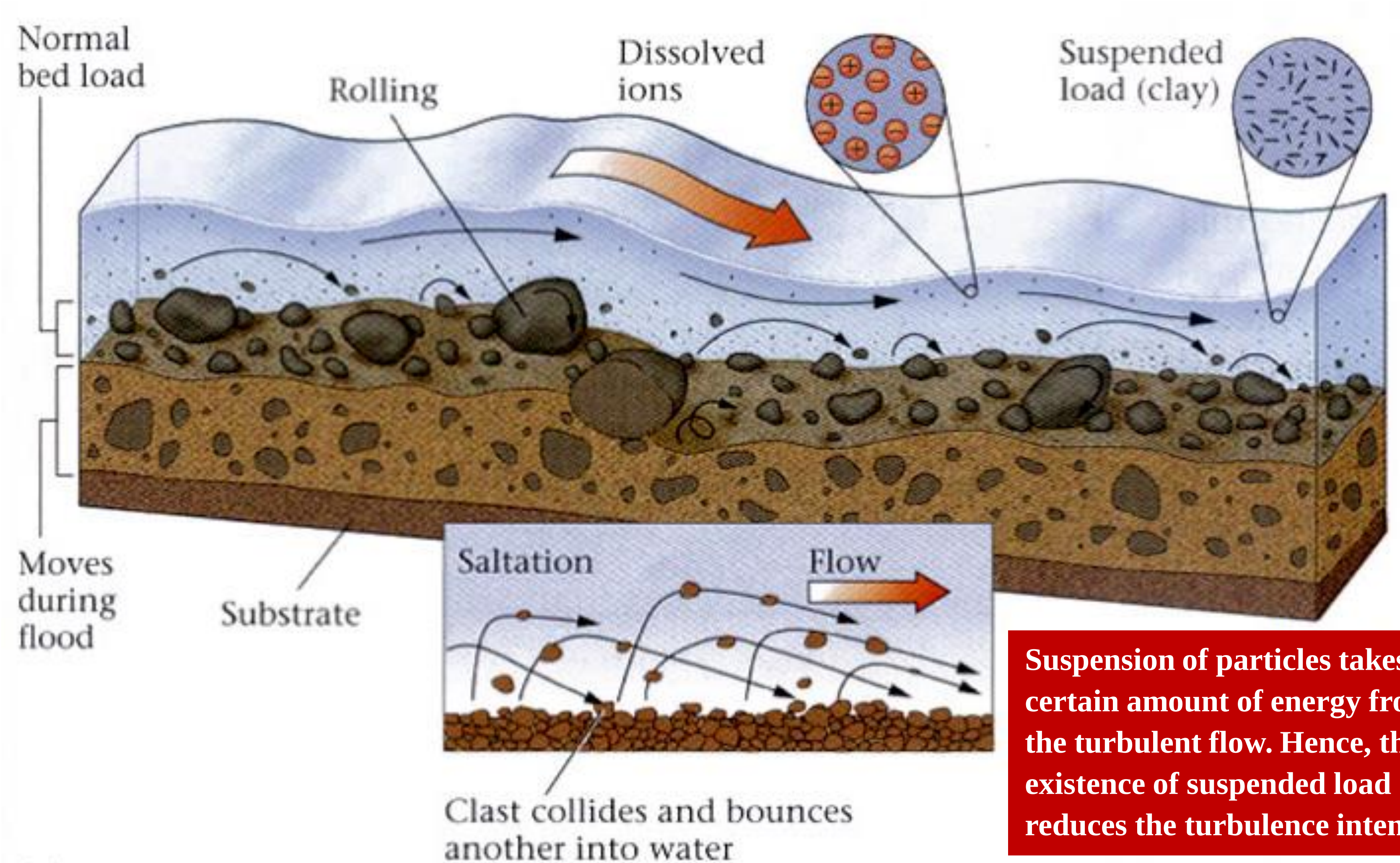
- To differentiate various types of particles, sediment is subdivided into groups.
- American geologists use Wentworth's classification (Wentworth, 1922).
- In 1947 the American Geophysical Union drew up a new standard for sediment classification that each group was subdivided (Subcommittee on Sediment Terminology, 1947).



https://pubs.usgs.gov/of/2006/1195/htmldocs/images/chart.pdf

Sediment load

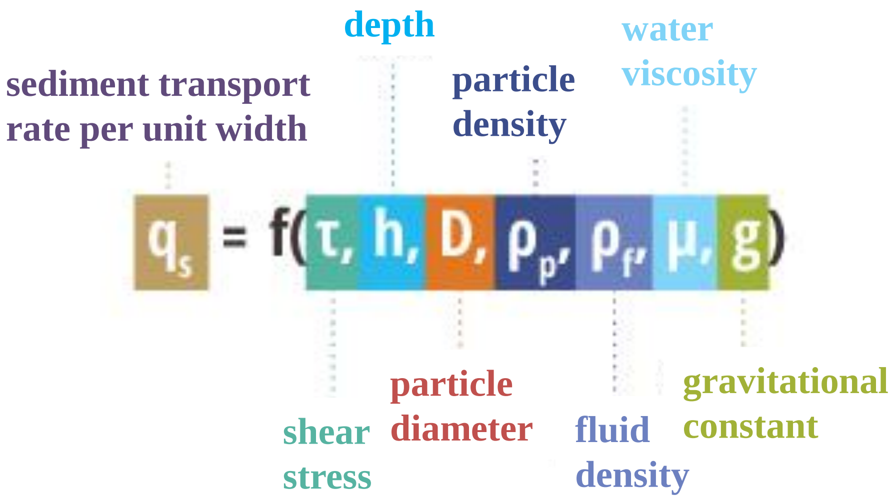
- **Sediment load** is the sediment carried by the flow or the sediment in motion.



Suspension of particles takes a certain amount of energy from the turbulent flow. Hence, the existence of suspended load reduces the turbulence intensity.

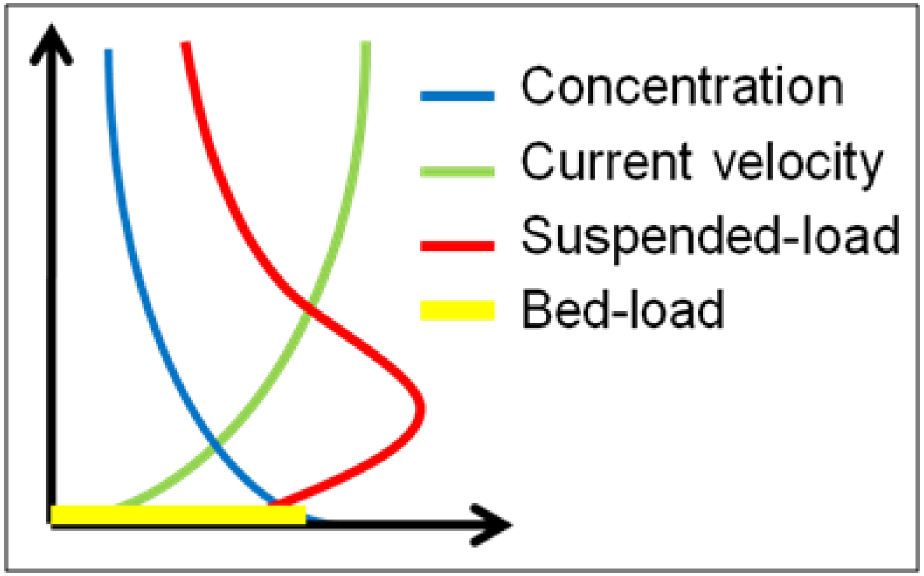
Marshak (2005)

Sediment transport rate

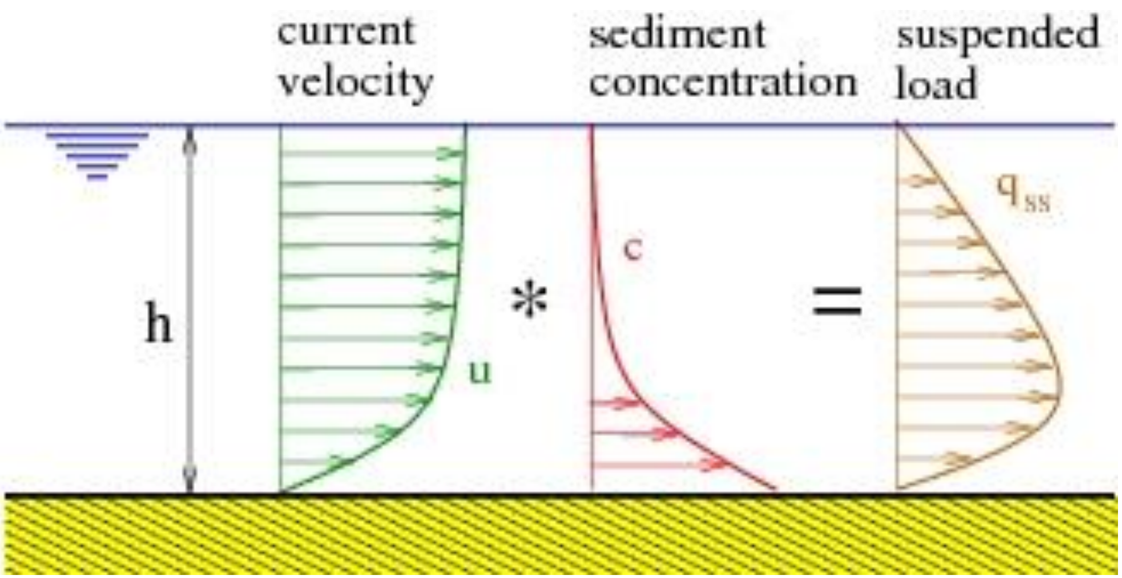


- The sediment transport rate is **a function of these seven variables**, as well as the **size-shape-density distribution** of the suspended particles.
- The **quantity and material** of the sediment particles, as well as the **geography of the local terrain** will still play a contributing role in the sediment load.

https://www.fondriest.com/environmental-measurements/parameters/hydrology/sediment-transport-deposition/



Wu, W. (2004).“Depth-averaged 2-D numerical modeling of unsteady flow and nonuniform sediment transport in open channels”. J. Hydraulic Eng., ASCE, 135(10), 1013–1024.



Schematic of sediment and current vertical profiles

Content

1. Basic concepts
2. Data collecting
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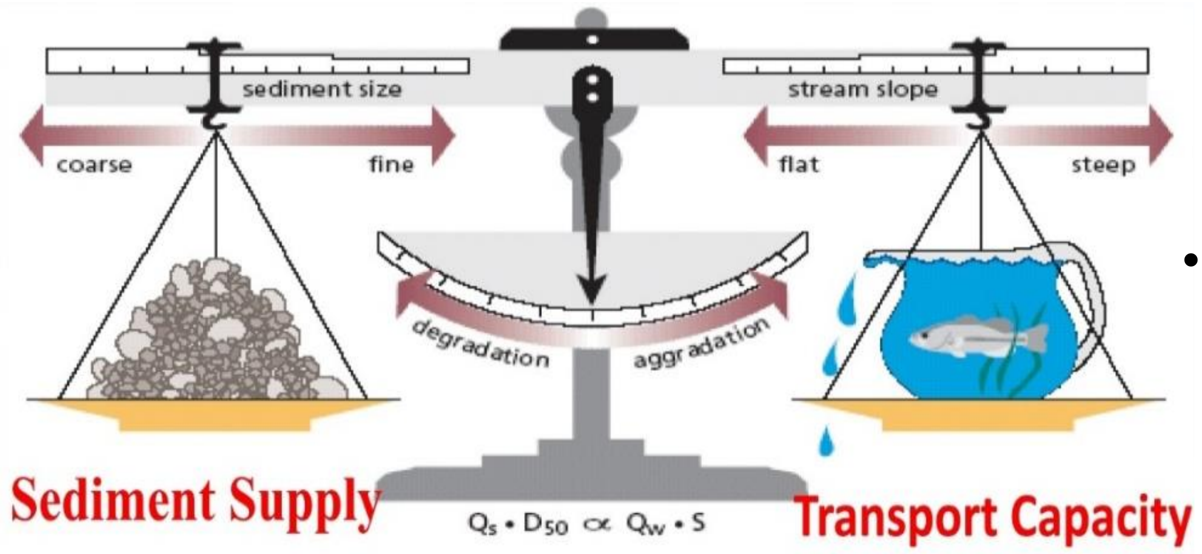
2. Data collecting

(1) Hydraulics

- **Flow velocity;**
- **Turbulence;**
- **Water depth.**

- **Shear stress**
- **Flow resistance**
- **Energy dissipation**

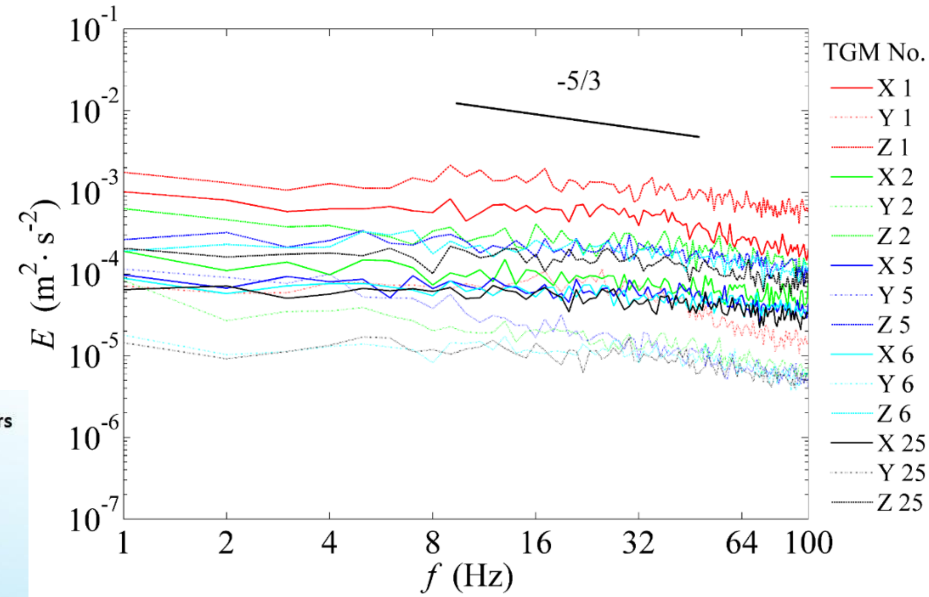
- **Transport capacity**

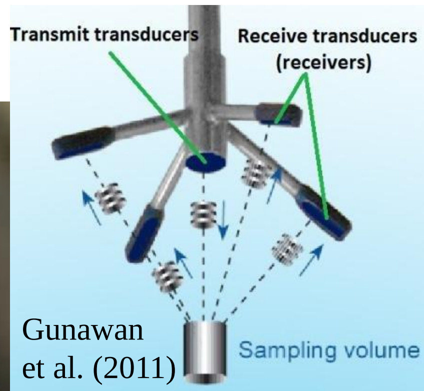


Lane (1955)

ADV-Acoustic Doppler Velocimetry

- **Point velocity**
- **Turbulence characteristics**
- **Steady frame**



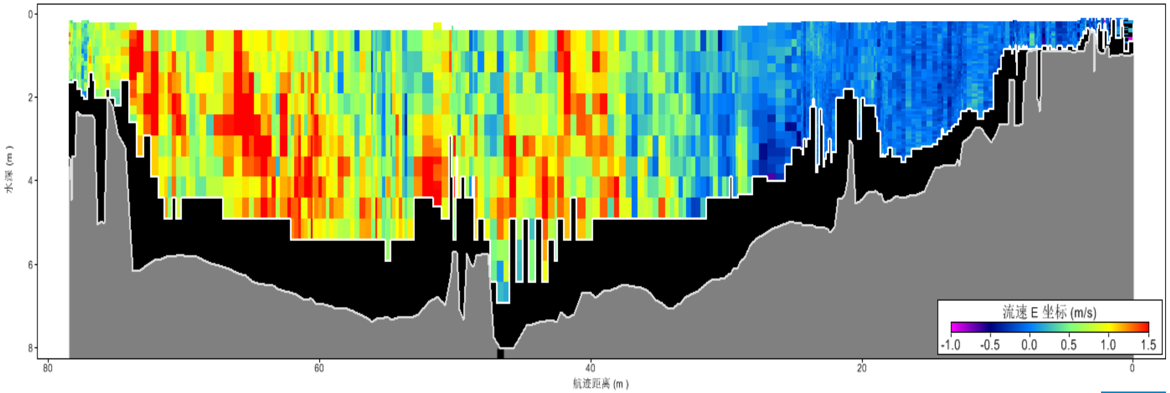


Gunawan et al. (2011)

Nortek Vectrino ADV

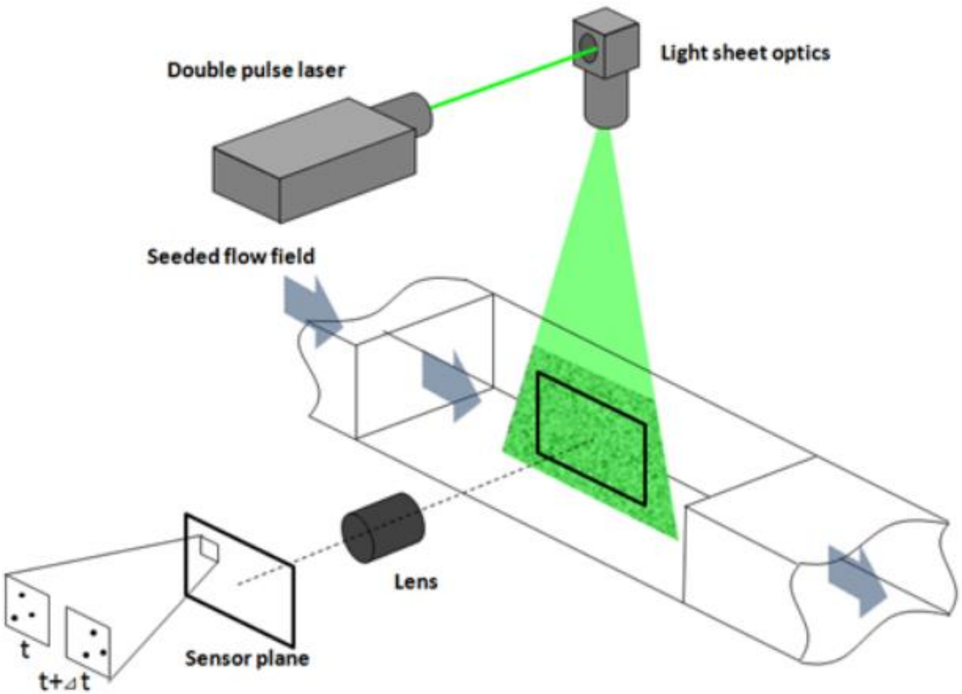
ADCP-Acoustic Doppler Current Profilers

- **Flow field of cross section**
- **Water depth & bed elevation**
- **Flow discharge**
- **Turbulence characteristics**
- **Not suitable for high flow velocity**



LSPIV-Large Scale Particle Image Velocimetry

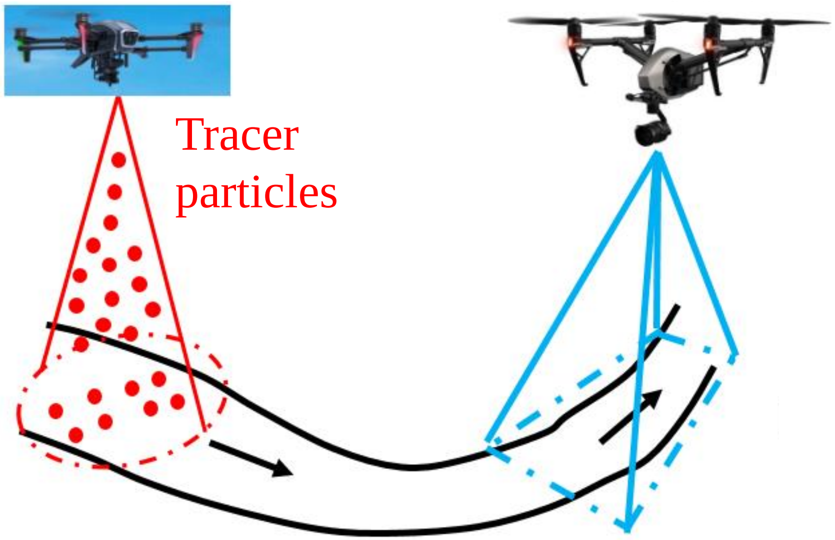
PIV



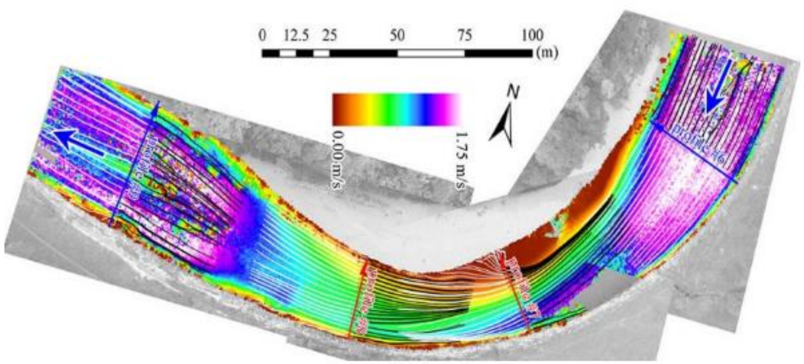
LSPIV

Carrying capacity 2 kg

Camera 3.9k 60fps



PIV+PTV



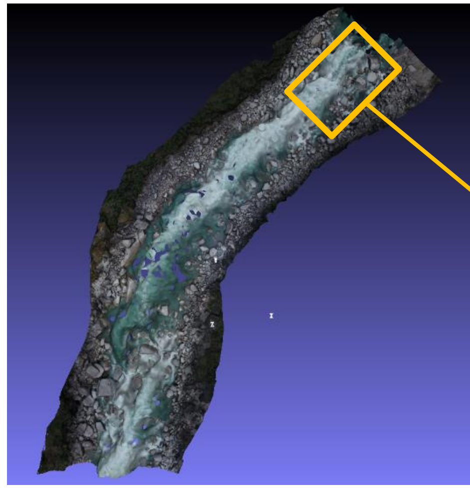
Surface flow field

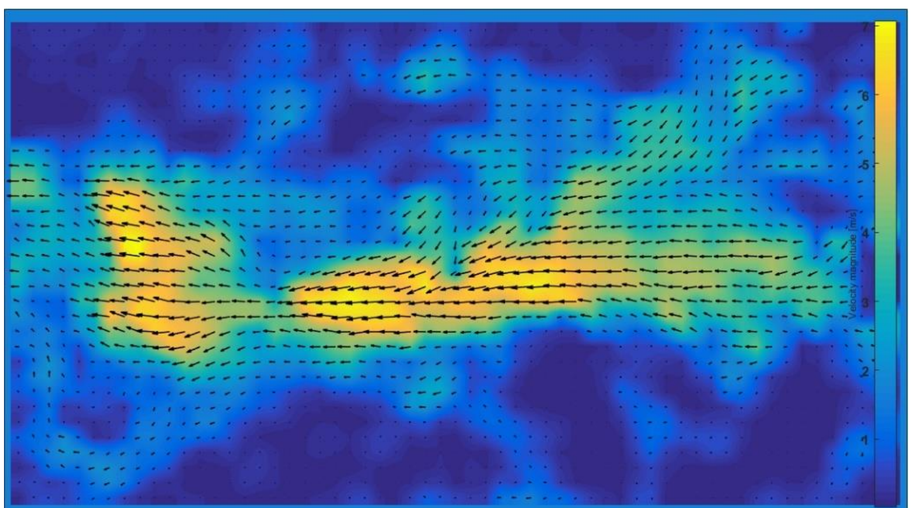
LSPIV-Large Scale Particle Image Velocimetry

