
LATERAL MIGRATION
of
ALLUVIAL CHANNELS
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Google

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

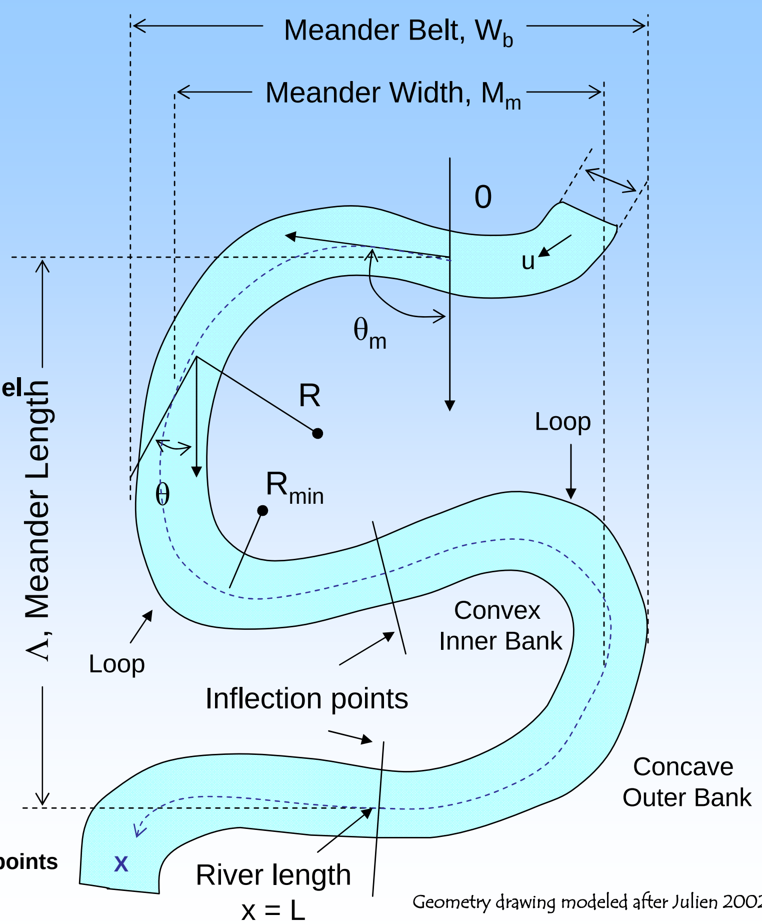
Main characteristics of meandering channels

- *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



Geometry drawing modeled after Julien 2002

<u>**Meander Geometry Variables**</u>

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
W_b = Belt width
Wm = Meander width
Λ = Length of meander

Radius of curvature is infinite at the inflection points

Sine-Generated Curve

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

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

θ = stream angle

θ_m = max angle

x = downstream distance

L = channel length

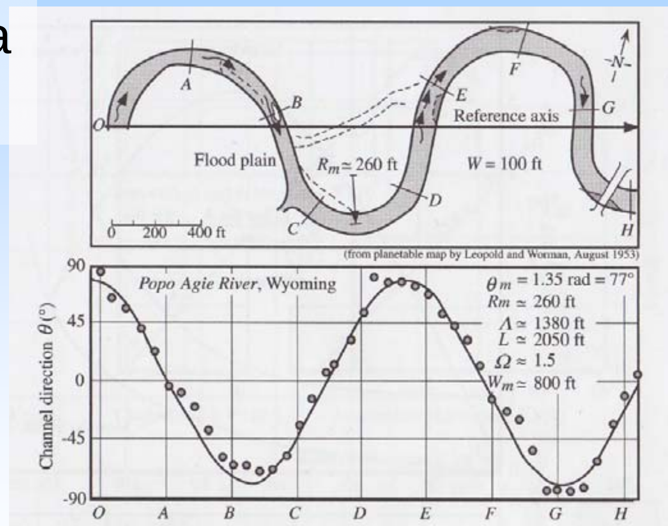


Figure 6.12. Meandering planform geometry (after Langbein and Leopold, 1966).

