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Lecture Note

Field survey and monitoring methods for river flow, sediment transport and river beds in mountain regions

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Lecture 4: Field survey and monitoring methods for river flow, sediment transport and river bed in mountain regions

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1. Brief introduction on rivers in mountain regions

A widely recognized classification of channel-reach morphology in mountain drainage basins synthesizes stream morphologies into seven distinct reach types(Montgomery and Buffington, 1997): colluvial, bedrock, and five alluvial channel types (cascade, step pool, plane bed, pool riffle, and dune ripple) (Figure 1, 2). Here we mainly focus on these five alluvial types below.

An incised river in the mountain regions is defined as a river that is experiencing bed-level lowering. From the viewpoint of geomorphological process, mountain rivers either were or are incised rivers. Large rivers may be incised rivers in the upper reaches, but fluvial rivers develop in the middle or lower reaches.

The essential cause of channel incision is high slope, non-equilibrium stream flow and bed roughness. Development of channel incision in mountainous areas depends on the rainfall, watershed vegetation, and soil and rock compositions. Channel incision may cause landslides and debris flows. Channel incision is a key process in drainage-network development and landscape evolution on Earth.

At the most fundamental level, without incision there is no alluvial channel. In a broad sense, therefore, one can consider channel incision as a requirement of denudation, drainage-network development, and landscape evolution. Channel incision has become a major concern of river managers because it disrupts transportation, destroys agricultural land, threatens adjacent structures, drastically alters environmental conditions, and produces sediment load that causes further problems downstream. Therefore, the causes of channel incision have been a topic of great interest because a better understanding of the phenomenon could lead to reveal geomorphological evolution and mitigate disaster prevention.

The most dramatic channel incision occurs on the east margin of the Qinghai-Tibet Plateau (QTP). Geologically, the Indian Plate moves northward at a rate of 50 mm/yr and collides with the Eurasian Plate, resulting in the uplift of the Himalaya Mountains and the QTP. The QTP has become the highest plateau in the world and is referred to as the Third Pole of the Earth. Uplift of the plateau resulted in accelerated fluvial incision because of the remarkable increase in stream bed slope at its margin. The fluvial incision into the plateau margin in response to tectonic motion resulted in isolating remnants of the original plateau surface. These remnants of the plateau surface can be used as reference surfaces against which to evaluate the impact of lateral erosion since the uplift. The high loads of sediment carried by the tributary streams of the Yellow, Yangtze, Lancang, Lujiang, Yarlung Tsangpo rivers on the QTP indicate rapid rates of denudation in the catchments.

Rapid fluvial incision into bedrock has been interpreted to reflect a tectonic uplift of similar magnitude, thereby sustaining topographic equilibrium. In uplifting mountain belts, an end-member scenario can be formulated in which the rate of bedrock uplift is matched by the rate of stream incision and valley lowering. The slopes steepen until topographic elements become unstable and collapse, producing rock falls, avalanches, and landslides. Tectonic uplift has been found to be responsible for the abandonment of valleys, formation of deep and incised river valleys, highly irregular longitudinal profiles of channels, and the varying number and tilting of terraces. Among these features, deep valleys formed by the incision of rivers with high flow velocity are a prominent characteristic of active, uplifting mountain areas. On a large scale, the ridge–valley landscape of the entire QTP was formed by the mechanism of intensive incision.

