LATERAL MIGRATION
of
ALLUVIAL CHANNELS

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Objectives

Discuss the lateral migration of alluvial channels and provide numerous examples on:

• Physical processes and morphology
• River mechanics and numerical modeling
• River engineering and management
• River morphology and restoration
Presentation Content

Main characteristics of meandering channels

- Mechanics of sediment transport in curved channels
- Numerical modeling of meander migration
- Morphology of chute and neck cutoffs
- River engineering and management
- River restoration and water quality
Main characteristics of meandering channels

(Photo by Bruce Molnia, Terra Photographics; American Geological Institute)
Meandering Channel Geometry

Meander Geometry Variables
L = length of meander along the channel
x = Distance along the thalweg
R = Radius of curvature
Rmin = Minimum radius of curvature
θ = Orientation angle
θm = Maximum orientation angle
Wb = Belt width
Wm = Meander width
Λ = Length of meander

Radius of curvature is infinite at the inflection points

Geometry drawing modeled after Julien 2002
Sine-Generated Curve

- Meander pattern can be approximated by a sine-generated curve

\[ \theta = \theta_m \cos \frac{2\pi x}{L} \]

- \( \theta \) = stream angle
- \( \theta_m \) = max angle
- \( x \) = downstream distance
- \( L \) = channel length

Figure 6.12. Meandering planform geometry (after Langbein and Leopold, 1960).
Radius of Curvature

\[ R = \frac{L}{2\pi \theta_m} \csc\left( \frac{2\pi x}{L} \right) \]

\[ R_m = \frac{L}{2\pi \theta_m} \]

- \( R \) = radius of curvature
- \( R_m \) = minimum radius of curvature
- \( \theta_m \) = max orientation angle
- \( x \) = downstream distance
- \( L \) = length of channel

Figure 6.11. Definition sketch of a meandering river. From Julien (2002)
Sinuosity

$\Omega = \text{sinuosity}$

$\Lambda = \text{meander wavelength}$

$L = \text{length of channel}$

From Julien (2002)
Length and Width

From Julien (2002)
Lateral Migration of Meandering Channels

Figure 6.19. Lateral migration rates (after Biedenharn et al., 1989).
Main characteristics of meandering channels

Mechanics of sediment transport in curved channels

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Morphology of chute and neck cutoffs

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Mechanics of sediment transport in curved channels

\[ \tan \lambda \sim 11 \frac{h}{R} \]

From Julien (2002)
Particle Stability on Slopes

From the method of moments, different particle sizes move in different directions

\[ SF = \frac{l_2 F_S a_0}{l_1 F_S \sqrt{1 - a_0^2 \cos \beta} + l_3 F_D \cos \delta + l_4 F_L} \]

\[ \beta = \tan^{-1} \left\{ \frac{\cos(\lambda + \theta)}{(M + N) \sqrt{1 - a_0^2} + \sin(\lambda + \theta)} \right\} \]

from Kawai and Julien (IAHR-JHR, 1996)
Laboratory experiments show that fine sand can deposit where coarse sand cannot, i.e. point bars from Kawai and Julien (IAHR-JHR, 1996)
Roaring River Alluvial Fan: Dramatic change in sediment supply

Single channel forming

\( Q_s \) since flood has resulted in reduced number of bifurcations and a central channel is forming.

After Bathurst and Ashiq (1998)
Sediment Transport in Sharp Bends

Field measurements in the sharp bends of the Fall River, Colorado demonstrate that particles of different sizes move in different directions.

Fig. 5  Center of mass curves for three bedload size fractions from Julien and Anthony (IAHR-JHR, 2002)
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**Numerical modeling of meander migration**

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Numerical modeling of meander migration

\[
\frac{\partial (h\bar{u})}{\partial t} + \frac{\partial}{\partial x} (h\bar{u}^2) + \frac{\partial D_{ux}}{\partial x} + \frac{\partial D_{uy}}{\partial y} = -gh \frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial x} (h \tau_{xx}) + \frac{\partial}{\partial y} (h \tau_{xy}) - \tau_{bx} \tag{1}
\]

\[
\frac{\partial (h\bar{v})}{\partial t} + \frac{\partial}{\partial x} (h\bar{v}^2) + \frac{\partial D_{vx}}{\partial x} + \frac{\partial D_{vy}}{\partial y} = -gh \frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial x} (h \tau_{yx}) + \frac{\partial}{\partial y} (h \tau_{yy}) - \tau_{by} \tag{2}
\]

