River morphodynamics

Part 2: Sedimentary patterns

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Alluvial rivers

Formed in and by sediment transported by the river (= "alluvium") under its current hydrologic and climatologic regime

"self-formed" channels are free to adjust their shape in response to changes in flow, because they are competent to move the material that forms their boundaries (and which could be transported again)

- Erodible channel boundaries (alluvial banks and bed)
- Transport Capacity ≤ Sediment Supply
- Storage can be quite high
- Input ≥ Output

Alluvial system(, 2006)

The river landscape

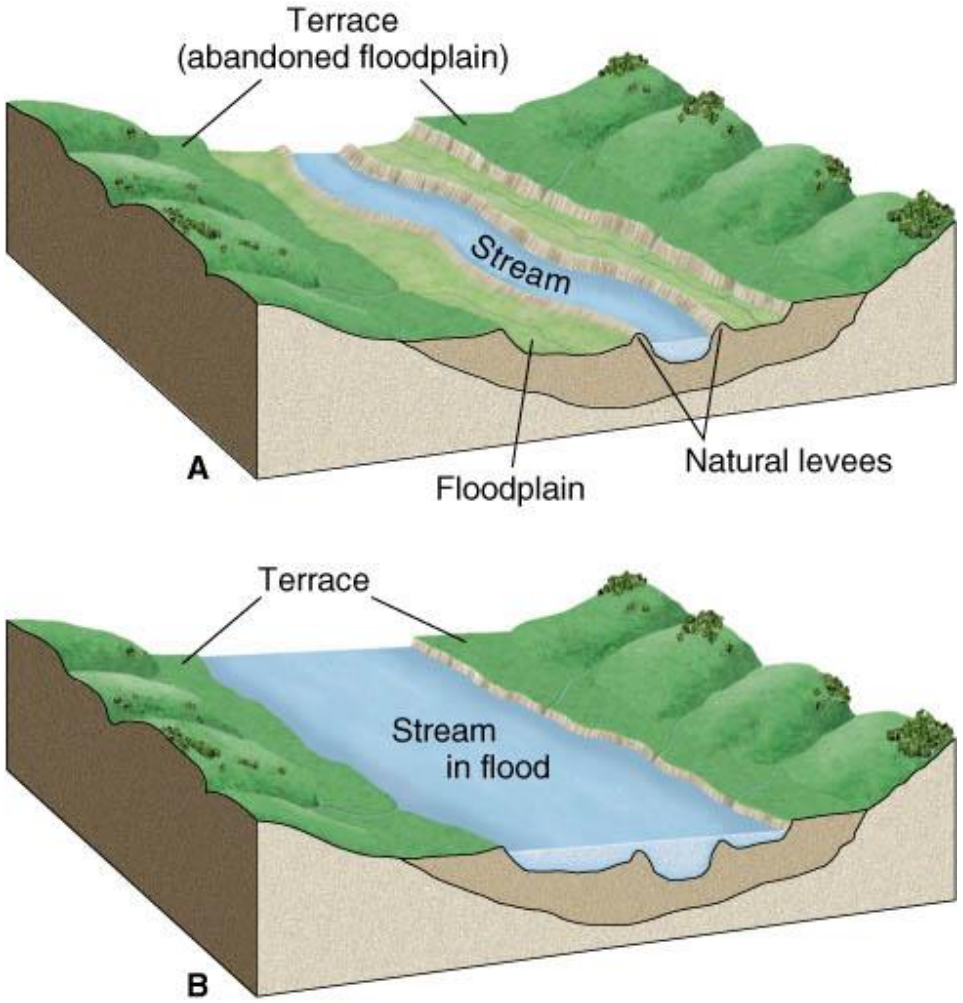
Changes in whether a stream is eroding or depositing in a given location can be caused by several different phenomena:

- tectonic uplift
- change in base level downstream
- change in climate modifying system's discharge

which brings us to river response…

Alluvial rivers shape the form of their valley:

- Natural levees
- Floodplain
- River terrace



Floodplain landforms

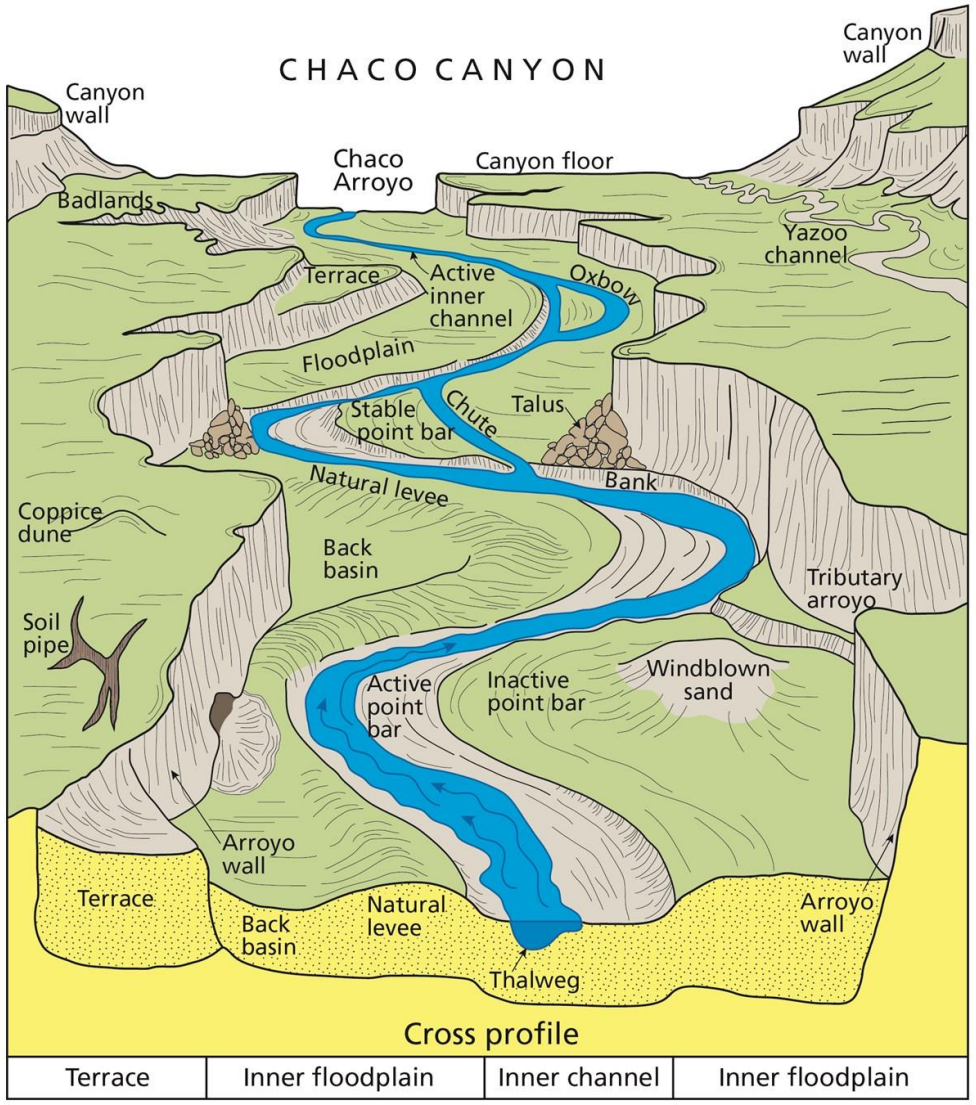
A **floodplain** is the relatively flat surface adjacent to the river or stream. During floods, when the stream overflows its banks, water flows over the floodplain and deposits sediment. Through fluvial processes, streams construct floodplains that accommodate their maximum flood capacity. Geomorphic features of the floodplain include:

Natural Levees: river may be immediately flanked by a build up of sediment that forms natural levees. These provide some defence against flooding, but are occasionally breached in areas producing flood-plain splays, coarse fan-shaped deposit of sediment created during high flow events.

– oxbows and oxbow lakes, features of a meandering stream

– point bars, features of a meandering stream

– terraces



Source: Trista L. Thornberry-Ehrlich, Colorado State University.

River morphology

Pattern formation

The amount of sediment that a fluid in motion is able to transport (**transport capacity**) depends on:

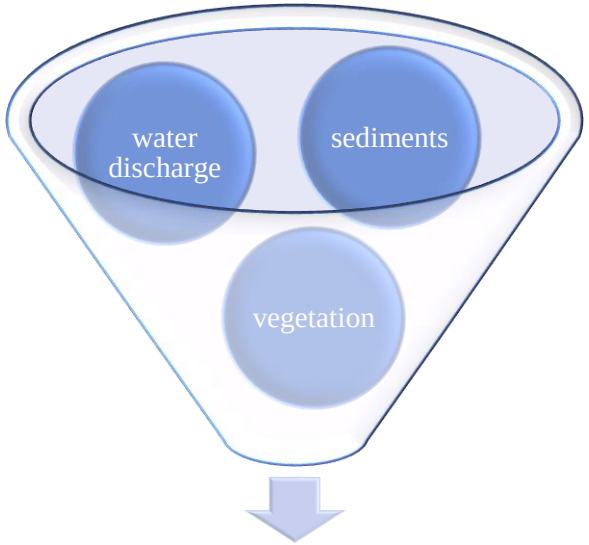
- motion intensity
- characteristics of the available sediments

A clear fluid subject to a sufficiently intense motion acting over a cohesionless bed progressively erodes the bed by entraining particles until its transport capacity is fulfilled, then sediments will be deposited.

