12.163/12.463 Surface Processes and Landscape Evolution

K. Whipple *September, 2004*

II. Alluvial Channels and Their Landforms

A. Definitions and Landforms

Types of Channel: Rill, Gully (erosion limited, no floodplain, usually straight and steep), Bedrock Channels, Mixed Bedrock-Alluvial Channels, Alluvial Channels

Bedrock and Mixed Channels are critical to the evolution of mountain ranges (erosional environment). Alluvial Channels are critical to sediment transport, development of stratigraphic record, flooding, water resources – the most studied and best understood.

Generally, Fluvial Channels can be conceptually classified into two groups, which I will term simply Type I and Type II channels. These classifications overlap with Bedrock/Mixed vs. Alluvial channels, but are somewhat distinct.

I	←continuum →	II
"Imposed Channel Form"		"Self-formed Channels"
Immobile bed: boulder-choked channel (landslides, debris flows, rock falls) or bedrock in bed + banks		Mobile bed + banks (transportable sediment)
Stochastic sediment supply hillslope (mass wasting) Controls morphology and transport rates Stochastic flooding		Both floods and sediment supply are less stochastic; less susceptible to big floods/less variation in sediment supply
Supply-limited Detachment-limited		Transport-limited
$E \propto \tau_b$		$E = \frac{\partial z}{\partial t} \cong \frac{\partial q_s}{\partial x}$
small drainage area		large drainage area (Exceptions!) • uplift rate patterns • patterns of bedload supply

Very long time scales

Type I → II: as relief reduces, mass-wasting impact reduces, bedrock and boulders weather, incision rates decline

Short time scales (temporary)

Type II→ I: landslide and debris flow input can derange (narrow, straighten, steepen, etc) alluvial channels and armor the bed with immobile blocks.

Time scale: 0rder 1-10s ka input to alluvial channel

Type I → II: increase sediment supply (due to fire, landuse (agriculture, deforestation),

climatic fluctuations (El Nino, Major Storm)

sediment dammed behind landslides, log jams, etc.

Thus Channel form and function may vary over time as a channel is hit by a frequency distributions of floods, sediment supply rates, mass wasting events, and variable sediment size inputs.

B. Alluvial Channels

Self-formed morphology

- set by entrainment, transport, and deposition

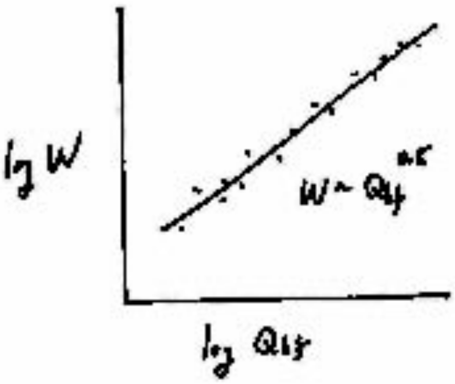
They move unconsolidated sedimentary materials present in the

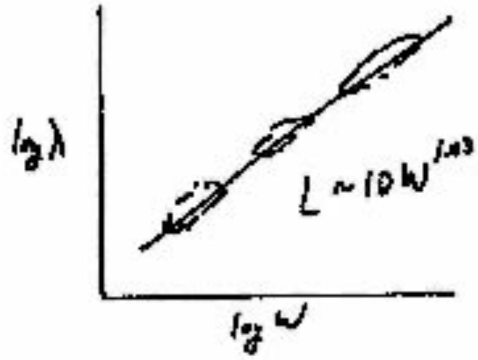
- valley fill
- flood plain/bank
- flow

Their Form is dependent on Environmental controls

- hydrology (how much water, when, how long?)
- sediment character (how large/small, hard/soft, dense, rounding)
- tectonics: uplifting, subsiding or stable?

Where these factors are constant within a drainage basin, River morphology can be stable, but channel is *not*. That is, stability is maintained in an aggregate, statistical sense only.
Examples: Channel width as a function of bankfull discharge; meander wavelength as a function of channel width.





Understanding alluvial rivers is important for:

Watershed management, River management (water resources – dams, irrigation, transport), recreational resources, fisheries, environmental management (River restoration efforts), Paleohydraulic and Sedimentological reconstruction.

C. Brief Definitions of Alluvial Landforms

Fill Terrace: abandoned alluvial surface, formed in alluvial sediments now well above the normal level of inundation; reason – river incised into floodplain (increase Q_w, decrease Q_s, uplift, sea-level fall, river capture).

Strath Terrace: erosional terrace cut into bedrock (may have a capping of alluvial sediments – the top of which is called the Terrace tread).