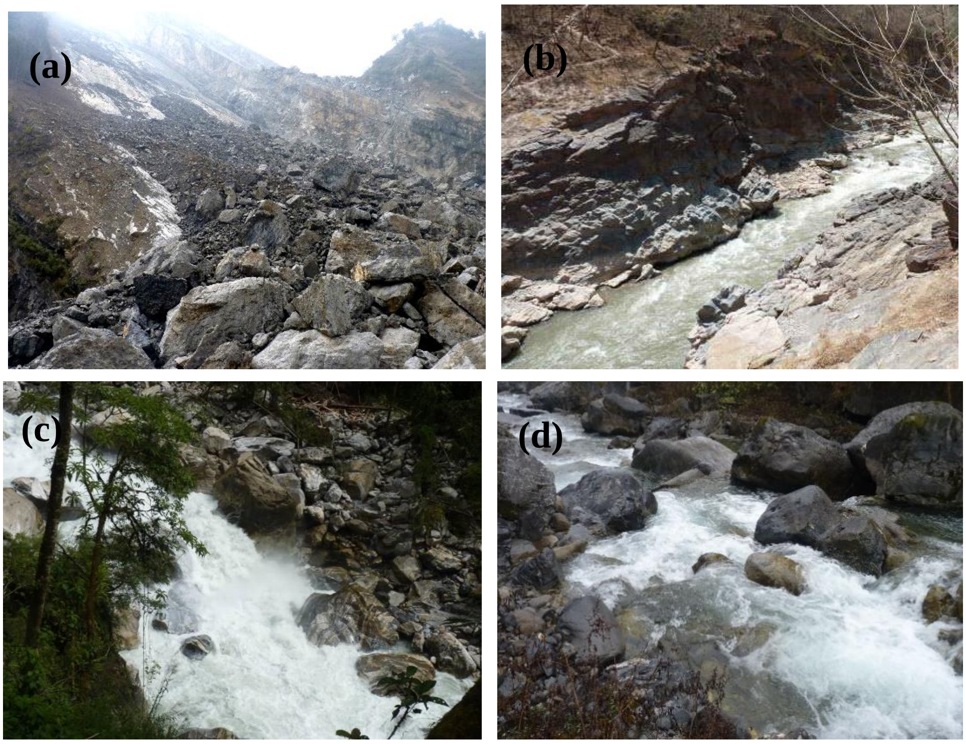

Figure 1 (a) colluvial type (b) bedrock channel (c) cascade (d) step-pool system

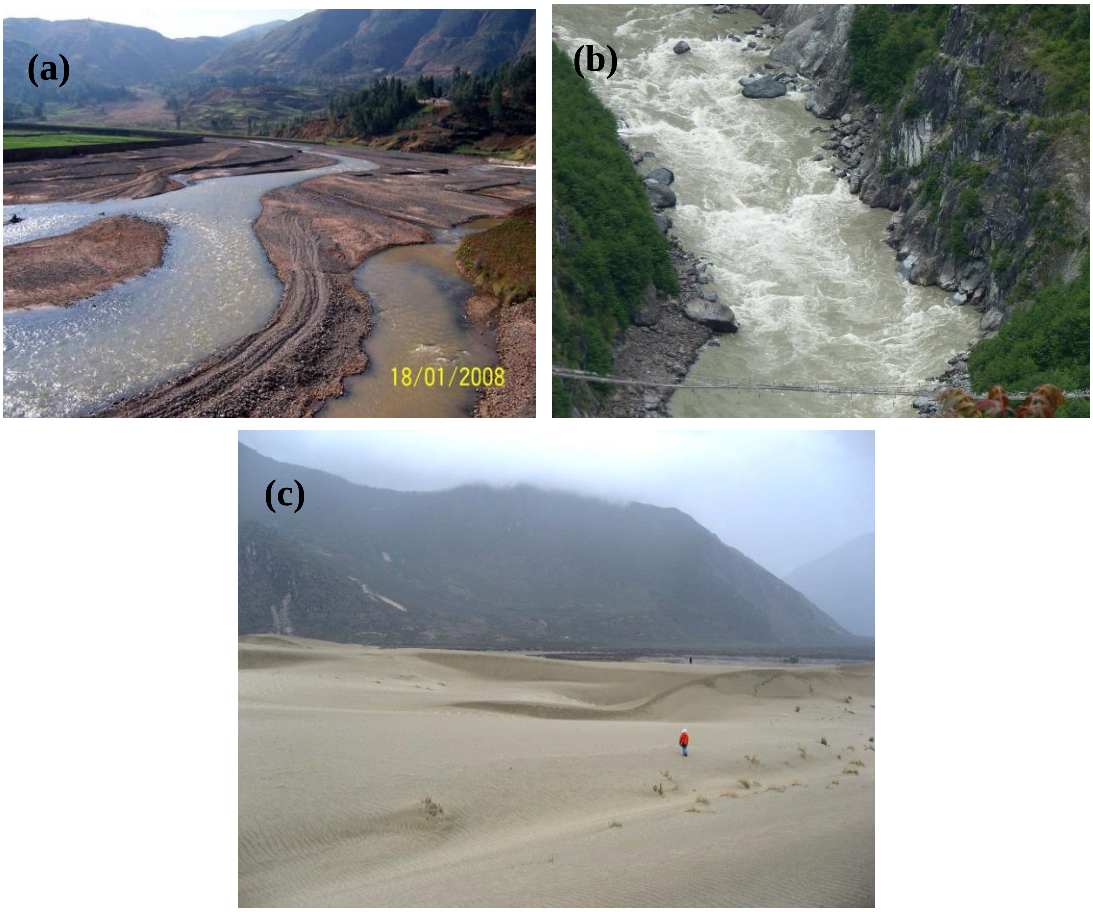

Figure 2 (a) plane bed (b) pool-riffle (c) ripple and dune

The continuous rising of the QTP has resulted in steep slopes and several active faults including the Longmenshan Fault where a great earthquake, known as the Wenchuan Earthquake, occurred on May 12, 2008. River-bed incision has dominated the fluvial process in the area. The frequent landslides on threshold hill-slopes is one means of relief adjustment to fluvial incision in the bedrock reach. Besides the rate of rock uplift and incision intensity, the characteristics of the underlying rock are another controlling factor. Limestone usually has great permeability, thus allowing rainfall to infiltrate to the subsurface and reducing incisions on the surface. Rocks with lower permeability, but vulnerable to weathering, usually are more prone to mass wasting; for example, the granite in the lower Minjiang River which is a main tributary of the Upper Yangtze River. Observations have revealed that steady incision during low and intermediate flow conditions leads to channel bed lowering while significant channel widening occurs during large floods. Crucially, such floods help transmit the effect of the accumulated thalweg lowering to adjacent hill slopes. Deep landscape dissection has produced high-relief, narrow river gorges, and threshold hill-slopes that frequently experience large landslides, making the entire region highly susceptible to quake lake formation. The quake lakes and their management play an important role in the morphological process and reclamation of the land in the earthquake area.

Table 1 lists the incised channels on the basis of size and location. Rills are small channels that form on steep slopes. They are ephemeral because they can be obliterated seasonally by frost action or by the ploughing of fields. They are of little concern except that they increase stream turbidity, and they can deepen and become permanent gullies. Gullies are incised channels that form where there was no existing channel. They form on valley sides and on valley floors. Entrenched streams are existing channels that have become incised. A stream in the Upper Yangtze River basin in Sichuan Province of China, which is developing into an entrenched stream in a process of channel incision. Composite incised channels are composed of reaches that are gullies, as defined above, and reaches that are entrenched streams. Depending upon the design and construction, a channelized stream can also be a composite incised channel. It is a composite incised channel, showing the different varieties of valley-floor gullies. Scarps are formed by erosion. Headward erosion occurs in the tributary gullies. The incision of the valley floor forms terraces. Rill erosion is still occurring on the floor and the rills will eventually develop into gullies and integrate into the drainage network.