The formation of patterns is the response of the sediment interface to spatio-temporal fluctuations of the sediment supply and/or of the transport capacity of the stream.

unbalance between sediment supply and transport capacity

Evolution of river landscapes depends on



planar forms and bedforms

River patterns

Type of mechanisms

- erosional patterns: transport capacity > sediment supply
- depositional patterns: transport capacity < sediment supply
- quasi-equilibrium patterns: transport capacity = sediment supply

Scale

- the scale of patterns depends on the physical mechanisms that drive the fluctuations of sediment supply and transport capacity which cause pattern development
- patterns of different spatial and temporal scales may coexist

Patterns formation

- free patterns: arise spontaneously from instabilities of the liquid-solid interface in the form of interfacial waves affecting the mobile boundary (bedforms)
- forced patterns: erosional and depositional patterns are forced by (typically geometric) constraints imposed at the boundary (such as deposits created by groynes)

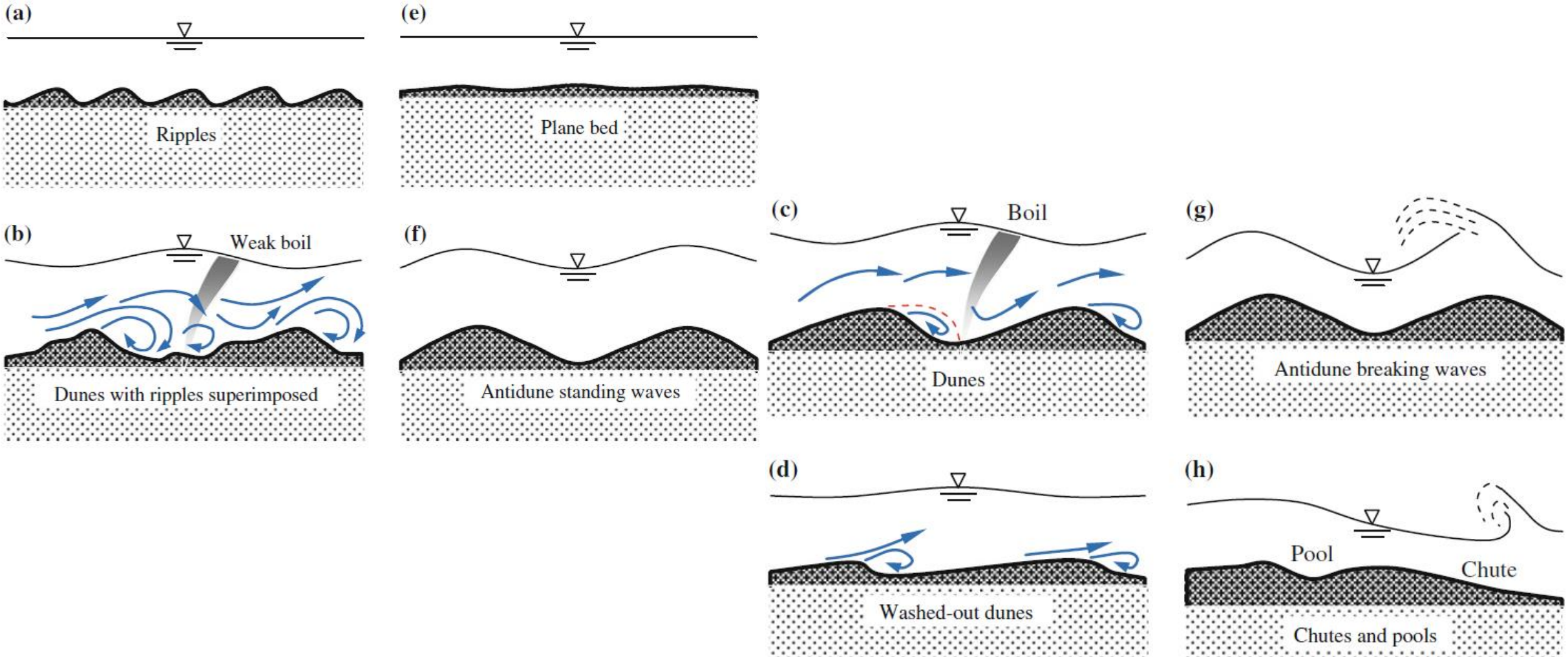
Free bedforms

River beds are perturbed by free bedforms, fairly regular oscillations of bed elevation which have the nature of interfacial waves arising spontaneously from an instability of the bed interface

Bedforms usually migrate downstream, but also stationary and upstream-moving forms can be observed

- *dunes*: small scale bedforms with wavelengths scaling with flow depth and amplitudes of the order of a fraction of flow depth. Dunes migrate invariably downstream
- *ripples*: smaller bedforms similar to dunes, typical of turbulent flow with weak sediment transport
- *antidunes*: typical of supercritical flow, small scale bedforms scaling with flow depth. Antidunes migrate either downstream or upstream
- *cyclic steps*: similar to antidunes, they have long waves with wavelengths much larger than flow depth and are fairly stable, preserving their pattern while migrating upstream
- *sand ridges*: bedforms having the front parallel to the stream, caused by secondary currents

Bedforms

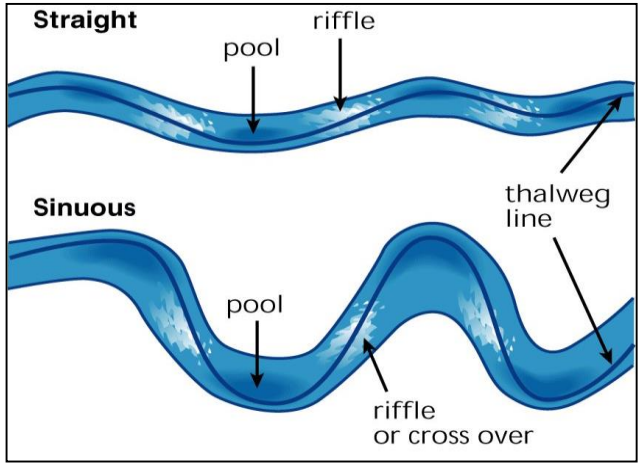

(a)
Ripples
(e)
Plane bed
(b)
Weak boil
Dunes with ripples superimposed
(f)
Antidune standing waves
(c)
Boil
Dunes
(g)
Antidune breaking waves
(d)
Washed-out dunes
(h)
Pool
Chute
Chutes and pools

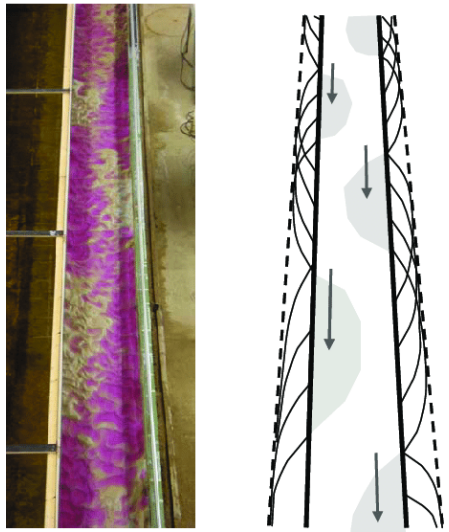
Free bars

At a larger scale, river beds display rhythmic perturbations of bed elevation called bars

They are organized in rows of periodic sequences of *riffles* and *pools* separated by oblique fronts, where the number of rows depends on the channel width

Very narrow channels do not allow for bar formation, in fairly narrow channels a single row pattern (alternate bars) is observed whereas multiple row patterns form in wide channels



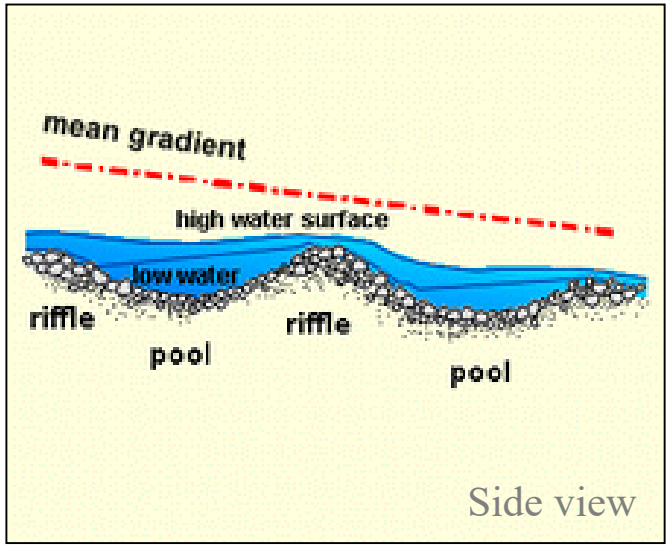


Free bars: experiments by Crosato et al. (2011)