- Tracer particles
- Orthoimage

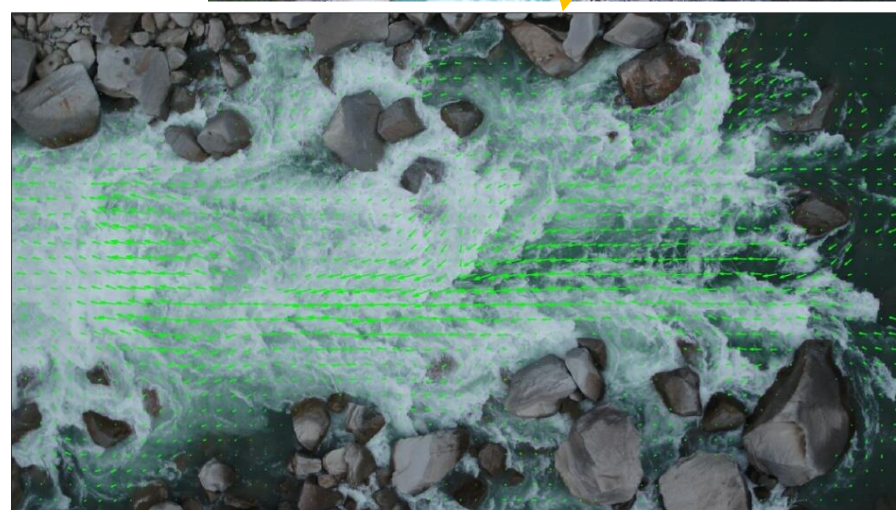
LSPIV-Large Scale Particle Image Velocimetry

- **Nujiang Canyon**



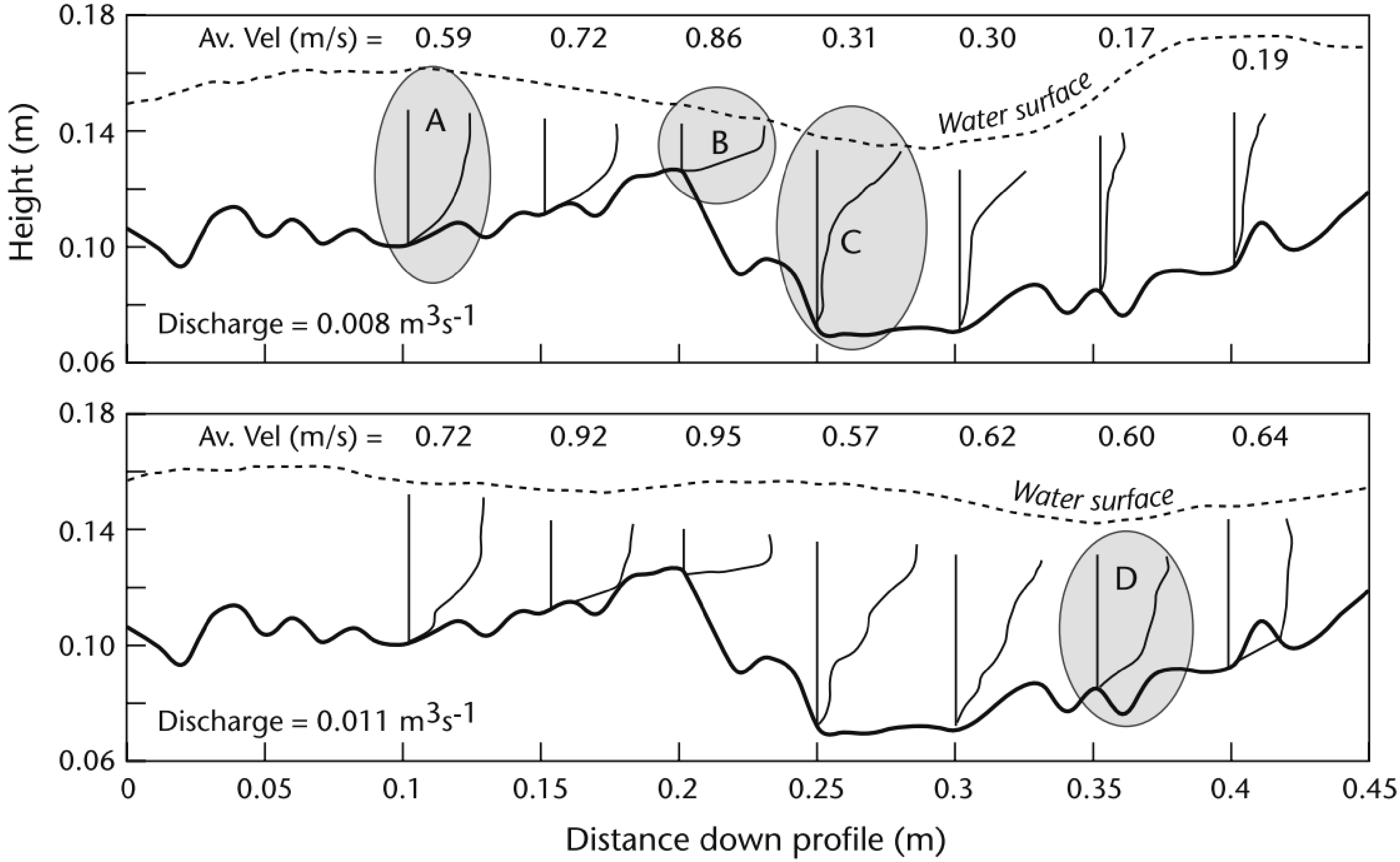


Surface flow field



Surface turbulence characteristics

Velocity profile



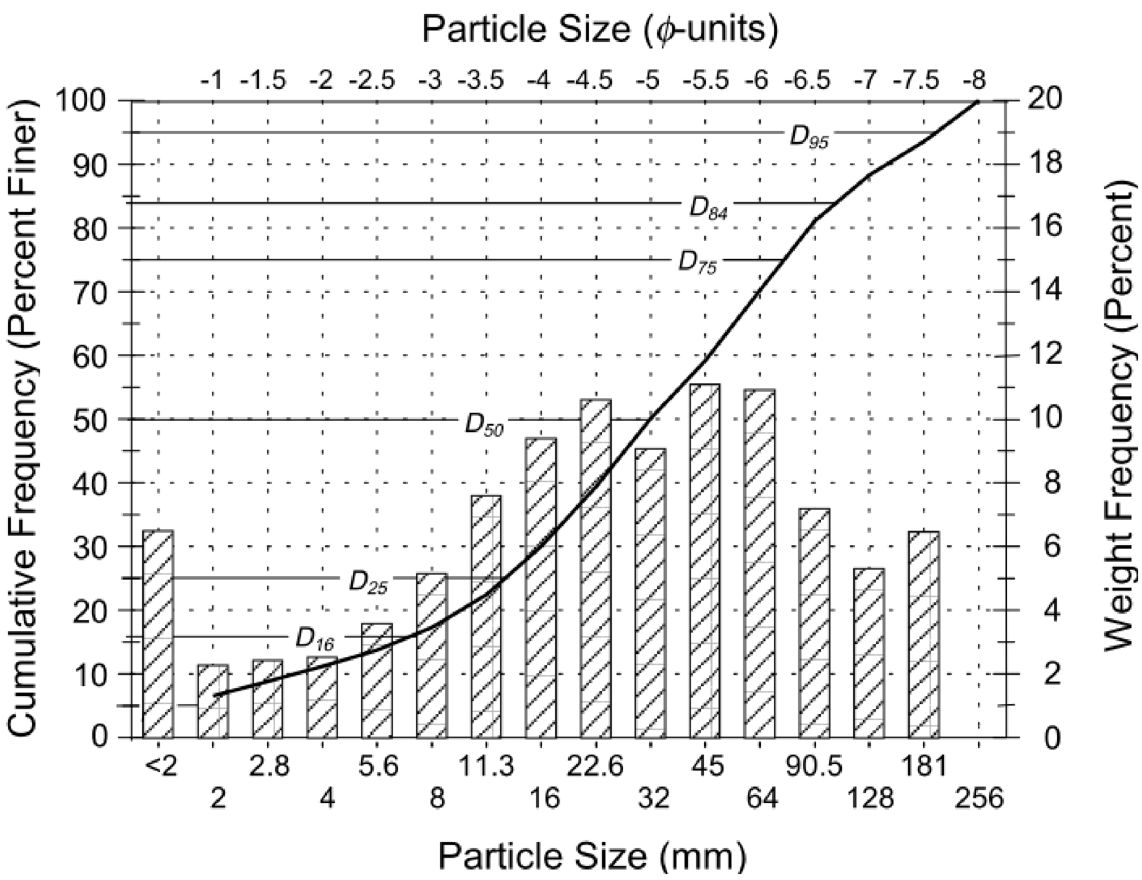
Velocity profiles measured by Lee (1998)

Lee A. The hydraulics of steep streams, PhD thesis, Sheffield: Univ. of Sheffield, U. K. 1998, 266 pp.

(2) Sediment texture

- Grain size distribution
- Characteristic grain size

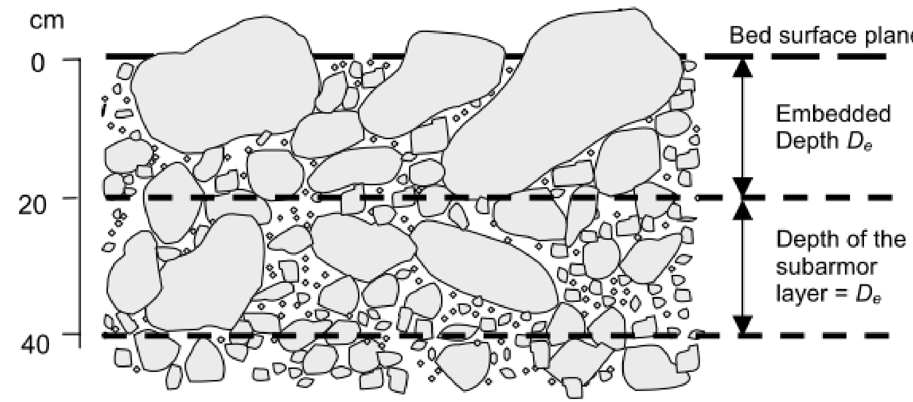
- Boundary layer
- Flow resistance

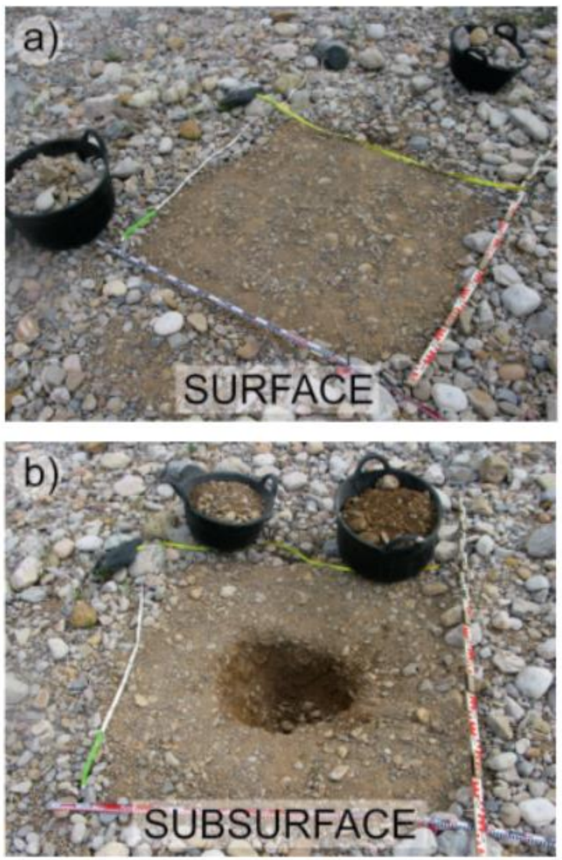


- Sediment transport
- Sorting coefficient

$(D_{84}/D_{16})^{0.5}$

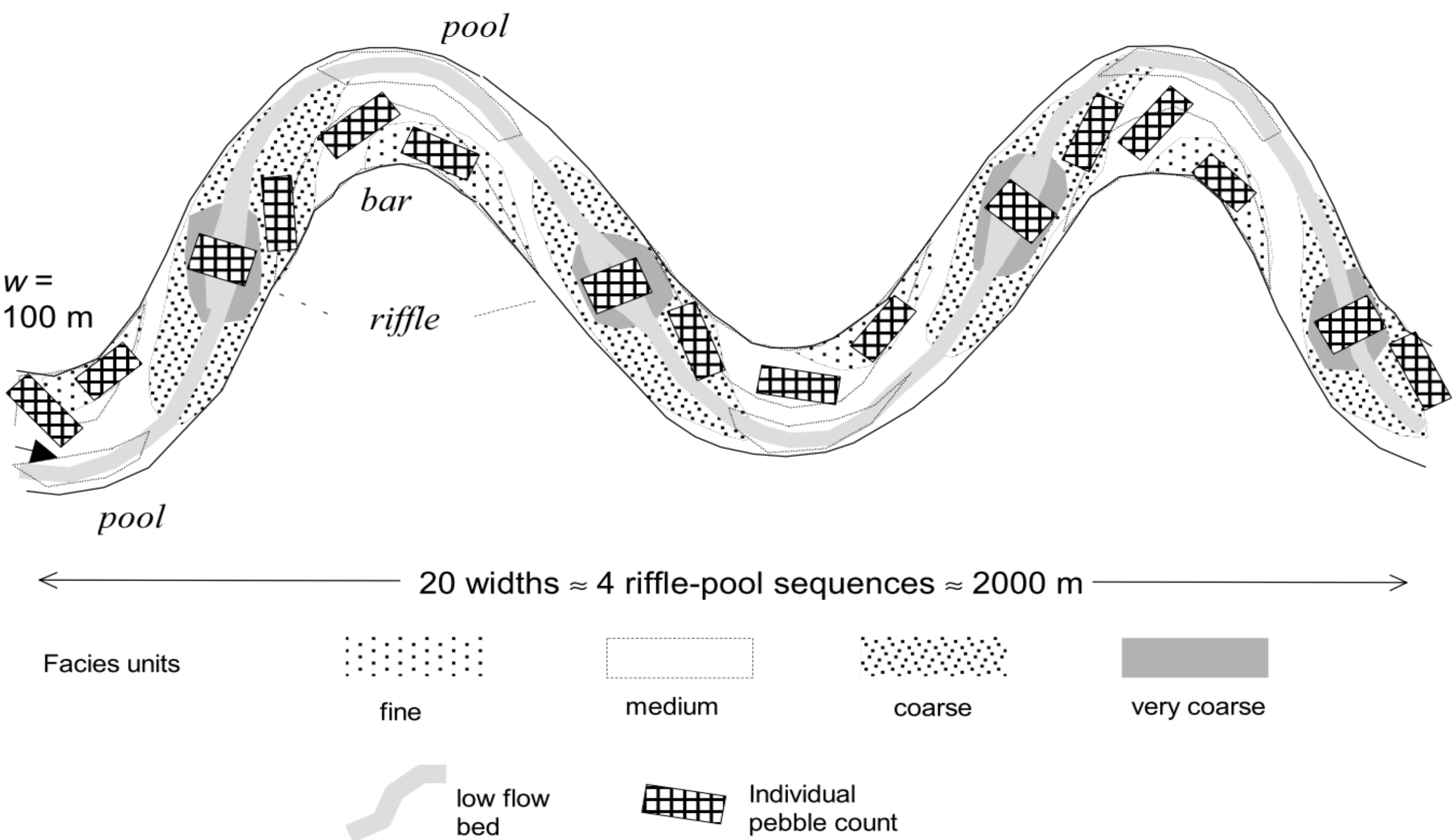
- **Bulk sampling**
  - **Time and labor consuming**
  - **Representing localized conditions**





Calle *et al.*, 2015, Zeitschrift für Geomorphologie, Vol. 59, Suppl. 3, pp 33–57.

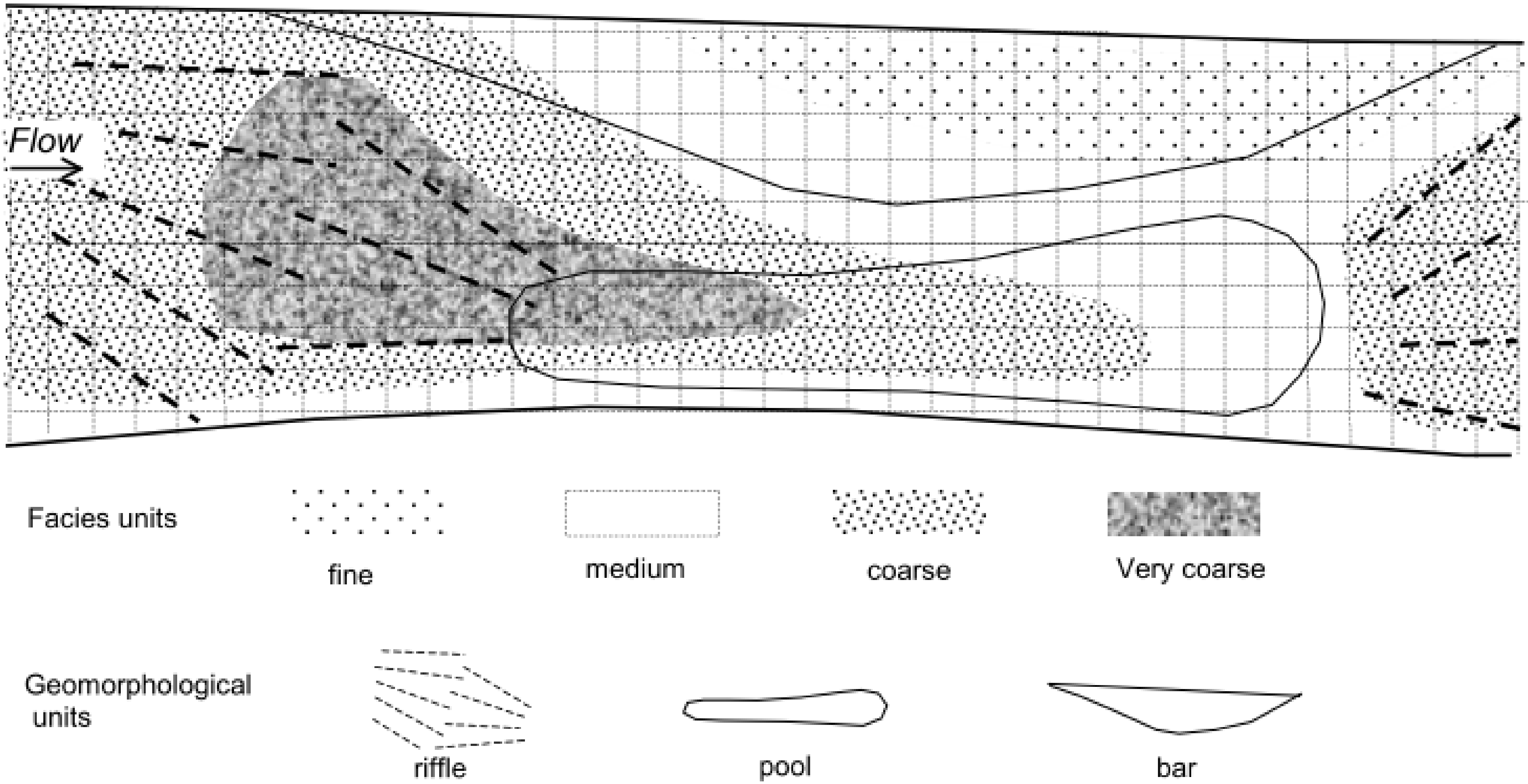
- **Bulk sampling**
  - **All the fractions in the sample are weighed**



Size distribution of a meandering stream (Bunte and Abt, 2001)

Bunte K. and Abt S R. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed rivers for analyses in sediment transport, hydraulics, and streambed monitoring, General Technical Report RMRS-GTR-74. United States Department of Agriculture, Forest Service; Rocky Mountain Research Station, Fort Collings, USA, 2001, 428 pp.

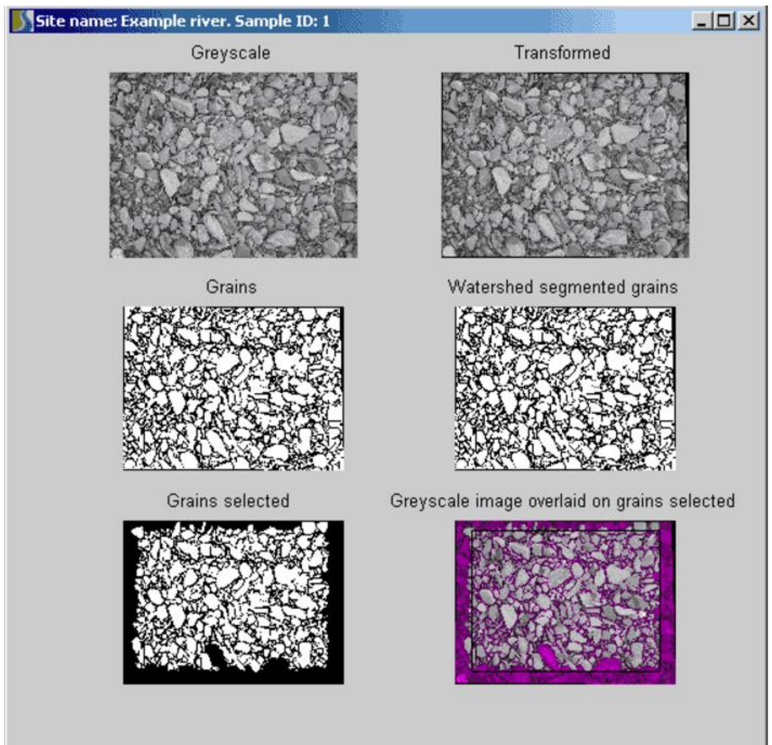
- Wolman pebble count
  - Sample large area quickly

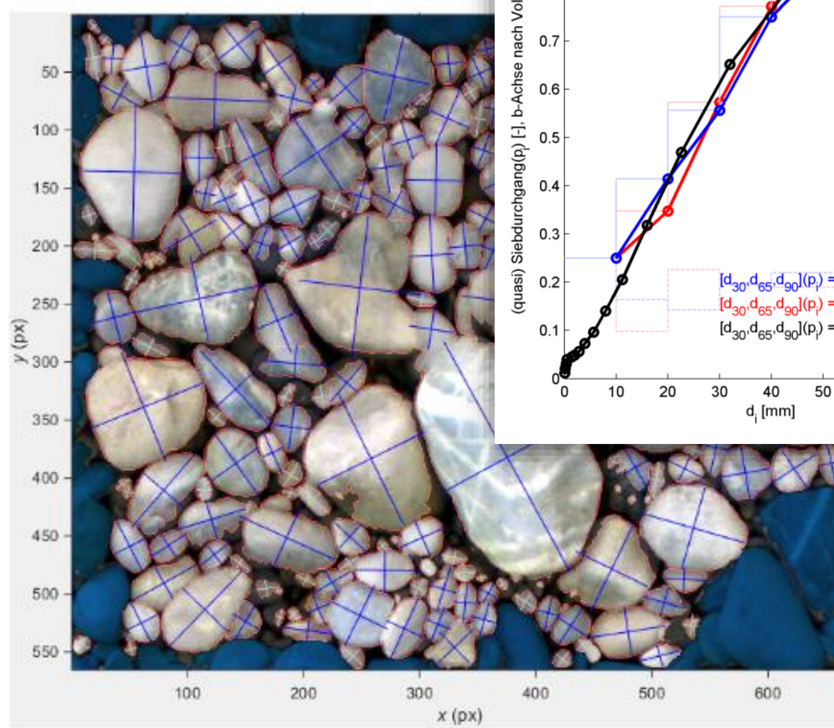


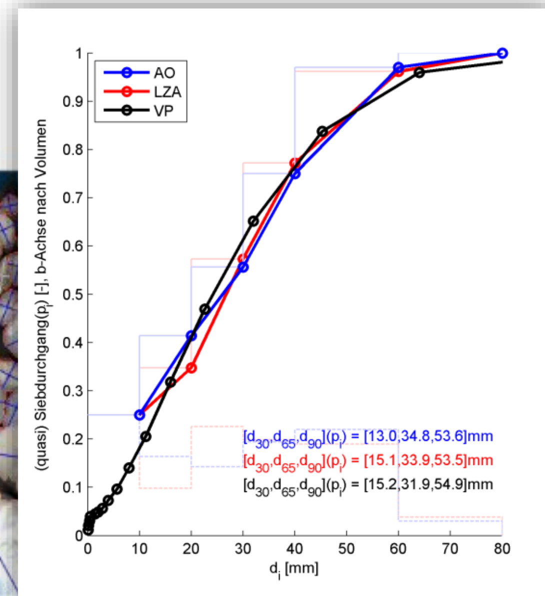
Sketch map of a reach with its facies units, the underlying geomorphological units, and a sampling grid (Bunte and Abt, 2001)