Table 1 Incised channels in different scales (based on Schumm et al., 1984)

Incised channels	Notes
Rill	Very small (centimeters) ephemeral channel on steep slopes
Gully	A relatively deep (meters) incised channel that formed where there was no pre-existing channel. There are valley-side gullies and valley-floor gullies which can be continuous or discontinuous
Entrenched stream	Incision of an existing channel produces a deep unstable channel such as a mountain stream experiencing continuous incision.
Composite incised river	A complex river system with incised main stem river and tributary channels (the middle reaches of the Yellow River for example)

A bedrock channel may be defined as one for which morphology and gradient are directly controlled by bedrock. A bedrock channel has bedrock exposed along the channel bed or walls for at least approximately half its length, or has bedrock limits to the magnitude and location of bed scour and bank erosion during floods. Bedrock exposure along at least half the channel length suggests that alluvium does not accumulate to a depth at which the active channel is formed entirely in alluvium. The presence of bedrock as channel boundaries during large discharges will facilitate different patterns of hydraulics, sediment transport, and channel morphology than those common along alluvial channels. Bedrock-constrained valley walls may limit floodplain development so that bedrock channels have low-flow and high-flow portions. A bedrock channel may also have a bedrock surface into which a low-flow inner channel is incised, thus, having inner channel flow in the dry season and high (flood plain) flow in flood season.

Bedrock channels most commonly occur in regions of high topographic relief. Relief may be a product of recent tectonic uplift, as in the Himalayan Mountains of central Asia, or the Colorado Plateau of the southwestern United States of America. High topographic relief in a drainage basin tends to produce high stream gradients, and, thus, the potential for high sediment transport capacity and flow energy per unit of discharge. The exposed bedrock implies that the channels may be particularly sediment-starved during floods.

A step-pool system is a geomorphologic phenomenon occurring in high-gradient (>3-5%) mountain streams with alternating steps and pools having a stair-like appearance. The step-pool system usually occurs on a stream with bed materials consisting of particles with diameters differing by several orders of magnitude with the largest diameter on the same order as the water depth. Cobbles and boulders generally compose the steps, which alternate with finer sediments in pools to produce a repetitive, staircase like longitudinal profile in the stream channel.

River bed configurations in natural streams are shaped by varying flows; at competent flows the least stable particles move into more stable positions to create structured bed forms. The step-pool system is the strongest bed structure resisting channel incision. Other commonly occurring bed structures in high gradient small mountain streams are ribbing structures occurring in less high gradient middle sized mountain streams, and star-studded boulders, bank stones, and pebble clusters occurring in low slope large mountain rivers. The additional mechanical strength of the bed structures is results from three sources: (a) grain-to-grain contact involving inter-granular friction; (b) particle interlock; and (c) shelter, especially of the particles in the wake tail. The structures reduce the lift and drag forces acting on the particles in the lee side of the structures. These structures function in resisting channel incision and stabilizing the channel bed.

2. Measured methods for river flow

Discharge is the volume of water flowing through a river cross-section per unit of time. Discharge measurements require skilled operators, a variety of techniques, sound, safe and stable procedures in the field.

(1) **Velocity-area method using current meters**. Discharge is equal to cross sectional area multiplying by average velocity (Q=A x V).

a. Measure cross sectional area: stream bed bathymetry; sufficient bathymetric sampling to catch the shape of the wetted area;
b. Determine average velocity over the cross section: stream velocity varies through the stream profile, and sufficient sampling to determine the average velocity;

c. Selection of the gauging cross-section: a stream reach as simple as possible (subcritical flow; uniform reach upstream and downstream without bridge, weir, dam, gorges; a cross section perpendicular to the flow);
d. Different supports depending on the accessibility of the river: wading rod, gauging truck, cableways;
e. Mechanical current meters: velocity by counting revolutions of rotor during a short-time period. Two types of current meter rotors: cup type with a vertical shaft and propeller type with a horizontal shaft;
f. Electromagnetic current meters: water moving through a magnetic field produced an electric current. Velocity of the water is proportional to the electric current;
g. Acoustic current meters: Transmit acoustic signals into a water column with a frequency f ; Signal is backscattered by particles moving in the water; Doppler effect-change of frequency of the backscatter signals; Computation of radial velocity on each beam; Computation of flow velocity.

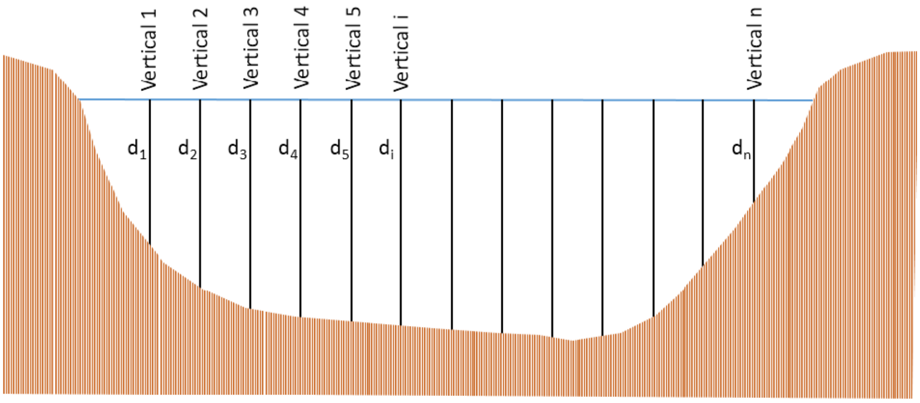

Figure 4 Measuring the stream bathymetry (Le Coz et al., 2018)

