

Channel Geometry – Module 7

I. Intro

II. Bed and Bank Process Δ Channel Shape

I. Incision & Aggradation

II. Bank Morphology & Bank Erosion Processes

III. Channel Shape: Putting Bed & Banks Together

IV. Hydraulic Geometry & Adjustments

V. Topographic Surveys

VI. Geomorphic Change Detection

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VII. Key Messages

Bank Conditioning...

- Pre-Wetting
- Desiccation
- Freeze-Thaw Activity

Bank erosion processes

Bank erosion entails two phases, namely detachment of grains from the bank and subsequent entrainment (removal) of that material. Lift and drag forces may be entirely responsible for detachment and entrainment, but in most instances, especially in cohesive materials, aggregates and soil micropeds are loosened and partially or completely detached by weakening or preconditioning processes prior to entrainment. The three most important weakening mechanisms are pre-wetting, desiccation and freeze-thaw activity. Hence, subaerial processes are important determinants of bank erosion. *Pre-wetting* influences rates of bank erosion as cohesive materials become more erodible when wet. When very wet, seepage can cause sapping of localised areas of the bank face. Piping may also be evident (see Chapter 4). The role of *desiccation* reflects the nature of clay fabrics that make up cohesive, fine-grained banks. Desiccation can encourage higher bank retreat rates. Materials derived from direct spalling of drier upper bank surfaces collect at the foot of the bank and become available for entrainment at higher flow stage. Cracking up and incipient exfoliation of bank surfaces allow flood water to seep around and behind unstable soil structures (referred to as peds). Slaking refers to 'bursting' of bank peds during saturation. This reflects build-up of air pressures created by the influx of water into the soil pores during rapid immersion. *Freeze-thaw* processes may be an important

Bank Erosion Mechanisms

Hydraulic action (also referred to as fluvial entrainment or corrasion) and mass failures are the primary mechanisms of bank erosion (Figure 7.2). **Hydraulic action** refers to grain-by-grain detachment and entrainment. It is typically associated with non-cohesive bank materials. Grain removal by hydraulic action is closely related to near-bank flow energy conditions, especially the velocity gradient close to the bank and local turbulence conditions, as these determine the magnitude of bank shear stress (see Chapter 5). **Fluvial entrainment** occurs when individual grains are dislodged or shallow slips occur along almost planar surfaces. In some instances a distinct notch may be left in the bank following a flood event, indicating the peak stage achieved. **Undercutting** occurs when velocity and boundary shear stress maxima occur in the lower bank region. High rates of bank retreat at the apex of a bend are explained by steep velocity gradients and high shear stresses generated within large-scale eddies against the concave bank of a bend. During the process of undercutting, flow not only entrains material directly from the bank face, it also scours the base of the bank. This leads to oversteepening, and eventually gravitationally induced mass failure.

The effectiveness of hydraulic action is determined by

The susceptibility of banks to **mass failure** depends on their geometry, structure and material properties. Deep-seated failures are rare in non-cohesive banks, where basal scour, oversteepening and collapse mechanisms are favoured (Figure 7.2). Along more cohesive banks, weakening and weathering processes reduce the strength of bank material, thereby decreasing bank stability. The effective-

flow-type failures.

Shallow parallel slips occur in cohesionless banks, while deep-seated **rotational slip** and **slab failures** are the dominant mechanisms in banks of high and low cohesiveness respectively. Rotational slips occur along a curved failure plane that induces rotational movement via slipping of material down the bank face. Retreat of near-vertical banks via slab failure occurs when blocks of sediment are released from the face of the bank and topple into the channel. Other mass failure processes include **fall or sloughing**, where small quantities of material dislodged from the top of the bank accumulate at the base, and **parallel slide**, where slices of material parallel to the bank slip down the bank face (Figure 7.2).

The effectiveness of these various bank erosion processes,

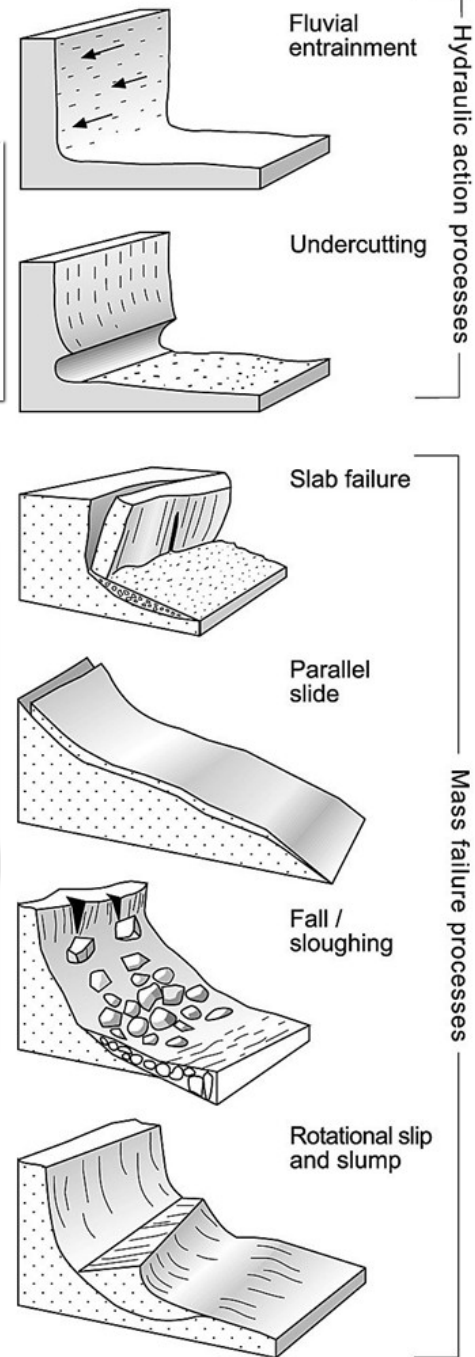


Figure 7.2 Bank erosion processes. Hydraulic action involves the shearing of sediment from a channel bank as water flows across it (entrainment and undercutting). Slab failure, parallel slide, fall/sloughing and rotational slumps are forms of mass failure whereby sections of bank fall into the channel. Modified from Thorne (1999) in Brierley and Fryirs (2005). © Wiley-Blackwell Publishing. Reproduced with permission.

Cycle of Bank Retreat

The effectiveness of these various bank erosion processes is greatly enhanced by basal scour or bed incision, which effectively increases bank angle and height (Figure 7.3). In

composite banks, where cohesive materials overlie non-cohesive sands or gravels, undercutting of the lower bank by hydraulic action generates an overhang or cantilever in the upper layer. These overhanging materials are prone to fail and blocks of bank material slide or fall towards the toe of the bank during bank failure and collapse. They remain at the toe of the bank until they are broken down or entrained by flow. Once a failed block is deposited on the channel bed, it locally modifies the morphology and flow. Failed blocks, in turn, may temporarily protect the toe of the bank from erosion. This pseudo-cyclic process plays an important role in controlling bank form, stability and rate of retreat (Figure 7.3).