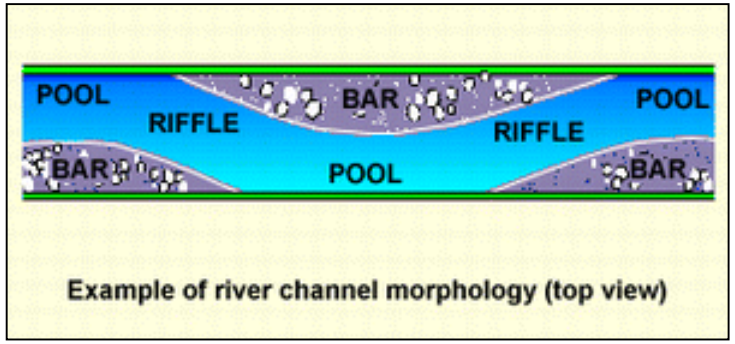
Free bars, from Schurmann (2015)

Pool and riffles or step and pools?

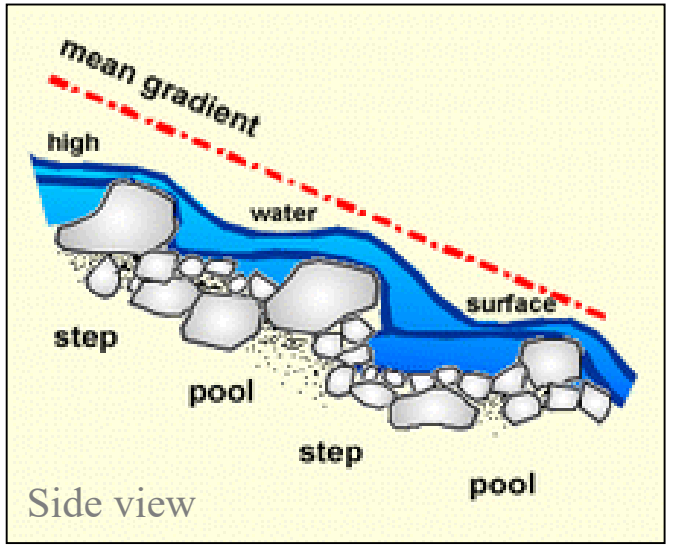
Mild to steep slopes (low-energy environments)



Planar view



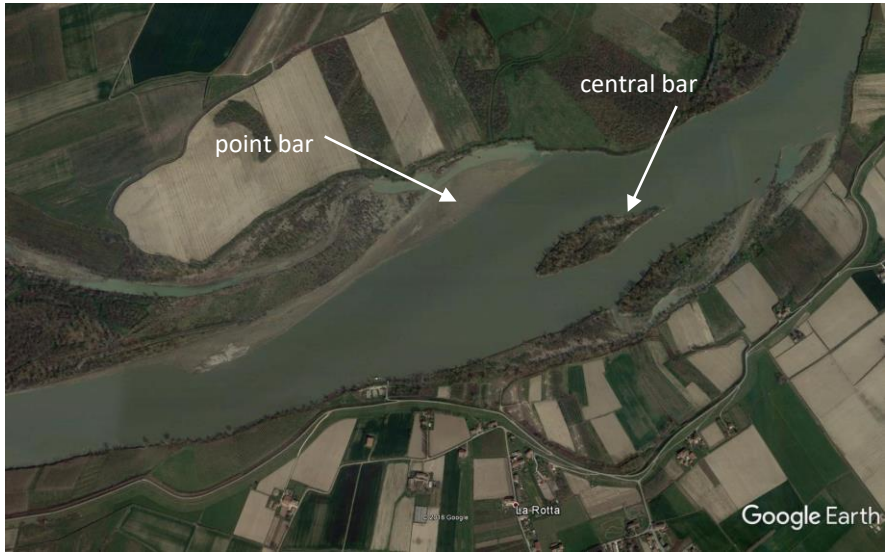
Very steep slopes (high-energy environments)



Forced bars

Forced fluvial patterns arise typically (but not only) in response to prescribed variations of channel geometry.

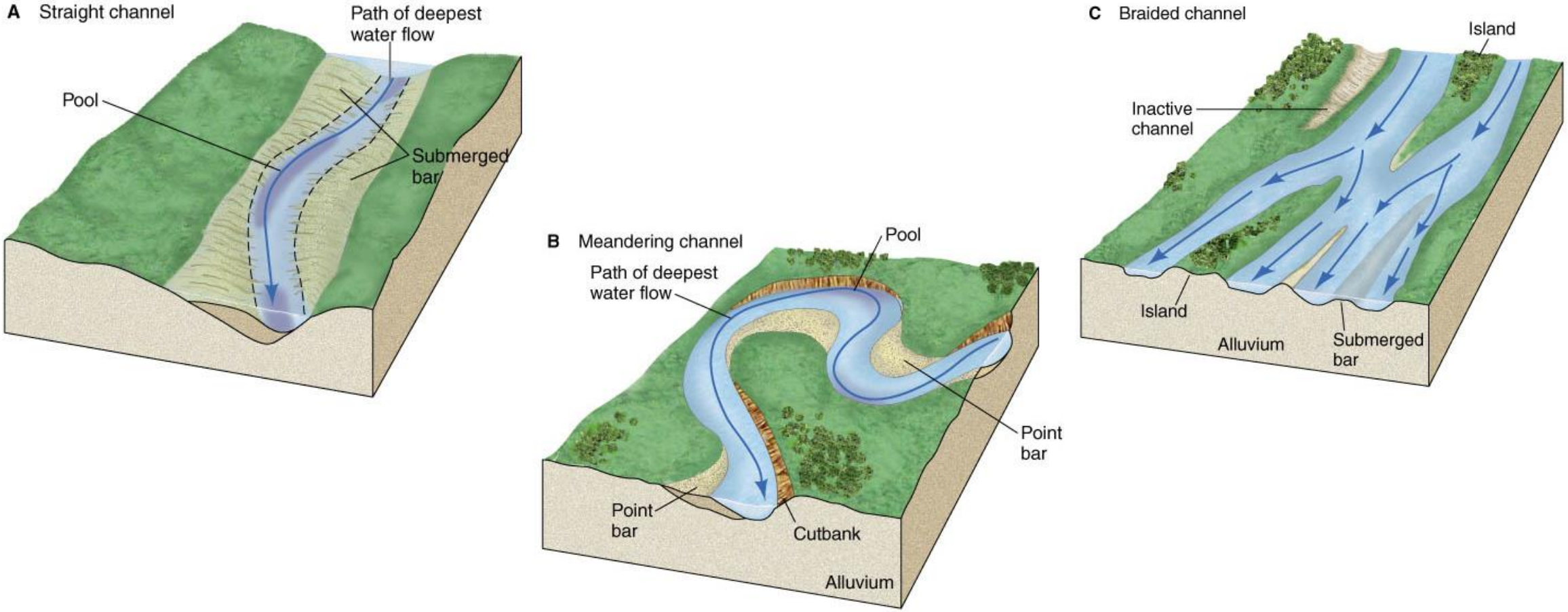
- *central bars*: caused by a channel widening, this pattern is the precursor of a river island
- *point bars*: created by the channel curvature. Accumulations of sediments along the inner bends of meandering rivers whereby the thread of high velocity of the stream is shifted towards the outer and deeper part of the bend reach is located
- *scroll bars*: result of the lateral migration of meander loops
- *steady bars*: observed upstream of channel reaches undergoing geometrical variations or where the transition between a straight and a curved reach is located



Forced bars after a bridge in the Po River, Nones (2018)

From bars to …

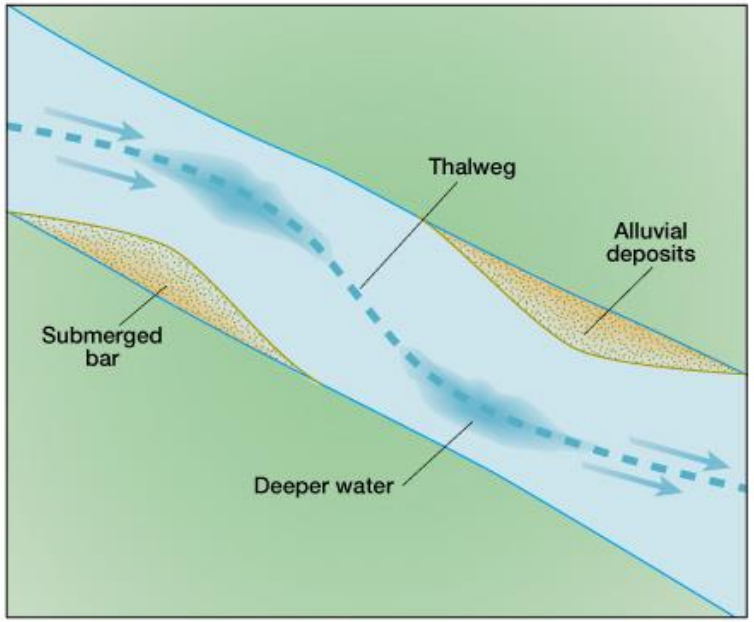
Bars are generated by *instabilities* (driven by small changes in the channel geometry)