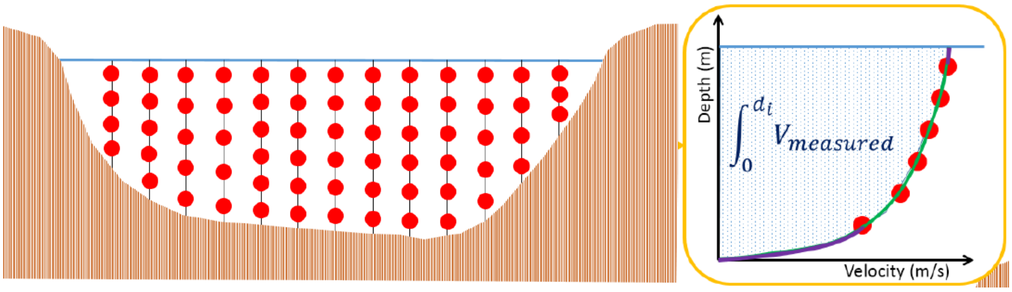

Figure 5 Computing depth-averaged velocity at vertical I (Le Coz et al., 2018)

Reduced point method: 1 to 6 velocity measurements per vertical: Computation of Vi with algebraic formula:

-1 pt method: $Vi=V_{0.6di}$

-2 pt method: $Vi=0.5(V_{0.2di}+V_{0.8di})$

-3 pt method: $Vi=0.25(V_{0.2di}+2V_{0.6di}+V_{0.8di})$

-5 pt method: $Vi=0.1(V_{surface}+3V_{0.2di}+3V_{0.6di}+2V_{0.8di}+V_{bed})$

-6 pt method: $Vi=0.1(V_{surface}+2V_{0.2di}+2V_{0.4di}+2V_{0.6di}+2V_{0.8di}+V_{bed})$

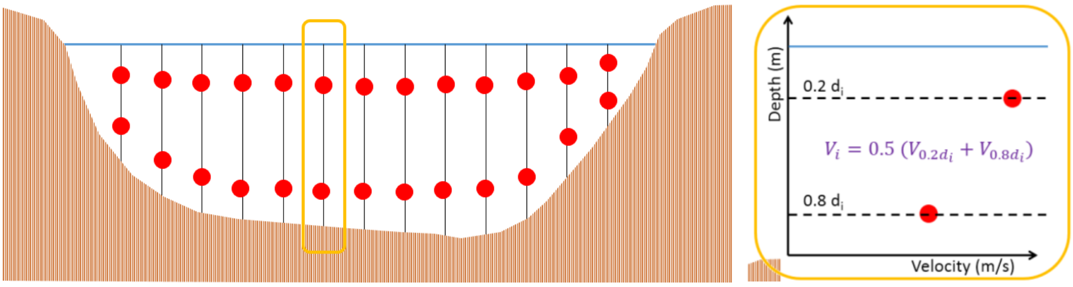

Figure 6 Computing depth-averaged velocity at vertical I (an example with 2pts method) (Le Coz et al., 2018)

- ☐ Integration method using mechanical current meters
- Current meter is lowered and raised through the entire depth at each vertical at a uniform rate
- Average number of revolutions per second is determined---depth-averaged velocity
- The speed at which the meter is lowered <5% of the flow velocity and between 0.04 and 0.10 m/s
- Two complete cycles are made in each vertical—if the results differ by more than 10 percent, the measurement is repeated.

(2) **Stream discharge using an ADCP (SonTek M9)**

- ☐ ADCP: **Acoustic Doppler Current Profiler**
- Ultrasonic measurement (300-3000 kHz)
- Sonar principle to measure the river bathymetry---wetted area
- Doppler shift to measure flow velocity
- ☐ Profiler:
- ADCP mounted on a float, generally pointing down
- Sending an ultrasonic acoustic wave in the water
- Backscatter by particles in suspension in the water
- Analyze of the Doppler shift between the transmitted and the backscatter signals

Figure 7 A photo of an ADCP and a boat (SonTek M9)

Sonar principle: Peak of retuned intensity when the echo hit the river bed

- Let postulate that the ADCP is not moving
- ADCP transmits an ultrasonic pulse in the water
- Pulse is backscattered by particles in the water
- ADCP received backscattered echo
- Analysis of Doppler shift between transmitted and backscattered pulsed---velocity of the particles
- Basic hypothesis: particles are advected by the water

Doppler shift---radial velocity: component of velocity in the beam axis

$V\cos\alpha = c\Delta f/f_0$ with $\Delta f = f_1 - f_0$

f_0 : frequency of the transmitted pulse

f_1 : frequency of the backscattered pulse

C : speed of the sound. C depends on the water temperature

--- it is crucial to measure accurately the water temperature

How measuring 3D velocity components (x, y, z)

- Geometric configuration:

- ☐ 2, 3, 4, divergent beams
- ☐ Measurement of radial velocity on each beam
- ☐ Trigonometric calculation to obtain 3D velocity