Image-based methods

- I-FM method (Chang and Chung, 2012)
- Digital Gravelometer, Loughborough University (Graham et al., 2005a, 2005b)
- Basegrain, ETH (Detert and Weibrecht, 2012, 2013; Stähly et al., 2017)



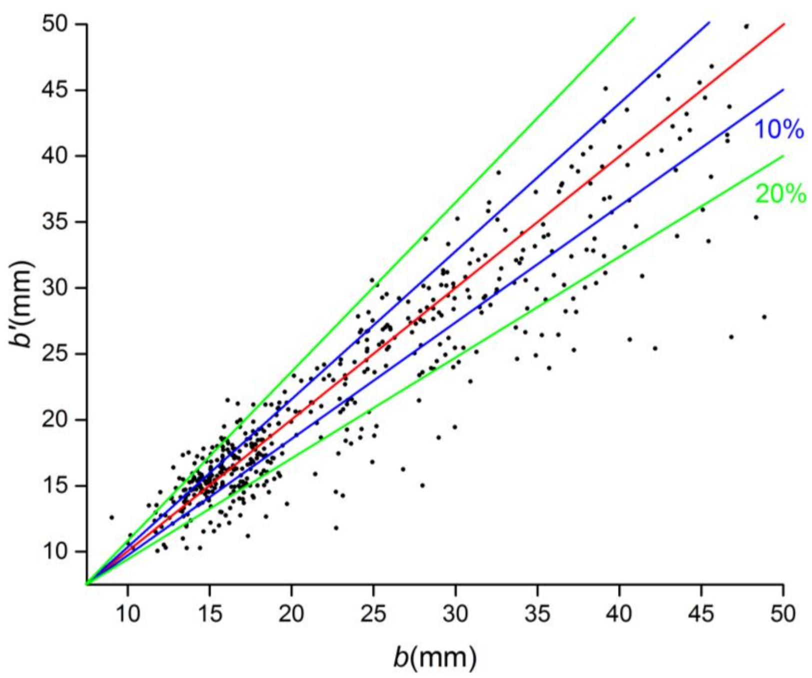


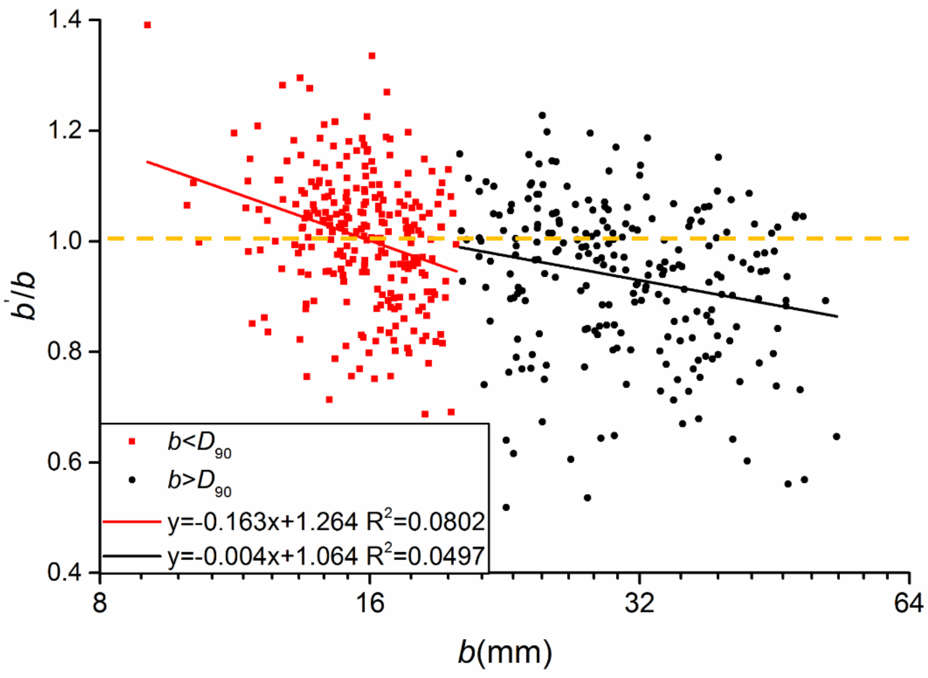


https://basement.ethz.ch/download/tools/basegrain.html

Image-based methods.

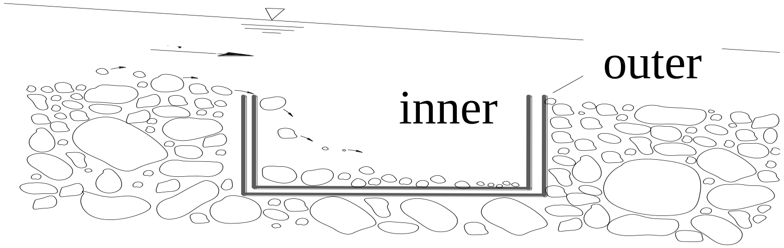
- Require little time and labor in the field
- Combined with UAV (Unmanned Aerial Vehicle)
- Represent for a large area
- Only work for clean surface sediments
- Too many adjusting variables





(3) Sediment transport

Sediment trap

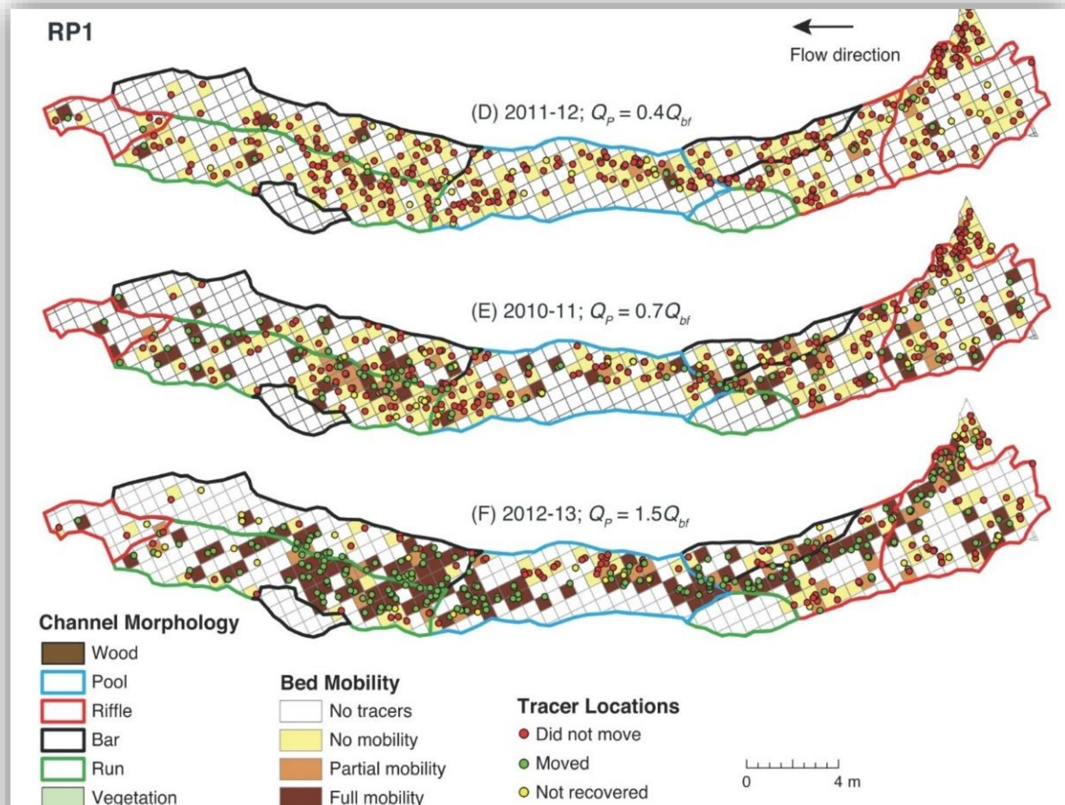


Helley-Smith sampler

Smart tracers

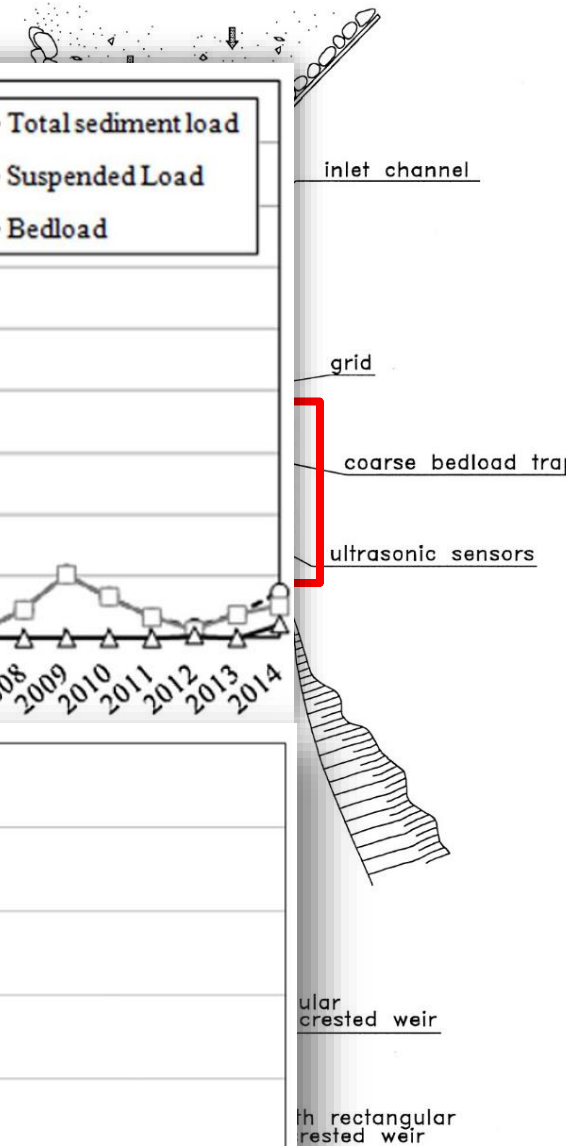
- Radio Frequency Identification (RFID)
- Passive Integrated Transponders (PIT)
- Trace the displacement of grains
- Signal decays quickly in water
- Several years to mix with the local bed material

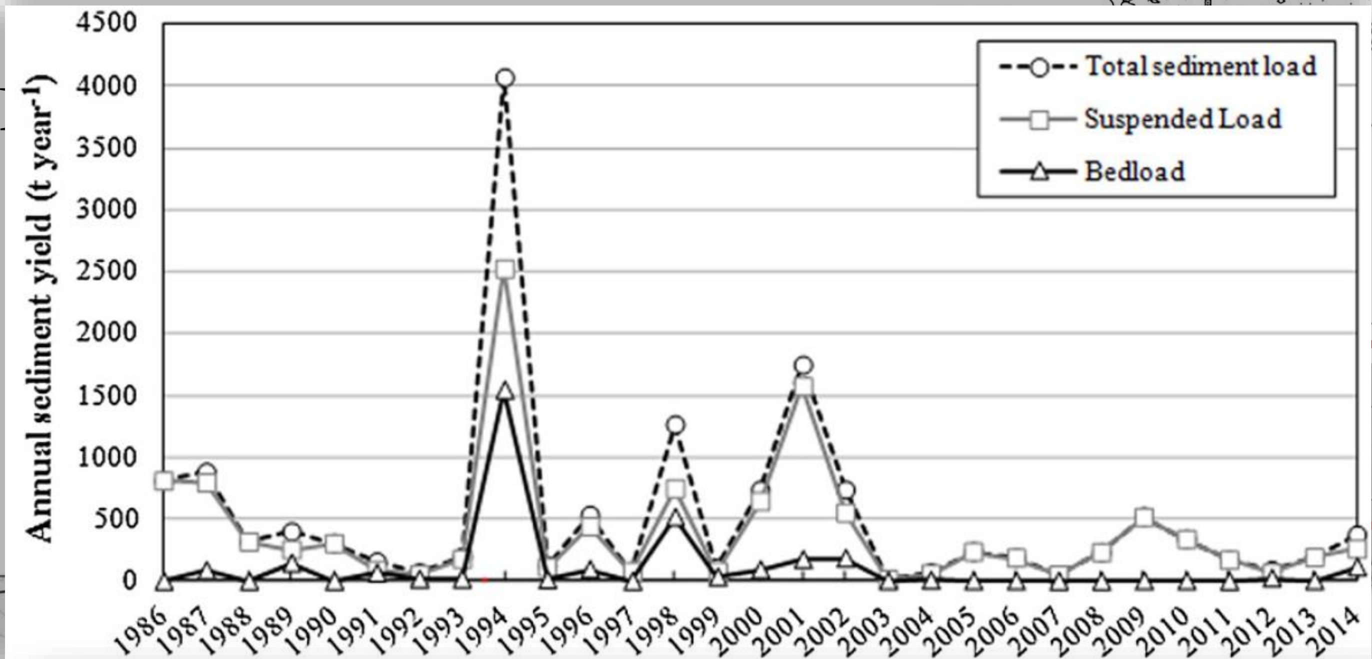
Nichols (2004)

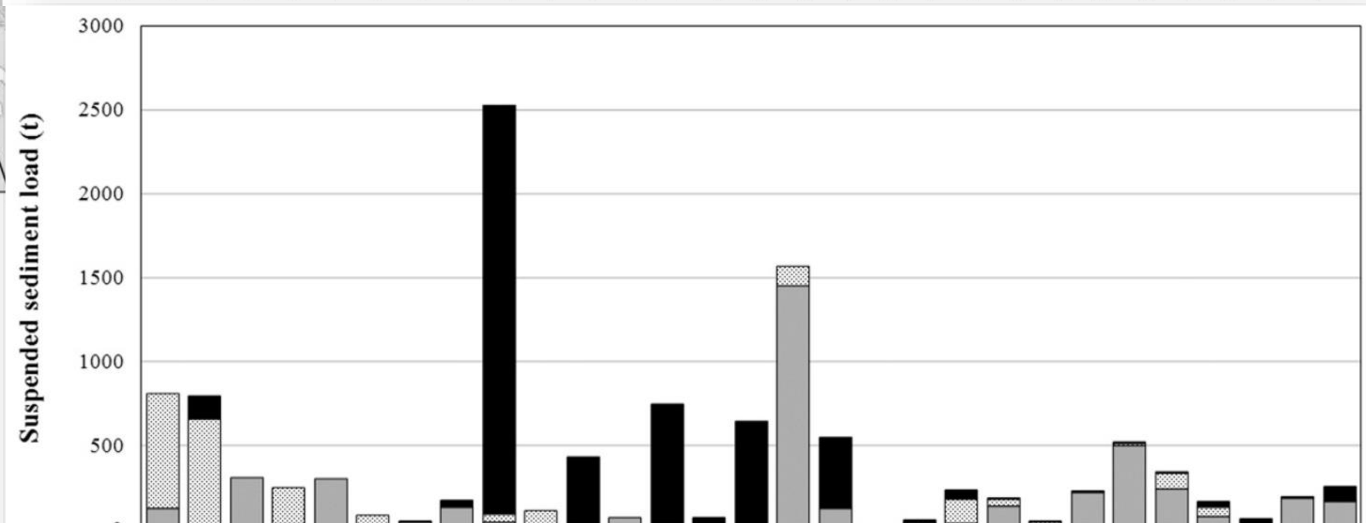


Papangelakis and Hassan (2016). https://doi.org/10.1002/esp.3980

Recording stations



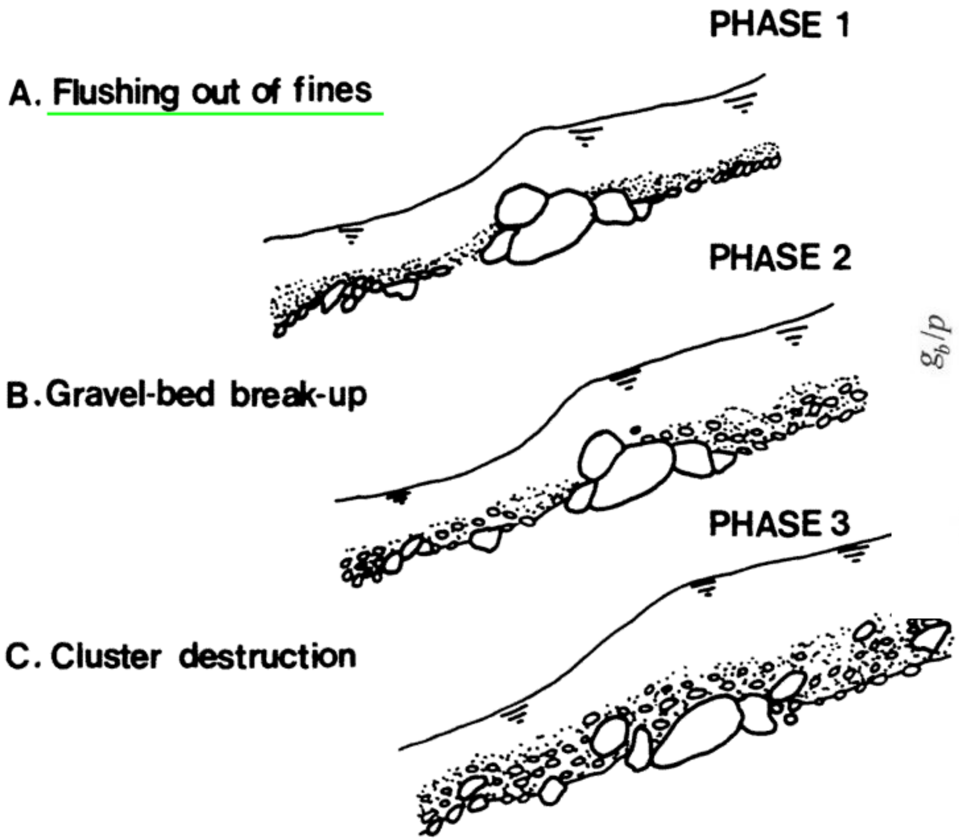




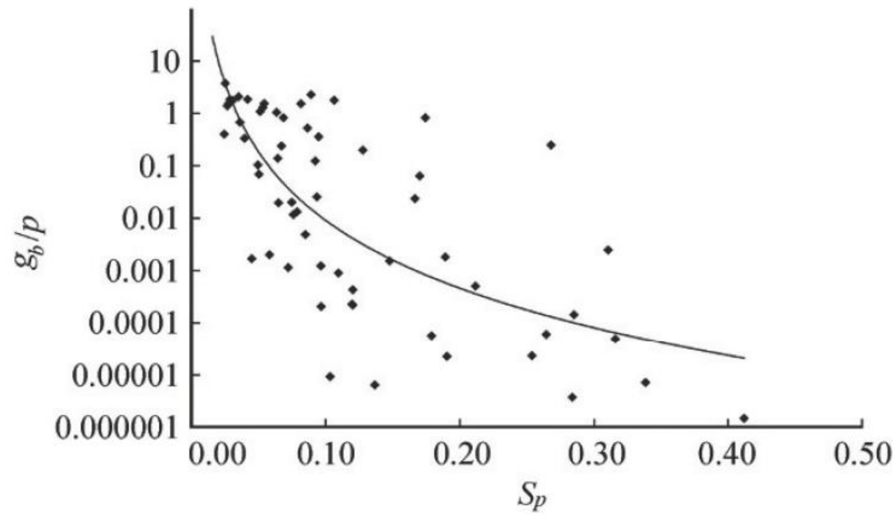
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
AUTUMN	0	132	0	0	0	0	5	41	2435	0	406	0	718	50	629
SUMMER	678	639	0	224	0	68	0	0	45	98	0	0	0	0	0
SNOWMELT	129	22	313	28	302	19	46	134	44	13	31	74	27	23	12

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
AUTUMN	0	428	8	19	56	3	7	7	1	1	37	61	1	85
SUMMER	119	0	0	27	143	43	18	0	10	94	51	1	2	9
SNOWMELT	1449	123	3	13	34	138	24	222	504	241	79	0	186	164

- Conventional bed load formulas tend to over predict sediment transport (Hayward, 1980)



Three phase model of bed load transport and bed break-up in mountain streams (Warburton, 1992)

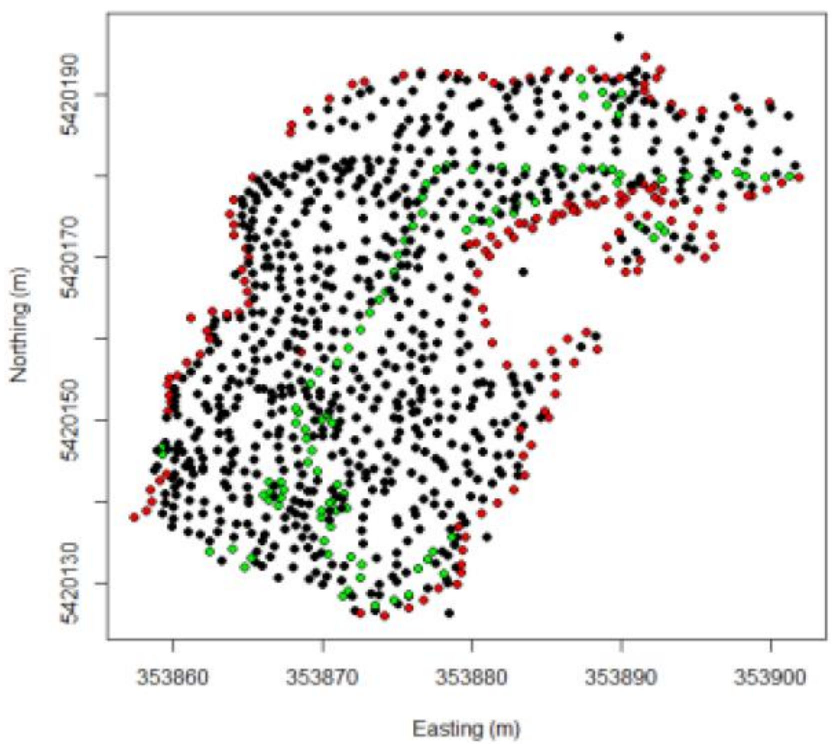


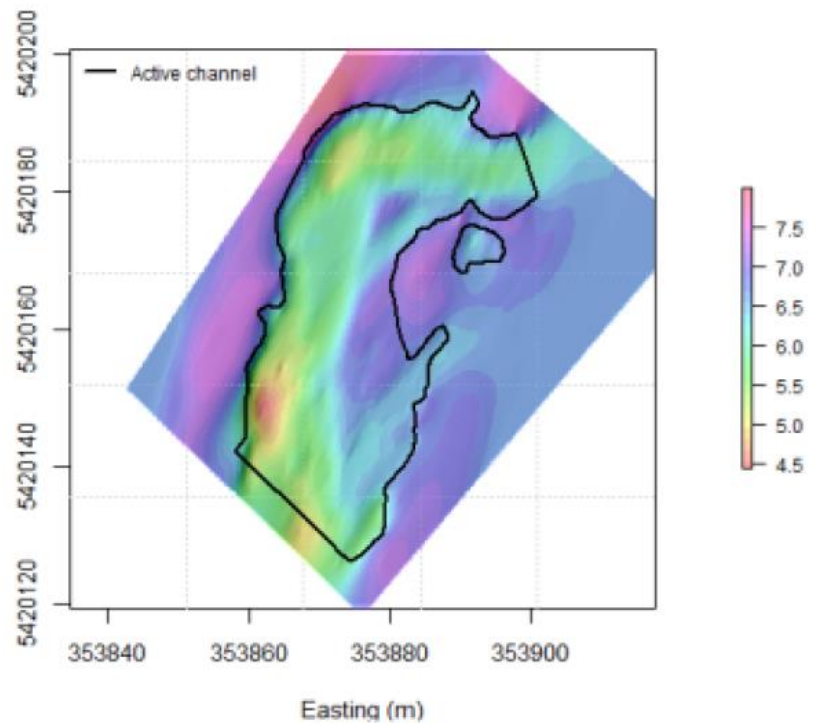
The ratio of bed load rate over stream power, g_b/p, as a function of the development degree of the step-pool system, *Sp* (Wang and Zhang, 2012)

