Controls on the lateral channel migration rate of braided alluvial channel systems.

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**Key question**
- What controls the rate of lateral channel migration in alluvial channels?

**Aim**
- Develop scaling between channel migration rates, the channel geometry and external boundary conditions
- Test the scaling against existing field data

**Main finding**
- Direct controls on migration rates, \( M_L \)
  - Strong influence of channel bank height \( H_b \)
  - Strong influence of water discharge, \( Q_w \)
  - Weak influence of sediment discharge, \( Q_s \)

\[
M_L = k \frac{Q_w^{0.9 \pm 0.2} Q_s^{0.1 \pm 0.2}}{D_{50} H_b}
\]

Presentation based on:
Bufo et al., (2019), Controls on the lateral channel-migration rate of braided channel systems in coarse non-cohesive sediment. ESPL (Link)
Occurrence of mobile channels

Meandering Rivers (Mississippi, USA)

River deltas (Yellow River China)

Braided Rivers (Rakaia, New Zealand)

Natural and experimental settings
Importance of channel mobility

- Sediment routing
- Bank erosion and river management
- Construction and destruction of stratigraphy
- Valley width across active structures

Figure: USGS

Straub et al., (2009)

Chenyoulan River; Photo: A. Bufe

Bufe et al., (2016), Nat. Geosci.
Two types of channel movement

Avulsions (abrupt)
• Dominant in rapidly aggrading systems

Migration (gradual)
• Dominant in bypass systems

Focus on
• Sediment bypass systems
• Systems dominated by migration
Controls on lateral channel migration rate

Hypothesized controls on channel migration rates

- Water discharge ($Q_w$)
Controls on lateral channel migration rate

Hypothesized controls on channel migration rates

- Water discharge ($Q_w$)
- Sediment discharge ($Q_s$)
Hypothesized controls on channel migration rates

- Water discharge \( (Q_w) \)
- Sediment discharge \( (Q_s) \)
- Bank height \( (H_b) \)

\[
\text{Dimensionless migration rate} = Q_s^* \\
\text{Suspended Sediment flux per channel width (Mt yr}^{-1} \text{ m}^{-1})
\]
Controls on lateral channel migration rate

Hypothesized controls on channel migration rates

- Water discharge ($Q_w$)
- Sediment discharge ($Q_s$)
- Bank height ($H_b$)
- (Bank cohesion ($\tau_w$) – not addressed here)

\begin{align*}
\text{suspended sediment flux per channel width} & \propto Q_s^* \\
\text{meander migration rate} & \propto Q_s^* \\
\text{suspended sediment flux} & \propto Q_s^* \\
\text{dimensionless migration rate} & \propto Q_s^*
\end{align*}

Malatesta et al., (2017), JGR


Wickert et al., (2013), JGR
**Challenges**

**Co-variation of parameters**
- For example, water and sediment discharge affect channel geometry => difficult to unravel independent controls on migration rates

**Absence of constraints on bank height**
- In many field and experimental datasets

**Experimental approach**
**Part 1: Migration rates under constant boundary conditions**
- Isolates control of channel geometry.

**Part 2: Migration rates under varying boundary conditions**
- With knowledge of (1), can isolate control of external boundary conditions.
- Effects of water and sediment discharges and gran size.
Experimental setup

Alluvial fan experiments
- Loose sand ($D_{50} = 0.52$ mm)
- Steady water flux
- Steady sediment flux
- Steady base level

Bufe et al., (2019), ESPL
Data analysis

Overhead photographs
- 1-minute interval
- Calculate average channel mobility

1 mm resolution topography without water
- 1-hour intervals
- Calculate channel geometry
Part 1: Constant boundary conditions

Hypothesis
Volumetric reworking rate is constant for constant boundary conditions:

\[ M_V = L_c H_b M_L \]

- \( M_V \) = volumetric reworking rate
- \( L_c \) = Length of channel
- \( H_b \) = Bank height
- \( M_L \) = lateral migration rate
Part 1: Constant boundary conditions