[Terraces can be paired or unpaired, and can be important indicators of climate change or uplift patterns – but one must be careful in interpretation].

Floodplain: depositional alluvial surface frequently inundated by overbank floods (legal definition – inundation by 100-year flood). May be either dominated by vertical accretion by settling of fine-grained suspended sediments, or lateral accretion by coarser bedload material.

Floodplain channels: smaller channels important in the flooding and draining of the floodplain (and in the distribution of sediment, development of stratigraphy)

Meander belt: zone on the floodplain that experiences frequent occupation by the river channel.

Paleochannels, oxbow lakes: abandoned channel segments (avulsion and meander cut-off events).

Levee: natural embankment of coarser-grained material immediately adjacent to the channel

Crevase splay: fan-shaped wedges of coarse sediment deposited downstream of levee breaks during floods.

Bars: In-channel accumulations of sediment that are often only inundated at bankfull flows. Very important to channel form and function – bars are important part of hydraulic roughness, deflect flow, and active migration of bar forms (slow movement over years, can be re-arranged by big floods) is an important component of sediment transport.

Mid-channel bar: common in zones of rapid deposition (rivers overloaded with coarse bedload), at channel widenings, etc. As these become common they will split flow into multiple threads.

Alternate bars: side-channel bars formed in straight channels (mobile bed) – a natural flow/sediment transport instability that will always form: positive feedbacks from virtually any initial perturbation to a straight, flat-bed channel.

Point bars: bar forms produced by deposition on the inside of meander bends, critical to meander migration and alluvial stratigraphy

Back-bar chute: high flow channel often formed at top, inside edge, of point bar.

Scroll-bar topography: series of arcuate topographic ribs left behind a migrating meander loop – related to migrating bar forms and back-bar chutes.

Thalweg: the trace of the deepest part of the flow (approximates, but is not equal to, the trace of the high velocity core).

Dunes: large migrating bedforms with avalanche faces on the lee side; forms have heights limited by flow depth (~1/3 *h*).

Ripples: small migrating bedforms, avalanche faces, forms not depth-limited – spacing controlled by flow velocity, grainsize, and fluid viscosity

D. Alluvial Channel Types

Diagram showing sketches of each
Straight channels (single thread)

- constrained; mobile alternate bars; gravel environments
- rare; unstable

Braided channels

- multiple-thread channels, dominated by mid channel bars, commonly gravel
- large width-to-depth ratios, very unstable with frequent lateral shifts
- often totally re-arranged by large floods, no levees, non-cohesive banks

Anastomosing (few interweaving channels)

- multiple-thread channels, but not channels filled with shifting mid-channel bars; stable compared to braided channels, but subject to frequent avulsions – river jumps between a few used and unused, but well-defined channels
- often developed in well vegetated settings with gravel beds

Meandering

- single thread channel, sinuous plan form, point bars in each bend
- moderate width-to-depth ratios, cohesive banks, associated with levees, fine-grained floodplain sediments

Environmental Controls on Dominant Channel Forms

Braided Channels	*Meandering Channels*
Non-cohesive banks Abundant bedload and rapid in-channel deposition Steep Flashy discharge	Cohesive banks Significant suspended load, floodplain sedimentation Gentler slopes Less flashy discharge
Unpredictable – flooding problems	More stable, predictable over short term

Viewgraphs: Examples from the Snoqualmie (WA) and Fly (Papua New Guinea) Rivers

Problem:
Alluvial channels are "self-formed" or "self-adjusted" to controlling variables: Q_w, Q_s, D_{50}, Vegetation. Channels develop "graded profiles", that is they steepen sufficiently to carry the sediment supplied from upstream.

So why is overbank flooding so common? What sets channel morphology – the combination of width, depth, slope, plan form? Of the entire histogram of floods that occur, which are most important in setting these properties?

E. The Magnitude and Frequency of Events: Dominant Discharge Concept

Concept: There is a flood discharge that dominantly sets channel morphology and dictates long-term mean sediment transport.