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
θ_m = max orientation angle
x = downstream distance
L = length of channel

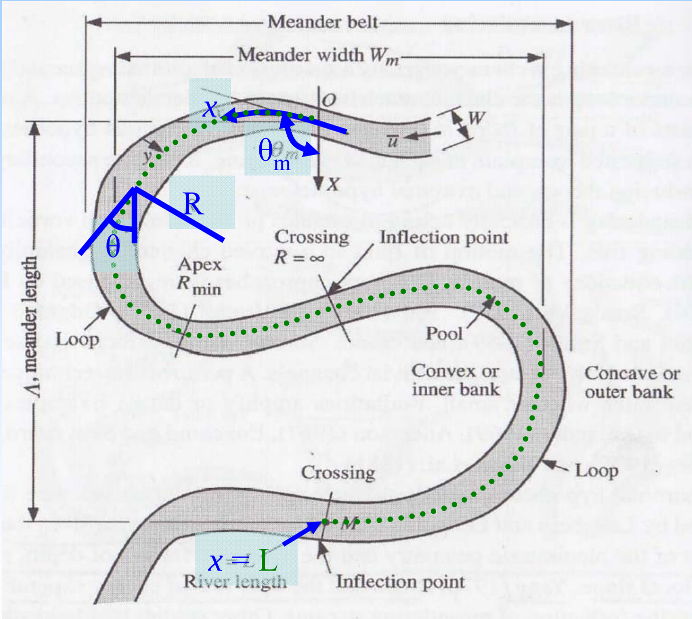


Figure 6.11. Definition sketch of a meandering river.

From Julien (2002)

Sinuosity

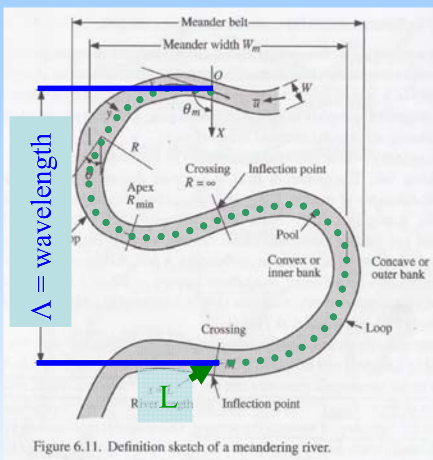
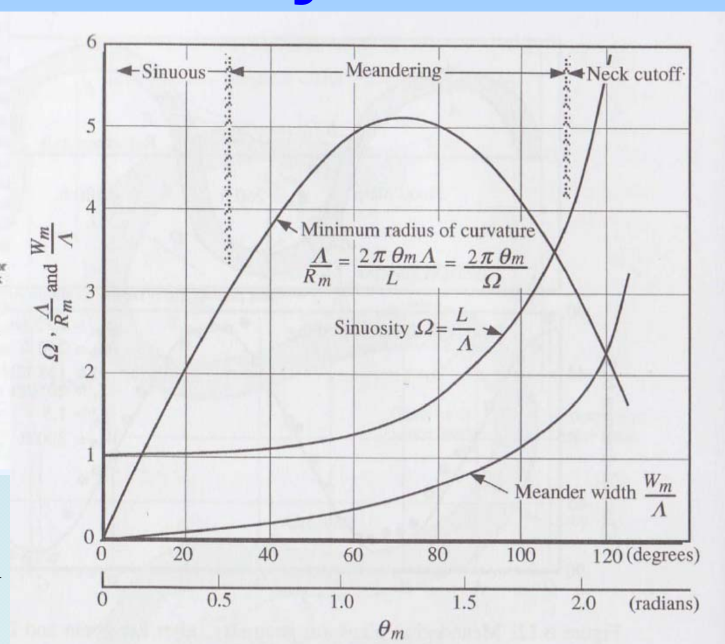


Figure 6.11. Definition sketch of a meandering river.