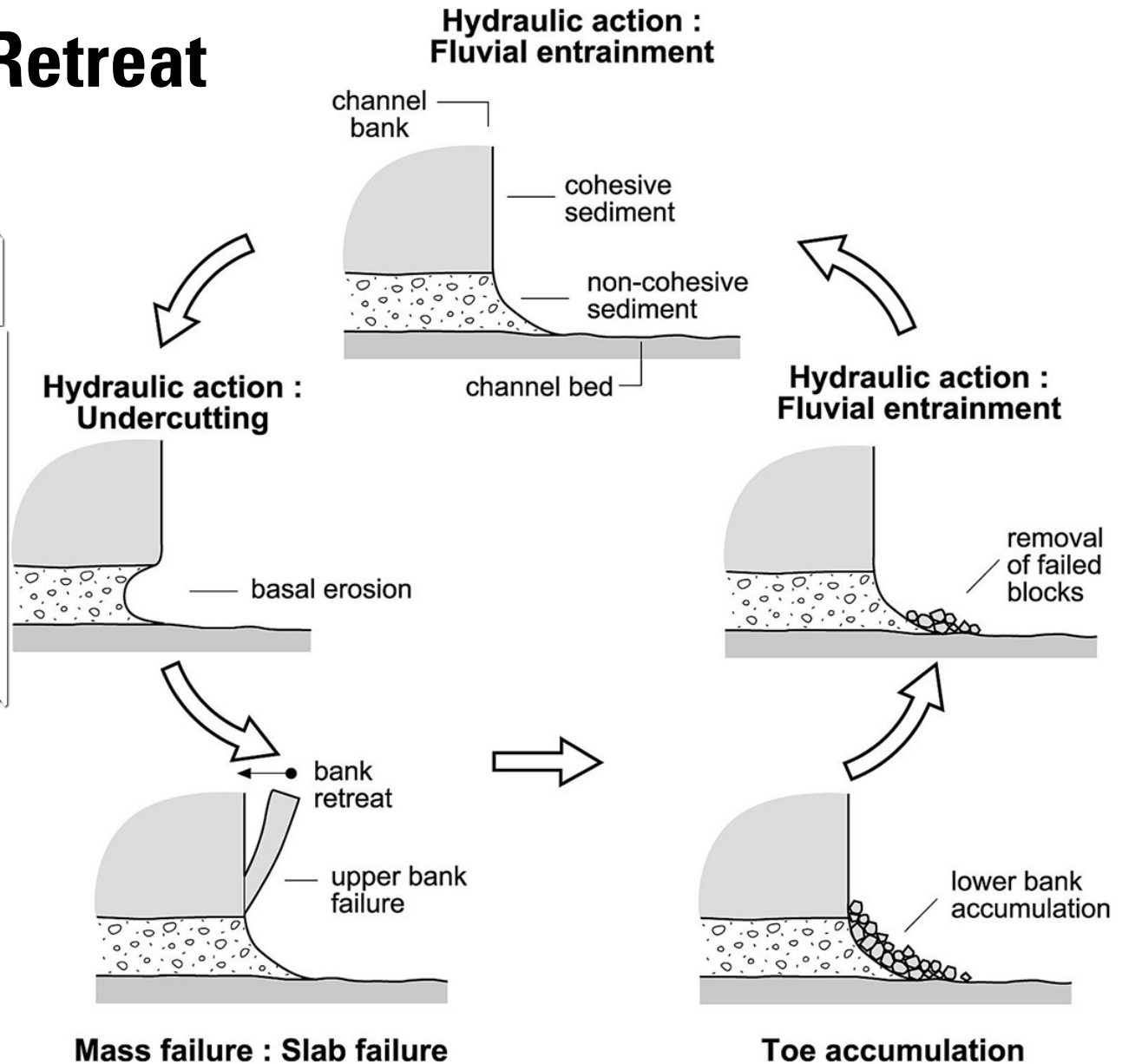
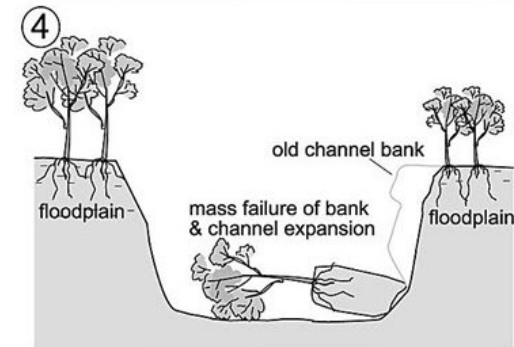
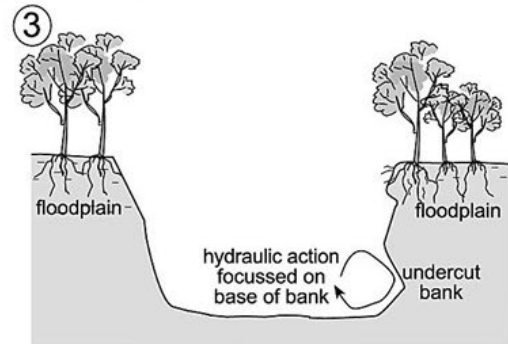
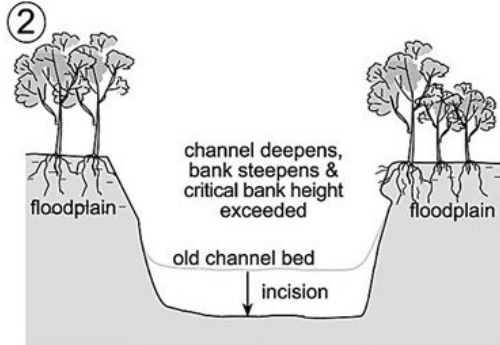
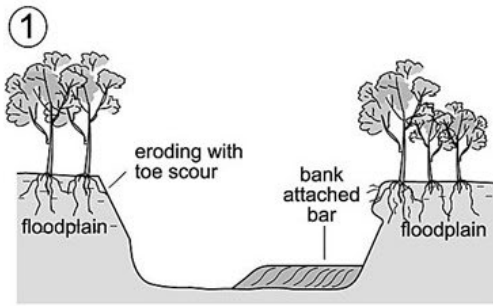


Figure 7.3 The cycle of bank retreat processes. The influence of hydraulic action and mass movement processes varies at different stages in the bank erosion cycle. Following mass failure, bank retreat cannot recommence until materials at the toe of the bank have been removed. Note how bank morphology changes at each phase of adjustment. From Brierley and Fryirs (2005). © Wiley–Blackwell Publishing. Reproduced with permission.

Fryirs & Brierley (2013)

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When Vertical Adjustment Impacts Lateral



- Incision (e.g. in response to change in base level) will increase bank height
- And can increase bank instability
- And accelerate bank erosion

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Figure 7.4 The influence of bed degradation upon bank-forming processes. If incision exceeds critical bank height, mass failure occurs and the channel widens. Incision of Jones Creek, Victoria, Australia, has triggered significant mass failure of banks. Photographs courtesy of Tim Cohen.

Bank Morphology $\approx f(?)$

Bank morphology

Bank morphology may reflect a range of differing conditions or processes. In some instances, similar forms may be produced by differing processes (the principle of equifinality). Hence, significant caution may be required in making interpretations of why banks have adopted a particular morphology. Appraisals of underlying causes must consider a range of possible scenarios, giving due regard to:

- The aggradational/degradational balance of the reach, i.e. bed processes that are operating.
- Bank position within the reach and its relation to flow alignment at differing flow stages.
- The balance of erosional and depositional processes operating on or adjacent to banks.
- The mix of materials that make up the bank and their sedimentology (including the presence of bedrock). This may include sediments that were deposited under a different flow regime and now represent inherited forms that are preserved in the banks.
- The stage of evolution of the bank, including the rate of delivery of materials to the toe of the bank and subsequent rates of removal.
- The primary origin of depositional features that may line (and protect) the bank (whether derived from further up the bank or from upstream sources).
- The combination of fluvial erosion and mass failure mechanisms that erode the bank.
- Vegetation associations and faunal interactions may influence the nature and effectiveness of bank-forming processes. This includes biogeochemical alteration of bank materials, biofilms, etc.

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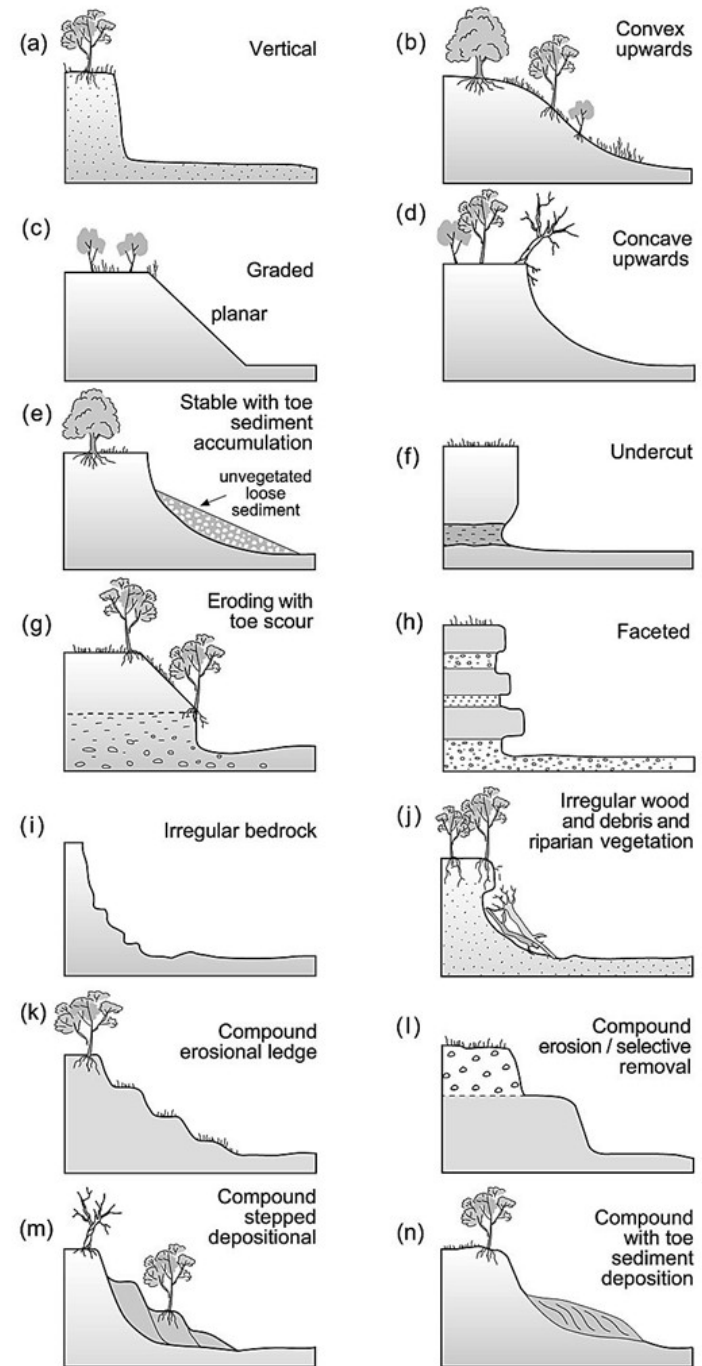
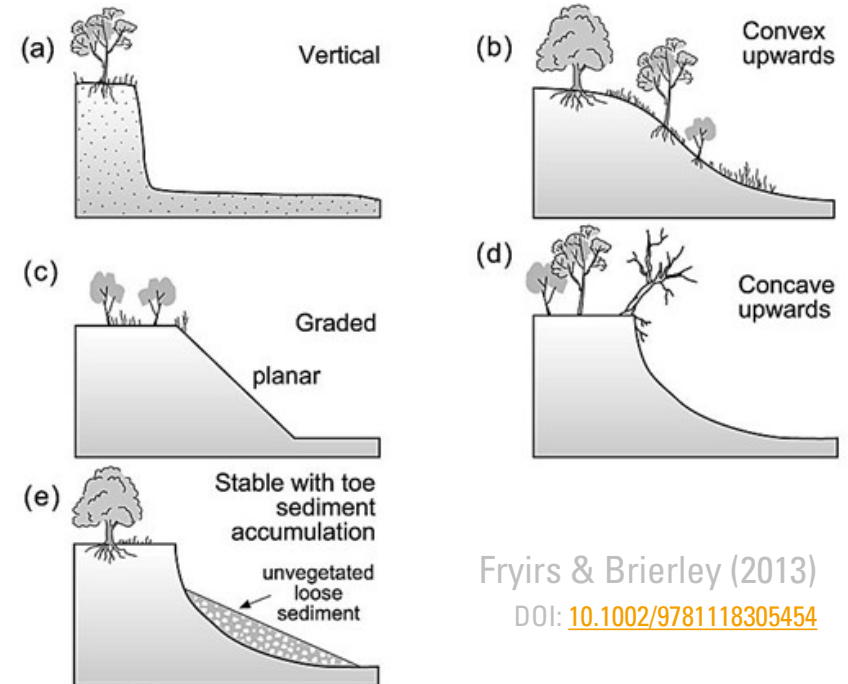