---under the assumption that the velocity is homogeneous on the 3 beams

---ADCP: A case in the Black River of the Yellow River Source in June 2019

Figure 8 ADCP measurement of the flow field in the lower Black River

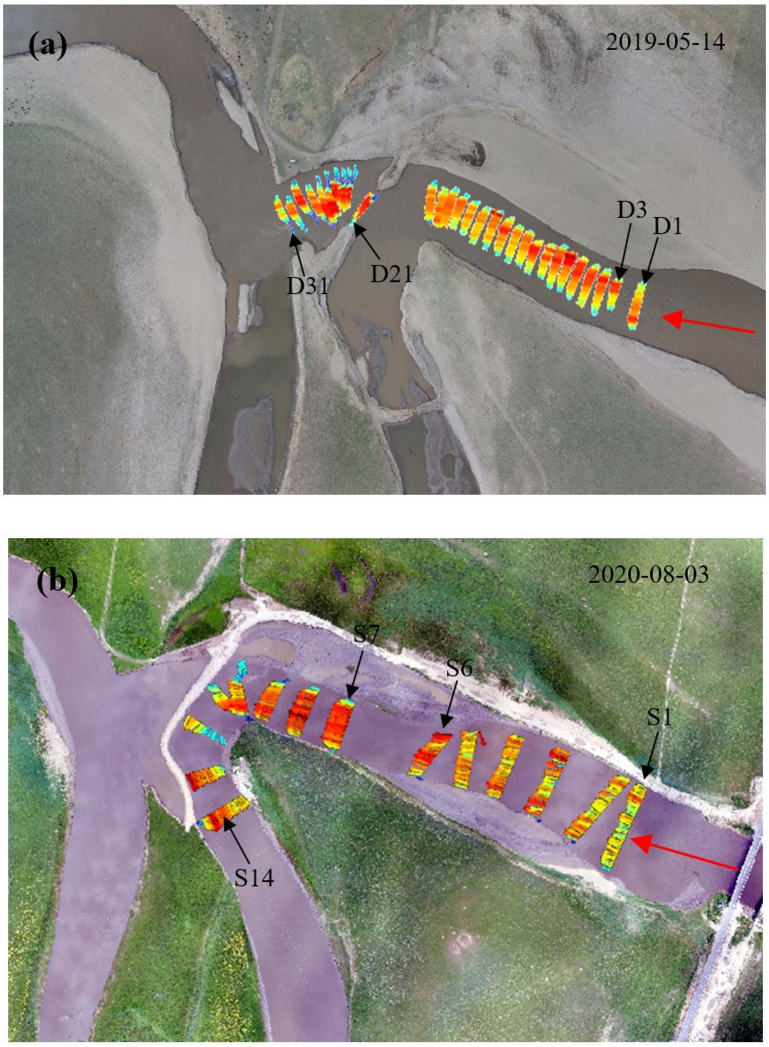

Figure 9 2D longitudinal velocity distribution at each cross section

3. Measured methods for sediment transport

Basin characteristics of sediment transport in the rivers of the mountain region.

- Suspended load may be neglected;
- Bed load dominates riverbed processes;
- Patterns of particles motion: rolling, sliding, saltation;
- Substrate mainly consists of cobbles and gravel;

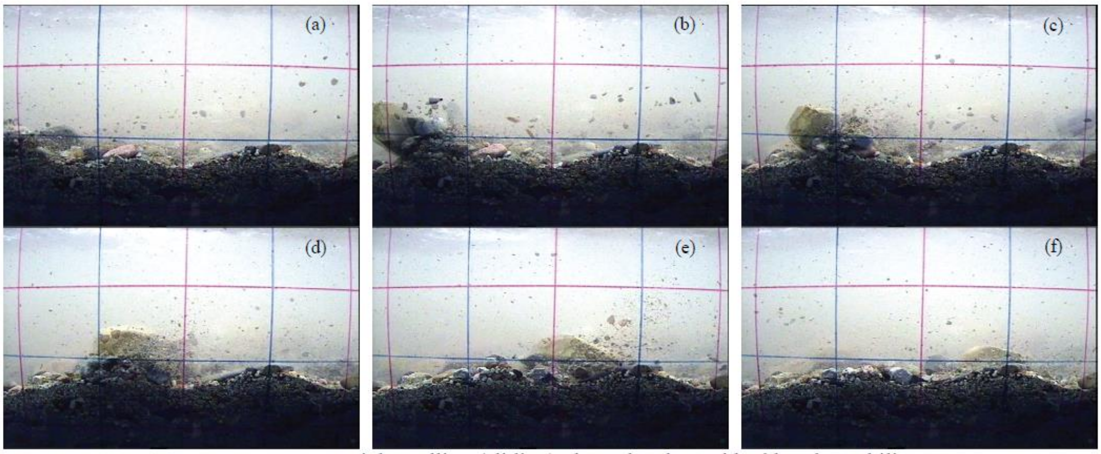

Figure 10 In situ observation on bed load transport in a mountain river (Yu et al., 2012)

(1) **Pit trap for bed load**

- The bedload monitoring station includes four Birkbeck-type pit traps (Reid et al. 1980), extending perpendicular to flow across the channel bottom in series.
- The bedload traps consist of a reinforced concrete vault and a stainless steel loading box insert resting on four submersible load cells.
- The total collection volume of each trap was 1.6 m^3.
- The four load cells in each vault were individually connected to a Campbell data logger (Model #CR1000) mounted on an instrument panel adjacent to the channel.
- Water level loggers were located 11 m and 27 m upstream and downstream respectively. They were time synchronized with the data logger at the bedload station and were tied to an established datum on the greenway adjacent to the site.

Figure 11 Pit trap for bed load in a stream (McMahon, 2013)

(2) Double-box bed load sampler

- The inner box was put into the outer box. The inner box was lifted out from the outer box when the inner box was nearly full of sediment;
- The time it took the inner box to fill with sediment was recorded. After the inner box was lifted, the wet weight of collected bed load sediment was measured;

- The sediment collected was sent to the laboratory to determine the bed load transport rate and the particle size distribution;
- The collected sediment was thoroughly and evenly mixed before the wet weight of the representative bed load measurement was taken;
- The sample sediment was dried, weighed, and sieved in the laboratory to attain the particle size distribution;
- The weight and diameter of the largest five particles of each bed load sample were measured.