Warburton, 1992. Observations of Bed Load Transport and Channel Bed Changes in a Proglacial Mountain Stream. Arctic and Alpine Research Vol. 24, No. 3, pp. 195-203

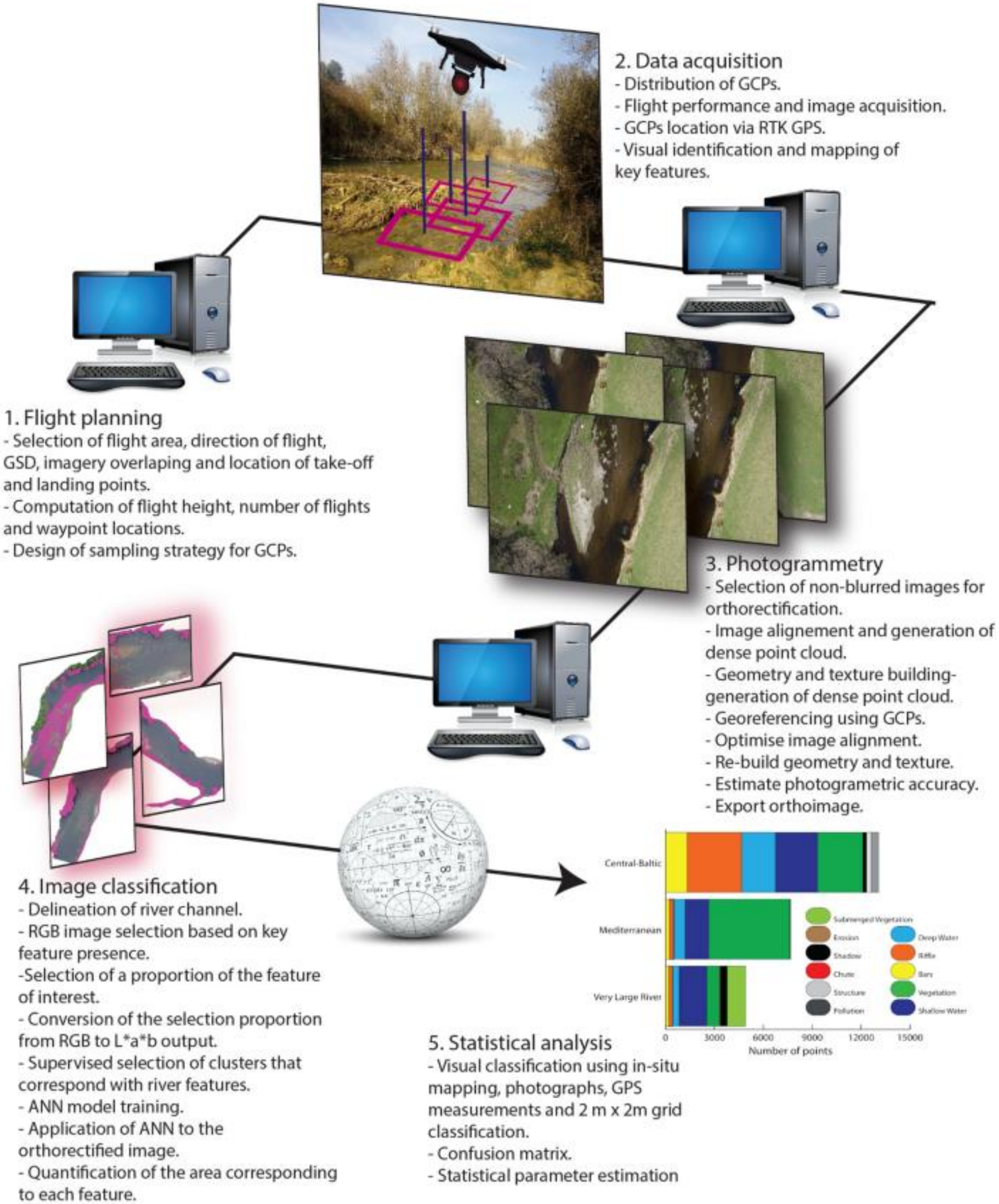
(4) Morphological 3D reconstruction

- Cross section & longitudinal profile
- DEM (Digital elevation model) differencing
- Experimental simulation
- Numerical simulation





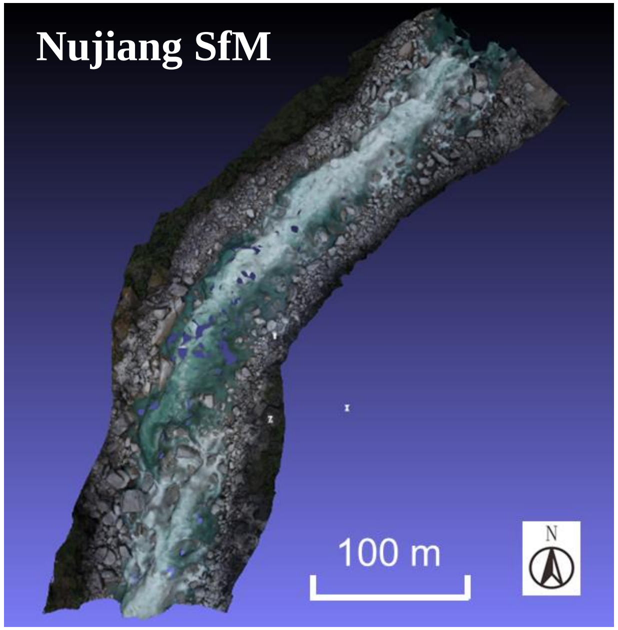
An example in Carnation Creek, B.C. Canada, Total station or RTK GPS + Interpolation



Workflow of SFM-MVS (Rivas et al., 2017)

- **Image-based surface reconstruction**
- **RTK-real-time kinematic**
- **algorithm**

- **UAV+SFM-MVS**
- **Structure from motion**
- **Multi-view stereo**
- **Low cost**



Laboratory application of bathymetric Structure-from-Motion (SfM) photogrammetry in topographic survey for gravel bed

Zhang Chendi[1], Sun Ao'ran[1], Liu Sujia[1], Ju Jingwei[1], Xu Mengzhen[1*], Wang Chenyang[1], Huang Qinglin[1], Han Lujie[1]

orthomosaic image

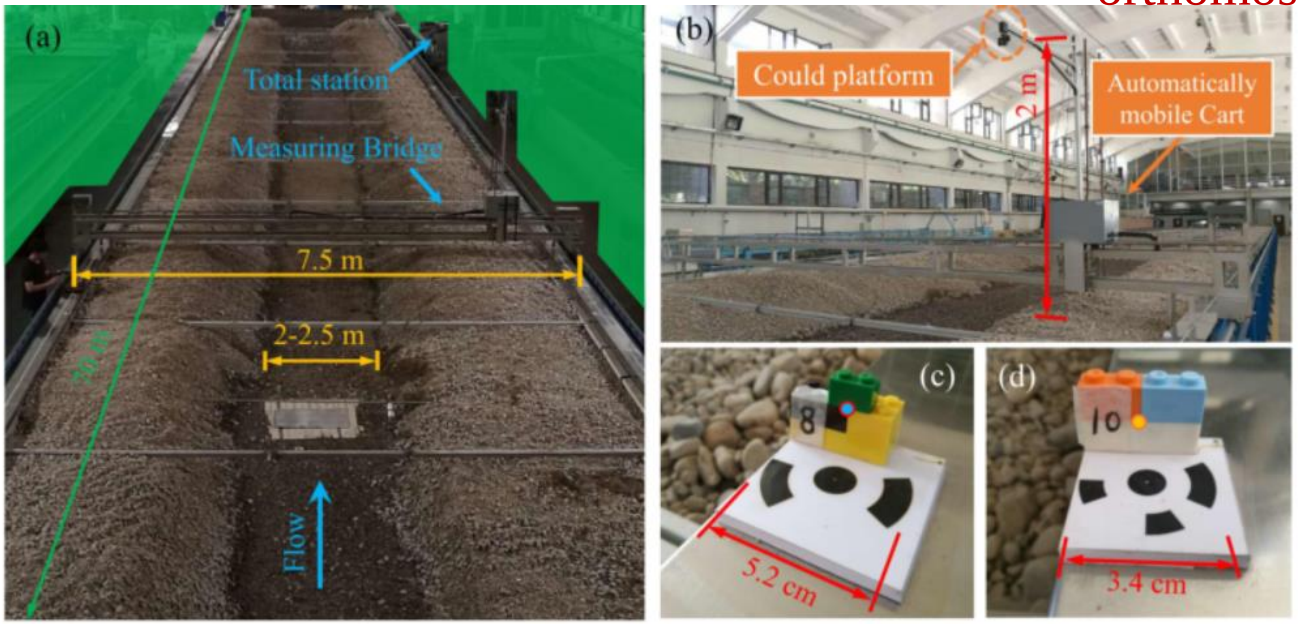


Figure 1. Photographs of the flume system: (a) Overview; (b) measuring bridge; (c) ground control point (GCP) for the upstream section; (d) GCP for the downstream section. The points measured by the total station on the vertical part of GCP for the upstream and downstream section are marked in (c) and (d), respectively.

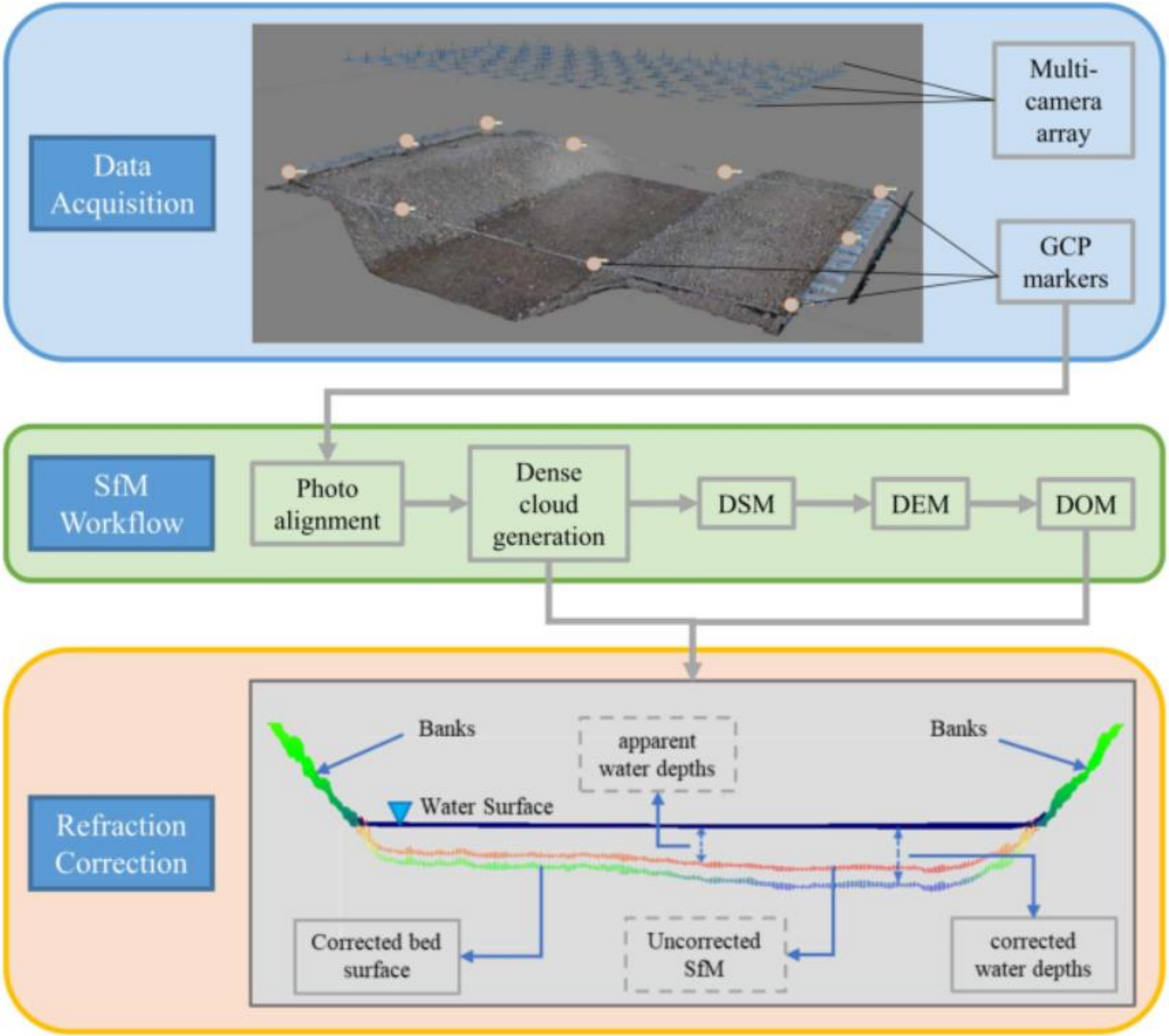
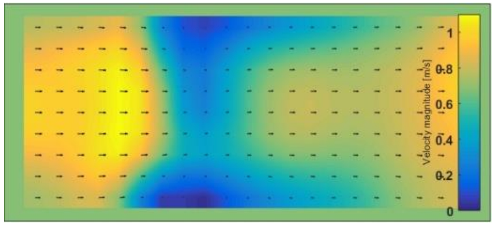
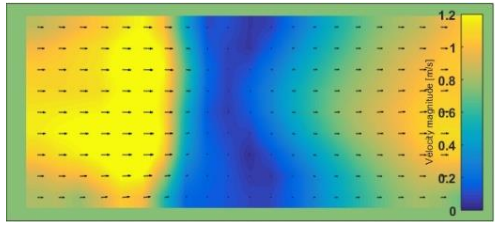


Figure 3. Workflow of bathymetric SfM photogrammetry with refraction correction.

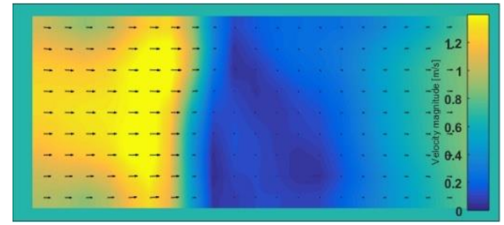
Application in step-pool measurement



CIFR 4 23.0 L/s

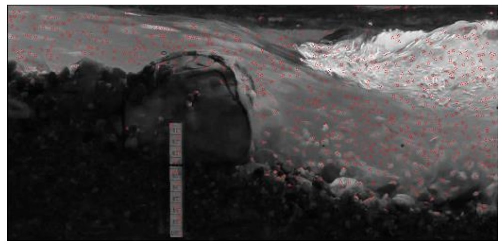


CIFR 4 47.8 L/s

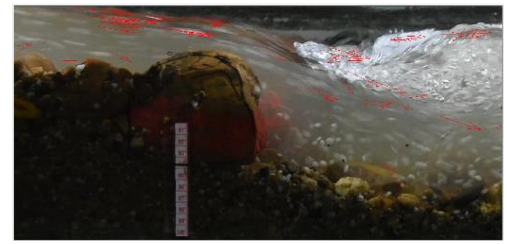


CIFR 4 66.1 L/s

PIV



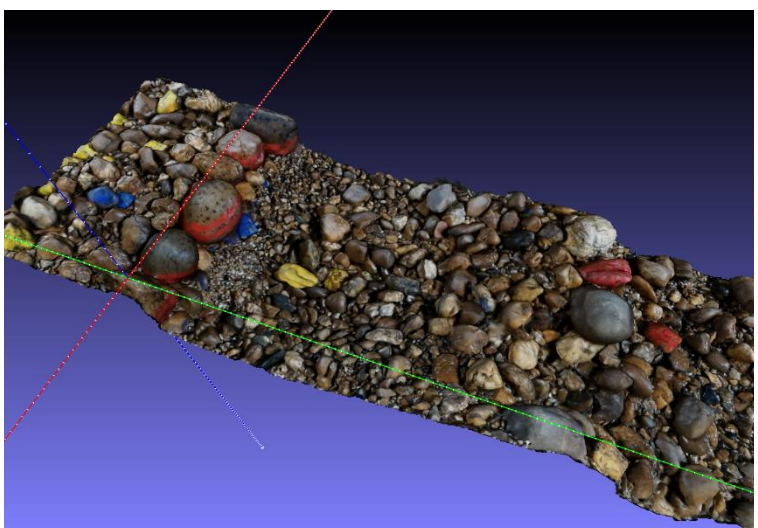
Particle track



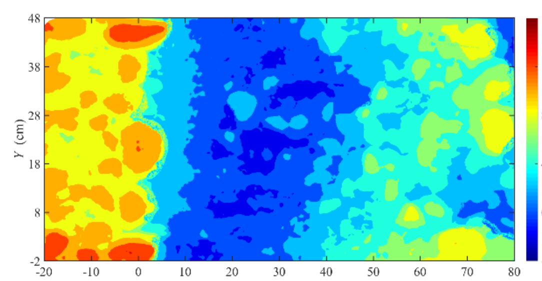
Calculating result

PTV

Flow field measurement



Grain size

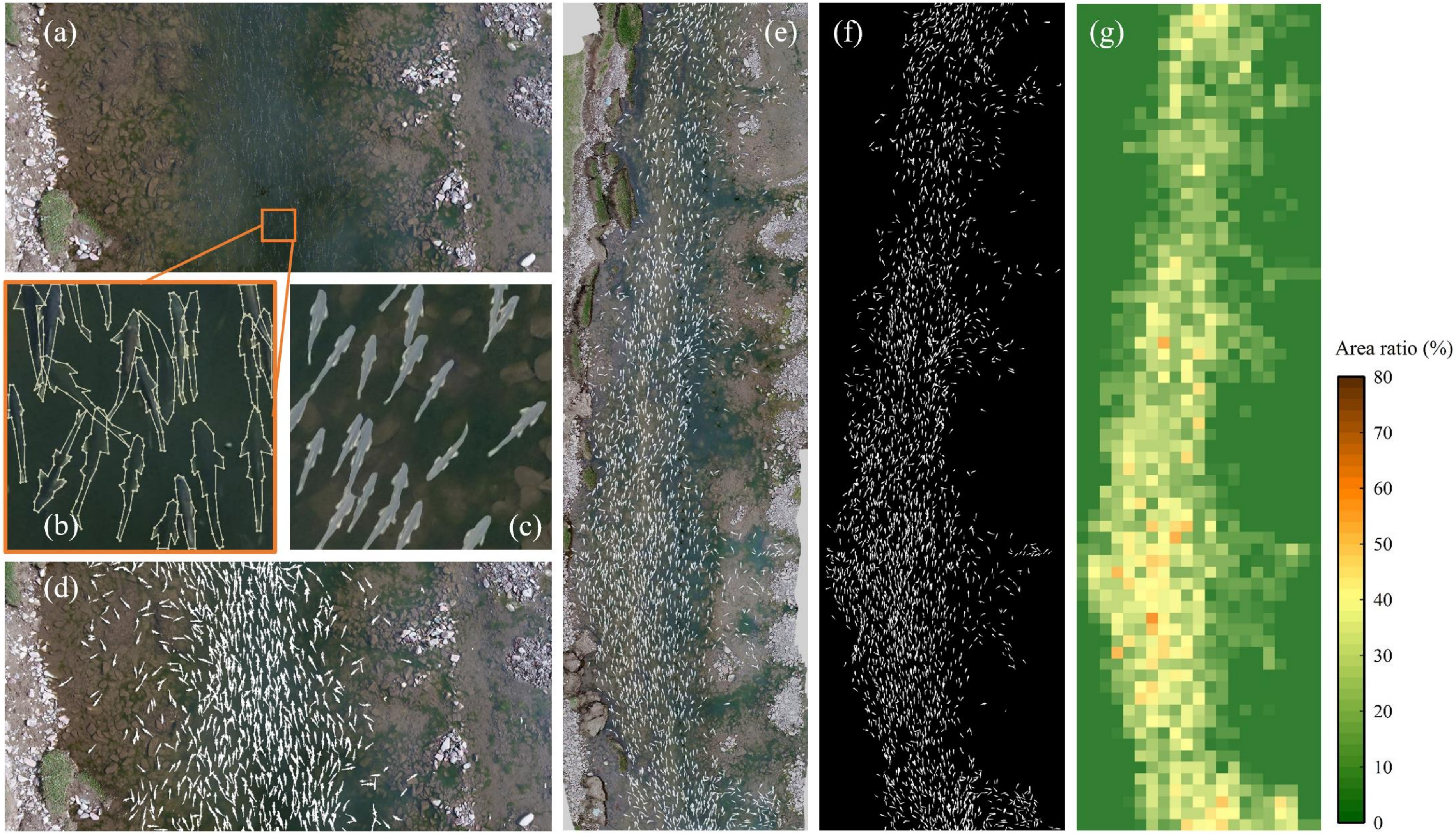


Water depth

Structure from motion (SFM) rebuild 3D topography

Application in the Qinghai lake tributaries

Fish detection and extraction



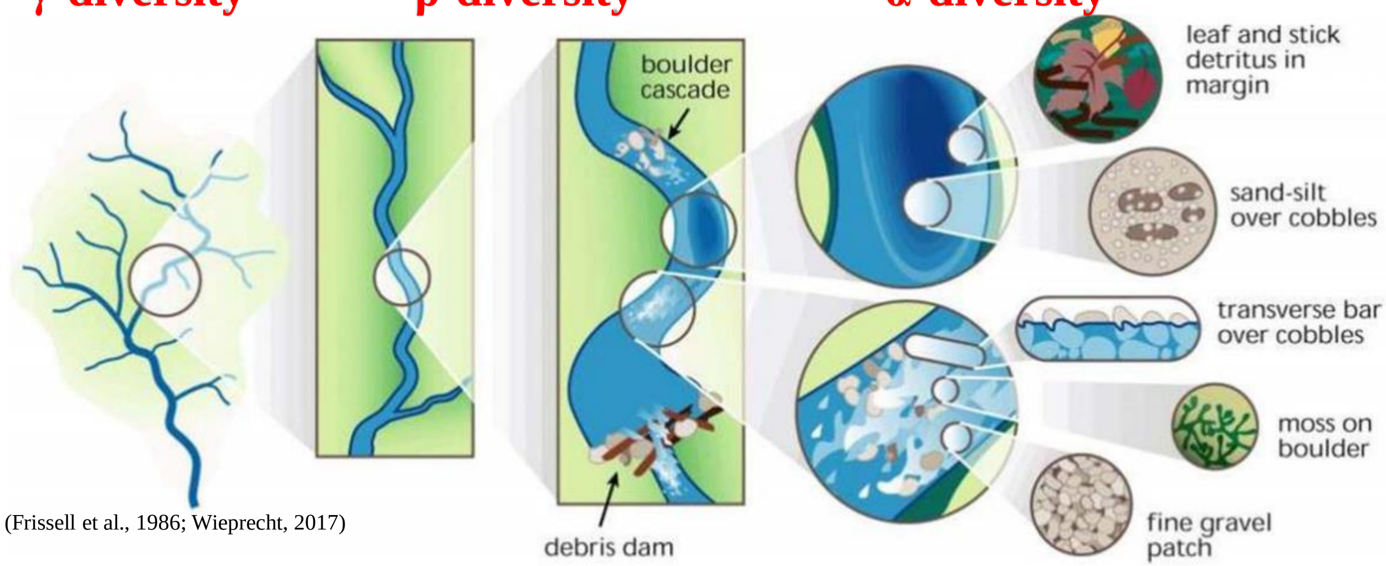
Content

1. Basic concepts
2. Data collecting
3. Environmental impacts of massive sediment movement
4. Water-sediment-ecology integrated management

3. Environmental impacts of massive sediment movement

Understanding the interactions among flora/fauna, water flow and sediment, river landscapes; simulating these processes for design/management plans; predicting effects of ecological restoration.