Figure 7.5 Bank morphology. Bank morphology reflects factors such as bank material properties (often inherited from former phases of river activity) and the nature/balance of erosion and deposition processes occurring along the bank. Similar forms may result from differing processes. Modified from Thorne (1999) in Brierley and Fryirs (2005). © Wiley-Blackwell Publishing. Reproduced with permission.

Bank Morphology – Homogenous Bank Deposits

Various bank morphologies are portrayed in Figure 7.5. Banks with a homogeneous sediment mix commonly have a uniform morphology. This may take a near-vertical form, where fluvial entrainment processes are effective (Figure 7.5a), or various forms of inclined bank (Figures 7.5b–d). In general terms, the sediment mix dictates bank angle. Cohesive sediment forms steeper banks, while sandy banks have a gentler angle of repose. Uniform bank morphologies may reflect hydraulic action processes such as fluvial entrainment or mass failure processes such as parallel sliding or rotational slips. Along convex-upwards banks, gradual mass movement mechanisms may be inferred (Figure 7.5b). Alternatively, overflow

mechanisms from the floodplain to the channel during the waning stages of floods may modify patterns of sedimentation on the bank, especially around vegetation. Graded banks represent a planar condition that may reflect grain-by-grain movement downslope at the angle of repose or parallel sliding down a slip face (Figure 7.5c). A concave-upwards bank profile may arise following removal of rotational slip and slump materials from the base of the bank (Figure 7.5d).



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Banks with coarsening upwards profiles, such as sand deposits overlying fine-grained, cohesive sediments, tend to have zones of sediment accumulation along the bank toe (Figure 7.5e). Mass failure processes, such as falling and slipping/slumping, deliver sediment to the toe of the bank, where it accumulates until it is removed by fluvial entrainment. In contrast to banks with bank-attached geomorphic units, the toes of these banks are comprised of materials derived directly from the adjacent bank. As such, sediment

Bank Morphology – Stratified Bank Deposits & Irregular

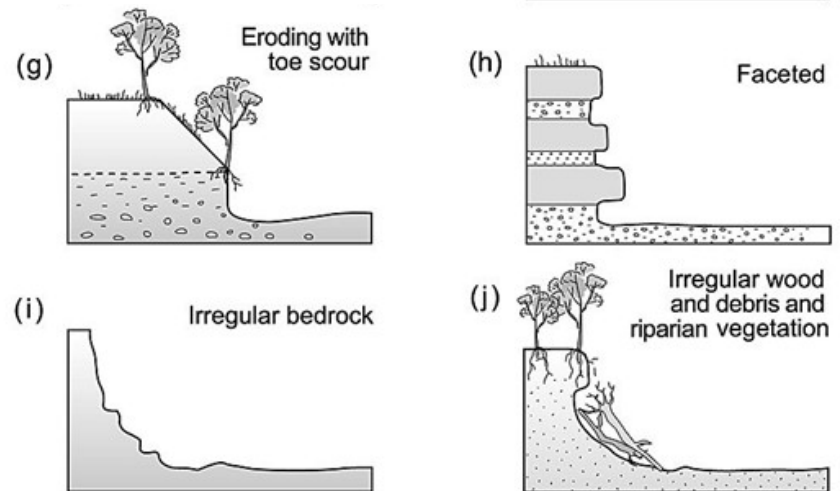
Undercut banks are commonly associated with upward-fining sediment sequences. Commonly, basal gravel lags are overlain by sand or mud deposits. Less cohesive units at the base of the bank are often undercut or eroded by hydraulic action (see Figure 7.5f). Toe scour leaves an overhanging bank of cohesive, finer grained materials. Mass failure by slab failure or fall results in sediment accumulation at the base of the bank. Differing stages of adjustment in this process have quite different bank morphologies. The resultant bank morphology following undercutting reflects the initial condition of the bank prior to commencement of toe scour. For example, Figure 7.5g represents a planar bank that is subsequently subjected to toe scour.

Banks that comprise multiple layers of sediment of varying texture tend to have a complex morphology, as coarse materials are selectively reworked. This produces a faceted bank with multiple overhangs (Figure 7.5h). Hydraulic action via fluvial entrainment and undercutting are common bank erosion processes that act as precursors to mass failure by slab failure or fall. In contrast, channels with bedrock margins tend to have an imposed, irregular morphology (Figure 7.5i). Irregular bank morphologies also occur along channels where resisting/forcing elements, such as wood and riparian vegetation, induce local variability in patterns of scour and deposition (Figure 7.5j).

Finally, compound bank morphologies with stepped

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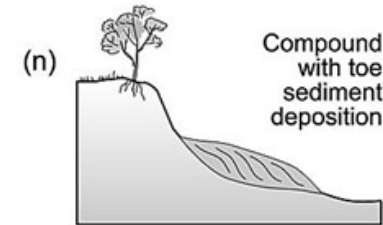
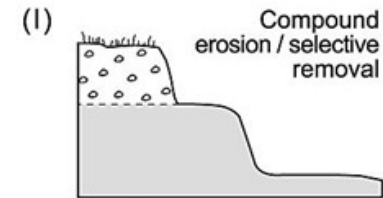
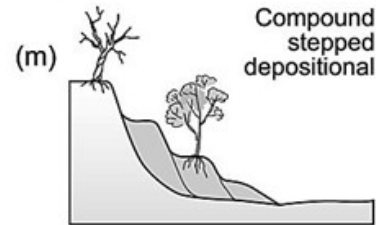
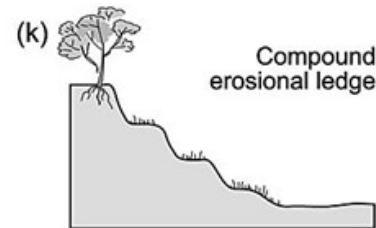
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Bank Morphology – Compound

such as wood and riparian vegetation, induce local variability in patterns of scour and deposition (Figure 7.5j).

Finally, compound bank morphologies with stepped profiles may result from differing sets of erosional and depositional processes. They are commonly found in reaches subjected to bed instability (whether degradation or aggradation). For example, ledge features may be observed along incised channels (see Chapter 8; Figure 7.5k). These erosional forms may reflect a slot channel inset within the broader trough. They are typically associated with phases of channel expansion. Alternatively, compound bank morphologies may reflect selective removal of less cohesive materials from the upper part of a bank profile. For example, reaches that are subjected to valley floor aggradation in response to upstream disturbance events commonly have coarser materials atop the banks. Subsequent channel expansion may selectively erode these less cohesive materials, producing a stepped bank morphology (Figure 7.5l). A compound bank morphology may also be derived from depositional mechanisms. For example, a stepped morphology may reflect multiple phases of deposition adjacent to the bank, in the form of inset features called benches (see Chapter 8; Figure 7.5m). These features are typically associated with phases of channel contraction.



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Classification of Channel Bed Conditions

Think back to bed material load.