Essential Observation:
Big floods → channels are *not* scaled to these (over bank flow)
Low flow → flow responds to channel, *not* channel-forming events

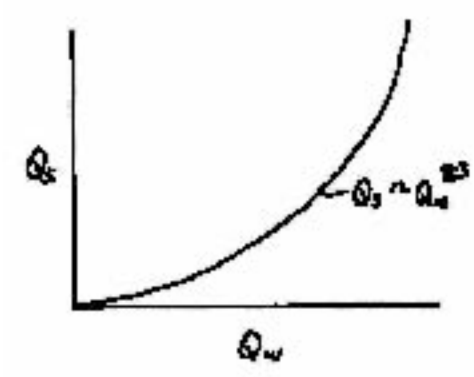
1960 Wolman and Miller, J. Geology "Magnitude and Frequency of Forces in Geomorphology"

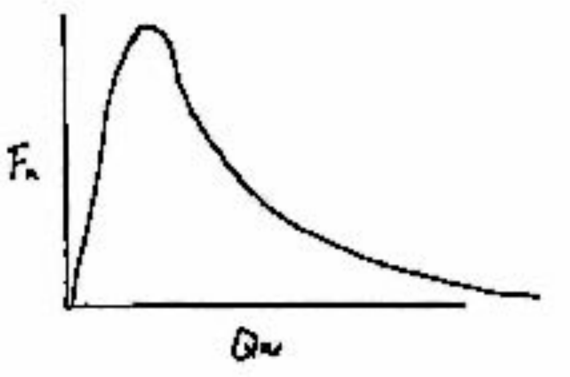
1. Q_s (suspended sediment – dominant part of load in sandy rivers) vs Q_w

$$Q_s \propto Q_w^{2-3} \quad \text{(mechanics of sediment transport)}$$

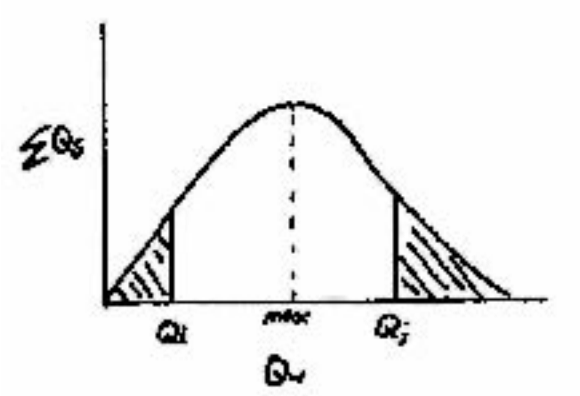
2. Frequency distribution of floods (right skewed – only few big floods)

3. Product of PDF and $Q_s(Q_w)$ curves → cumulative contribution to long-term sediment transport as a function of Q_w; exhibits a clear maximum at relatively low flood discharge.





Identify cut-off discharges Q_i and Q_j where $Q_w < Q_i$ and $Q_w > Q_j$ make only minor contributions.



Summary: peak in net transport is accomplished by relatively small, but frequent events.

Typically Observed from Data:

Forested catchments, Common	Some Rangeland
$Q_{\max} = Q_{1-2}$	$Q_{\max} = Q_{3-5}$

Leopold and Maddock, 1953 show that $Q_{bf} \approx Q_{1-2}$ is correspondingly very common. Qualitatively these are logically the channel-forming flows, or the dominant discharge.

> Recall the Continuum of Type I → Type II channels. Wolman and Miller & Leopold and Maddock data and analysis only apply to Type II alluvial channels with dominant suspended sediment and mobile bed and banks.
>
> Type I channels (even ones temporarily in this state due to recent landslide or debris flow disruption) are probably more sensitive to big floods and Type II → Type I shifts are often accomplished by big floods, recovery to Type II forms will be gradual. That is, river morphology will have a long memory of these big floods [such memory can be antipated to be longer in steep lands and arid regions with flashier discharges and restricted riparian vegetation].

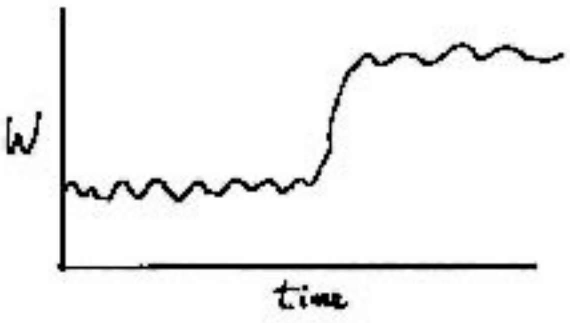
Channel Width (and sometimes channel morphology, e.g. meandering → braided) is the variable most commonly adjusted by big floods or changes in sediment load.

Schumm and Lichty (1964) USGS PP 357-D show a classic example. They present historical data in which a stable channel suddenly (over 1-2 years) widens and shallows

Causes: (1) a series of big floods
(2) a wave of sediment arrives

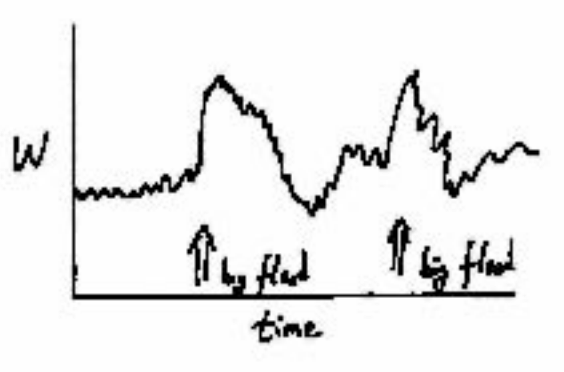
{at smaller scale, debris flows, input woody debris, logging *can* do the same thing}

SKETCH: Width vs. time observed.



