River channel formation and response to variations in discharge, sediment and vegetation

PART 2: RIVER PLANFORM

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Tagliamento River, Italy
PART 2 RIVER PLANFORM

1. Bars and river planform
2. Bar and planform prediction
3. Comparison with empirical relations
4. Role of floodplain vegetation
5. Summary
1 Bars and river planform

Mow River, Bhutan
River bars are large periodic sediment deposits that emerge during low flows.

Missouri River, Nebraska-South Dakota border

Canalized Rhine River, Switzerland
But there are also non-periodic bars

Point bars inside river bends

Usumachinta River, Guatemala

Red River, Texas
Periodic alternate bars characterize meandering rivers

Alatna River, Alaska
Periodic multiple bars characterize braided rivers

Waimakariri River, New Zealand (courtesy M. Hicks)

Hii River, Japan (courtesy T. Hosoda)
The river planform is related to bar characteristics, particularly to the number of bars in the cross-section.

- Meandering
- Transition
- Braiding

- No bars
- Alternate bars
- Multiple bars
How are bar characteristics related to water, sediment and vegetation?
2 Bar and planform prediction

Mow River, Bhutan
Bar characteristics

- size in transverse and longitudinal direction
- migration rate
- growth rate
- number of bars per cross-section
We can distinguish three types of bars, caused by two different mechanisms: forcing and instability:

- **Forcing**
  - Forced bars
  - Hybrid bars
- **Morphodynamic instability**
  - Free bars

The types of bars are divided into:
- **Steady**
- **Periodic**
Forcing is every geometrical constraint of the river channel that fixes the flow pattern.

Forcing can be caused by a bend, a groyne, a local narrowing....
Due to the centrifugal force (inertia) the water flow concentrates near the outer bank.
A flat river bed surface may be unstable and generate waves of different size: ripples, dunes, periodic bars.
Two types of periodic bars

Free bars

Periodic:
morphodynamic instability
migrating
(downstream but also upstream)

Kander River, Switzerland
Two types of periodic bars

Hybrid bars

Periodic: morphodynamic instability and forcing

steady

Adige River, Italy
Stability analyses: periodic bars

TWO APPROACHES

GENOA
- Initial growth in infinitely long rivers
- Focus: free bars

DELFT
- Initial steady bar configuration in rivers with forcing
- Focus: hybrid bars

(definition “Genoa and Delft schools” after Parker, 1989)
Bar schematization

Waves in transverse and longitudinal direction
The number of bars per cross section is indicated by bar mode $m$

$m = 1$ alternate bars

$m = 2$ one bar in the middle/two bars near banks

$m \geq 3$ multiple bars

$m$ indicates the intensity of braiding of the river

$m = 2$
Results for free alternate bars

Longitudinal wave number \( k = \frac{2\pi}{L_p} \)

Initial growth in infinitely long rivers
Focus: free bars

Marginal (critical) growth curve \( m = 1 \)

Damping (no bars)

Longitudional wave number \( k = 2\pi/L_p \)
Results for periodic free bars

\[ \beta = \frac{B}{h} \]

\[ \beta_{\text{crit}} \]

\[ \beta_{\text{crit}} \]

\[ m = 1 \]

\[ m = 2 \]

Wave number \( k = \frac{2\pi}{L_p} \)

Curve of highest growth

Focus: free bars

GENOA

Initial growth in infinitely long rivers
Bars are governed by the flow width-to-depth ratio

Multiple bars are found in shallow and wide rivers
River channels with no bars have small width-to-depth ratios

(Engelund, 1970; Tubino and Seminara, 1990)
Important for bars is also sediment mobility

<table>
<thead>
<tr>
<th>$D_{50} = 0.37$ mm</th>
<th>$D_{50} = 0.50$ mm</th>
<th>$D_{50} = 1.00$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>well sorted</td>
<td>well sorted</td>
<td>poorly sorted</td>
</tr>
</tbody>
</table>

Same discharge, almost the same $B/h$, but different sediment

(experiments Roelvink, Lako, Le, Crosato, 2015)
Results for hybrid bars

(Crosato and Mosselman, 2009)

bar mode

\[ m^2 = 0.17 g \frac{(b - 3)}{\sqrt{\Delta D_{50}}} \frac{B^3 i}{CQ_W} \]

\( b = 4 \) for sand-bed rivers

\( b = 10 \) for gravel-bed rivers

(for width-depth ratio < 100 and assuming uniform flow)
If $m < 0.5$ no alternate bars

If $0.5 < m < 1.5$ alternate bars

If $1.5 < m < 2.5$ central bars: transition between meandering and braiding

If $m > 2.5$ multiple bars: braiding
Factors influencing the river planform

\[ m^2 \sim \frac{(b - 3)}{\sqrt{\Delta D_{50}}} \frac{B^3}{C} \frac{i}{Q_W} \]

Braiding increases with
- Channel width: \( B \)
- Slope: \( i \)
- Sediment transport non-linearity: \( b \) (gravel/sand)
- Bed roughness: \( 1/C \)

Braiding decreases with
- Discharge: \( Q_W \)
- Sediment size: \( D_{50} \) (but in this case \( b \) might increase too)
3 Comparison with empirical relations

Leopold & Wolman (1957)
Empirical relations for river planform: 
braiding if ratio \((i/Q_w)\) exceeds threshold

Leopold & Wolman (1957): bankfull discharge and slope can discriminate between meandering and braiding

\[
i_{\text{crit}} = 0.06 \ Q_{bf}^{-0.44}
\]

Henderson (1963) added the size of bed material

\[
i_{\text{crit}} = 0.64 D_{50}^{1.14} \ Q_{bf}^{-0.44}
\]

(threshold slope increases if \(D_{50}\) increases)

(bankfull is assumed to be the formative discharge)
Parker (1976) accounts for bar formation and relates the critical slope to the channel with-to-depth ratio and Froude number:

\[ i_{\text{crit}} \sim \left( \frac{h}{B} \right) \frac{u}{\sqrt{gh}} \]

Ferguson (1987): the factors controlling the channel planform are: flow strength, amount and type of sediment load and bank strength.