Table 7.1 Classification of channel boundary conditions^a

| Primary type | Characteristics |
|----------------------------|--|
| Bedrock channel | Imposed (forced) morphology (bed and banks). Typically have an irregular cross-section. May have a partial cover of consolidated material. Common in steep headwater reaches. |
| Non-cohesive boulder bed | Irregular channel morphology as flow moves around coarse boundary materials that are only mobilised during major floods. A surface armour is common. As bed materials may be relatively 'locked in place', many attributes of boulder streams are essential 'forced'. |
| Non-cohesive gravel bed | Mixed-load systems characterised by intermediate width/depth ratios. Differing bedload fractions are transported at differing flow stages. A surface armour may protect underlying materials. Banks commonly have cohesive finer grained materials atop the bedload material base (i.e. these are composite banks). Channel shape is largely determined by channel alignment and the recent history of formative events. In meandering reaches, for example, the channel is asymmetrical at bends and symmetrical at points of inflection. |
| Non-cohesive sand bed | 'Live-bed' channels are active over a wide range of discharges. Bedform attributes reflect flow stage (depth and velocity) and grain-size relationships. Channels have a high width/depth ratio. |
| Cohesive silt-clay channel | Suspended-load systems with a limited capacity to rework their boundaries and adjust their form. Channels have a low width/depth ratio, and commonly have a symmetrical form. Once entrained, materials are maintained in transport even if flow energy decreases significantly. |

^aModified from Knighton (1998).

Channel Shapes as Predictors/Reflectors of Process (Form-Process linkages)

Table 7.2 Putting the beds and banks together to assess channel shape^a

| Channel shape | Bank process | Bed process | Energy distribution |
|-------------------------|--|--|--|
| Symmetrical | Erosion (e.g. fluvial entrainment). | Erosion (e.g. headcut formation) or deposition (e.g. sand sheets). | Evenly distributed across channel. |
| Asymmetrical | Deposition along convex bank (point bar); erosion along concave bank (often undercut). | Deposition (point bar formation along convex bank), and erosion (pool scour along concave bank). | Thalweg along concave bank. Secondary circulation cells are common. |
| Irregular | Imposed condition, such as a bedrock or coarse boulder stream. Influenced by erosion (e.g. slumping) or deposition (e.g. bank-attached bar formation). | Erosion (e.g. sculpted pools or cascades) or deposition (e.g. mid-channel bars and island formation). | Unevenly distributed around alluvial materials or bedrock outcrops. Rough surfaces generate turbulent flows. |
| Compound (macrochannel) | Deposition (e.g. bench formation) or erosion (e.g. ledge formation). | Deposition (e.g. sand sheet formation) or erosion (e.g. headcut formation that creates an incised (slot) channel). | Similar to symmetrical channels, but varies with flow stage as differing surfaces are inundated. |

^aFrom Brierley and Fryirs (2005). © Wiley–Blackwell Publishing. Reproduced with permission.

Channel Shapes & W/D Ratios in Different Valley Settings

Controls on channel shape (width : depth)

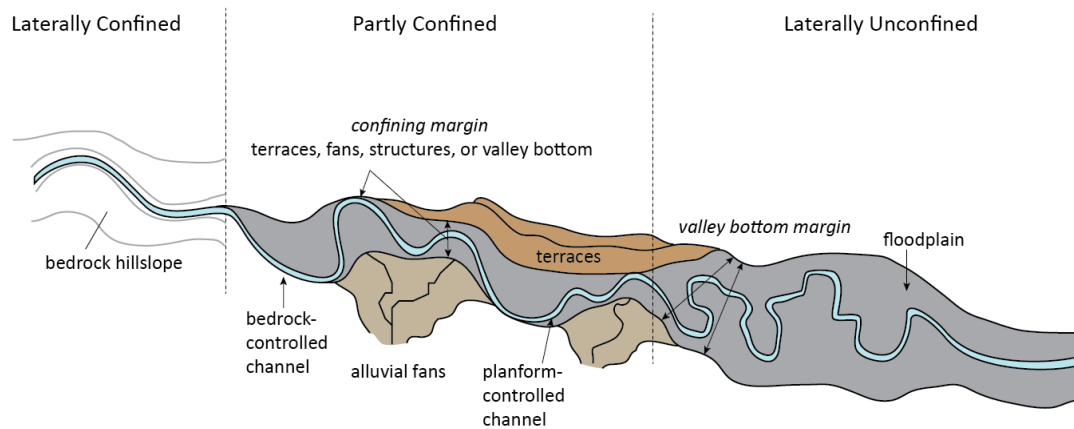
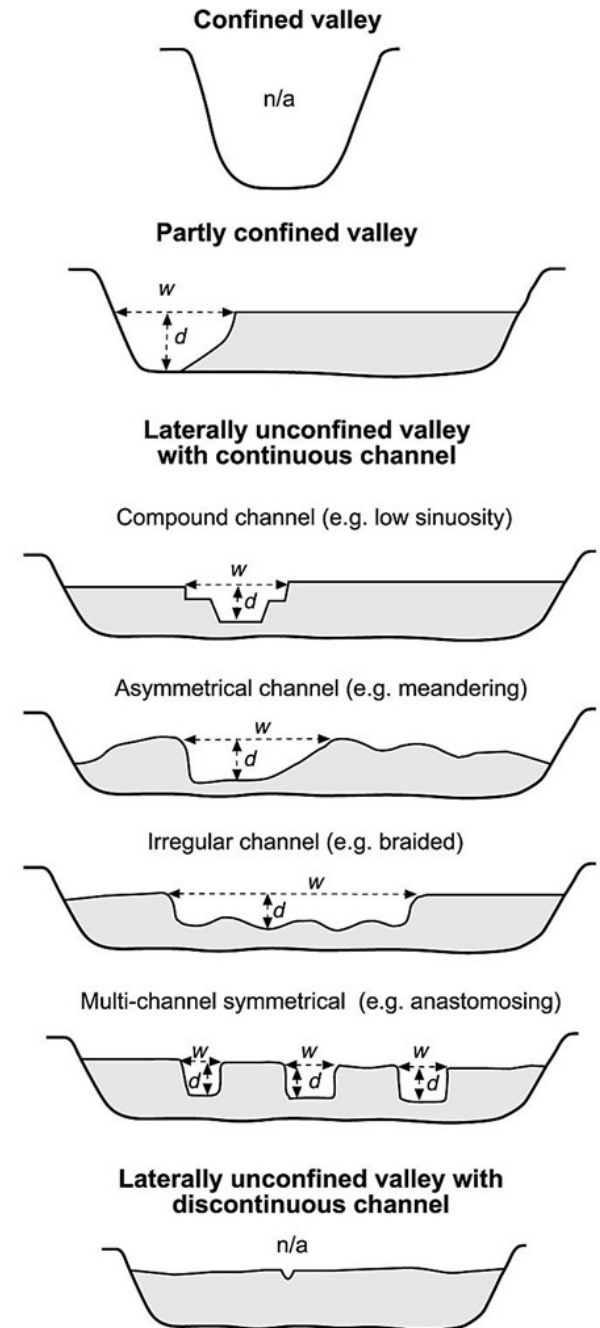


Figure 7.6 Schematic representations of channel shape and width/depth ratio for a range of river types. Width/depth ratio in confined rivers and discontinuous watercourses is a less meaningful measure than it is in more freely adjusting rivers with floodplains. In partly confined rivers, the depth component is often constrained by bedrock, whereas a range of channel sizes and shapes can result in laterally unconfined rivers where both the bed and the banks are comprised of deformable alluvial sediment.

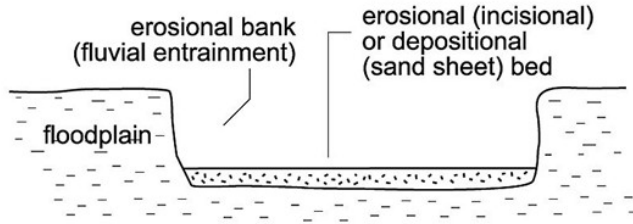


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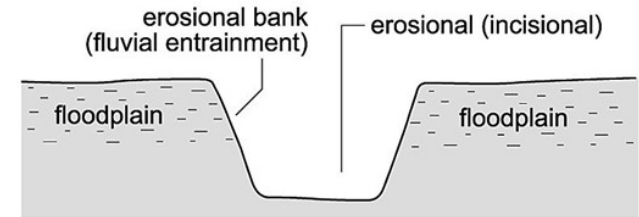
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Channel Shapes