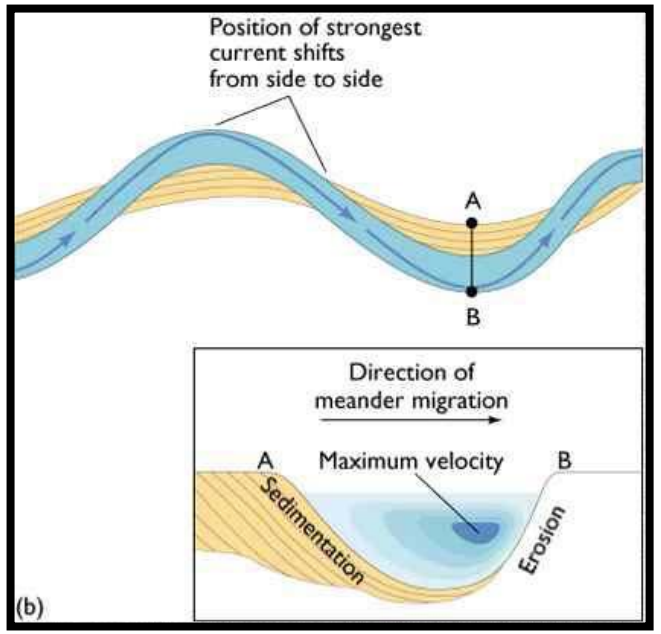


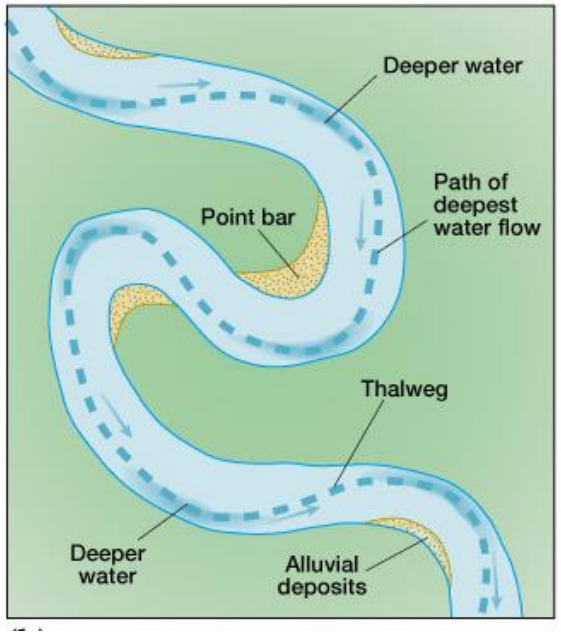
From bars to … larger planforms

When the channel is bounded by vegetated levees, vegetation plays a stabilising role for the banks, reducing erosion and fostering the formation of a sinuous stream

→ meanders form







Fluvial planforms

Among others, Rosgen classified rivers based on geometry and grainsize composition of the bed