In non-cohesive banks, vegetation (roots) is the key to the stability of banks and therefore channel width – the bed is mobile and often big floods rearrange the channel, rip out vegetation and cause major, but temporary, perturbations of channel width.

SKETCH: Width vs. time over longer scales (100s years) and hypothetical frequency distributions of channel width at a location through time.



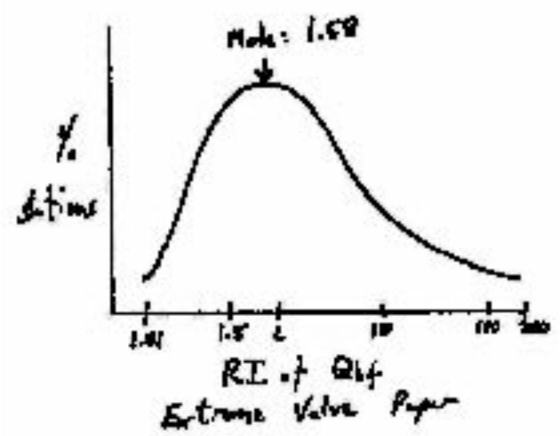
Channel Width and the Bankfull Discharge

So what about Leopold and Maddock's (1953) data that showed that $Q_{bf} \approx Q_{1-2}$ is very common? If big floods suddenly disrupt channel form and greatly increase width, this implies channels are being re-sized by big floods. That is, following a sudden increase in channel width during a big flood, the bankfull discharge will correspondingly increase. One may then anticipate that over some number of years, the channel will gradually recover as many smaller floods rework the mobile bed and banks, deposit sediment where the channel is too wide and shallow, and vegetation is reestablished.

Many papers in the 1960's confirmed the earlier result that $Q_{bf} \approx Q_{1.5}$. A couple paper since, however, have emphasized variability around this mean condition.

Gar Williams (1978) Water Resources Research.

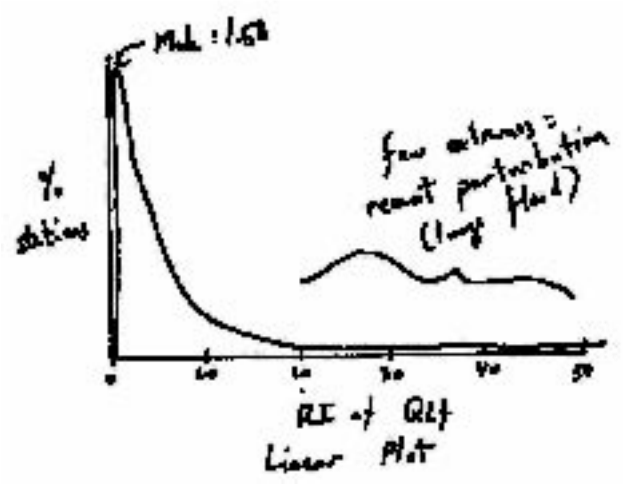
> Field study: uses many methods to assess Q_{bf} from field observations and then compares these data to Q_w records from USGS gauging stations on these rivers.
>
> SKETCH: Resulting data on Extreme Value Paper (similar to log scale)



> William's summary of this data: Q_{bf} is "anything from $Q_1 - Q_{200}$" (the extreme values observed in the data set).

But from another perspective, his data are actually a strong confirmation of the concept that $Q_{bf} \approx Q_{1.5}$, allowing for occasional distruptions by big floods with a finite recovery time, as is intuitively expected.

SKETCH: William's data on Linear plot.



Problem: How do we describe processes of flow, sediment transport, erosion, and deposition quantitatively? How assess the controls on morphology, migration / avulsion styles and rates, the production of alluvial stratigraphy, response to changes in climate or tectonics?

Needed puzzle pieces: Conservation of Mass (water and sediment); Conservation of Momentum (e.g., shear stress distributions, controls on velocity); Sediment Transport Law; Channel Width "Rule"; Bedform mechanics and how they interact with channel morphology, flow, and sediment transport.

Sources: Empirical (lab/field) and Theoretical (modeling) studies.