γ-diversity β-diversity α-diversity

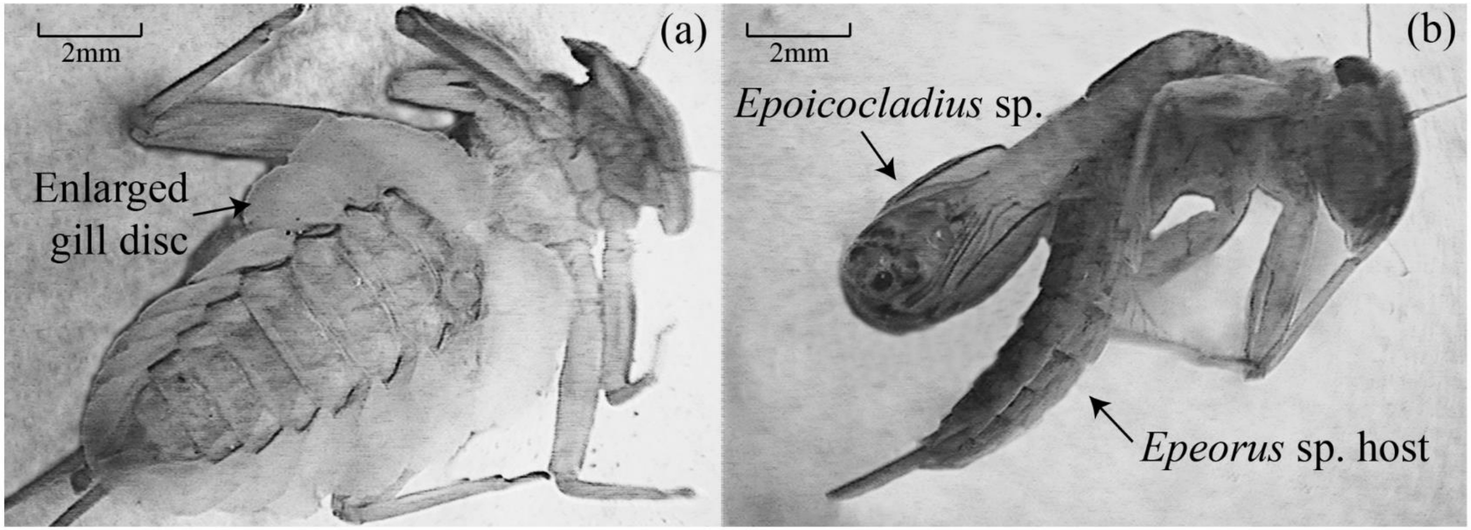


(Frissell et al., 1986; Wieprecht, 2017)

Catchment	River System	Grain Structure	Single Particle
(Macro 10^3)	(Meso 10^2 - 10^1)	(Micro 10^0 - 10^{-1})	(Pico 10^0 - 10^{-1})

River Hierarchical Organization

- **Adaptation of macroinvertebrates to habitat condition**
- **The biological traits of the species survival in high stream power rivers**



(a) Enlarged gills of *Rhithrogena* sp. meet beneath abdomen to form a ventral disc, and (b*) Epoicoladius* larva lives commensally *on Epeorus* sp. nymph.

- **The most disastrous consequence of riverbed incision is causing bank failure, landslides and avalanches**

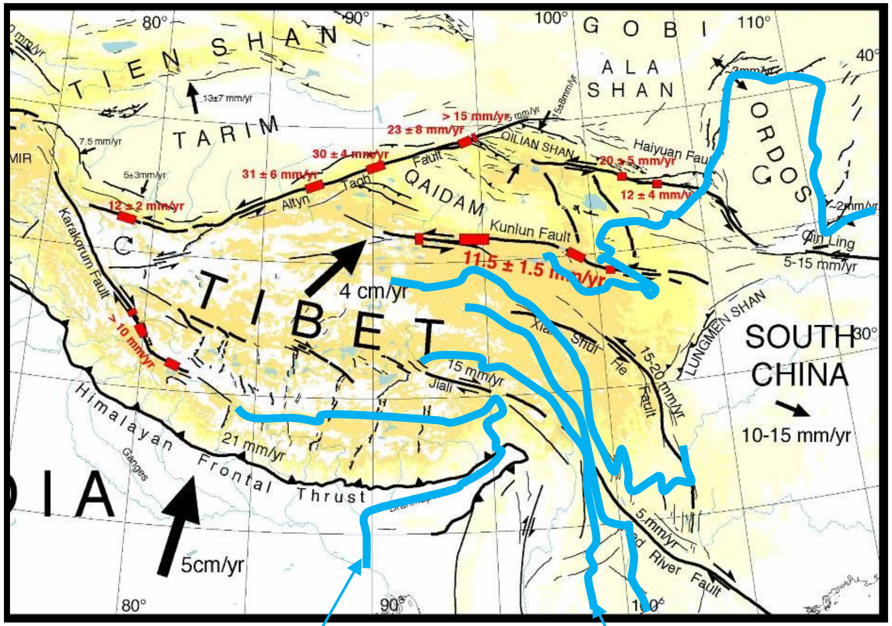
- **The most disastrous consequence of riverbed incision is causing bank failure, landslides and avalanches**

- **Typical natural disaster chains along with bank failure**

- **Landslide dam, increased soil erosion and sediment yield may cause a new cycle of fluvial process of the river**
- **The process may last for a century or a longer period**

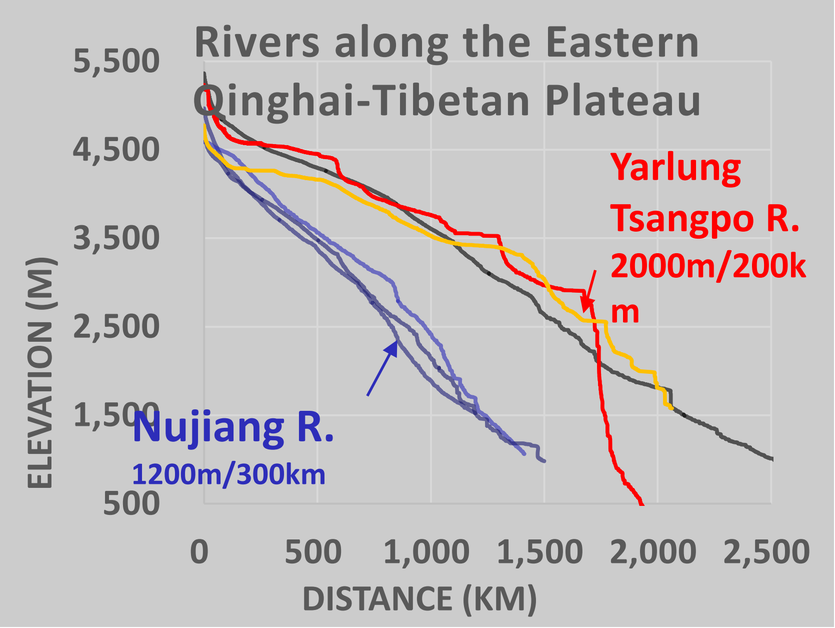
The Tangjiashan landslide (> 20 million m^3) triggered by the 2008 earthquake dammed the river, forming a barrier dam with height of 80 m and length of 800 m

- **Uplift of the plateau has been affecting the fluvial process, reshaping the river morphology, and significantly influencing the river ecology**



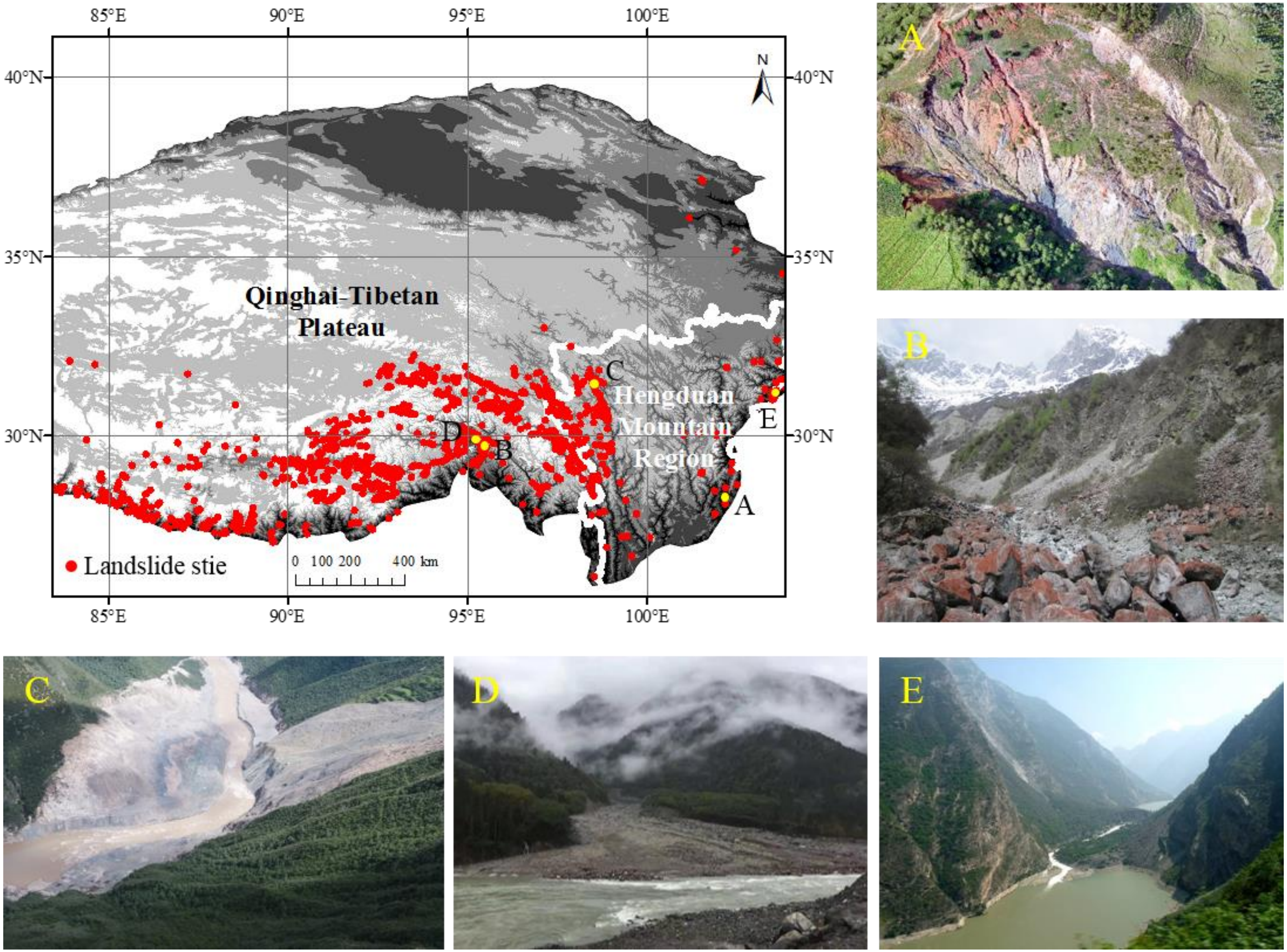
Yarlung Tsangpo R., Upper Brahmaputra

Nujiang R. Upper Salween

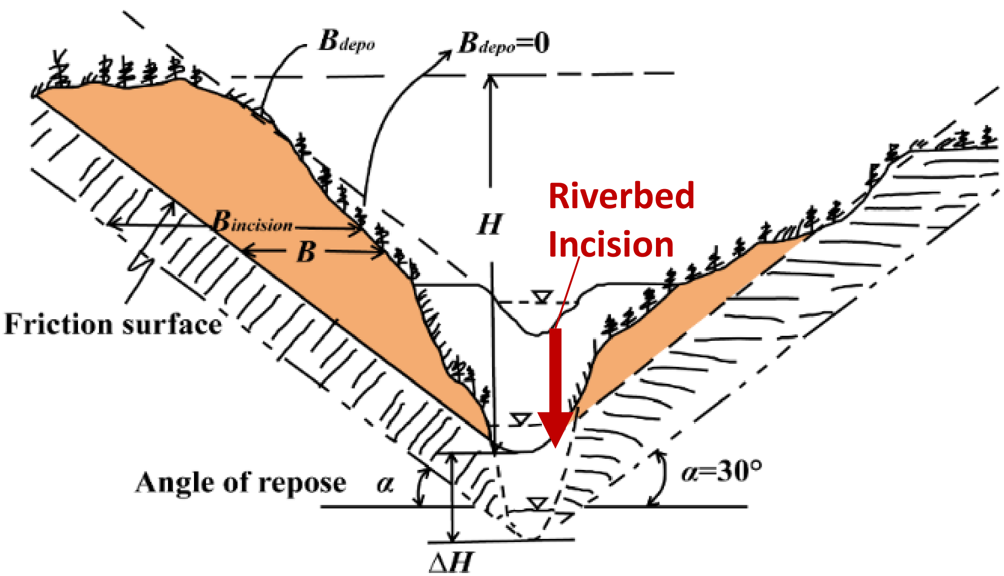


High stream power rivers

- # Landslides and avalanches caused by river incision



- **High stream power → Riverbed Incision → Bank failure**



Riverbed incision increases potential energy and bank failure risk

Potential energy at initial riverbed:

$$Ep = \int_0^H \gamma_s B(z) z dz$$

Potential energy at incised riverbed:

$$Ep_{incision} = \int_{-\Delta H}^{H} \gamma_s B'(z)(z +$$

Potential energy at deposited riverbed:

$$Ep_{depo} = \int_{H_D}^{H} \gamma_s B_D(z)(z -$$

Other environmental impacts of incision

- **Damage to bridges**

A buried part of the bridge piers is exposed due to incision on the Weihe River at Baoji

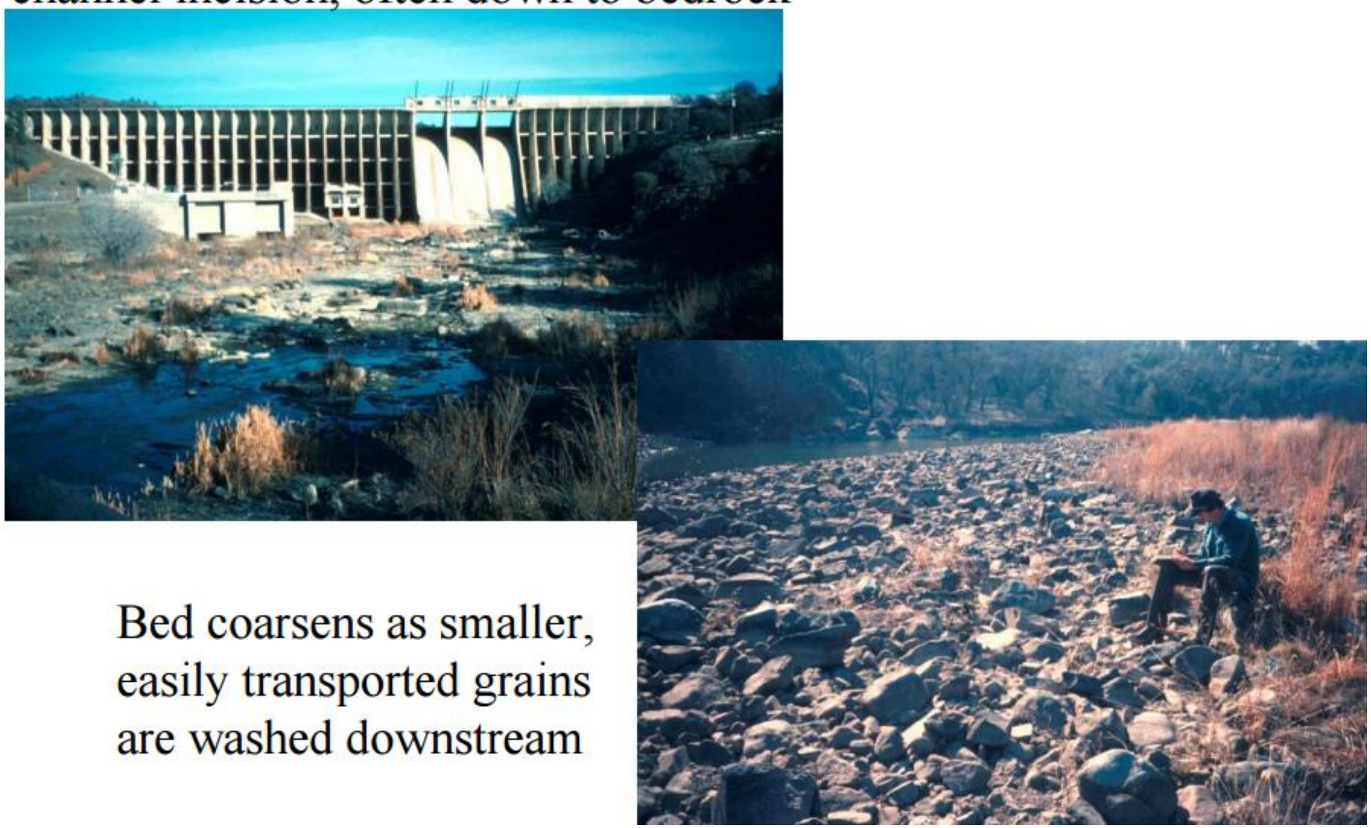
- **Loss of gravel bars and, consequently, the loss of habitat and biodiversity, and damage to riparian vegetation**

Downstream of dams: Hungry Water

Dams release sediment-starved water with excess energy

Result: erosion of bed and banks

- channel incision, often down to bedrock



Bed coarsens as smaller, easily transported grains are washed downstream

Kondolf M., 2008. Hungry Water: Managing Sediment in Rivers. Presentation to the MRC Sediment Workshop.

Content

1. **Basic concepts**
2. **Data collecting**
3. **Environmental impacts of massive sediment movement**
4. **Water-sediment-ecology integrated management**

4. Water-sediment-ecology integrated management

- **Mechanically incision is essentially due to high flow velocity and insufficient bed load. Therefore, two strategies to control incision:**

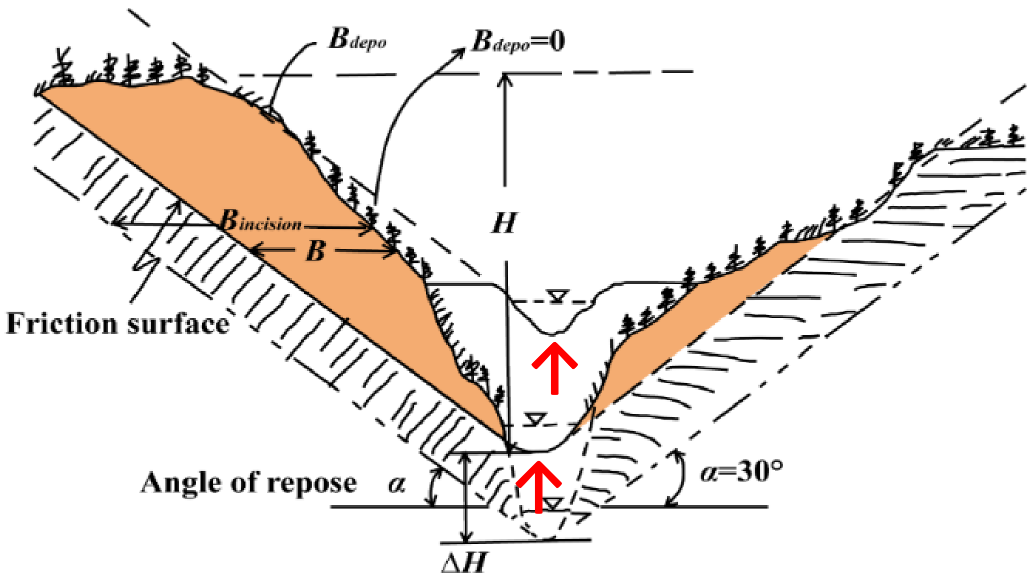
  1) enhance the bed resistance and reduce flow velocity

  2) increase bed load

- **There are many technologies and design frameworks for incision control**

- **Nature-based Solution：**

Stream power reduction ↓ Riverbed deposition ↑ Bank stability ↑



$$Ep = \int_0^H \gamma_s B(z) z dz$$

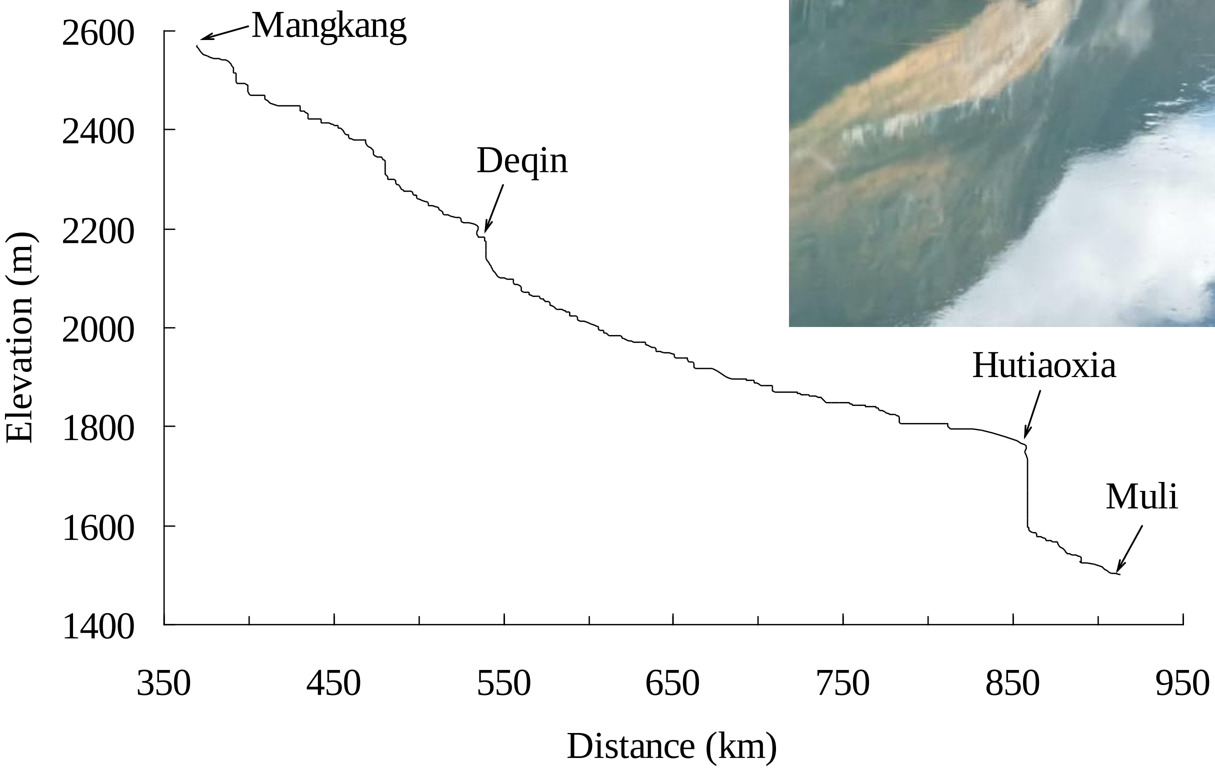
$$Ep_{incision} = \int_{-\Delta H}^{H} \gamma_s B'(z)(z+\Delta H)dz \gg Ep$$

$$\boxed{Ep_{depo} = \int_{H_D}^{H} \gamma_s B_D(z)(z-H_D)dz \approx 0}$$

(1) Enhance the bed resistance and reduce flow velocity

- **Morphologically riverbed incision is controlled by knickpoints, such as landslide dams. Stabilization of natural dams may stop incision.**
- **Human constructed dams, after filling with sediment, may be regarded as knickpoints as well and control stream bed incision.**