Hypothesis
Volumetric reworking rate is constant for constant boundary conditions:

\[ M_V = L_c H_b M_L \]

Expectation
Inverse scaling of migration rate and bank height:

\[ M_L = \frac{M_V}{L_c H_b} \]

- \( M_V \) = volumetric reworking rate
- \( L_c \) = Length of channel
- \( H_b \) = Bank height
- \( M_L \) = lateral migration rate

Bufe et al., (2019), ESPL
Four experiments

Run 1: Constant sediment and water discharge
\[ Q_s = 790 \text{ mL/s} \]
\[ Q_w = 15.8 \text{ mL/s} \]
\[ D = 0.52 \text{ mm} \]

Run 2: Constant sediment and water discharge
\[ Q_s = 790 \text{ mL/s} \]
\[ Q_w = 15.8 \text{ mL/s} \]
\[ D = 0.52 \text{ mm} \]

Run 7: Constant sediment and water discharge
\[ Q_s = 790 \text{ mL/s} \]
\[ Q_w = 15.8 \text{ mL/s} \]
\[ D = 0.52 \text{ mm} \]

Run 7: Constant sediment and water discharge
\[ Q_s = 790 \text{ mL/s} \]
\[ Q_w = 2.4 \text{ mL/s} \]
\[ D = 0.52 \text{ mm} \]

85% lower
Autogenic variability of bank height

Unincised

Run time: 6h

Run time: 18h

Incised

Same experiment

Run time: 6h

8h difference

Run time: 18h

Bufe et al., (2019), ESPL
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Inverse scaling of migration rate and bank height:

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- \( L_c \) = Length of channel
- \( H_b \) = Bank height
- \( M_L \) = lateral migration rate

Theoretical inverse fit
\[ M_L = 7.2 H_b^{-1} \]
\[ r^2 = 0.78 \]

Best fit
\[ M_L = 7.2 H_b^{-0.84} \]
\[ r^2 = 0.81 \]
Part 1: Constant boundary conditions

Results
- bank height = first-order control on migration rate
- Inverse scaling between migration rate and bank height fits well
- Define a “bank-sediment yield”: $M_L H_b$

Hypothesis
- Bank-sediment yield encompasses all autogenic variability
- Bank-sediment yield is independent of other channel geometry parameters
  - Channel-system width
  - Channel slope
  - Water depth
  - $M_L = \text{lateral migration rate}$

Theoretical inverse fit:
$$M_L = 7.2 H_b^{-1}$$
$$r^2 = 0.78$$

Best fit:
$$M_L = 7.2 H_b^{-0.84}$$
$$r^2 = 0.81$$

Run 1 (High Qs)  Run 5 (Low Qs)
Run 2 (High Qs)  Run 7 (High Qs)
Hypothesis

- Bank-sediment yield encompasses all autogenic variability
- Bank-sediment yield is independent of other channel geometry parameters
  - Channel-system width
  - Channel slope
  - Water depth

Part 1: Constant boundary conditions

- Independent of channel width
- Independent of water depth
- Independent of channel slope
Hypothesis
• Bank-sediment yield encompasses all autogenic variability
• Bank-sediment yield is independent of other channel geometry parameters
  • Channel system width
  • Channel slope
  • Water depth

Part 1: Constant boundary conditions

Results for Part 1: constant boundary conditions
• Variations in bank height can explain variations in migration rates
• When bank heights are accounted for, none of the other main channel geometry parameters scale with migration rates. I.e. Bank sediment yield = constant
• \( \Rightarrow \) Volumetric rate of sediment reworking is constant under constant boundary condition.