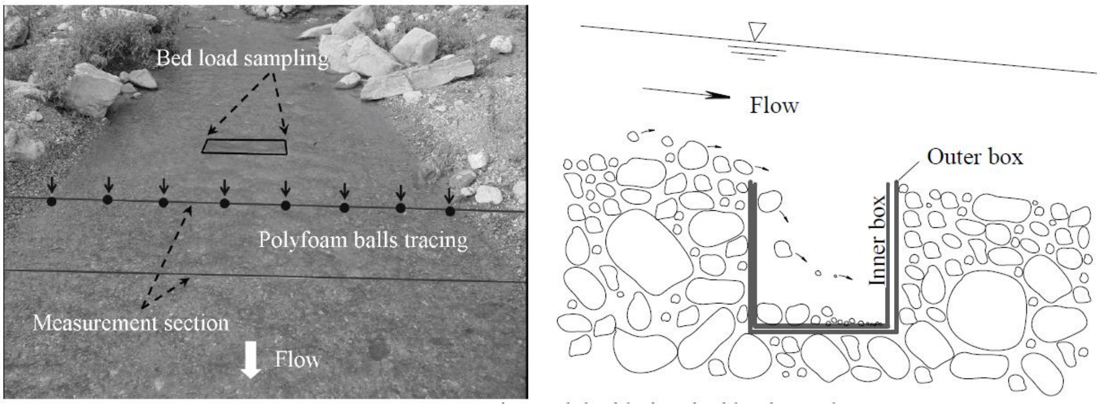

Figure 11 Double-box bed load sampler (Yu et al., 2012)

(3) Bed load trap

-A photograph of a bedload trap installed on a ground plate in a stream channel ready for sampling.

-The metal stakes hold the trap in place to the stream bottom and the nylon straps and shaft collars secure the trap to the ground plate.

-The trailing 3.5 mm fishnet serves to trap sediment particles. The trap can be left in place during the entire sampling period without disturbing the stream bottom.

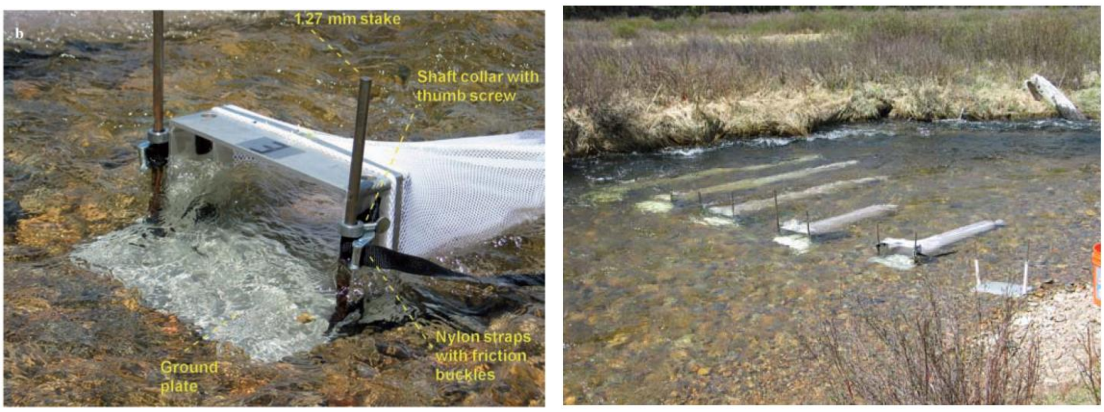

Figure 12 Bed load trap (Bunte et al., 2008)

(4) **Differential pressure sensor**

- A differential pressure sensor, similar to those used in the Pitot tube, was buried with one port 70 mm below the bed surface and the other flush with the bed surface.

- The upper port was situated in the middle of a 50mm diameter flat circular plate to avoid any local, form-induced pressure variations.
- The flat plate was situated level with the tops of bed roughness elements and bed particles were packed beneath the plate in an attempt to reproduce local bed conditions. Because a flat plate surrounded the upper port, the instrument recorded uplift (and downdraft) pressures being advected by the overlying flow, not pressures being generated by the (arbitrary) streamline curvature over a specific particle as is assumed in many lift and drag models.

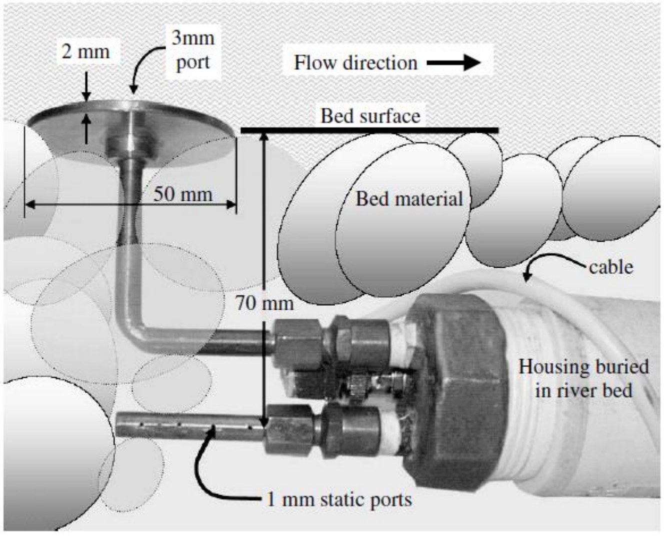

Figure 13 Schematic section through a gravel riverbed showing the buried instrument for measuring differential pressures in the bed surface layer (Smart and Habersack, 2007)

4. Measured methods for river bed

Some emerging approaches to acquiring high-resolution river bed topography:

(1) Remotely sensed or aerial surveys: spectral-depth correlation, photogrammetry, Structure From Motion, LiDAR