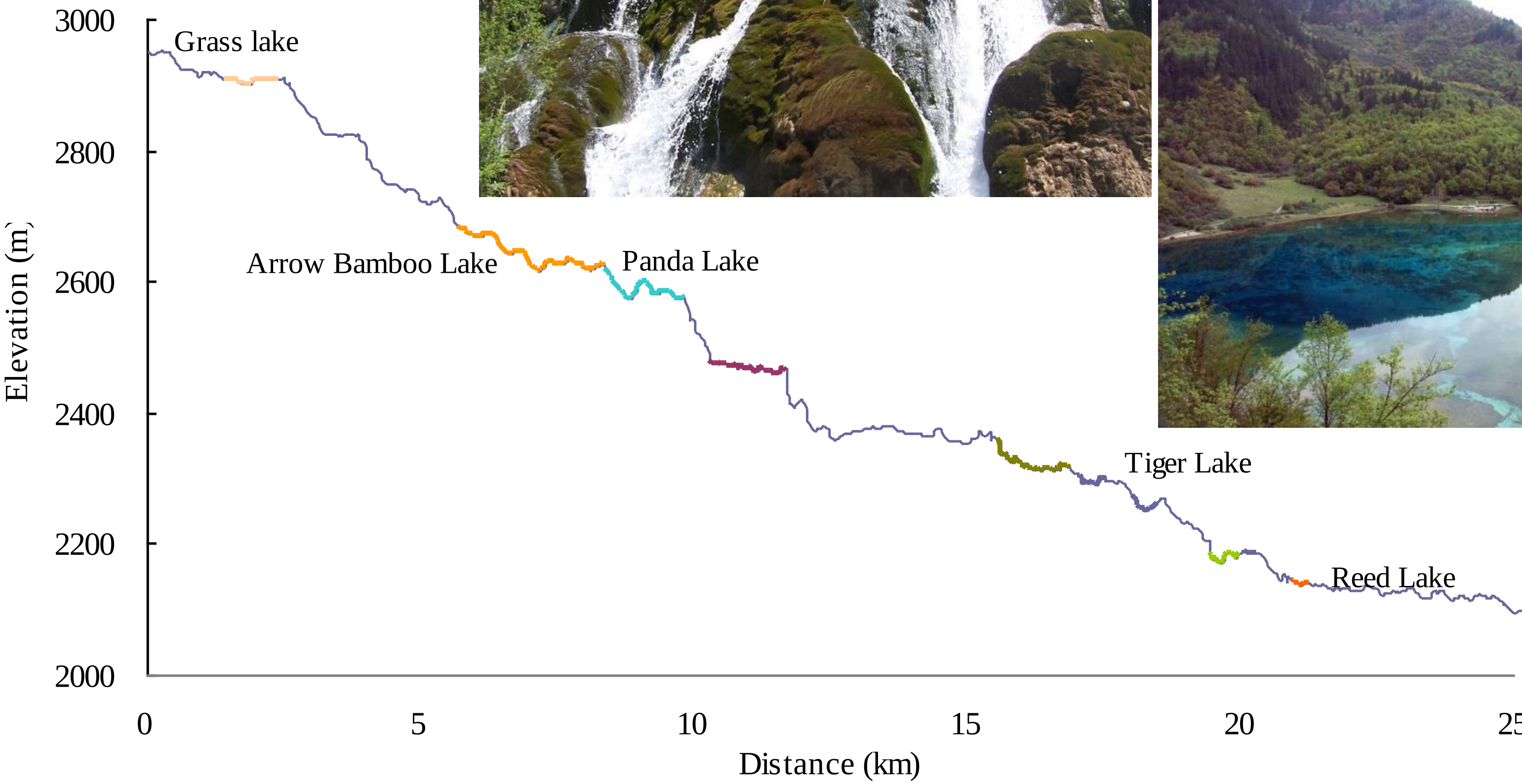
The knickpoint of the Kettle Fall on the Yellow River controls the bed incision



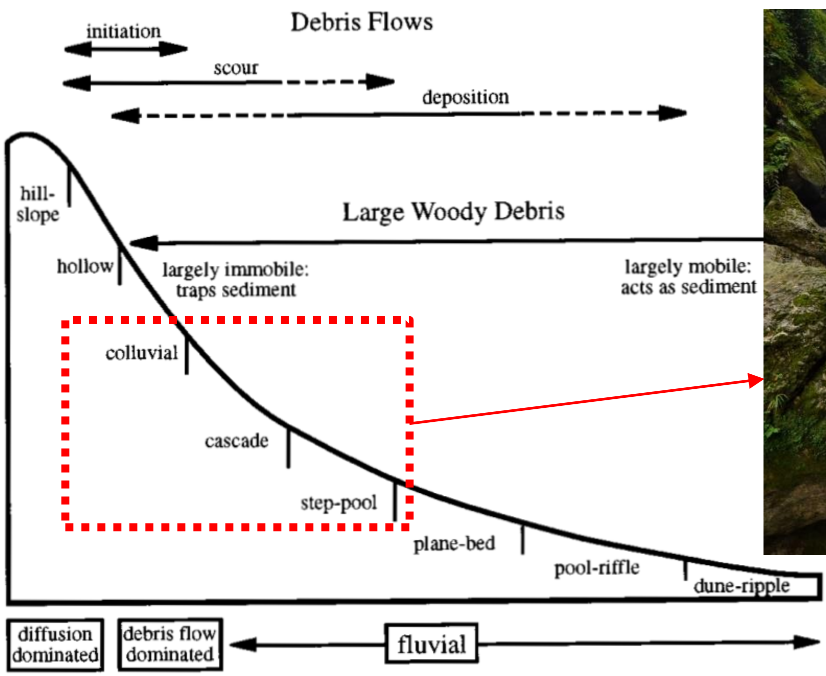
Huge step-pool system at Hutiaoxia (213m)

Bed profile of the Jinsha River showing the large knickpoints at Hutiaoxia (Tiger Leaping Gorge), Deqin and Mangkang

Profile of the Jiuzhaigou Creek - Numerous landslides resulted in several Knickpoints and control the riverbed incision



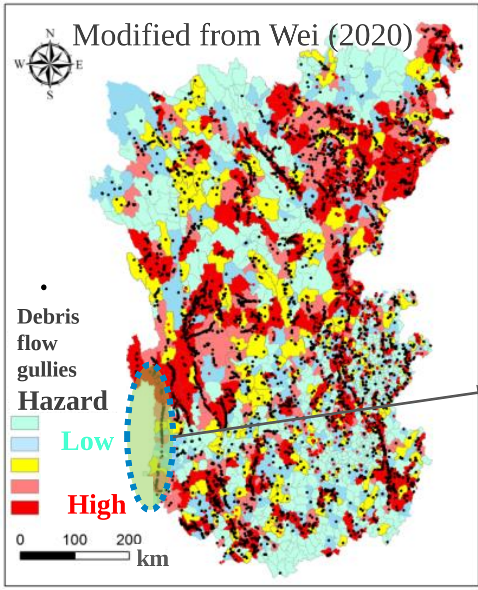
- **Natural cascades/step pools enhance flow resistance, dissipate flow energy, provide diverse habitats for aquatic organisms**



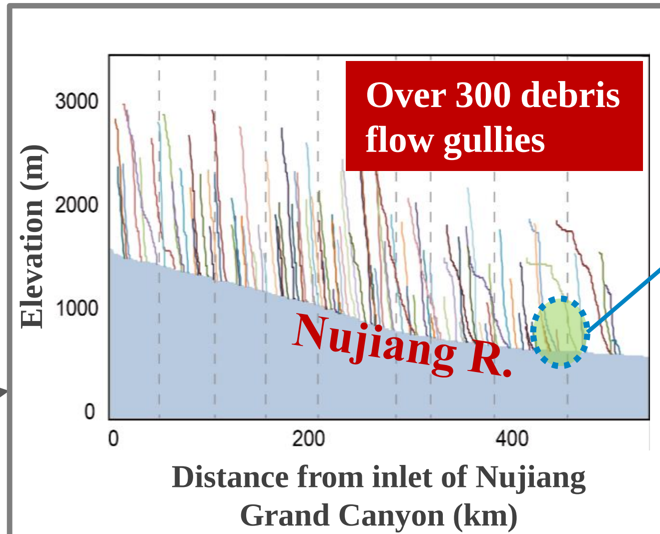
(Montgomery and Buffington 1997)

Natural cascades/step pools

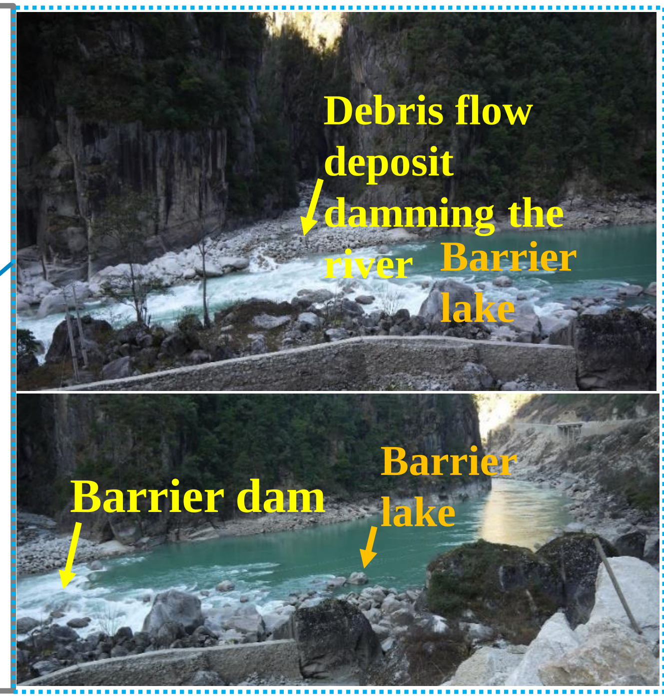
- **High flow energy dissipation rate of barrier dam-lakes along the Nujiang R.**

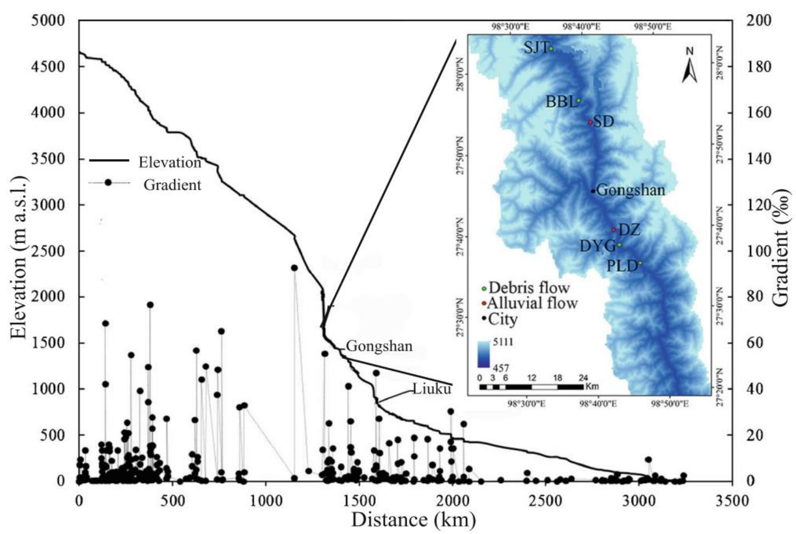


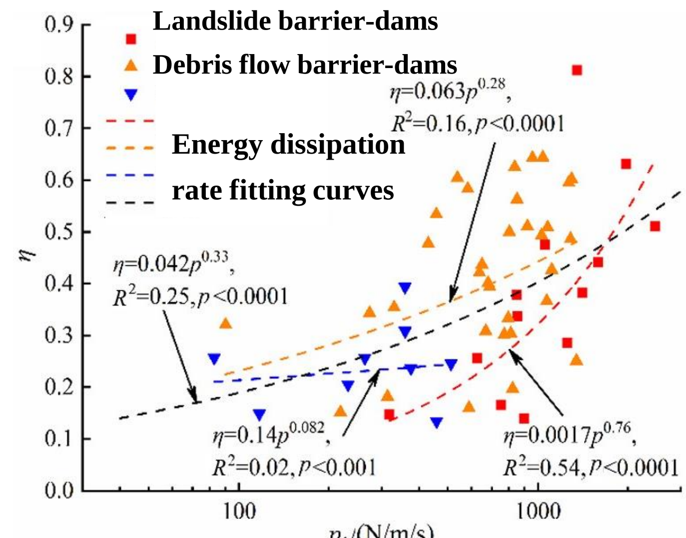
Debris flow hazards along the eastern boundary



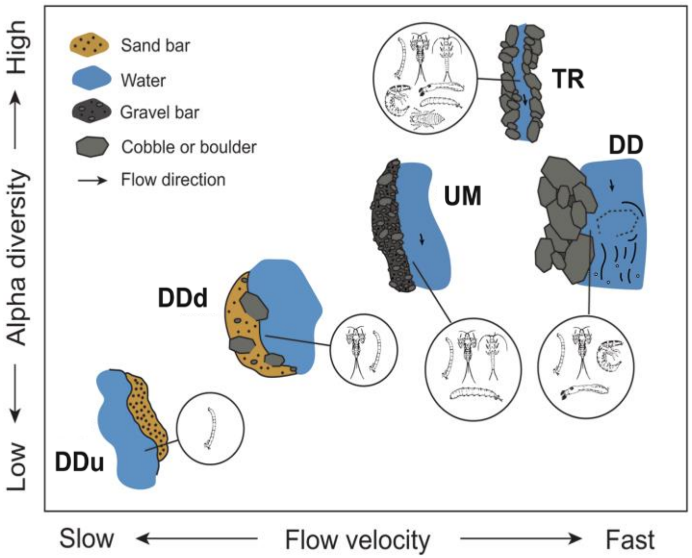
Debris flow deposits dammed the Nujiang R. and formed over 300 barrier dam-lakes, one per km

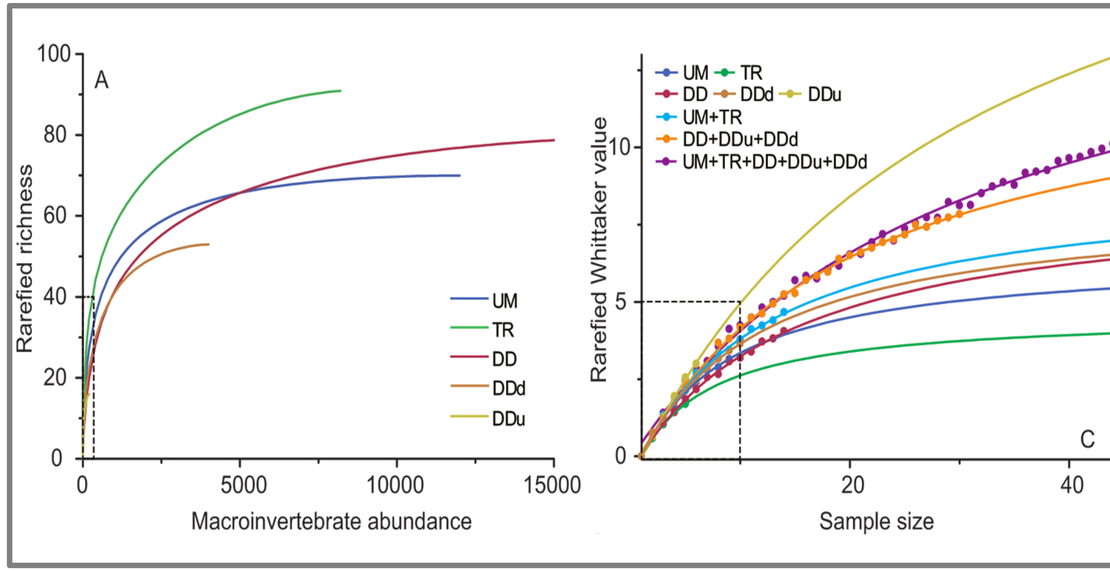






- **A higher habitat diversity supports a higher biodiversity, e.g. biodiversity of macroinvertebrate assemblages:**



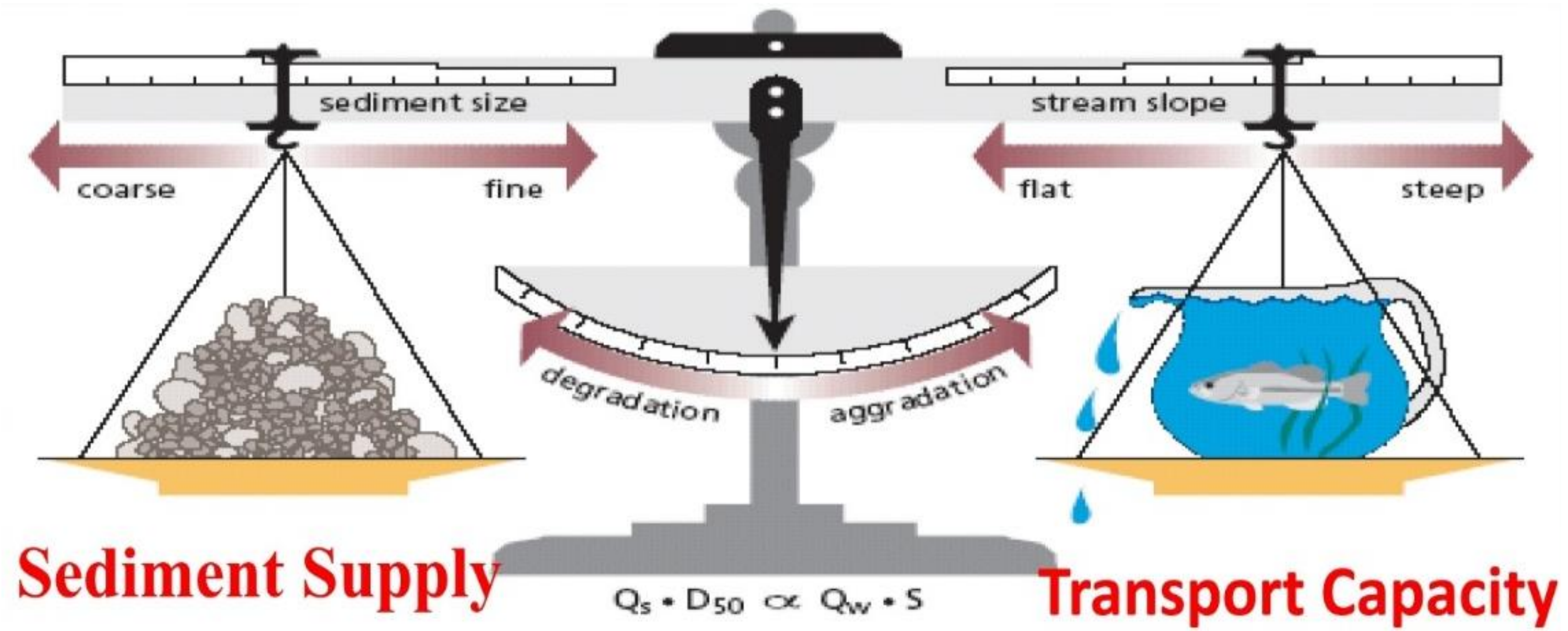


Habitat condition and macroinvertebrate composition

Alpha diversity indicated by rarefied richness and beta diversity indicated with rarefied Whittaker value

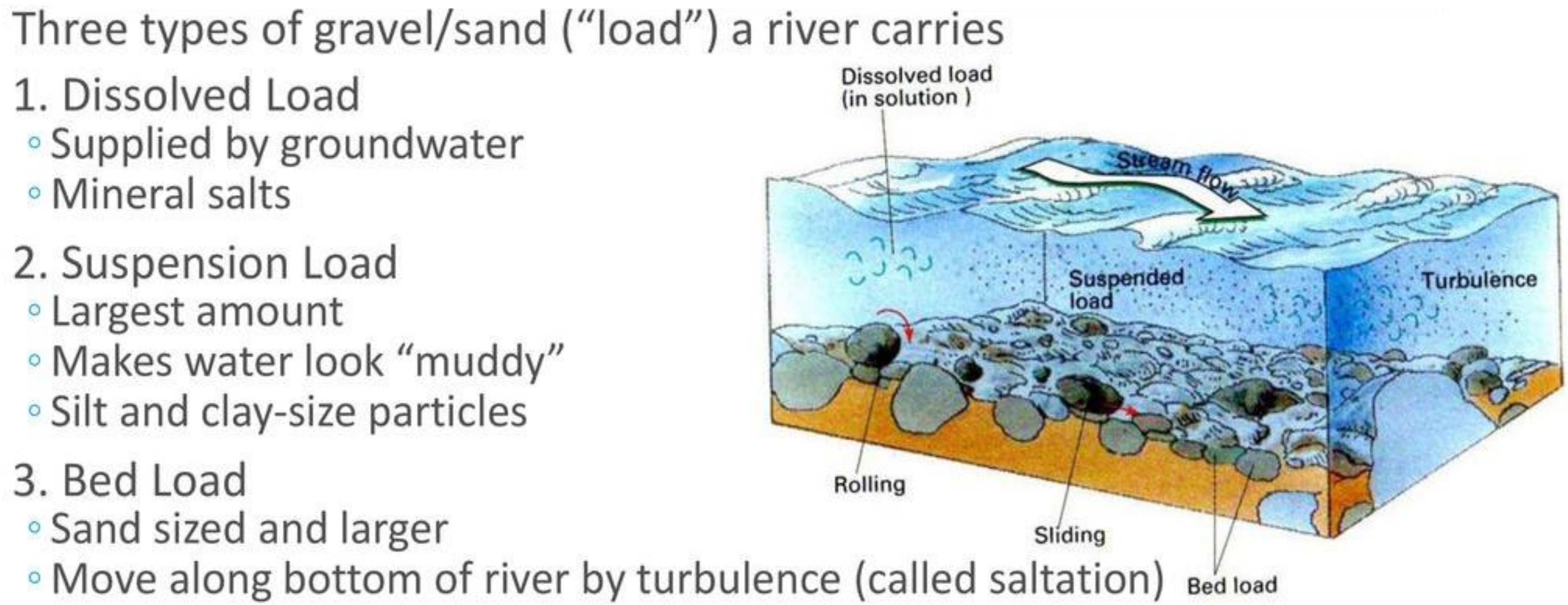
(2) Increase bed load

- **The incision of the river channel indicates a period of vertical instability or disequilibrium by degradation**
- **Degradation occurs if $Q_w s > kQ_s D_{50}$**
- **where Q_w is the channel-forming discharge (m^3s^{-1}), s is the channel gradient, k is a coefficient, Q_s is the unit bed-material discharge (m^2s^{-1}), and D_{50} is the median grain size of the bed material (m)**

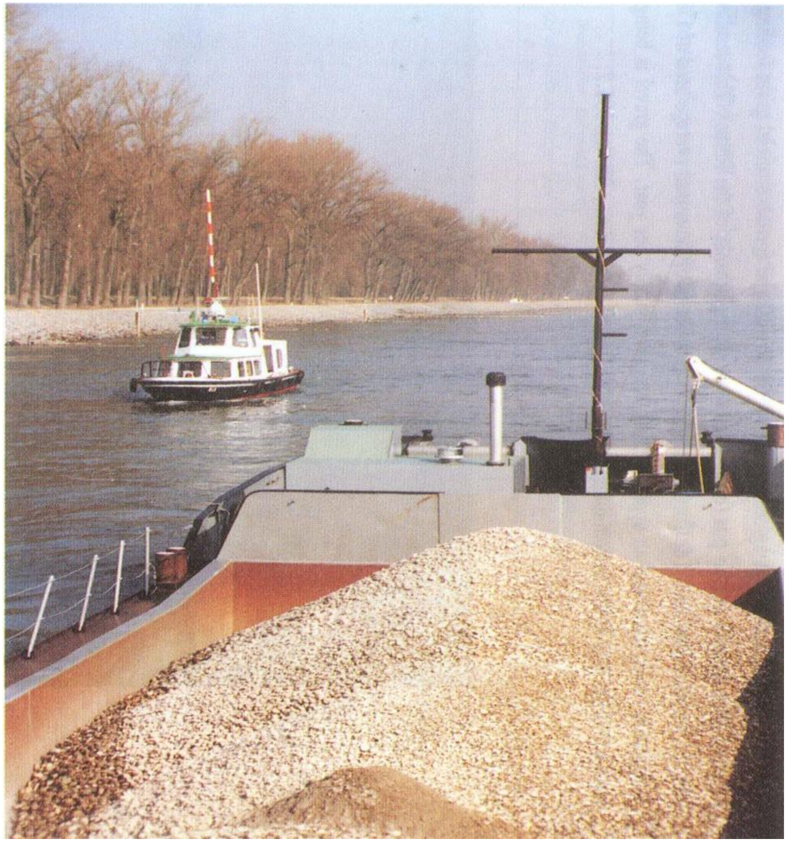


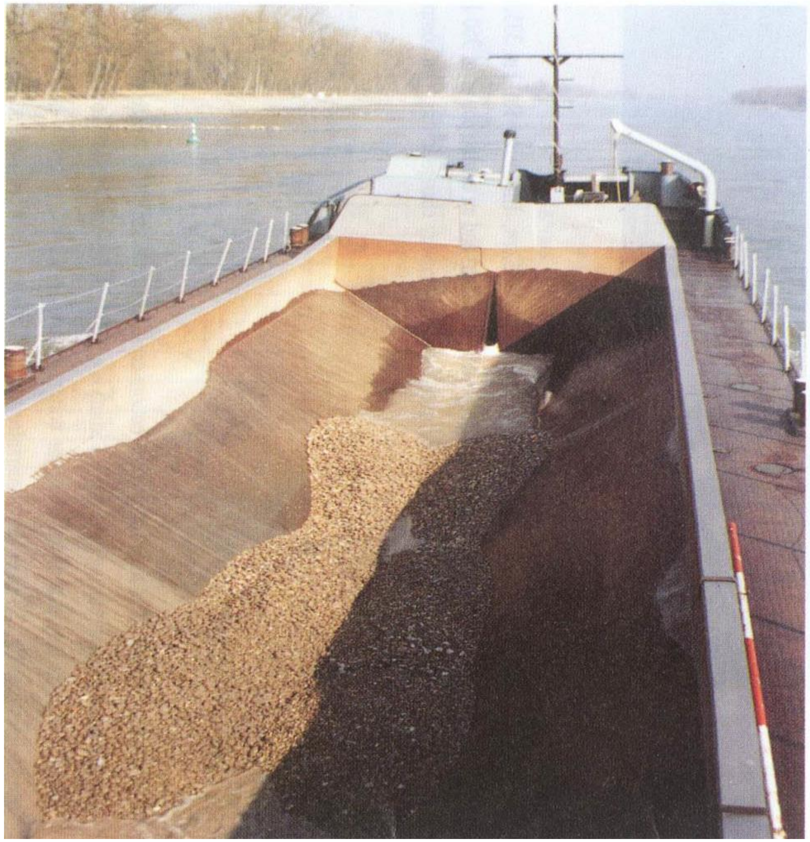
Factors affecting channel degradation (↓) or aggradation (↑) (Lane's equation)