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (h\bar{u}) + \frac{\partial}{\partial y} (h\bar{v}) = 0 \tag{3}
\]

where \(\bar{u}\) and \(\bar{v}\) are depth-averaged velocity components in \(x\) and \(y\) directions, respectively; \(t\) is time; \(\zeta\) is surface elevation; \(h\) is flow depth; \(g\) is acceleration due to gravity; \(\tau_{xx}\) and \(\tau_{xy}\) are friction shear stress terms at the bottom in \(x\) and \(y\) directions, respectively, written as

\[
\tau_{bx} = \frac{n^2 g}{h^+} \bar{u} U \quad \text{and} \quad \tau_{by} = \frac{n^2 g}{h^+} \bar{v} U
\]

Model from Duan and Julien (ESPL, 2005)
Sediment Transport

\[ q_s = C_a [(s - 1)g]^{0.5} d_{50}^{0.5} (\mu' \tau_c - \tau_c)^{1.5} \]  
(17)

where \( q_s \) is the total bedload transport rate per unit width; \( \tau_c = (\rho_d \bar{v}_c)/\left( (\rho_d - \rho) \bar{u} d_{50} \right) \) is the effective particle mobility parameter; \( \tau_c = \tau_c / \left( (\rho_d - \rho) \bar{u} d_{50} \right) \) is the critical value of \( \tau_c \) for incipient motion depending on particle Reynolds number \( (Re_s = (u - \bar{u}) d_{50} / \nu) \), and \( \tau_c = 0.047 \) when \( Re_s > 100 \); constant coefficient \( C_a = 8.0 \); and the bed-form effect was ignored so that the factor \( \mu' \) was omitted in this model; \( d_{50} \) is the mean particle diameter; \( s = \rho_d / \rho \), where \( \rho_d \) and \( \rho \) are densities of sand and water, respectively.

\[ \frac{C}{C_a} = \left( \frac{h - z}{z} \right)^{z} \left( \frac{a}{h - a} \right)^{z} \]  
(25)

where \( a \) is the reference bed level; \( z \) is the distance from the bottom; \( Z \) is the Rouse number; and \( C \) and \( C_a \) are concentrations of suspended sediment and its value at \( z = a \), respectively. The expression of the Rouse number is given as

\[ Z = \frac{\omega}{\kappa \beta \bar{u}} \]  
(26)

The sediment continuity equation is then used for calculating bed-elevation changes

\[ (1 - \rho) \frac{\partial z_b}{\partial t} + \frac{\partial (q_{x0} + q_{x1})}{\partial x} + \frac{\partial (q_{y0} + q_{y1})}{\partial y} = 0 \]  
(33)

where \( \rho \) is the porosity of the bed and bank material, and \( z_b \) is the bed elevation.

Model from Duan and Julien (ESPL, 2005)
Bank Erosion

The mass volume contributing to the main channel from basal erosion can be calculated as

\[ q_{ne} = \frac{\xi (1 - p) h_b}{\sin \beta} \]  

(35)

where \( q_{ne} \) is the net volume of sediment contributed to the main channel from bank erosion, and \( h_b \) is flow depth at near-bank. To account for the porosity \( p \) of the bank material, the factor \( 1 - p \) is multiplied at the denominator. If \( \xi = 0 \), the riverbank is not undergoing erosion, so the near-bank, suspended sediment concentration reaches the value of equilibrium. The term \( \sin \beta \) converts the distance of bank erosion to the volumetric net bank material from basal erosion.

In natural environments, vegetation, heterogeneity in bank material and pore water pressure will add an apparent cohesion to the original non-cohesive material. The planar bank-failure model (Osman and Thorne, 1988; Darby and Thorne, 1996) is more appropriate as compared to the slumping model. In this study, the slumping bank-failure model was combined with the parallel retreat method. It assumes that mass wasting from bank failure is the product of the rate of basal erosion and height of the bank surface above the water surface. Therefore, the amount of bank material from mass failure is calculated as

\[ q_{ne} = \frac{\xi}{\sin \beta} \Delta h_{bank} \]  

(36)

where \( q_{ne} \) is the sediment material eroded per unit channel width from bank failure, and \( \Delta h_{bank} \) is the bank height above the water surface.