(2) Ground-based surveys: Total station surveys, GPS, Terrestrial laser scanning

(3) Boat-based bathymetry surveys: multibeam sonar, singlebeam sonar

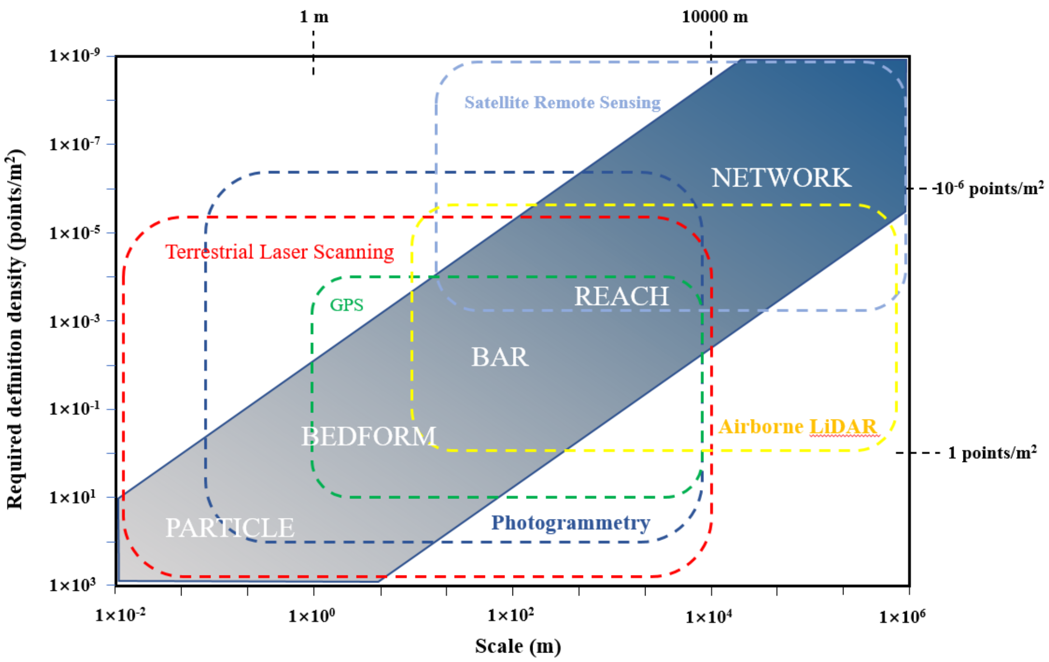

Figure 14 Spatial scale and point cloud density in different methods (Brierley, 2018)

(1) **Multisource, long-term, hyper-spectral satellite imagery**

- Remote Sensing Image: recording of various objects electromagnetic wave size film or photos, mainly divided into aerial photographs and satellite photos.
- According to the geometric and physical properties of the image, the quality and quantity characteristics of the object or phenomenon and their relationship are analyzed and revealed synthetically, and then the occurrence and development process and distribution law of the object or phenomenon are studied.
- Spatial resolution: 30 m、10 m、4 m、2 m、0.8 m、0.5 m、0.3 m.

(2) **Unmanned Aerial Vehicle (UAV)**

- DJI UAV plus RTK low altitude aerial survey has been widely used in river landscape, surface flow field and river topographic observation.
- Use Pix4D mapper, Cloud Compare, ArcMap software to generate point cloud, noise processing of DEM data, high precision data, sub-meter resolution.

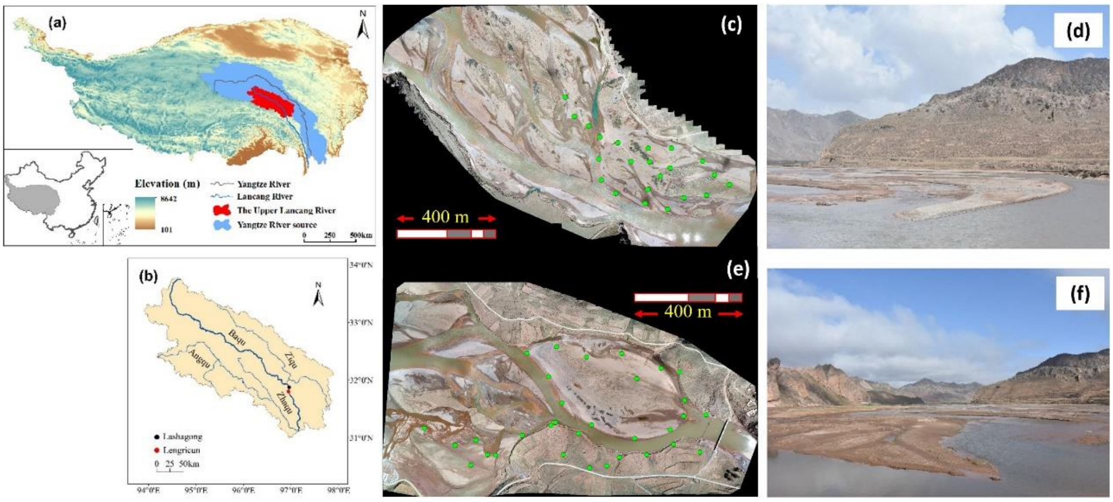

Figure 15 A UAV survey case study in the Upper Lancang River in May 2018

(3) **LiDAR application**

- A system which integrates laser, global positioning system (GPS) and inertial navigation system (INS) to obtain point cloud data and generate accurate digital 3D model.
- The most basic working principle of LiDAR is that the radar transmitting system sends a signal, which is collected by the receiving system after the target is reflected, and the distance of the target is determined by measuring the running time of the reflected light. The radial velocity of the target can be determined by the Doppler shift of the reflected light, or two or more distances can be measured, and the velocity can be obtained by calculating the rate of change.
- Spatial resolution = 1m, vertical accuracy = 0.1m.

(4) **Terrestrial laser scanning (TLS)**

- A detection 3D laser scanning system is mainly composed of 3D laser scanner, computer, power supply system, support and system supporting software.
- The 3D laser scanner, as the main component of the 3D laser scanning system, is composed of laser emitter, receiver, time counter, motor controlled rotatable filter, control circuit board, microcomputer, CCD machine and software. It is a technological revolution in the field of surveying and mapping after GPS technology.
- It breaks through the traditional single point measurement method and has the unique advantages of high efficiency and high precision. Three-dimensional laser scanning technology can provide three-dimensional point cloud data on the surface of scanning objects, so it can be used to obtain high precision and high resolution digital terrain model.