- **Provide bed load is an effective strategy to control incision**
- **Coarse sediment particles, like gravel, slide or move in saltation on the bed, acting a grain pressure on the stationary bed materials**
- **The pressure is known as dispersive pressure defined by Bagnold**
- **It may balance the lift force or suction force of the flow and thus control erosion**



- **The bottom-dump scow loaded with sand-gravel mixture is dumping gravels on to the Rhine River bed downstream of the Iffezheim Dam to mitigate the incision of the river**
- **The managers on the Drome River are considering destabilizing landslides in the catchment to increase the rates of bed load sediment supply as a remedial measure against incision downstream**





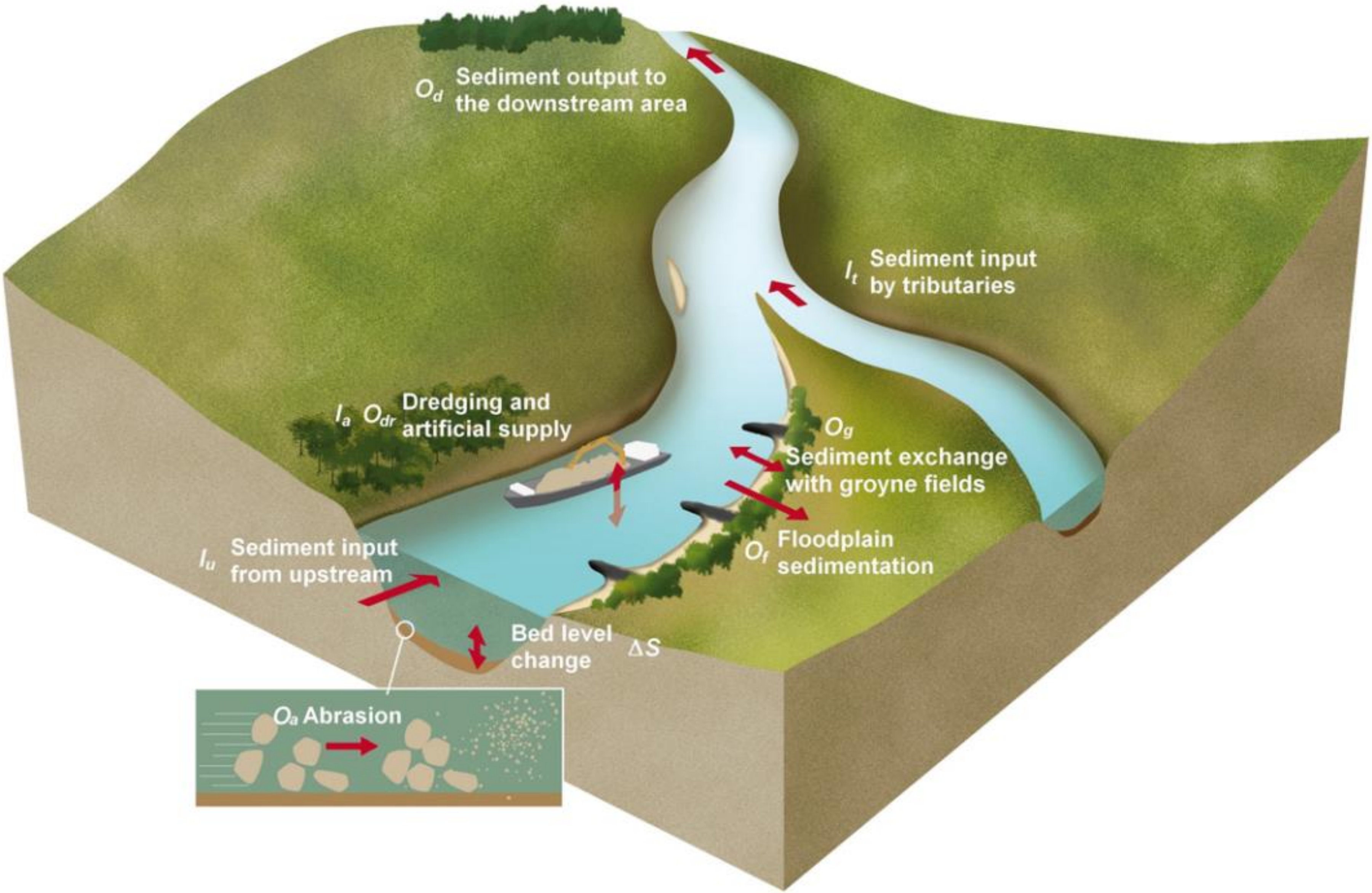


Fig. 6. Sediment budget terms for the Rhine.

R.M. Frings et al. / Geomorphology 204 (2014) 573–587

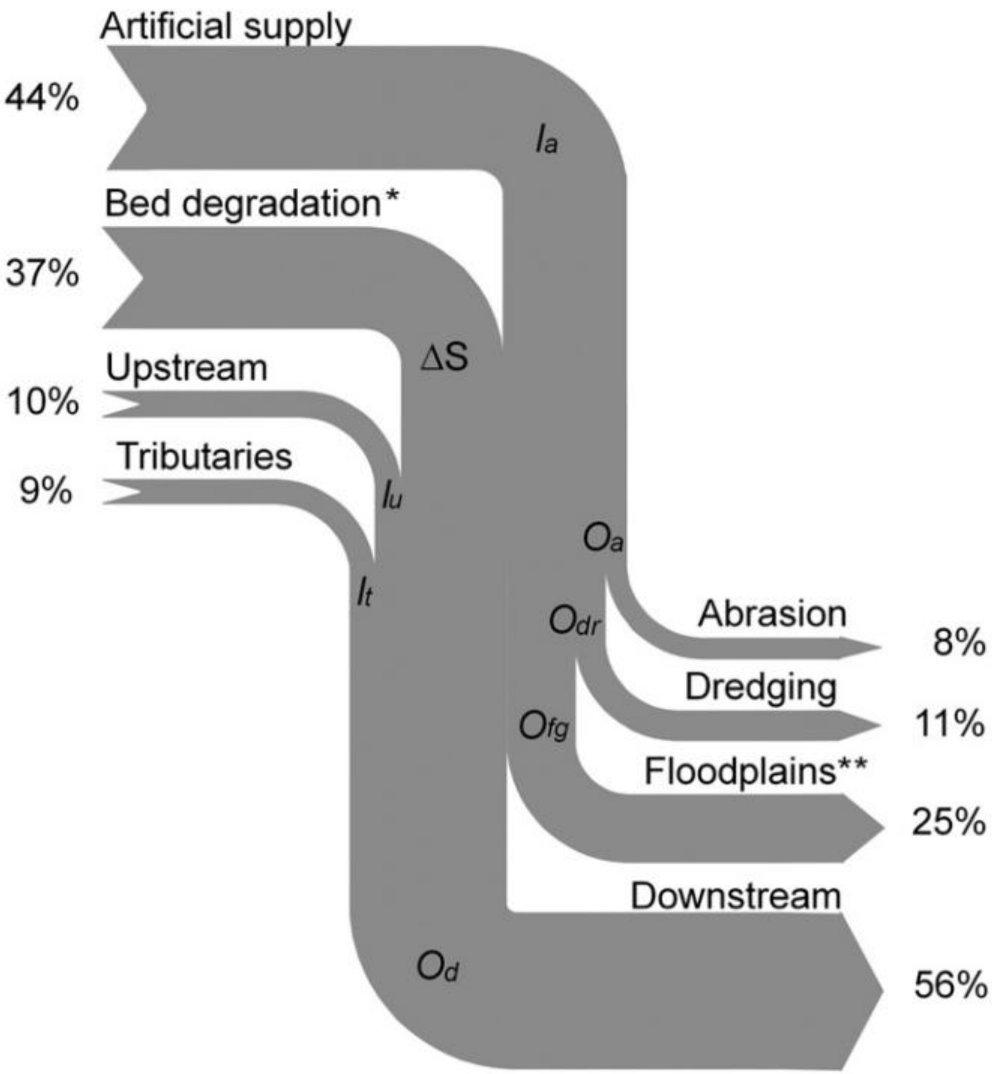


Fig. 13. Sediment budget for gravel and sand for the Rhine reach between km 336 and km 621 (period 1985–2006). *Internal component of the channel itself, **estimated, including groyne field deposition.

- **Sand being eroded from the bed is primarily washed away in suspension, indicating a rapid supply of sand to the Rhine delta.**
- **Degradation results from the 19th and 20th century's river training works that increased the sediment transport capacity and reduced upstream supply.**
- **Erosion events are triggered by disruptions of the armour layer.**

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(3) Techniques for incision control

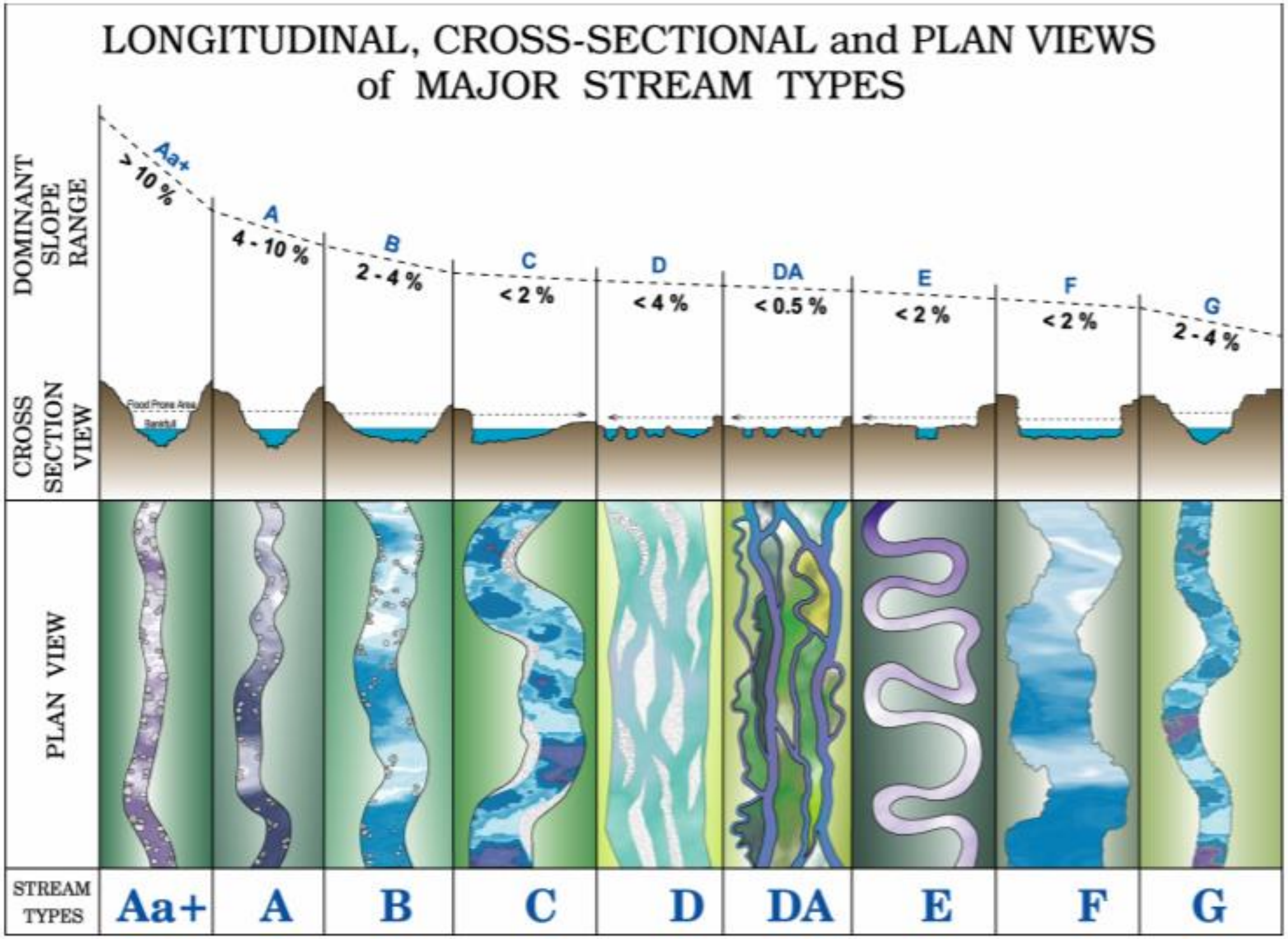
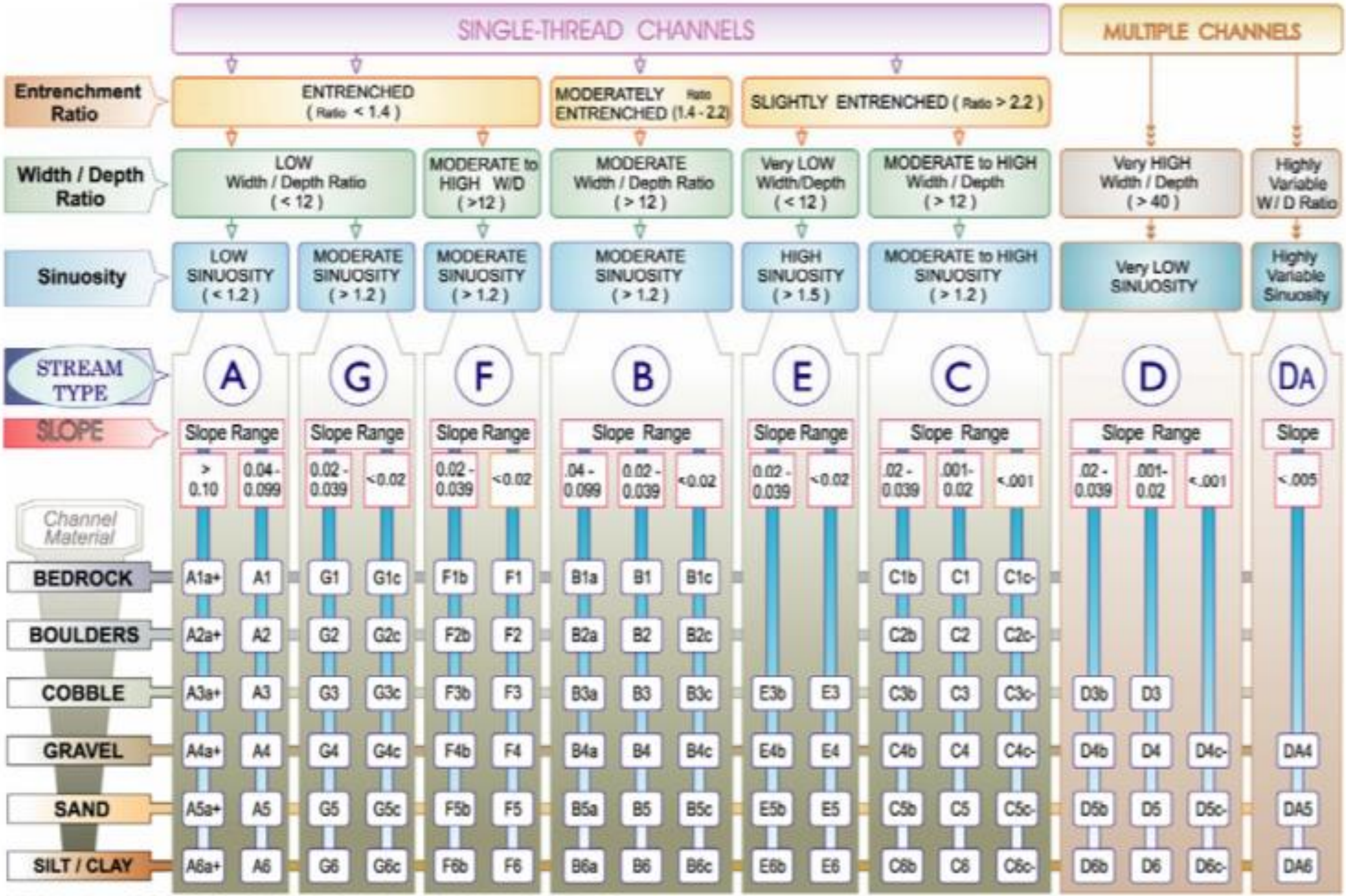


Figure 1. Broad-level stream classification delineation showing longitudinal, cross-sectional and plan views of major stream types (Rosgen, 1994).

David L. Rosgen. A geomorphological approach to restoration of incised rivers. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 1997 S.S.Y. Wang, E.J. Langendoen and F.D. Shields, Jr. (eds.) ISBN 0-937099-05-8



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units, while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

- **Incision control techniques:**
- **Refer to stable channels**
- **Priorities, descriptions, and summary for incised river restoration**

David L. Rosgen. A geomorphological approach to restoration of incised rivers. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 1997 S.S.Y. Wang, E.J. Langendoen and F.D. Shields, Jr. (eds.) ISBN 0-937099-05-8

Table 1. Priorities, descriptions and summary for incised river restoration

DESCRIPTION	METHODS	ADVANTAGES	DISADVANTAGES
Priority 1 Convert G and/or F stream types to C or E at previous elevation (Fig.5a)	Re-establish channel on previous floodplain using relic channel or construction of new bankfull discharge channel. Design new channel for dimension, pattern and profile characteristic of stable form. Fill in existing incised channel or with discontinuous oxbow lakes level with new floodplain elevation.	Re-establishment of floodplain and stable channel: 1) reduces bank height and streambank erosion, 2) reduces land loss, 3) raises water table, 4) decreases sediment, 5) improves aquatic and terrestrial habitats, 6) improves land productivity, and 7) improves aesthetics.	1.Floodplain re-establishment could cause flood damage to urban agricultural and industrial development. 2.Downstream end of project could require grade control from new to previous channel to prevent head-cutting.
Priority 2 Convert F and/or G stream types to C or E. Re-establishment of floodplain at existing level (Fig.5b and 5c)	If belt width provides for the minimum meander width ratio for C or # stream types, construct channel in bed of existing channel, convert existing bed to new floodplain. If belt width is too narrow, excavate streambank walls. End-haul material or place in streambed to raise bed elevation and create new floodplain in the deposition.	1. decreases bank height and stream bank erosion 2. allows for riparian vegetation to help stabilize banks 3. establishes floodplain to help take stress off of channel during flood 4. improves aquatic habitat 5. prevents wide-scale flooding of original land surface 6. reduces sediment 7. downstream grade control is easier.	1. does not raise water table back to previous elevation 2. shear stress and velocity higher during flood due to narrower floodplain 3. upper banks need to be sloped and stabilized to reduce erosion during flood.
PRIORITY 3 Convert G to B stream types or F to Bc (Fig.5d and 5e)	Excavation of channel to change stream type involves establishing proper dimension, pattern and profile. To convert a G to B stream involves an increase in width/depth and entrenchment ratio. Shaping upper slopes and stabilizing both bed and banks. A conversion from F to Bc stream type involves a decrease in width/depth ratio and an increase in entrenchment ratio.	1, reduces the amount of land needed to return the river to a stable form 2. developments next to river need not be re-located due to flooding potential 3. decreases flood stage for the same magnitude flood 4. improves aquatic habitat.	1. high cost of materials for bed and streambank stabilization 2. does not create the diversity of aquatic habitat 3. does not raise water table to previous levels.
PRIORITY 4 Stabilize channel in place (Fig.5f)	A long list of stabilization materials and methods have been used to decrease stream bed and stream bank erosion including concrete, gabions, boulders and bio-engineering methods.	1. excavation volumes are reduced 2. land needed for restoration is minimal	1. high cost for stabilization 2. high risk due to excessive shear stress and velocity 3. limited aquatic habitat depending on nature of stabilization methods used.