Part 2: Varying boundary conditions
• Dimensional analysis with varying boundary conditions
• Test against compilation of experiments
Dimensional analysis

Governing variables
Governed variables

- Bank-sediment yield: \( H_b M_L \left[ \frac{L^2}{T} \right] \)

From Part 1:

- Bank-sediment yield encompasses direct control of channel geometry on migration rate
- All other variations can be directly linked to external boundary conditions
Governing variables

- Bank-sediment yield: $H_b M_L \frac{L^2}{T}$
- Water discharge: $Q_w \frac{L^3}{T}$
- Sediment discharge: $Q_s \frac{L^3}{T}$
- Grain size: $D_{50} \ [L]$
**Governing variables**

- Bank-sediment yield: $H_b M_L \left[ \frac{L^2}{T} \right]$
- Water discharge: $Q_w \left[ \frac{L^3}{T} \right]$
- Sediment discharge: $Q_s \left[ \frac{L^3}{T} \right]$
- Grain size: $D_{50} [L]$

**Buckingham π theorem**

- 2 parameters ($\pi_1, \pi_2$)
- $\pi_2 = f(\pi_1)$

**Dimensionless parameters:**

- $\pi_1 = \frac{D_{50} H_b M_L}{Q_s}$
- $\pi_2 = \frac{Q_s}{Q_w}$

**From Part 1:**

- Bank-sediment yield encompasses direct control of channel geometry on migration rate
- All other variations can be directly linked to external boundary conditions

**Compilation of experiments**

- Parameters varied in compiled experiments

**Theory**

For $n$ variables and $k$ physical dimensions:

- $n-k$ independent dimensionless parameters describe the physics of the system
- Each single parameter can be expressed as a function of the other parameters

**Chosen parameters**

- The parameters can be chosen as desired as long as they are (1) independent and (2) among them, include all governing variables.
Governing variables

- Bank-sediment yield: $H_bM_L \left[ \frac{L^2}{T} \right]
- Water discharge: $Q_w \left[ \frac{L^3}{T} \right]
- Sediment discharge: $Q_s \left[ \frac{L^3}{T} \right]
- Grain size: $D_{50} [L]

Buckingham π theorem

- 2 parameters ($\pi_1, \pi_2$)
- $\pi_2 = f(\pi_1)$

Dimensionless parameters:

- $\pi_1 = \frac{D_{50}H_bM_L}{Q_s}$
- $\pi_2 = \frac{Q_s}{Q_w}$

Regression against compilation of experiments

- $M_L = k \frac{Q_w^{1.1 \pm 0.4} Q_s^{-0.1 \pm 0.4}}{D_{50}H_b}$

- $r^2 = 0.45$

- Wickert et al., 2013

- Run 1: Behind other data
Governing variables

- Bank-sediment yield: $H_b M_L \left[ \frac{L^2}{T} \right]$
- Water discharge: $Q_w \left[ \frac{L^3}{T} \right]$
- Sediment discharge: $Q_s \left[ \frac{L^3}{T} \right]$
- Grain size: $D_{50} \left[ L \right]$

Buckingham π theorem

- 2 parameters ($\pi_1, \pi_2$)
- $\pi_2 = f(\pi_1)$

Dimensionless parameters:

- $\pi_1 = \frac{D_{50} H_b M_L}{Q_s}$
- $\pi_2 = \frac{Q_s}{Q_w}$

\[ M_L = k \frac{Q_{w}^{0.9 \pm 0.2} Q_s^{0.1 \pm 0.2}}{D_{50} H_b} \]

Including base-level changes – see Bufe et al., (2019), ESPL
Application to the field?

Adapted from Hickin & Nanson (1984), JHE

\[ M_L = k \frac{Q_{w}^{0.9 \pm 0.2} Q_{s}^{0.1 \pm 0.2}}{D_{50} H_b} \]

Missing constraints on \( Q_s \)

\[ y = 0.22x^{0.68} \]

\[ R^2 = 0.62 \]
Application to the field?

\[ M_L \sim k \, Q_s^{0.28} \]


\[ M_L = k \frac{Q_w^{0.9 \pm 0.2} \, Q_s^{0.1 \pm 0.2}}{D_{50} H_b} \]
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  - Strong influence of water discharge, $Q_w$
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- $M_L = k \frac{Q_w^{0.9 \pm 0.2} Q_s^{0.1 \pm 0.2}}{D_{50} H_b}$

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