(5) **Ground Penetrating Radar (GPR)**

- An effective means of detecting underground targets, it is a non-destructive detection technology, which has the advantages of fast detection speed, continuous detection process, high resolution, convenient and flexible operation and low detection cost. It is mainly used in sedimentology, archaeology, mineral exploration, disaster geological survey, geotechnical engineering survey, engineering quality inspection, building structure inspection.
- GPR is a geophysical method that uses antenna to transmit and receive high frequency electromagnetic wave to detect the material characteristics and distribution law inside the medium.

(6) Framed bent for measuring bed structure

The most important hydraulic feature of step-pool systems is the extremely high bed roughness, which maximizes the resistance and reduces the flow velocity. To represent the bed roughness of a step-pool system a parameter, S_P, is introduced, which may be used to describe the development degree of a step-pool system:

$$S_P = \frac{length\text{-}of\text{-}thalweg}{length\text{-}of\text{-}straight\text{-}line} - 1 \quad (1)$$

The length-of-thalweg is the total length of the curved bed surface with boulders or gravel along the thalweg, and the length-of-straight-line is the length of a straight line from the beginning point to the end point of the measured bed section. For a flat bed with fine sediment, S_P = 0. For beds with step-pools, sand dunes, or other bed structures, S_P is larger than 0.

Wang et al. (2014) designed an instrument and measured the development degree of a step-pool system, S_P. The instrument, shown in Figure 16, consists of thirty measuring rods with a space of 5 cm between them placed on a horizontal aluminum steel frame that may slide down onto the bed surface. The upper ends of the rods describe the bed profile in front of a screen. Moving the frame along the thalweg of the stream and each time taking a picture, the bed profile along the thalweg can be measured. The S_P value is then calculated by the following formula:

$$S_P = \frac{\sum_{i=1}^{m} \sqrt{(R_{i+1} - R_i)^2 + 5^2}}{\sqrt{[5(m-1)]^2 + (R_m - R_1)^2}} - 1 \quad (2)$$

in which R_i is the reading of the upper end of the measuring rods on the screen in cm, and m is the total number of the readings, which is generally larger than 300. Figure 17 shows the measurement of S_P with the instrument in the Yigong Tsangpo River in the QTP. For a stream without step-pools S_P is smaller than 0.1. If a step-pool system is well developed the value of S_P may larger than 0.3. For extremely developed step-pool on steep slope the value of S_P can be as large as 0.5. Only for very huge step-pool systems composed of huge stones with diameter of larger than 10-20 m the value of S_P can reach 1.0.

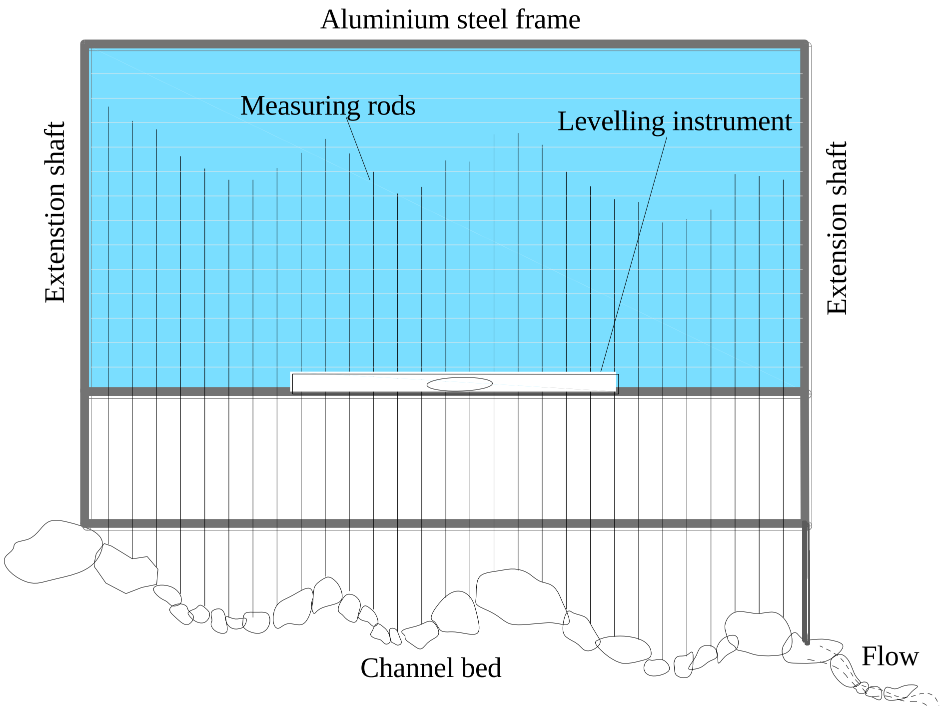

Figure 16 A framed bent for measuring bed structure

Figure 17 A measured case study in the Yigong Tsangpo River in the lower Yarlung Tsangpo River on the QTP in 2009

5. Concluding remarks

- It is essential to understand basic concepts on pattern, form, and process of river morphology in mountain regions.
- The prerequisite of field survey and measurement is to formulate feasible

objectives, detailed plans, and adequate preparation.

- The selection of a suitable velocity meter should be considered according to the maximum velocity, water depth, channel width, and the requirements of spatial resolution and accuracy.
- The main difficulty of sediment transport observation is the strong movement of bed load transport in flood periods and the low transport rate in non-flood periods. Moreover, the sampling process has large errors uncertainty, and low repeatability using various samplers.
- Emerging approaches to acquire the high-resolution topography include remotely sensed or aerial survey (LiDAR and UAV), ground-based survey (TLS), boat-based bathymetry survey (ADCP and multi-beam sounding system).

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