Rosgen D.L. (1994) A classification of natural rivers. Catena 22(3), 169-199

A,B: steep channels

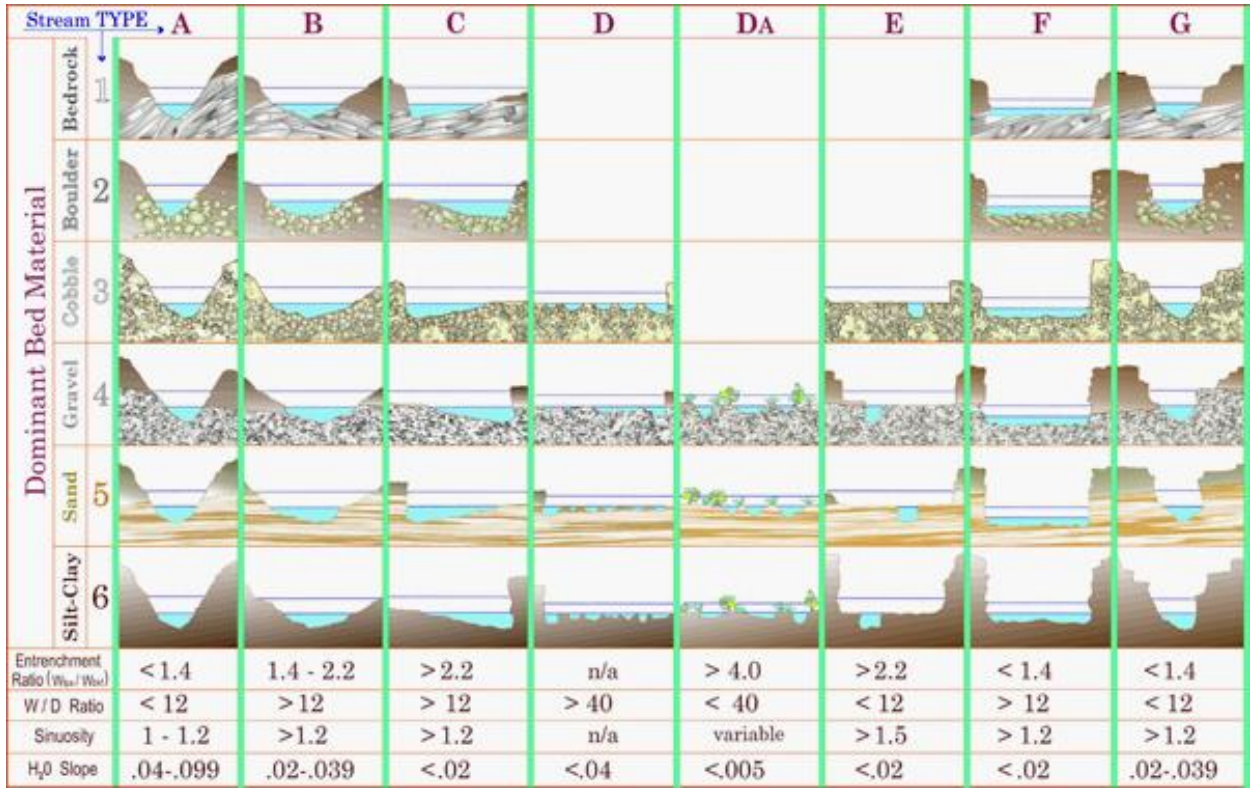
C: meandering channels

D, DA: braiding channels

E: relatively wide and shallow channels

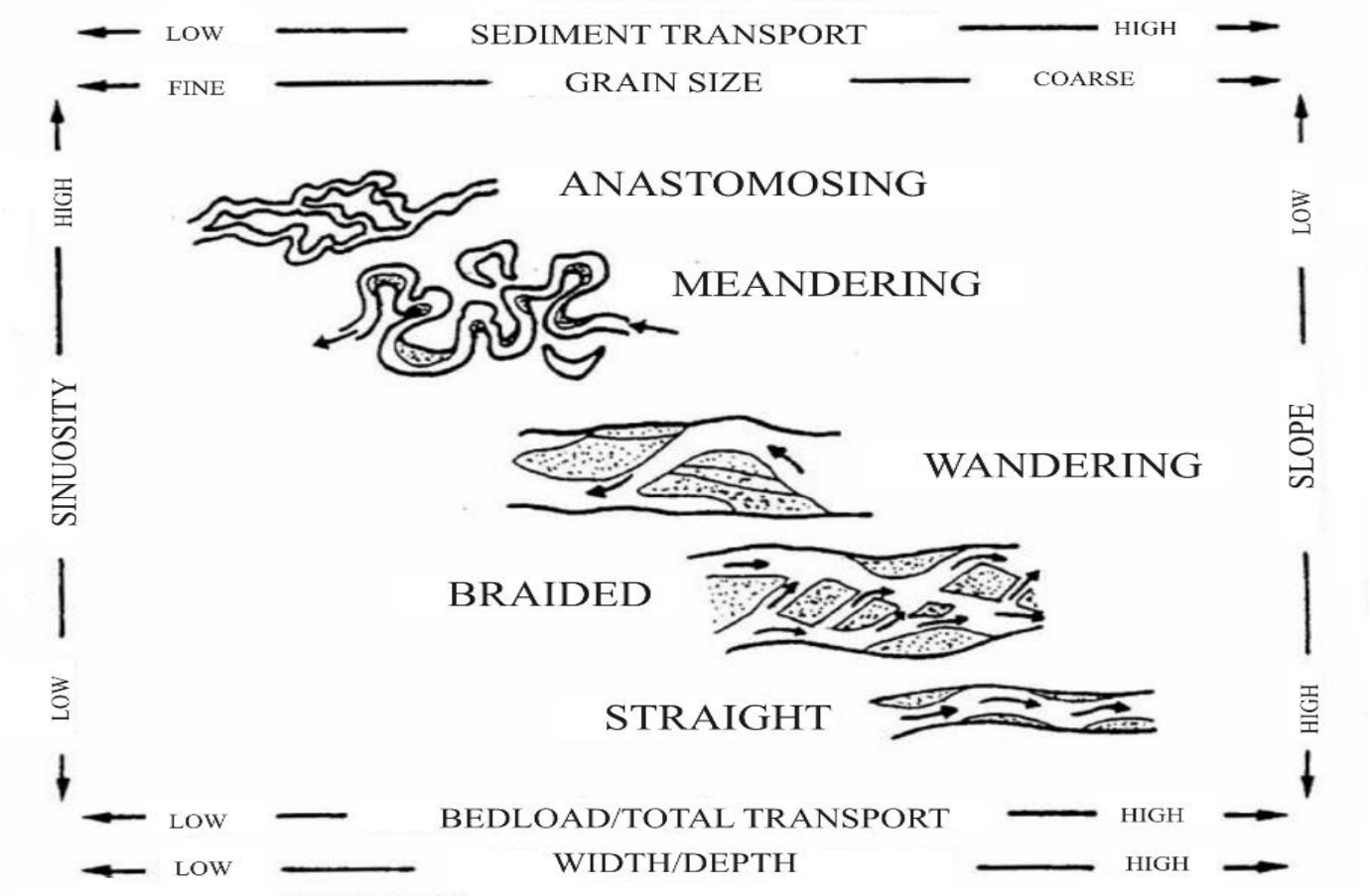
F: highly sinuous vegetation lined channels

G: gullies-like channels



River planform classes(Rosgen, 1994)

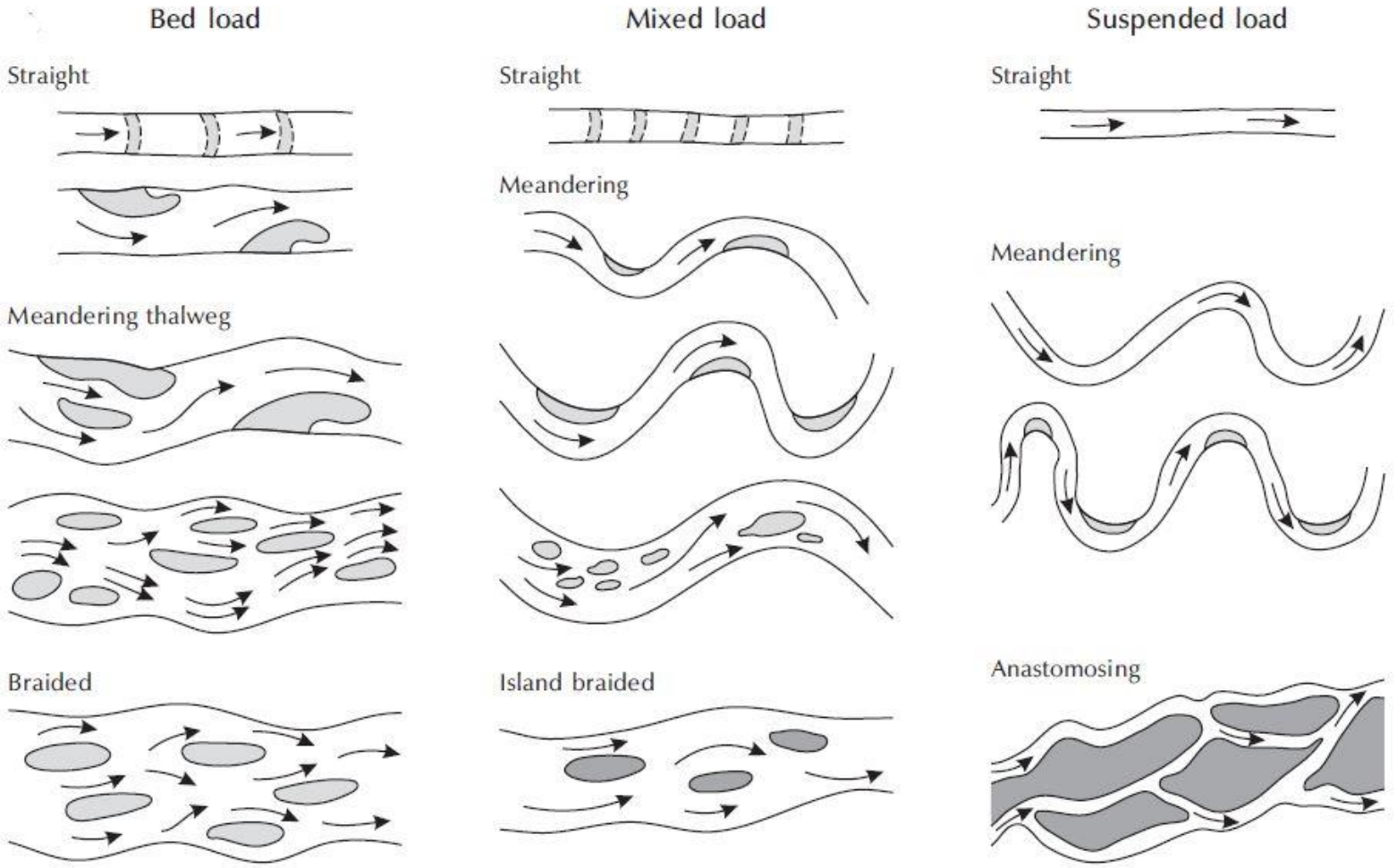
Planar forms



Channel pattern (Di Silvio, 2006)

Planar forms

Channel form classified according to channel pattern (*straight*, *meandering*, *braided*, and *anastomosing*) and sediment load (suspended load, suspended-load and bed-load mix, bed load).



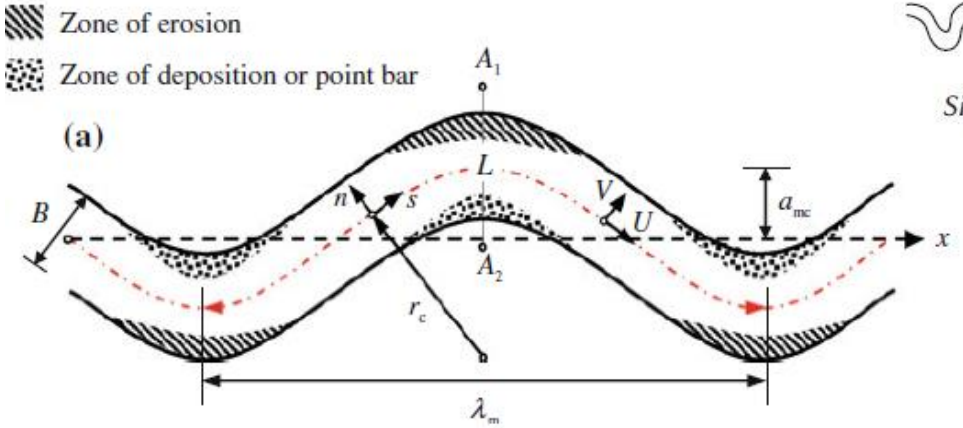
Planar forms depend on the transport (Hugget, 2013) adapted from Schumm (1981, 1985b) and Knighton and Nanson (1993);