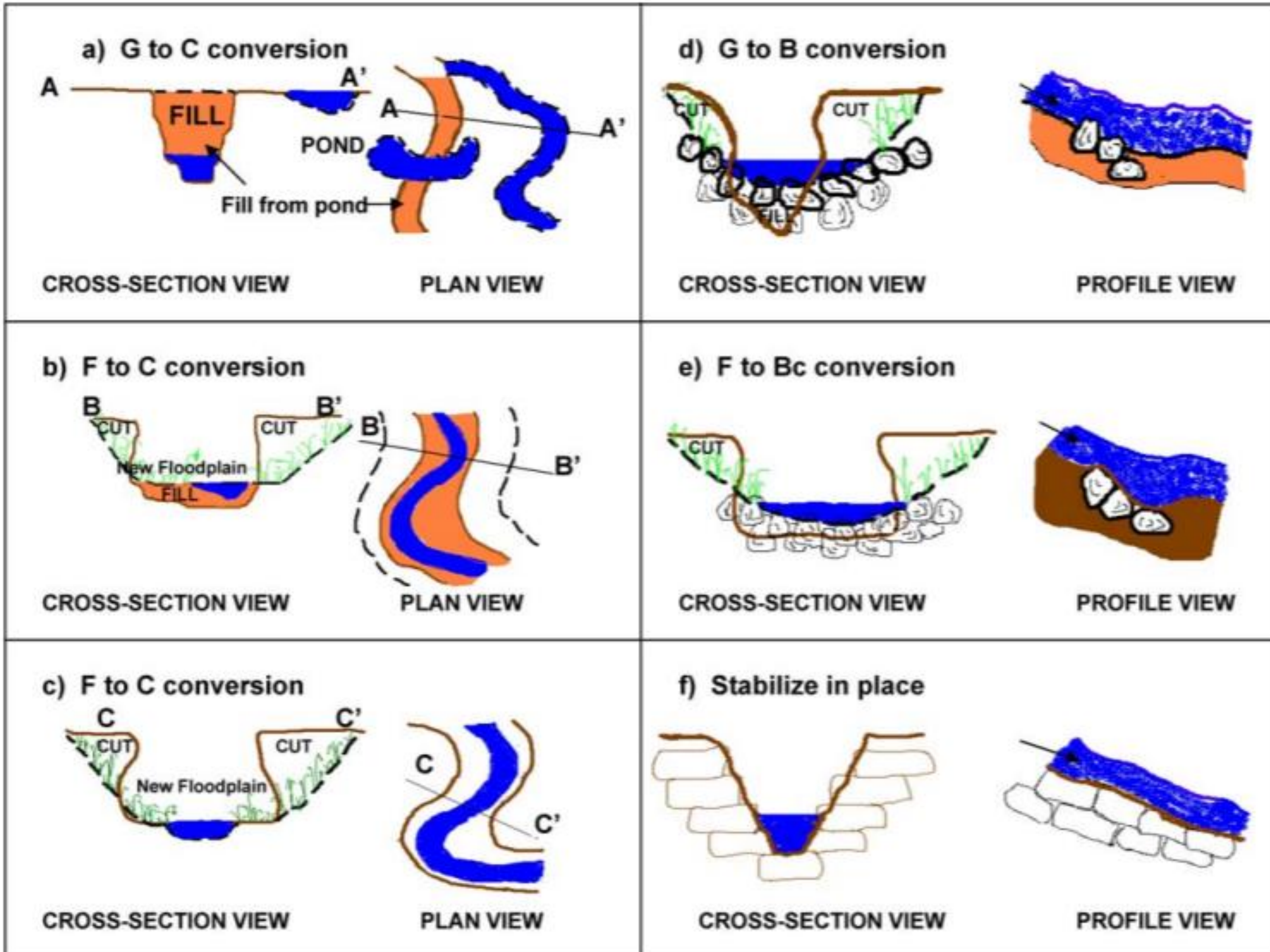
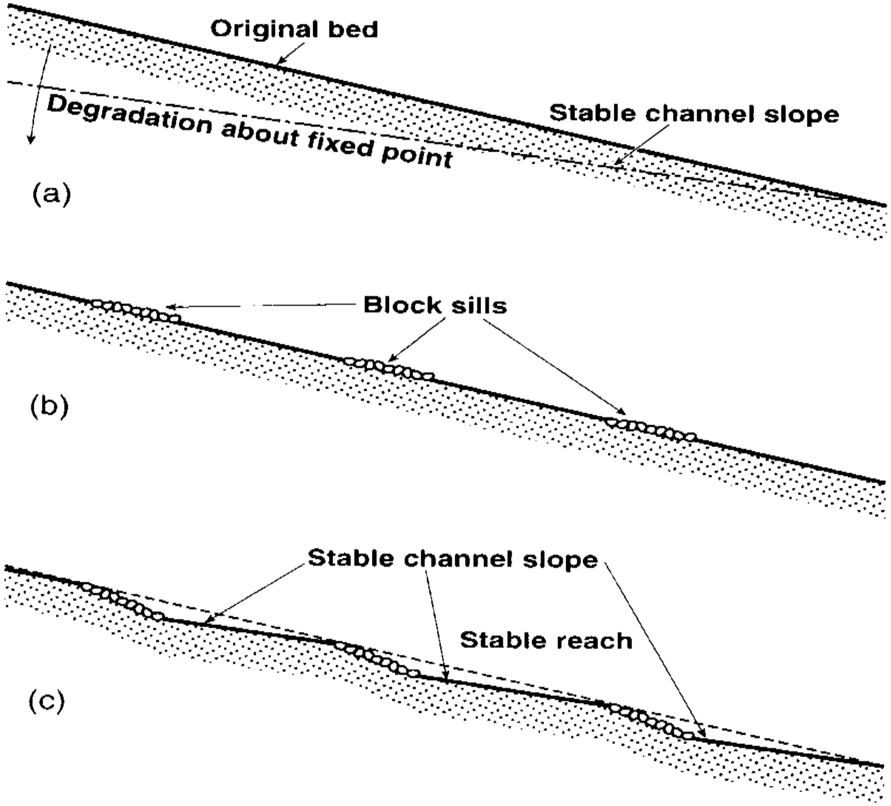


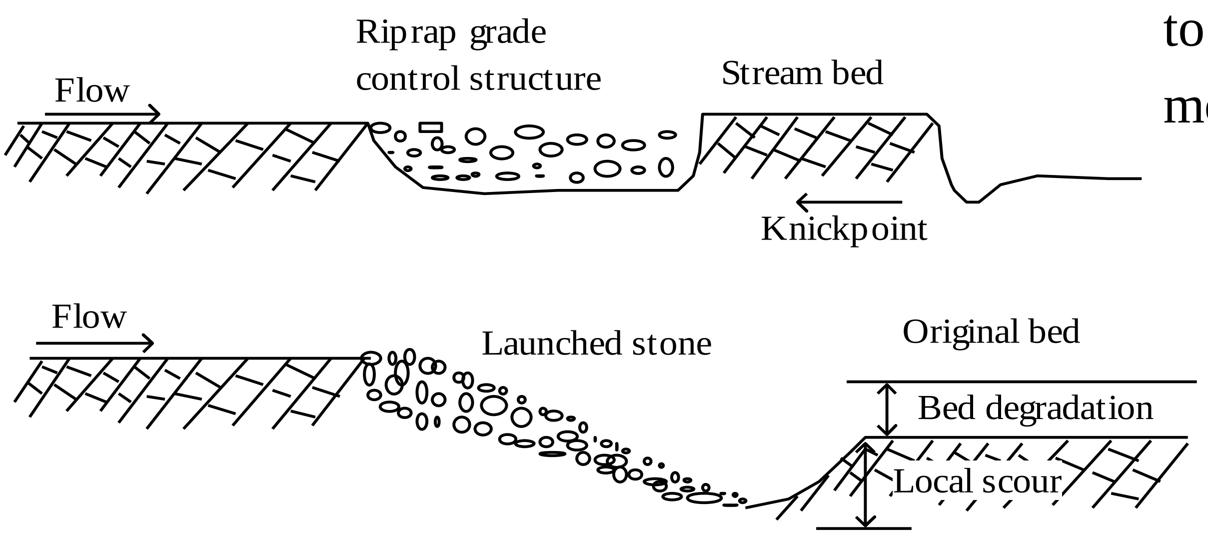
Figure 5. Various restoration/stabilization options for incised channels.

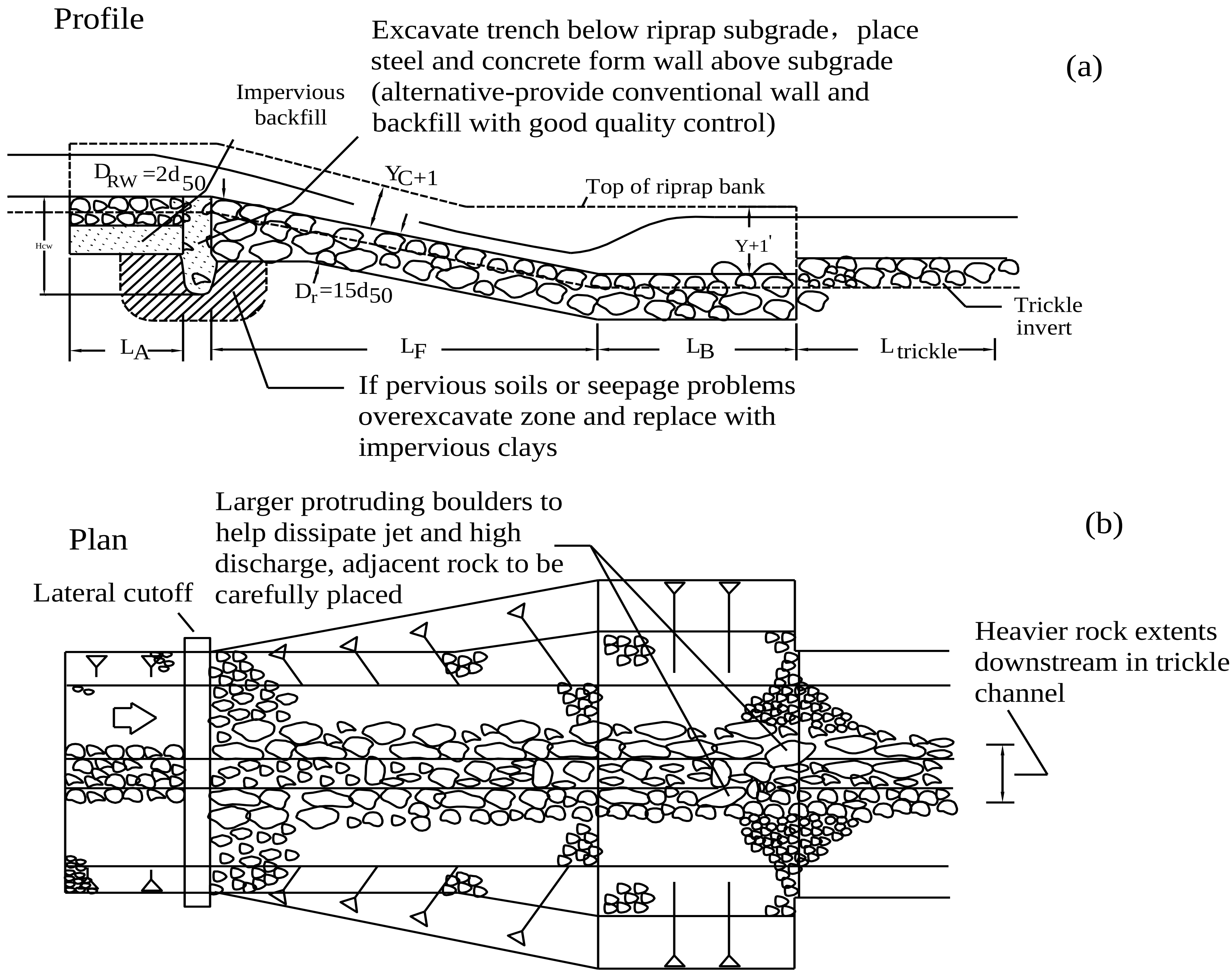


Incision control with structures

Rock sills, or bed sills (simply placing the rock along the streambed)

A riprap control structure to stop headward movement of knickpoint



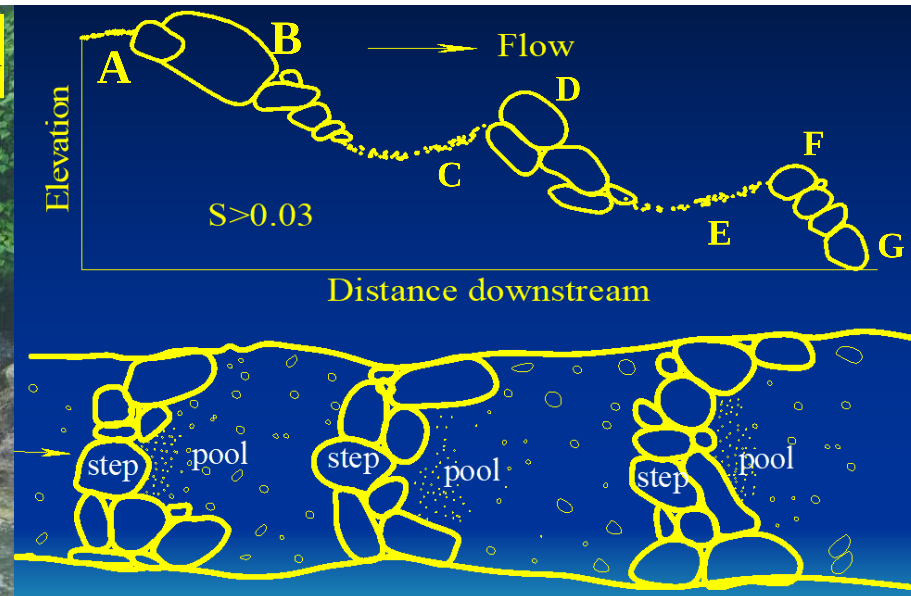


Profile
Excavate trench below riprap subgrade， place steel and concrete form wall above subgrade (alternative-provide conventional wall and backfill with good quality control)
(a)
Impervious backfill
$D_{RW} = 2d_{50}$
$Y_{C}+1$
Top of riprap bank
Hcw
$Y+1'$
$D_r = 15d_{50}$
Trickle invert
L_A
L_F
L_B
$L_{trickle}$
If pervious soils or seepage problems overexcavate zone and replace with impervious clays
Plan
Larger protruding boulders to help dissipate jet and high discharge, adjacent rock to be carefully placed
(b)
Lateral cutoff
Heavier rock extents downstream in trickle channel

- **Artificial step-pool system**

✓ **Artificial bed structures, especially step-pools, may effectively control incision**

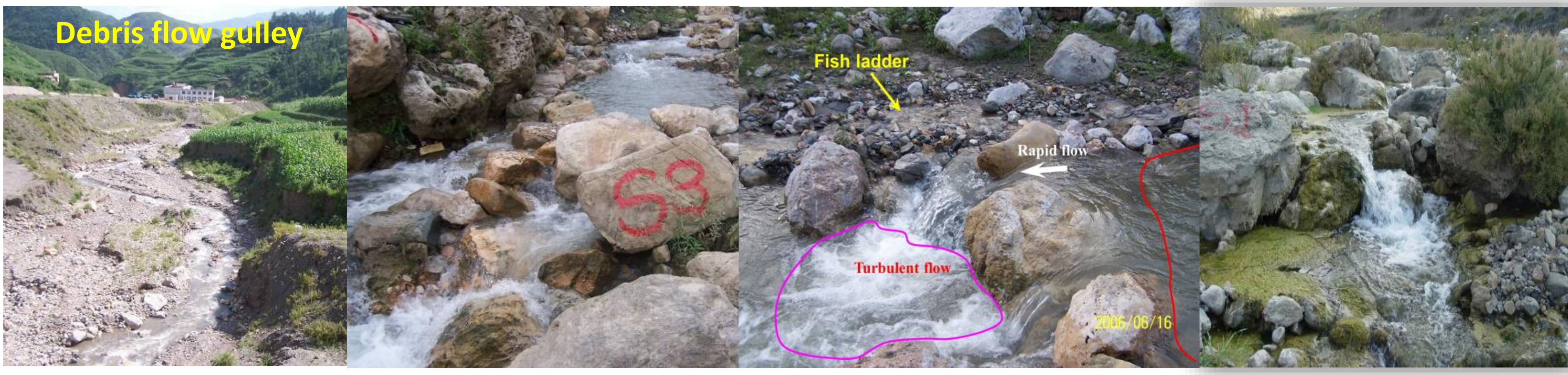
- **Nature-based Solution：** **mimicking natural step-pool system**

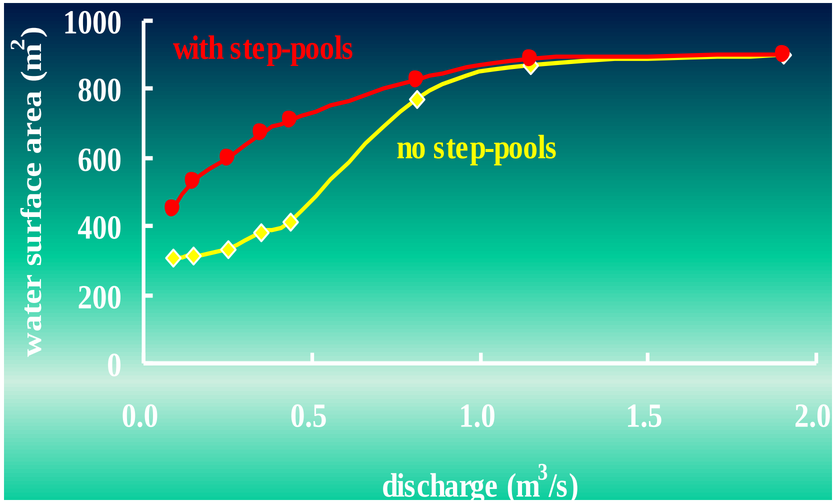


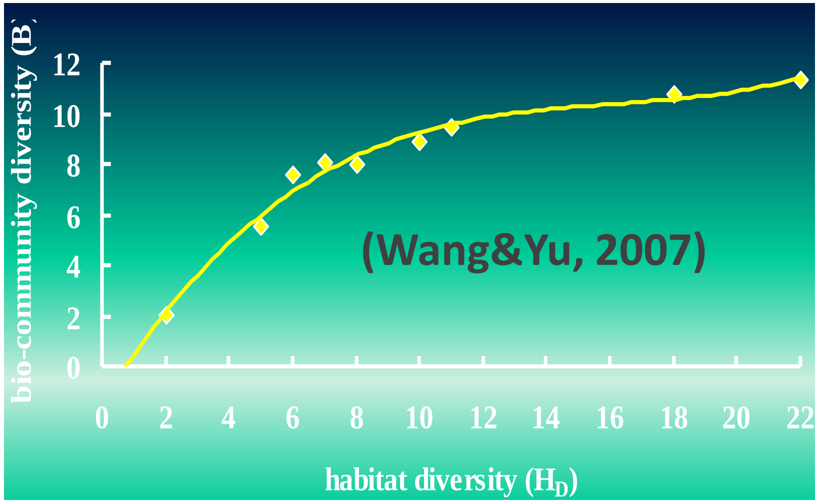
Schematic plot of typical step-pool system

Regular step-pool system is developed during the degradation of the river bed. Large stones, boulders and cobbles are rearranged to form a structure like steps.

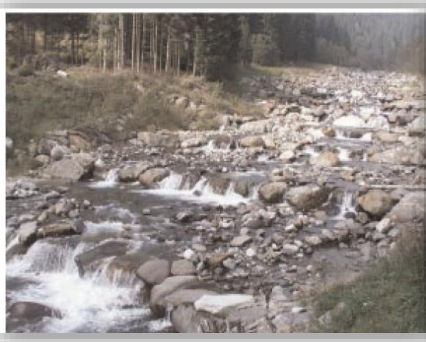
- E.g. artificial step-pool system successfully reduced debris flows, and stabilized aquatic habitat, improved biodiversity, Diaoga River, Yunnan, China







- **Other successful application of step-pool systems in natural hazard reduction/river restoration**



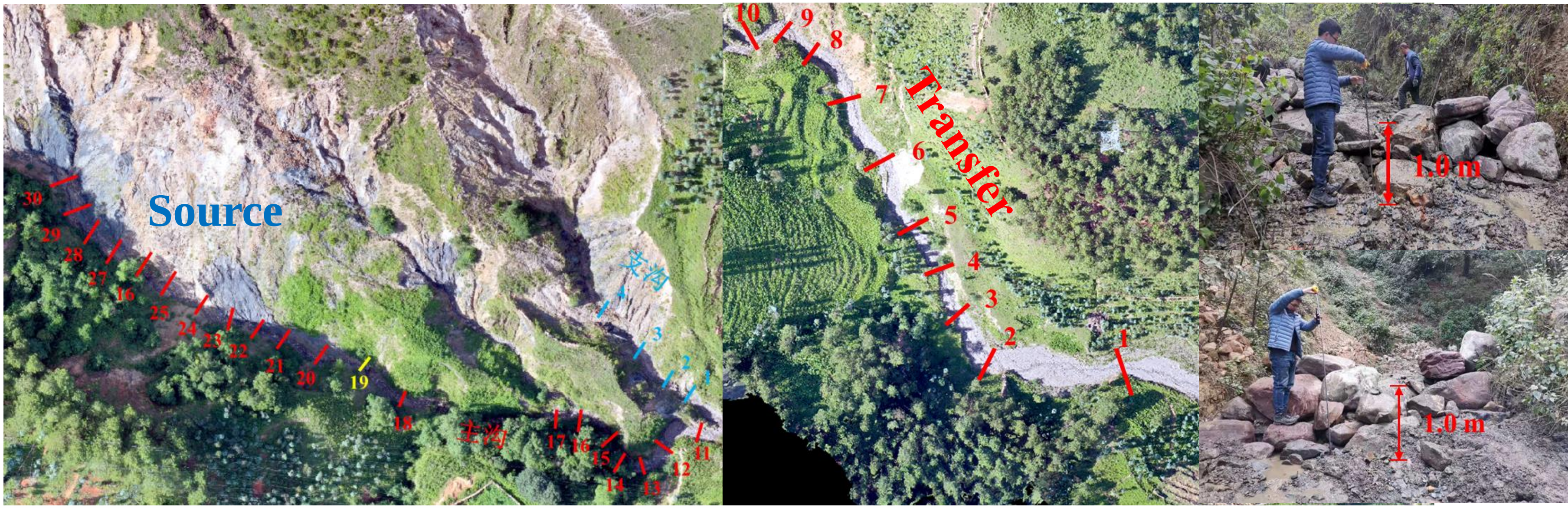
Maso di Spinelle, Italy
(Comiti et al., 2009)

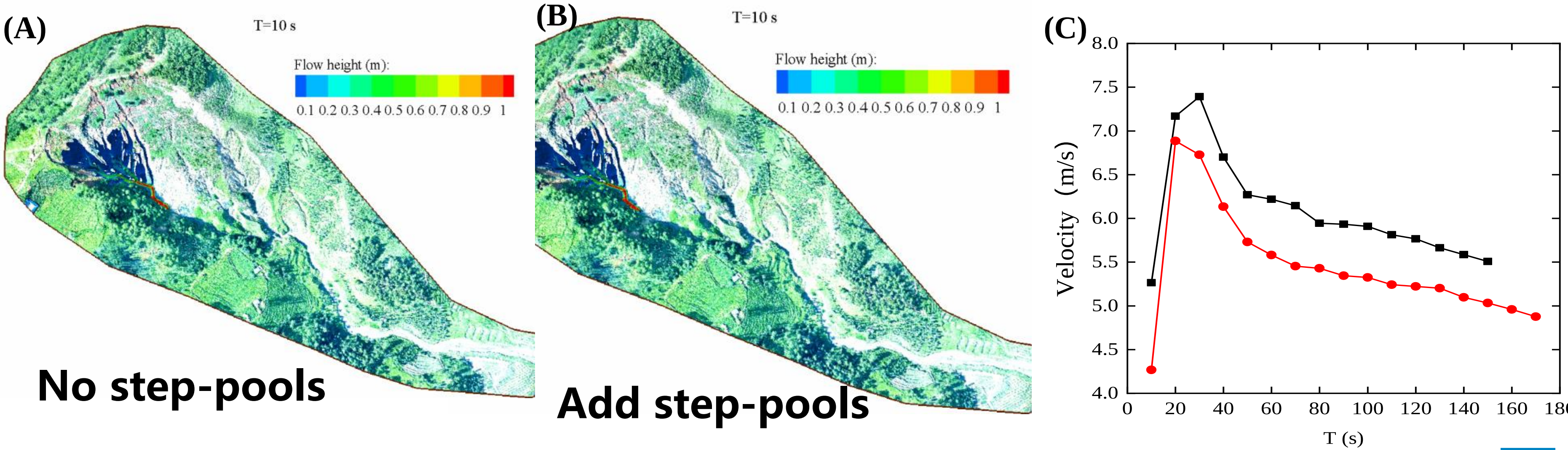
Karnowsky Creek, USA
(Chin et al., 2009)

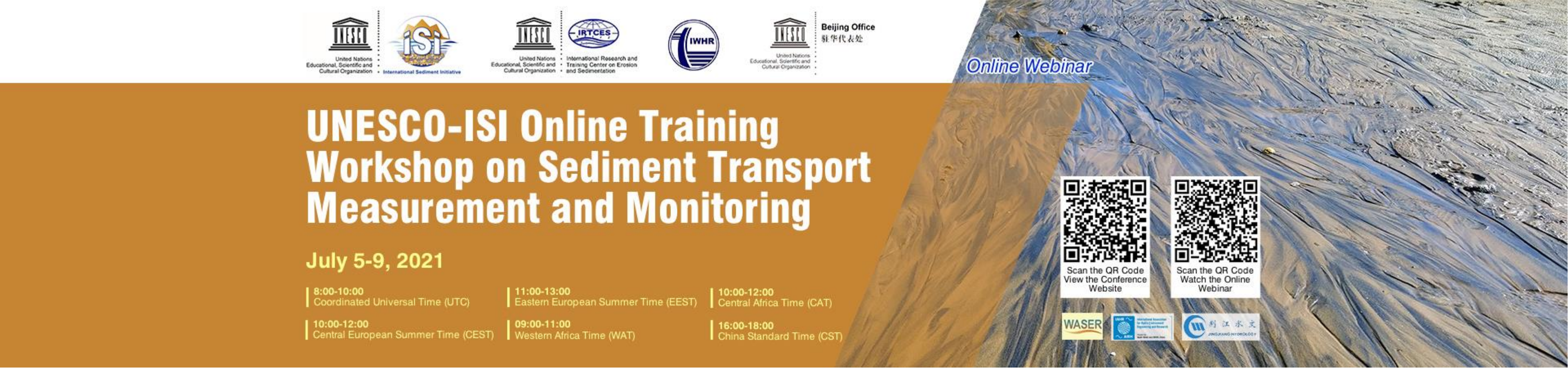
Mühlenhagen fish passage, Germany (Marmulla and Welcomme, 2002)

Baxter Creek, USA
(Chin et al., 2009)

- **Debris flow control, tributaries of Anning River, China**







Thank you for your attention!

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