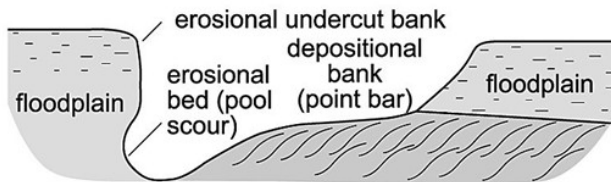
(a) Symmetrical: coarse-grained



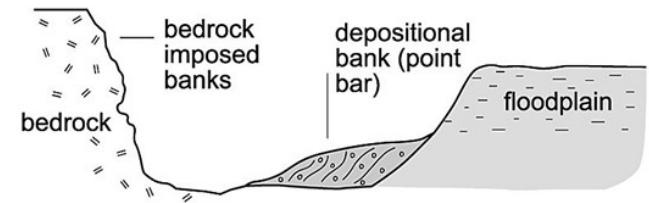
(b) Symmetrical: fine-grained



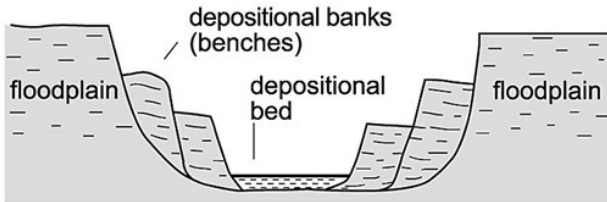
(c) Asymmetrical: meander bend



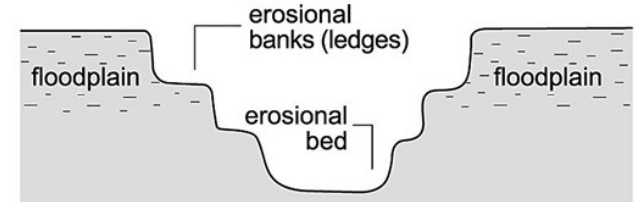
(d) Asymmetrical: partly confined valley



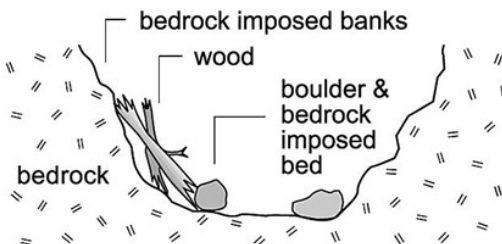
(e) Compound: depositional benches



(f) Compound: erosional ledges



(g) Irregular: bedrock imposed by wood



(h) Irregular: depositionally imposed by riparian vegetation

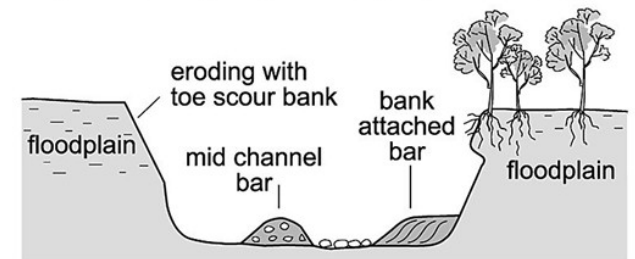
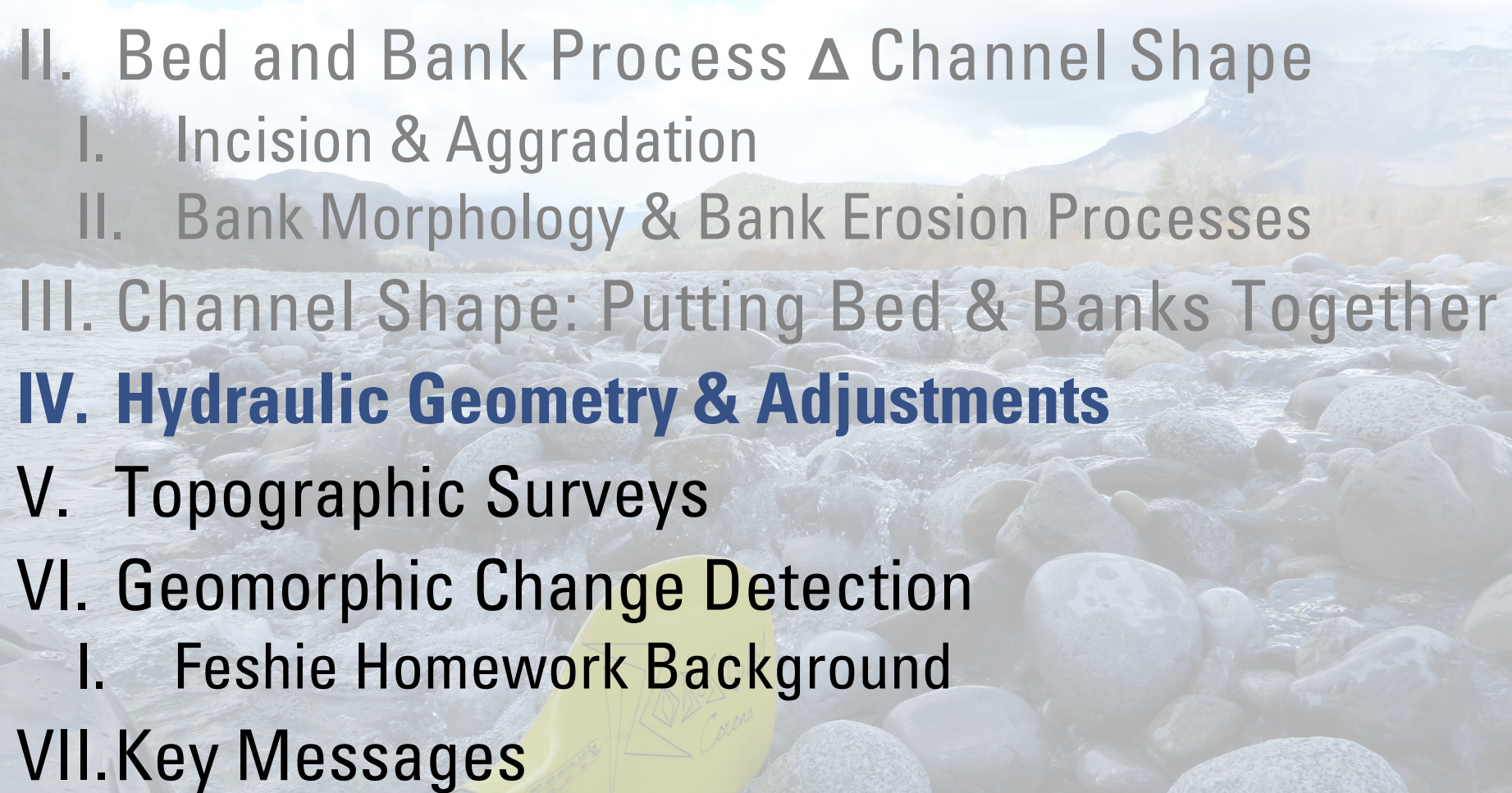


Table 7.4 Morphological responses to changes in discharge and sediment load^a

| Relationship | Equation ^b | Types of triggers |
|---|---|--|
| Decrease in discharge alone | $Q_s^0, Q_w^- \approx s^+, D_{50}^-, d^-, w^-$ | Abstraction of water from channel resulting in narrower channel. |
| Increase in discharge alone | $Q_s^0, Q_w^+ \approx s^-, D_{50}^+, d^+, w^+$ | Water release from a reservoir. |
| Increase in bed material load | $Q_s^+, Q_w^0 \approx s^+, D_{50}^-, d^-, w^*$ | Increased sediment supply from catchment. |
| Decrease in bed material load | $Q_s^-, Q_w^0 \approx s^+, D_{50}^-, d^-, w^-$ | Reduced erosion in the catchment. Riparian revegetation. |
| Significant decrease in bed material load | $Q_s^{--}, Q_w^0 \approx s^-, D_{50}^+, d^+, w^*$ | Sediment starvation. |
| Decrease in bed material load and decrease in water discharge | $Q_s^-, Q_w^+ \approx s^-, D_{50}^+, d^+, w^-$ | Intensification of vegetation cover. Shift in climate from semi-arid to temperate conditions. Diversion of water into a river channel, e.g. from a dam. |
| Increase in bed material load and increase in water discharge | $Q_s^+, Q_w^+ \approx s^+, D_{50}^+, d^+, w^+$ | Land use change from agricultural to semi-urban. |
| Increase in bed material load and significant increase in water discharge | $Q_s^+, Q_w^{++} \approx s^-, D_{50}^+, d^+, w^+$ | Increasing frequency and magnitude of water and sediment discharge (e.g. urbanisation, sequence of flood events). |
| Significant increase in sediment supply and no change in discharge. | $Q_s^{++}, Q_w^0 \approx s^+, D_{50}^-, d^-, w^*$ | Sediment slug formation and movement. |
| Significant increase in bed material load and increase in water discharge | $Q_s^{++}, Q_w^+ \approx s^+, D_{50}^-, d^-, w^+$ | Land use change from forested to agricultural. Sediment discharge increases more rapidly than water discharge. Bed changes from gravel to sand, wider shallower channel. |
| Decrease in bed material load and decrease in water discharge | $Q_s^-, Q_w^- \approx s, D_{50}^+, d^+, w^-$ | Dam construction. |
| Decrease in bed material load and significant decrease in water discharge | $Q_s^-, Q_w^{--} \approx s^+, D_{50}^-, d^-, w^-$ | Dam closure. |

^aSchumm (1969).^b Q_s : sediment load; Q_w : water discharge; s : slope, D_{50} : median grain size; d : flow depth; w : flow width; +/–: increase or decrease; 0: no change; ++/—: change of considerable magnitude; *: unpredictable.