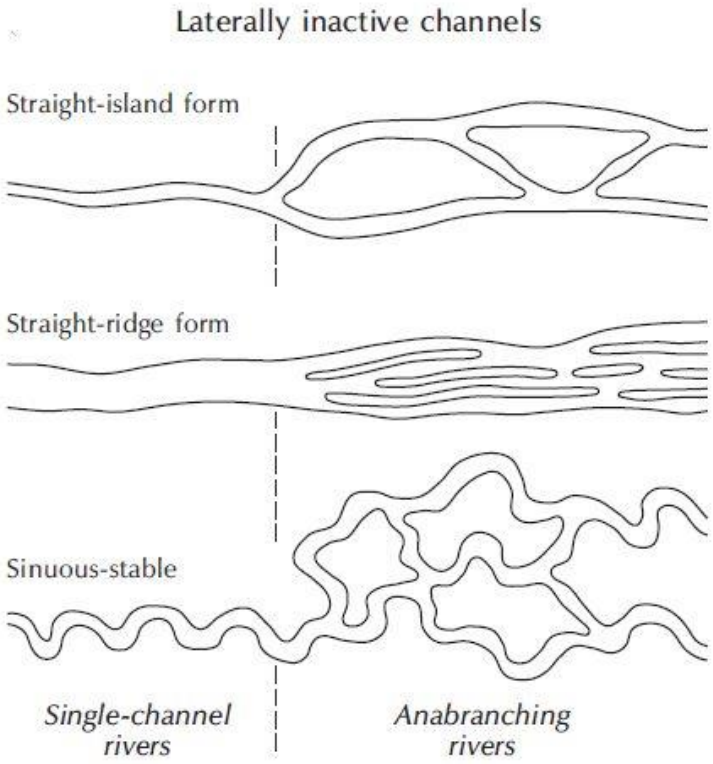
Planforms

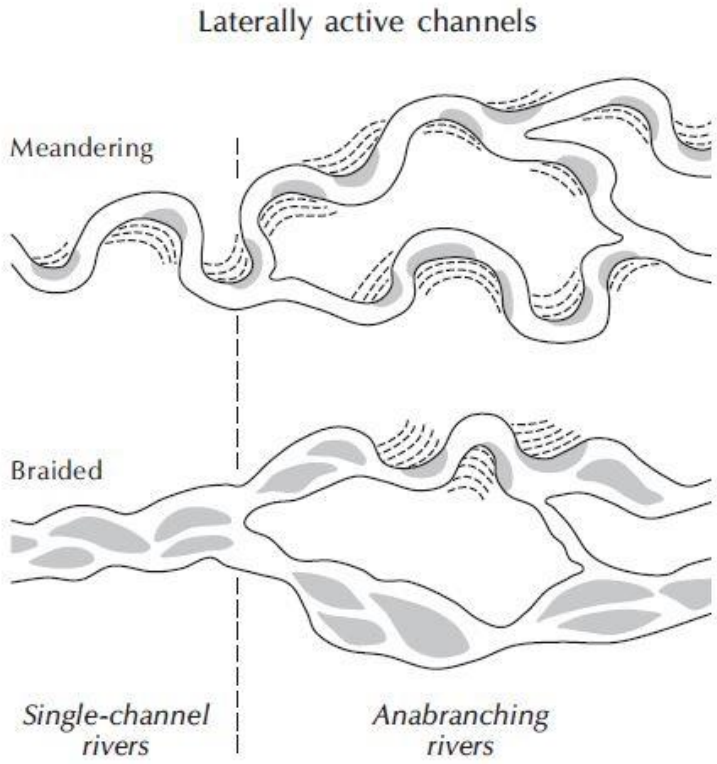
River patterns can be according to single-channel and anabranching forms

Sinuosity

$$P = \frac{L_{channel}}{\lambda_m}$$







Planar forms according to channel pattern (Huggett, 2013) adapted from Knighton and Nanson (1996)

Straight rivers

Naturally uncommon because they are inherently unstable: any minor perturbation of the flow, such as caused by a hard projection or a small hollow in the bank, will tend to establish the oscillation of the thalweg that leads to concentrated scour of pools, pointbar formation, and a meandering pattern

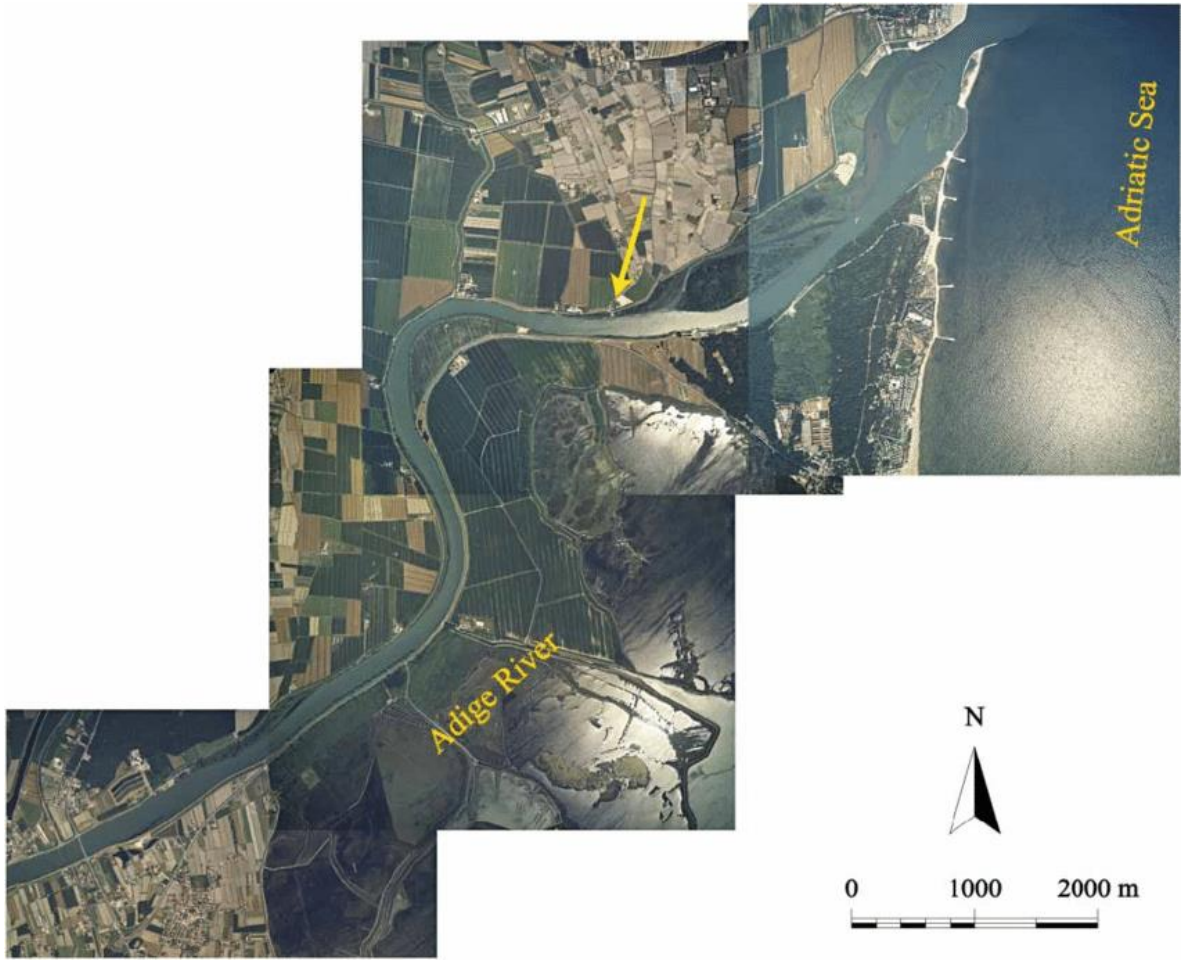
Relatively rare:

– represent a relatively immature channel form

– straight channels common where streams are confined by topography or follow geologic structures

– often mountain streams or artificial canals

Spatial and temporal scales in modelling (Bogoni et al., 2015)