Ω = sinuosity

Λ = meander wavelength

L = length of channel

From Julien (2002)

Length and Width

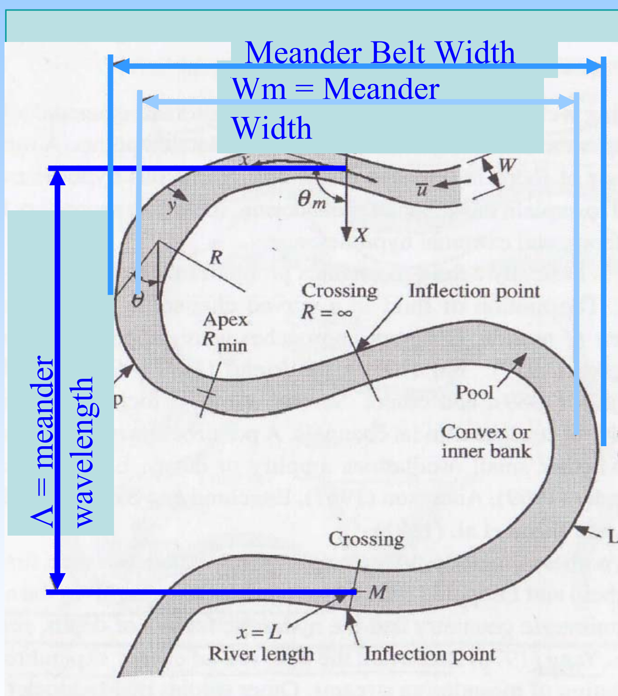
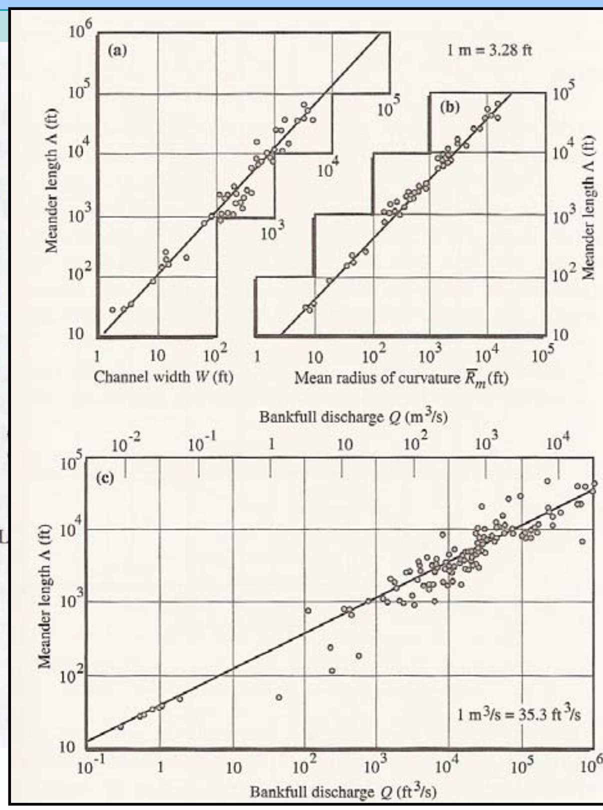


Figure 6.11. Definition sketch of a meandering river.



From Julien (2002)