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Hydraulic Geometry

sented by the diagram in the lower right.

The two diagrams of the watershed are introduced to emphasize the points, first, that at a given cross section different discharges have different frequencies; and second, that at cross sections situated at various points along the stream the rates of discharge are usually different, one from another. Comparison of the various cross sections along a stream is made in this paper only under the assumed condition that they are experiencing equal frequency of discharge.

The term "at a station" is used in this paper to mean at a given cross section, and the term "in a downstream direction" refers to cross sections situated along the length of a stream. "Change of discharge downstream" means different discharges of the same frequency at cross sections situated along the length of a stream.

The differences in discharge both at a station and in a

The Hydraulic Geometry of Stream Channels and Some Physiographic Implications

By LUNA B. LEOPOLD and THOMAS MADDOCK, Jr.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 252

Quantitative measurement of some of the hydraulic factors that help to determine the shape of natural stream channels: depth, width, velocity, and suspended load, and how they vary with discharge as simple power functions. Their interrelations are described by the term "hydraulic geometry."



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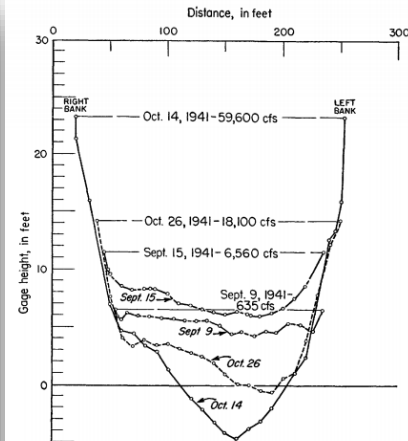


FIGURE 22.—Channel cross sections during progress of flood, September-December 1941, San Juan River near Bluff, Utah.

- Two key concepts about discharge:
 - **At a station**, different discharges have different frequencies/durations
 - **Change of discharge downstream**
- Hydraulic geometry variables: width, depth, velocity

4

THE HYDRAULIC GEOMETRY OF STREAM CHANNELS

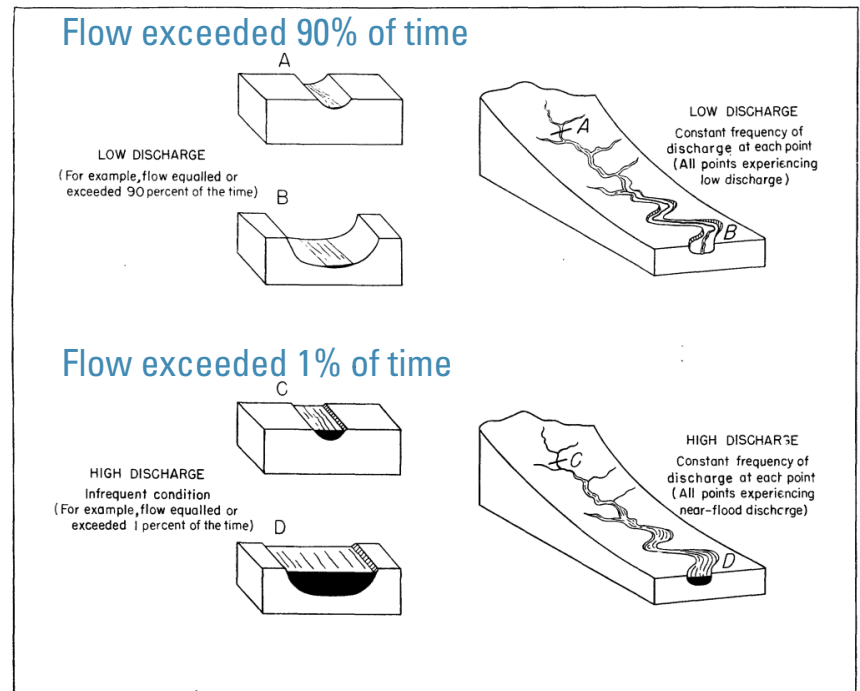


FIGURE 2.—Comparison of different rates of discharge at a given river cross section and at points downstream.

At a Station

$$w = aQ^b$$

$$d = cQ^f$$

$$v = kQ^m$$

Flow duration curve

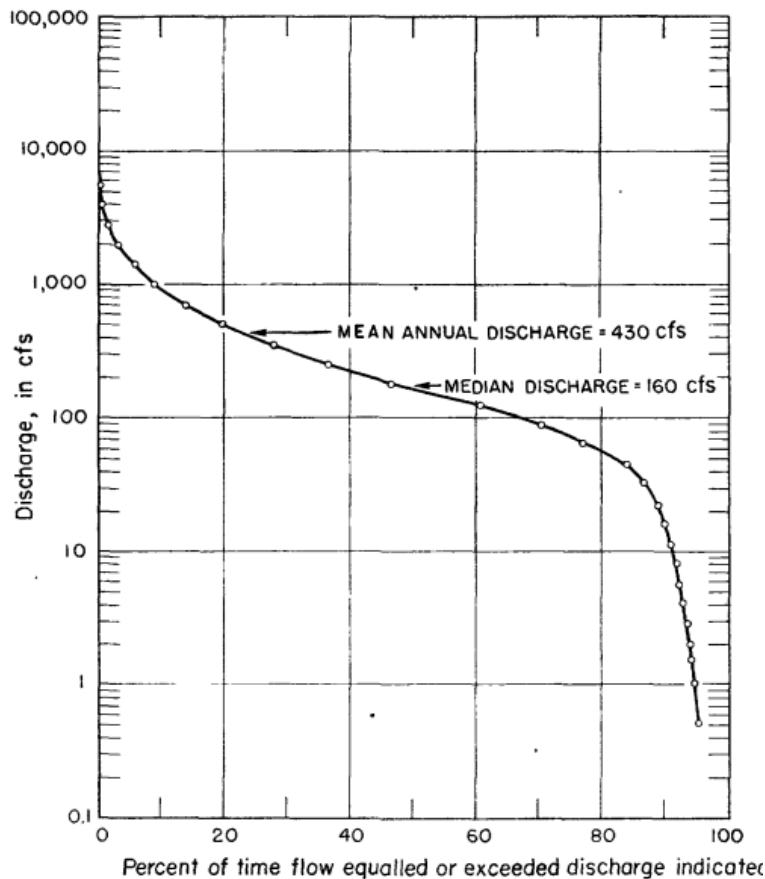
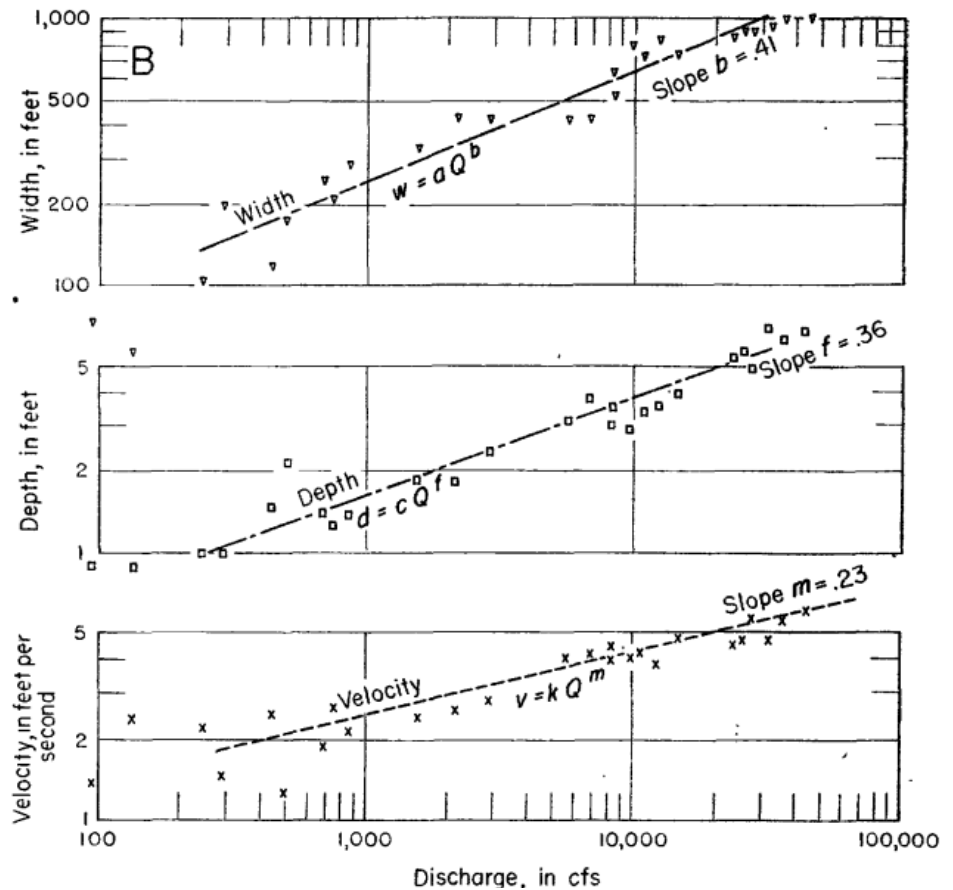


FIGURE 1.—Cumulative frequency, or flow-duration, curve for Powder River at Arvada, Wyo., 1917-50.