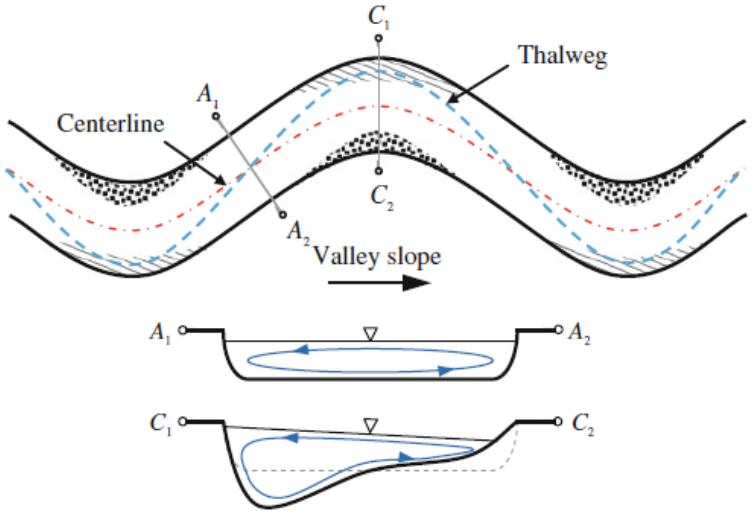
Meandering rivers

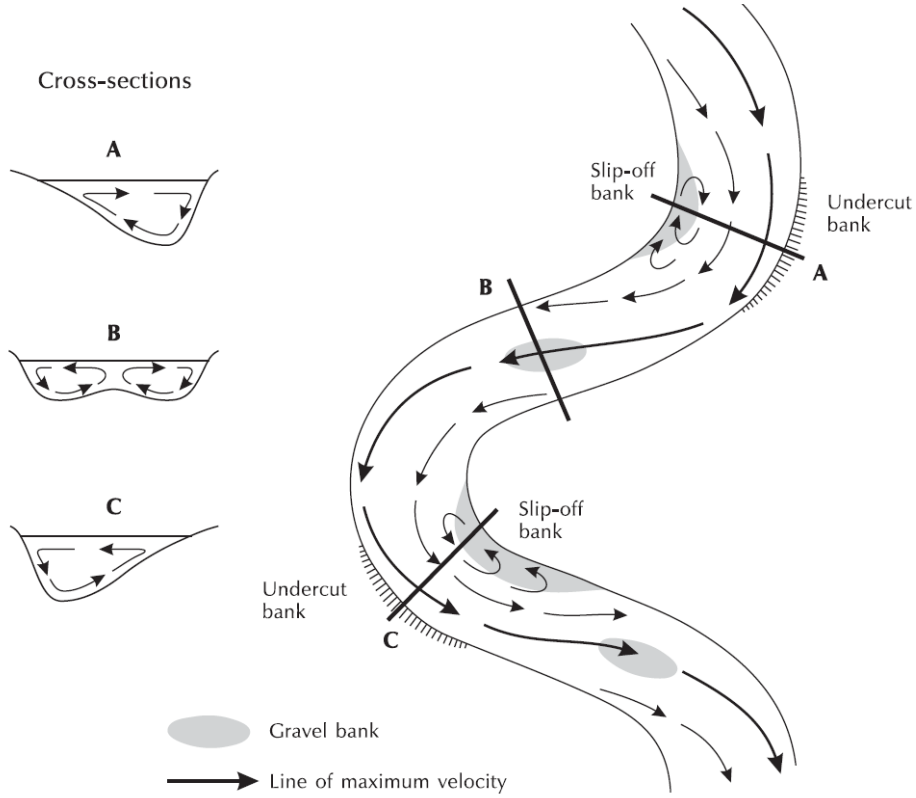
A meandering stream has a single channel that winds snakelike through its valley, so that the distance 'as the stream flows' is greater than 'as the crow flies.' As water flows around these curves, the outer edge of water is moving faster than the inner. This creates an erosional surface on the outer edge (a **cut bank**) and a depositional surface on the inner edge (a **point bar**). Where the bends of two meanders meet, they bypass the curve of river, creating an **oxbow** lake which may then be infilled with overwash sediment.

meandering river Severn at Leighton, UK
(photo by R. Davis)

Meandering rivers

Meandering is favoured where banks resist erosion, so forming deep and narrow channels. However, why rivers meander is not entirely clear. Ideas centre on: (1) the distribution and dissipation of energy within a river; (2) helical flow; and (3) the interplay of bank erosion, sediment load, and deposition. A consensus has emerged that meandering is caused by the intrinsic instabilities of turbulent water against a movable channel bank.





Planar forms according to channel pattern (Huggett, 2013) adapted from Knighton and Nanson (1996)

Braided rivers

Braided channels are not as common as meandering ones, but they are of special interest because their rates of lateral shifting and of bank erosion are generally very much greater.

Conditions necessary for braiding:

(1) Sediment must be actively and frequently transported, and

(2) The banks of the channel must be very easily eroded.

commonly also associated with braided channels:

(3) Rapidly changing ("flashy") discharge, and

(4) A heterogenous (very mixed-size) sediment load.

Bifurcations and confluences in the Rakaia River (New Zealand). Surian, 2015

In combination, these conditions suggest that irregular but very active transport and deposition of sediment characterize the braided environment.

Braided rivers

Can be identified by:

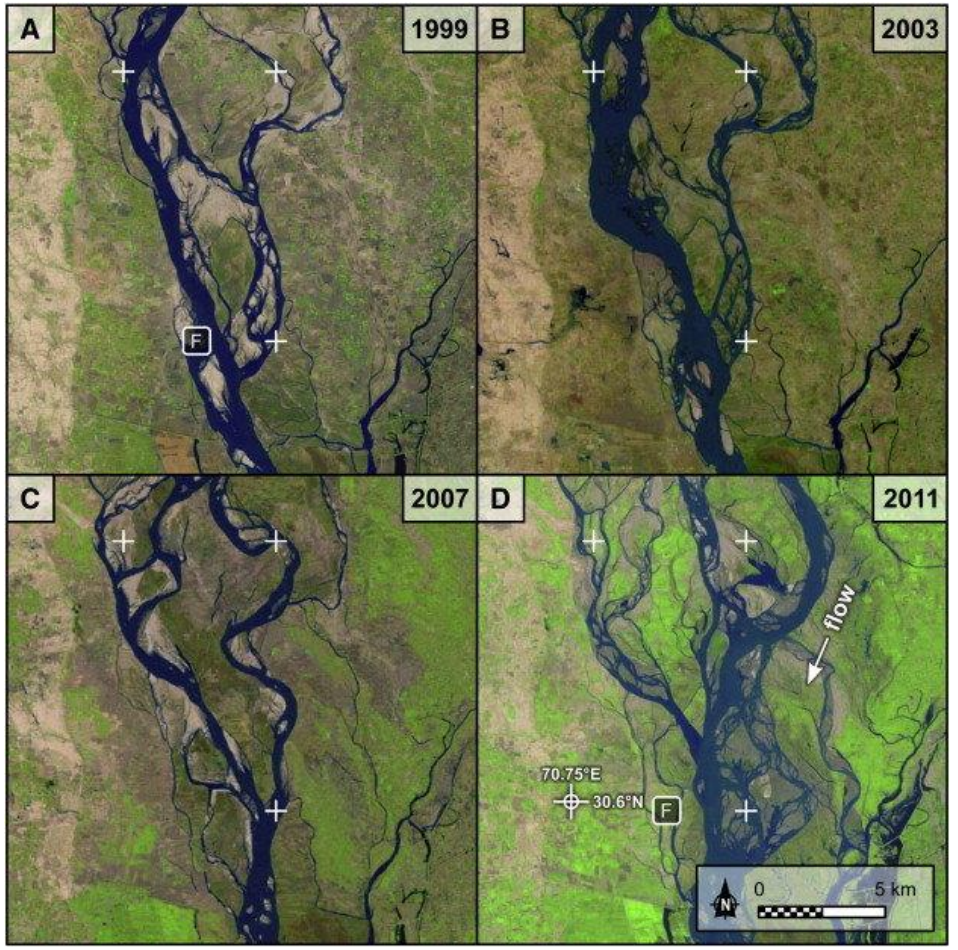
- multi-threaded channels that branch and merge to create the characteristic braided pattern
- highly dynamic behaviour with mid-channel bars which are formed, consumed, and re-formed continuously

These conditions reflect the frequency at which small concentrations of gravel in the channel can begin to grow into midchannel bars, and the requirement that the concentration of the flow around these growing islands is as likely to erode the opposite bank as it is to sweep away the island itself.

Bifurcations and confluences in the Rakaia River (New Zealand). Surian, 2015

Anabranching rivers

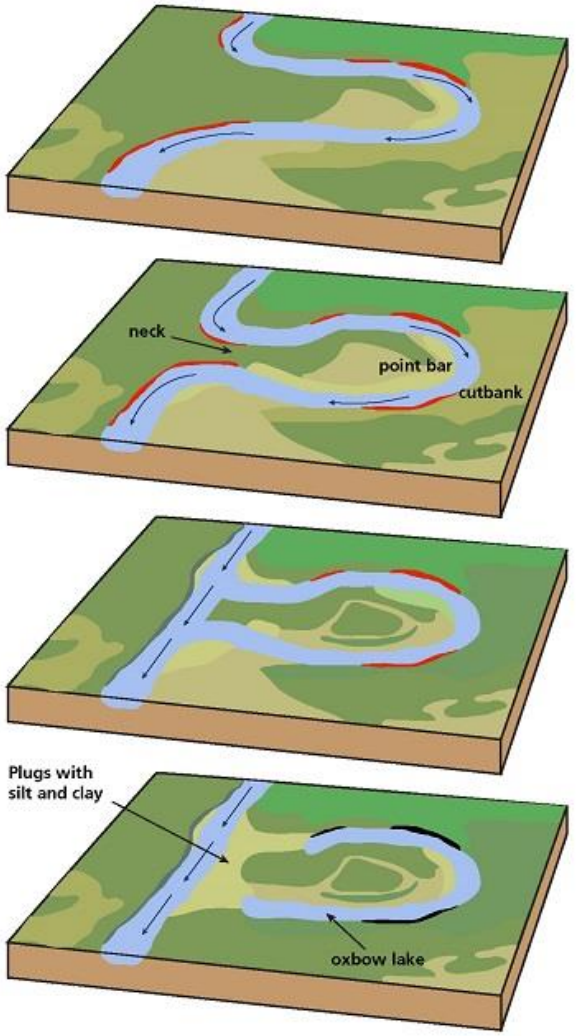
They consist of multiple channels separated by vegetated and semi-permanent alluvial islands or alluvial ridges. The islands are cut out of the floodplain or are constructed in channels by the accretion of sediments. Anabranching is a fairly uncommon but a widespread channel pattern that may affect straight, meandering, and braided channels alike.