Model from Duan and Julien (ESPL, 2005)
Lateral Migration

\[
\varepsilon = -\frac{\left(\frac{\partial q_l}{\partial l} \frac{dr}{2} + q_r - q_{br}\right)}{h_b}
\]

Model from Duan and Julien (ESPL, 2005)
Meandering Simulations

Initial Conditions
- sine-generated
- deflection angle 30°
- discharge 2.1 \( l/s \)
- width 0.4 m
- length 13.2 m
- sediment size 0.45 mm

Model from Duan and Julien (ESPL, 2005)
Meandering Evolution

Example starting from a straight channel on the Rio Puerco, New Mexico

Model from Duan and Julien (ESPL, 2005)
Meandering Simulations

T=1.5 hrs

T=6 hrs

T=12 hrs

from Duan and Julien (J. Hydrol., 2010)
Meandering Simulations

from Duan and Julien (J. Hydrol., 2010)
Meandering Evolution

Stage 1 - Downstream Extension

from Duan and Julien (J. Hydrol., 2010)
Meandering Evolution

Stage 2 - Lateral Extension

from Duan and Julien (J. Hydrol., 2010)
Meandering Evolution

Stage 3 – Near Equilibrium

Duan and Julien (J. Hydrol., 2010)
Meandering Evolution

Stage 4 - Upstream Migration

from Duan and Julien (J. Hydrol., 2010)
Meandering Evolution

Stage 5 - Rotation and Cutoff

from Duan and Julien (J. Hydrol., 2010)
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**Morphology of chute and neck cutoffs**
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- River restoration and water quality
Morphology of chute and neck cutoffs

**Chute cutoffs**
- Occur when river cuts through the point bar, thus decreasing sinuosity
- Channel forms a middle bar.

**Neck cutoffs**
- Lateral migration increases sinuosity of the channel until two bends connect
- Sedimentation plug forms an abandoned channel called oxbow lake.
Natural Chute Cutoffs

• Often in response to an increase in sediment load

• Chute cutoffs on Williams River, AK
(Photo by N.D. Smith)
Natural Neck Cutoffs

- Geologic cutoff, San Juan River, UT
  (Photo by Roger Weller; Cochise College)

- Neck cutoff, Green River WY
  (Photo by Michael Collier; American Geological Institute)
Oxbow Lake
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River engineering and management

Mississippi River near Greenville, MS

From Winkley (1977)
Example of Engineered Cutoffs

- Earth plug separating pilot channels
- Dynamite removal of earthen plug
- One hour after opening cutoff
- Greenville Bends
  Ashbrook, Tarpley and Leland Cutoffs

Mississippi River
Leland and Tarpley Cutoffs

From Winkley (1977)
Engineered Chute Cutoff
Choctaw Bar, Mississippi River

(red line = stone dikes, yellow = bare sandbar, blue = water and green = vegetation)

From USACE (1999) and Julien (2002)
River Widening
Nakdong River near Busan, South Korea
Gupo Bridge during Typhoon Maemi in 2003
Retrofitting Bridge Piers after Riverbank Shifting

From Park et al. ASCE-JHE 134(11), 2008
Figure 14. Gupo and Subway Bridge Piers before and after retrofitting construction

Park et al. ASCE-JHE 134(11), 2008.
River Management
Rio Grande below Cochiti Dam, NM

1935 1972 1992

From Richard et al. ASCE-JHE 131(11), 2005
Hydraulic Geometry of the Rio Grande

Reach 2

- 1992 Active Channel
- 1985 Active Channel
- 1972 Active Channel
- 1962 Active Channel
- 1949 Active Channel
- 1935 Active Channel
- 1918 Active Channel

From Richard et al. ASCE-JHE 131(11), 2005
Jetty fields and vegetation of the Rio Grande

Jetty System near Bernardo NM, in 1963
Jetty System near Bernardo NM, in 2002
Sediment Plugs on the Rio Grande
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River restoration and water quality
River restoration and water quality

Cheongmi Stream South Korea from Kim et al. (2011)
Historical Planform

Cheongmi Stream, South Korea
Water Quality Issues
Near the neck cutoffs of the Red River, LA
Water Quality Issues
Near Imha Dam, South Korea

From An, Sangdo, CSU and K-Water, 2011
Water Quality Modeling
Interflow turbidity currents at Imha Dam, SK

from S.D. An, CSU, 2011
Conclusions

Physical processes and morphology
• Sine-generated curves describe meandering channels

Mechanics and numerical modeling
• Secondary flow and particle stability are most important in curved channels
• Numerical models should include basal erosion and bank sliding processes

River engineering and management
• River engineering requires mastery of hydraulics and sedimentation
• Engineering design during extreme events should be emphasized

Stream restoration and water quality
• Restoration efforts include stream ecology and water quality
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