VARIATION OF HYDRAULIC CHARACTERISTICS IN A PARTICULAR CROSS SECTION OF A RIVER

Changes in velocity, depth, and width of flowing water take place as the discharge increases at a particular cross section of a river. Because river cross sections tend to be roughly semielliptical, trapezoidal, or triangular, increasing discharge results in an increase of each of the other three factors. Typical relations of width, depth, and velocity to discharge will be shown for various points on different rivers. These relations will show that these three factors generally increase with increasing discharge as simple power functions.

In figure 2 A a number of variables are plotted.

Hydraulic Geometry: Typical values of b , f & m

Analysis of hydraulic geometry assumes that discharge Q is the dominant independent variable and that the dependent variables of channel width w , mean depth d and mean flow velocity v are related to it in the form of simple power functions:

$$w = aQ^b$$

$$d = cQ^f$$

$$v = kQ^m$$

From the continuity/discharge equation (see Chapter 4):

$$Q = wdv = aQ^b cQ^f kQ^m$$

where Q (m^3s^{-1}) is the discharge, w (m) is the width, d (m) is the channel depth and v (ms^{-1}) is the mean velocity. It follows that:

$$ack = 1 \quad \text{and} \quad b + f + m = 1$$

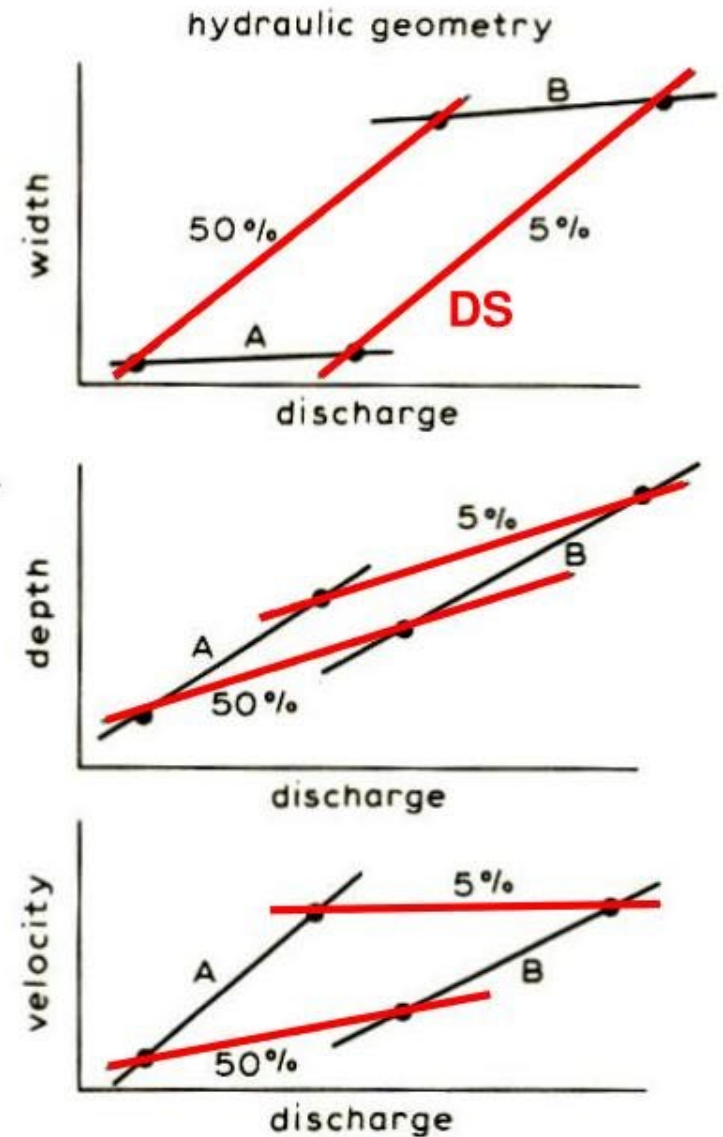
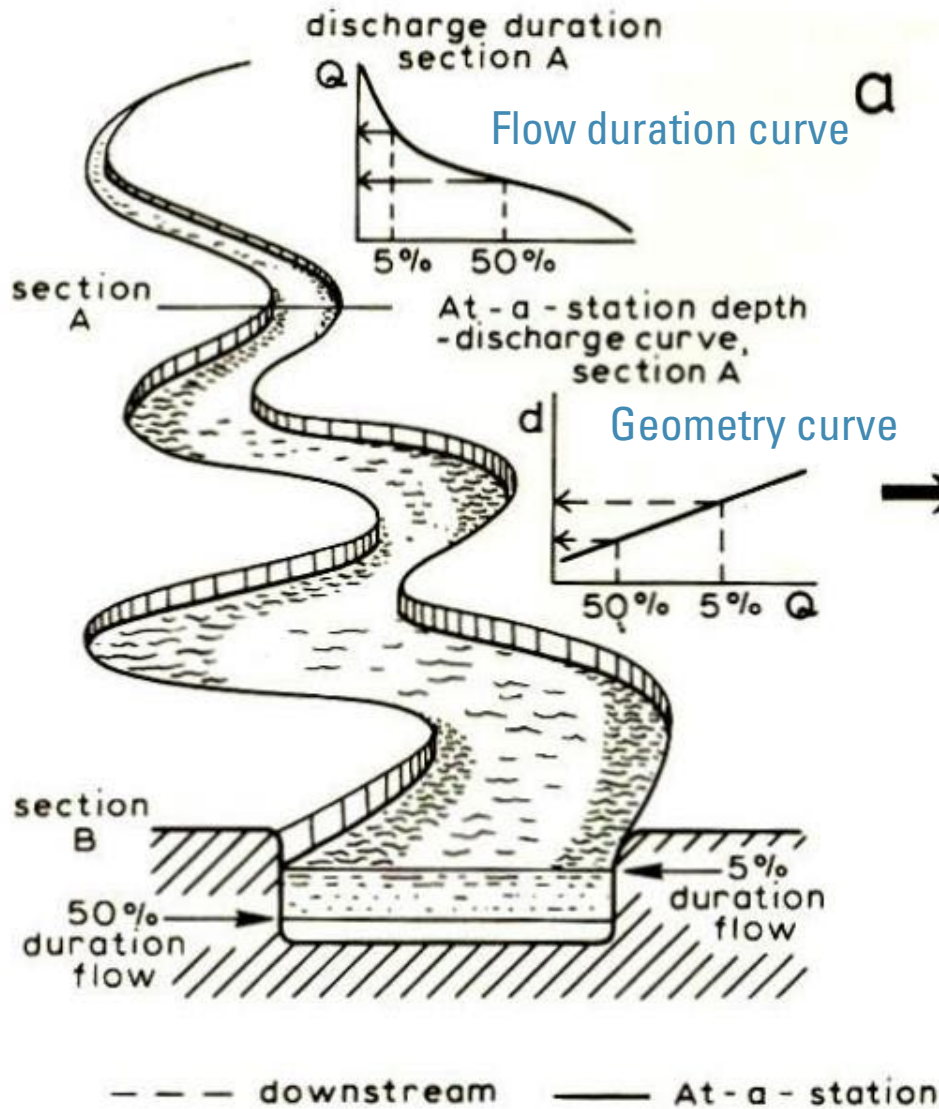
At-a-station hydraulic geometry considers channel responses to temporal variations in flow at a cross-section. The exponents b , f and m indicate the proportional increase in that component with increasing discharge. These relationships vary markedly with bed and bank material attributes

Table 7.3 Width, depth and velocity components of different channels at-a-station^a

| Type of channel | Width b | Depth f | Velocity m |
|---|-----------|-----------|--------------|
| Cohesive, near-vertical banks (incised channel), fine-grained bed | 0.05 | 0.45 | 0.50 |
| Cohesive, near-vertical banks; sand and gravelly beds | 0.01 | 0.52 | 0.47 |
| Cohesive but non-vertical banks; sand and gravelly beds | 0.08 | 0.50 | 0.42 |
| Non-cohesive, readily erodible boundaries | 0.54 | 0.26 | 0.20 |
| One cohesive, one non-cohesive bank; sand and gravelly beds | 0.40 | 0.31 | 0.29 |

^aModified from Knighton (1974, 1998).

(see Table 7.3). The increase in depth is the primary response



Determining hydraulic geometry

(Richards, 1982)

Downstream & At-A Station in 1

relations constituting the hydraulic geometry.