Indus river and its anabranches. Lewin and Ashworth, 2014 (adapted from USGS 2011)

Floodplain

- **Cutbanks** form along the outer convex margin of meander bends, and are actually erosional features formed by the lateral movement of the channel across the flood plain. Flood plain sediments are eroded from the cutbank and deposited on pointbar surfaces.
- **Pointbars** are concave, depositional landforms that form opposite of the eroding cutbanks, and they develop in concert with the laterally migrating river channel. Pointbars are typically composed of sands, gravel, silts, and clay deposits, that form arcuate, meander-scroll ridges.
- **Oxbow lakes** or infilled channels form when a meander bend is cut off from the main river and abandoned in the floodplain.
- **Natural levees** are depositional landforms formed from the vertical accumulation of sediments deposited during flood events. Natural levees form topographically higher surfaces adjacent to the river channel, that generally consist of stratified, well-sorted sands, silts, and clays.

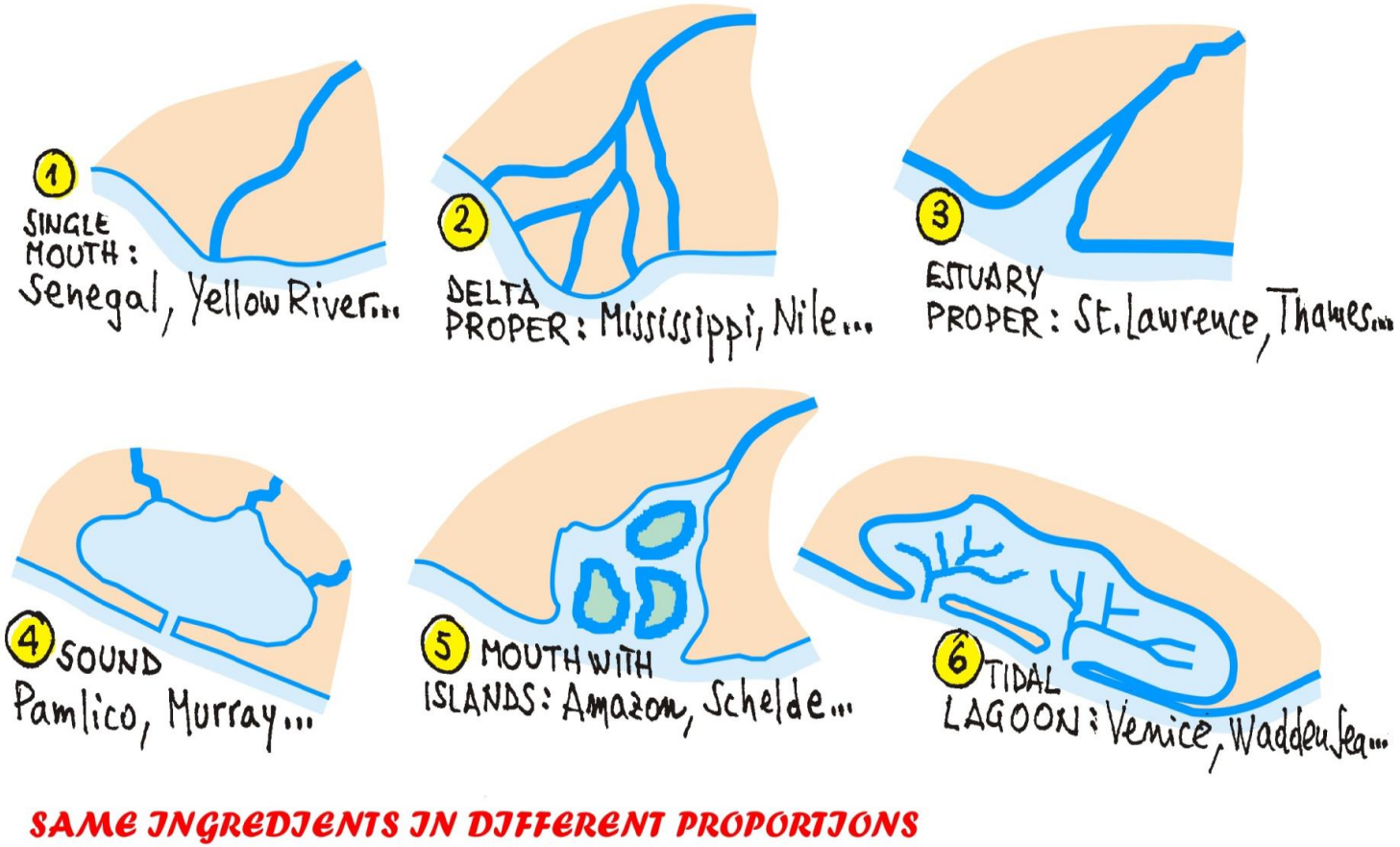


Source: Phil Reiker, NPS Geologic Resources Division

River mouth

Depending on the solid and liquid discharge, and on the coastal margin geology, rivers shape differently their mouth.

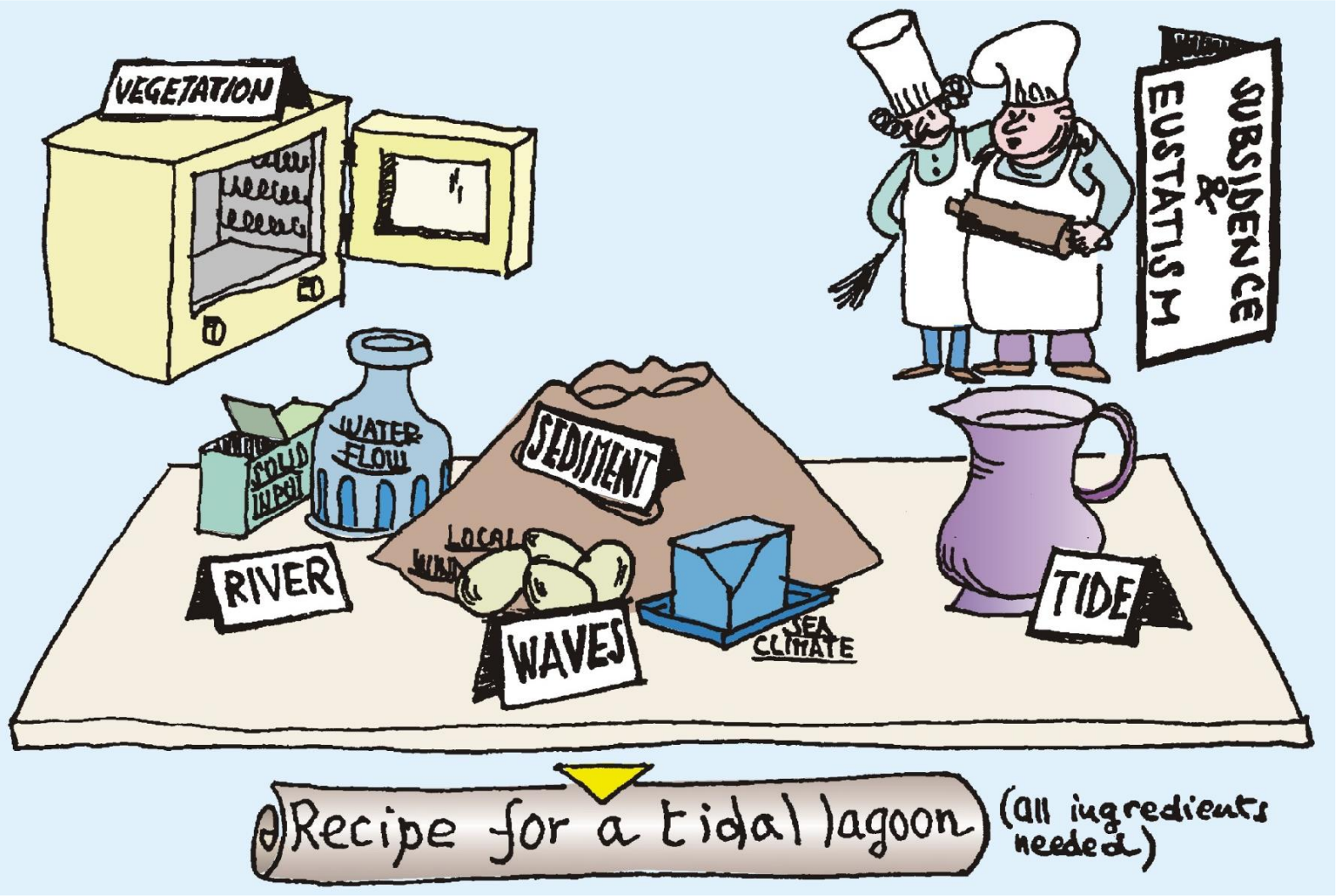
Types of river mouths (Di Silvio, 2006)



Lagoons

Very delicate inteplay between the liquid and solid discharges, mediated by tidal effects, waves, brackish water vegetation, and eventually subsidence and eustatism.

Ingredients for a tidal lagoon (Di Silvio, 2006)



Factors affecting river morphology