Millar 2000 includes the bank stabilizing effects by vegetation through the bank friction angle (bank strength)

\[ i_{\text{crit}} = 0.0002 D_{50}^{0.61} \phi^{1.75} Q_{bf}^{-0.25} \]
Threshold based on bar mode

Imposing $m = n$ as threshold:

$$i_{crit} \sim \frac{\sqrt{\Delta D_{50}}}{(b - 3)} \frac{u}{\sqrt{gh}} \frac{Q_W}{B^3}$$

- Formative discharge
- Channel width
- Froude number
- Sediment and sediment transport characteristics

Some aspects of Parker’s (1976)
The width is assumed to be known
By affecting the width, what is the role of vegetation?
4 Role of floodplain vegetation

Results of some recent studies

River Atrato, Colombia
(courtesy A. Montes Arboleda)
By decreasing the width and increasing the depth, Floodplain vegetation is expected to affect the bar mode and thus the river planform.

Observation: meanders are dominant within luxuriant forests and braids are dominant within scarce vegetation.

River Tagliamento, Italy

Meandering river in the Amazon
Effects of vegetation on river planform - Experimental study

(Tal and Paola, 2010)

Unvegetated baded channel transforms in predominantly single-channel

(no flows on floodplains, no colonization by plants of emerging deposits)
Effects of vegetation on river planform
Numerical study: floods + colonization

(Crosato and Samir Saleh, 2011)

2D morphodynamic model inspired by the Allier River (France)
Straight channel with high/low flow sequences
Colonization by vegetation of bed surfaces that emerge during low flows
Results: river planform

With vegetation:

Colonization of bars stabilizes accreting banks and pushes the flow toward the opposite bank.

Bank erosion decreases.

The river tends to have a single channel and a meandering pattern.
Results: flow velocity

With vegetation:
- High plant roughness diverts the flow into the main channel
- Higher flow velocity in the main channel
- Lower flow velocity at channel edges and on floodplains
Results: bed shear stress plan view

WITH

WITHOUT
Results bed shear stress (cross-section)

WITH VEGETATION

WITHOUT VEGETATION
Results: cross-sections

Bed level at M=60

Bed level at M=88

Bed level at M=124

Bed level at M=134
Results high vs. low vegetation density

With lower vegetation density:
- Higher braiding intensity
- Longer meander wave length
Results high vs. low vegetation density

With lower vegetation density:
- higher flow velocity on vegetated zones
- lower flow velocity in non-vegetated zones
Effects of bar colonization by plants on river planform - Experimental study

(Vargas-Luna, Duró, Crosato, Uijttewaal 2019, in review)

Large flume: 50x5 m
10,000 plastic plants
Results with and without vegetation: three scenarios

No vegetation

Vegetation on floodplains only

Bar colonization by vegetation
No vegetation: Channel at transition between meandering and braiding
Vegetation on floodplains only: reduced bank erosion narrower channel
Bar colonization by vegetation: increased opposite bank erosion, higher sinuosity, anabranching.
Results

Colonization by vegetation results in meandering and anabranching

Waterpark Bosscherveld along Border Meuse River, the Netherlands
5 Summary

Discharge
Sediment
Vegetation

CLIMATE

GEOLOGY
If sediment load and size remain constant:

- Floodplain vegetation density:
  - Higher discharge:
    - Width decreases
    - Depth decreases
  - Lower discharge:
    - Width increases
    - Depth increases

- Drier climate:
  - Bars decrease
  - Depth increases

- Wetter climate:
  - Bars increase
  - Depth decreases

Discharge:

- Higher:
  - Width decreases
  - Depth increases
  - Slope decreases

- Lower:
  - Width increases
  - Depth decreases
  - Slope increases
If the discharge remains constant:

- **Floodplain vegetation density**
  - HIGHER:
    - width↓
    - depth↑
    - slope↓
    - bars↓
  - LOWER:
    - width↑
    - depth↓
    - slope↑
    - bars↑

- **Sediment size and/or load**
  - HIGHER:
  - LOWER:
If floodplain vegetation remains constant:

- **HIGHER**
  - Discharge
  - incision
  - slope \(\downarrow\)
  - bars \(\downarrow\)
  - depth \(\uparrow\)

- **LOWER**
  - dam
  - depth \(\downarrow\)
  - bars \(\uparrow\)
  - slope \(\uparrow\)

- **wetter climate upstream**
  - incision
  - depth \(\uparrow\)
  - bars \(\uparrow\)
  - slope \(\uparrow\)

- **aggradation**
  - depth \(\downarrow\)
  - bars \(\uparrow\)

- **Sediment size and/or load**

**Notes:**
- Higher discharge leads to incision and lower slope.
- Lower discharge results in deposition and higher slope.
- Greater precipitation and wetter climate upstream cause incision and increased sediment transport.
- Floodplain vegetation helps to stabilize the system and maintain a balance between erosion and deposition.
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