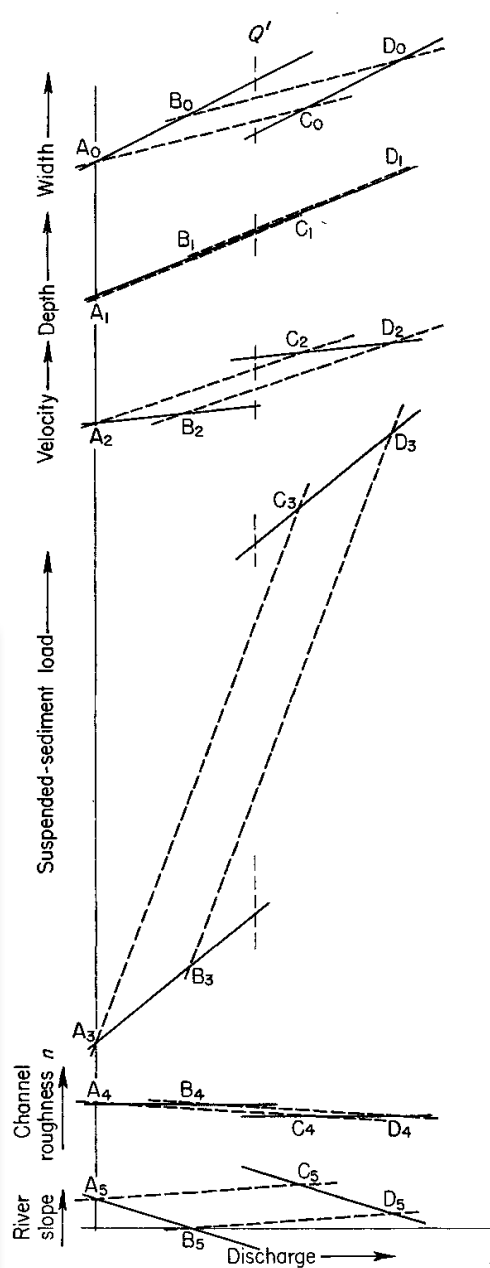
Figure 19 summarizes the average conditions observed in the numerous rivers studied. Cross section A represents the conditions at a headwater station during low flow. Its position will be noted in the upper physiographic diagram of a watershed in which low flow prevails. Cross section C represents the same headwater station under conditions of high discharge. Similarly, B is a downstream section at low flow, and D the same section at high discharge.

The slopes of the lines in the graphs of figure 19

Conclusion

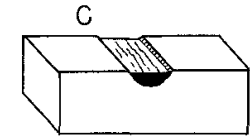
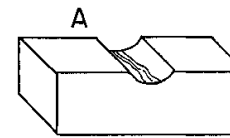
The interactions just summarized operate in both ungraded and graded reaches. They account for the maintenance of grade once the condition of equilibrium is achieved, but their influence is sufficiently potent, even in reaches not yet graded, to cause the drainage system to develop in a highly coordinated and systematic manner. Because of these interactions, rivers tend to increase in width and depth downstream with increase of discharge in a remarkably consistent manner.

Each branch in the channel system of a river tends to occupy a valley proportioned to its size. This interrelationship is so similar in rivers widely different in physiographic setting that its importance to the understanding of land forms was recognized more than a century ago. Geomorphology cannot move ahead, however, if we remain content to describe processes of land sculpture only in qualitative terms. When viewed quantitatively, the interactions of the various hydraulic factors are found to be more complex than the qualitative analyses have led us to believe, but the unravelling of their complexities constitutes advance of knowledge.

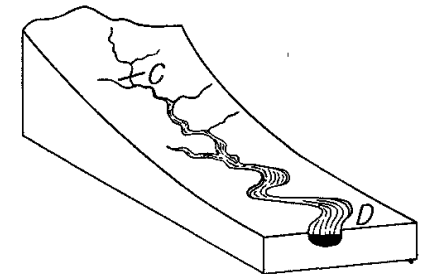
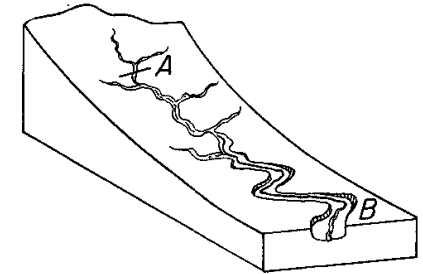
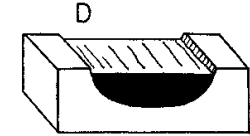
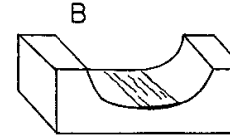


NOTE: ALL SCALES ARE LOGARITHMIC

Headwater Station



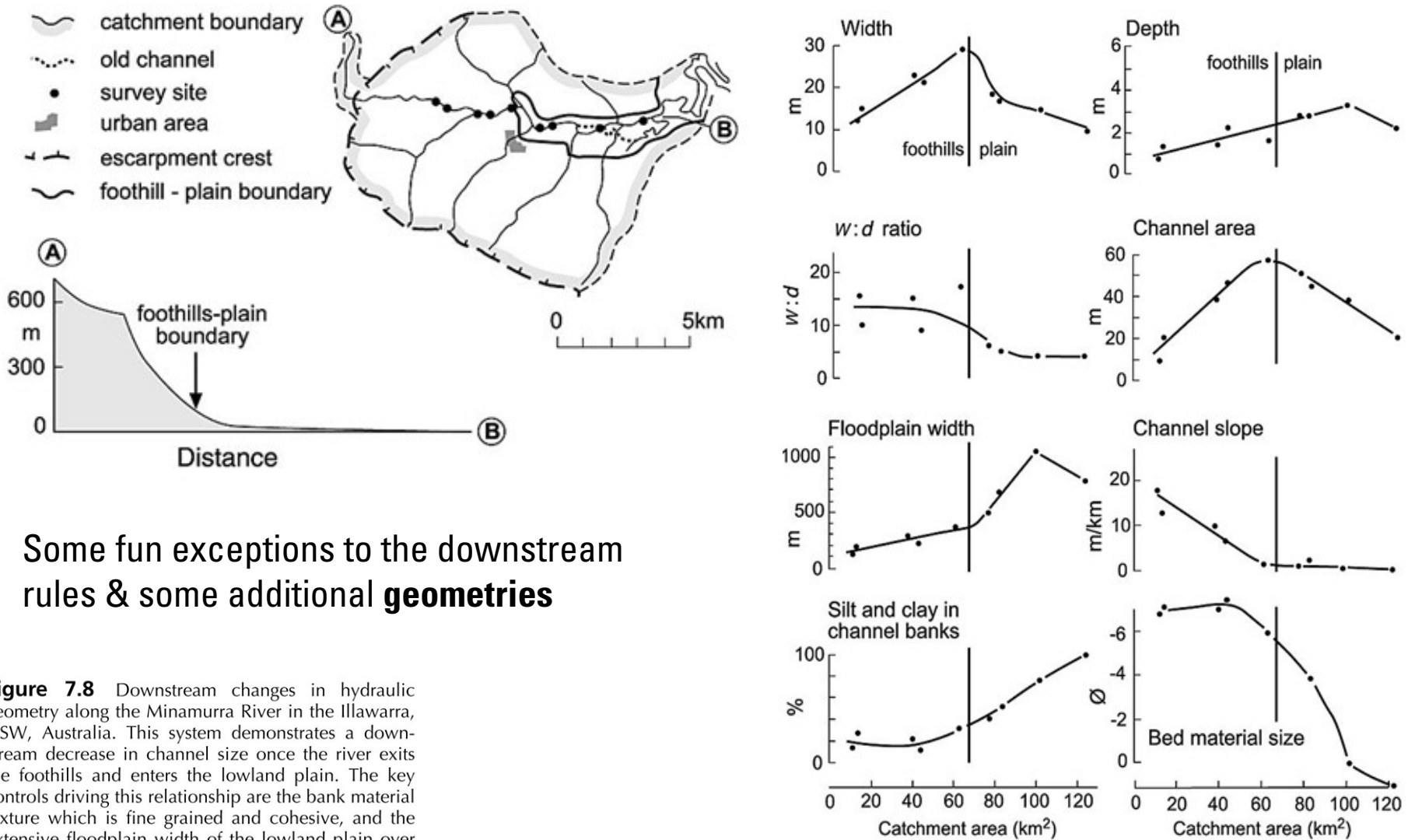
Downstream Station



EXPLANATION

- CHANGE DOWNSTREAM FOR DISCHARGE OF GIVEN FREQUENCY
- - - CHANGE AT GAGING STATION FOR DISCHARGES OF DIFFERENT FREQUENCIES

Patterns of Downstream Hydraulic Geometry



Some fun exceptions to the downstream rules & some additional **geometries**

Figure 7.8 Downstream changes in hydraulic geometry along the Minamurra River in the Illawarra, NSW, Australia. This system demonstrates a downstream decrease in channel size once the river exits the foothills and enters the lowland plain. The key controls driving this relationship are the bank material texture which is fine grained and cohesive, and the extensive floodplain width of the lowland plain over which flows are regularly dispersed. This means that channels do not have the erosive energy to form large channels in downstream reaches. Modified from Nanson and Young (1981a,b). ©Elsevier. Reproduced with permission.