Lateral Migration of Meandering Channels

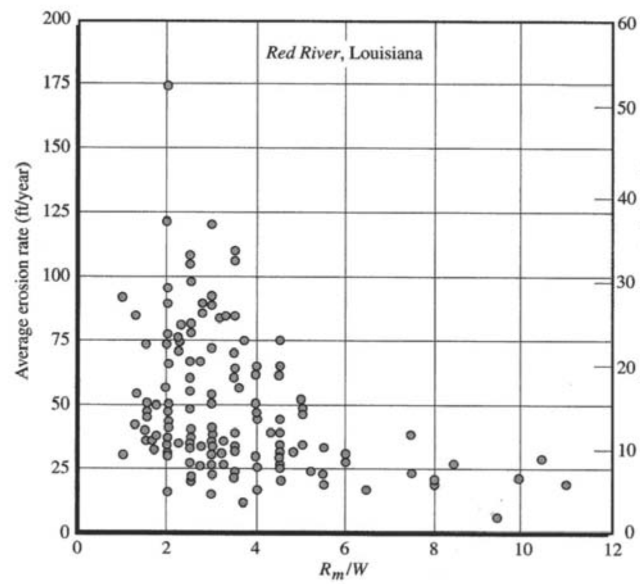


Figure 6.19. Lateral migration rates (after Biedenharn et al., 1989).

Presentation Content

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Mechanics of sediment transport in curved channels

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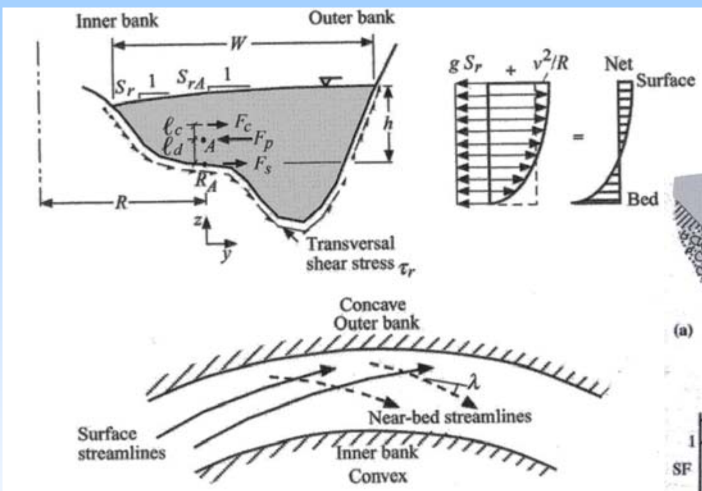
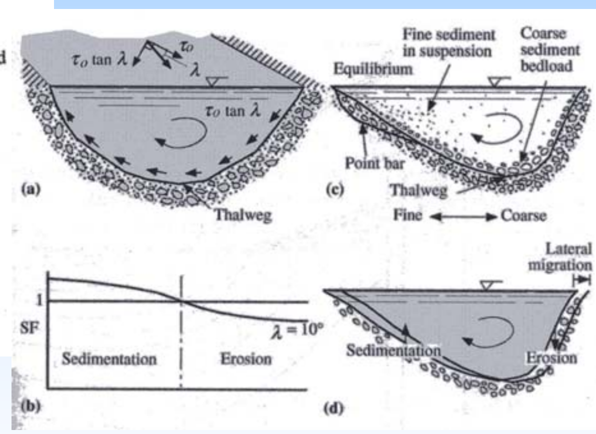
Mechanics of sediment transport in curved channels

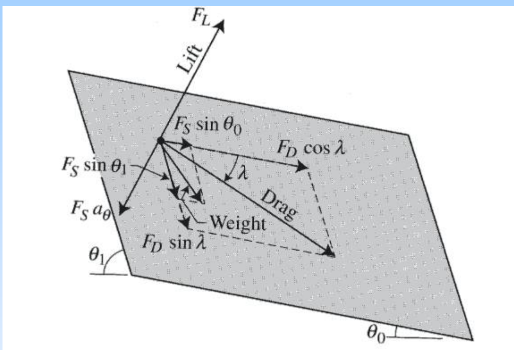




$$\tan \lambda \sim 11\ h/R$$

From Julien (2002)

Particle Stability on Slopes



$$SF = \frac{l_2 F_S a_\theta}{l_1 F_S \sqrt{1 - a_\theta^2} \cos \beta + l_3 F_D \cos \delta + l_4 F_L}$$

$$\beta = \tan^{-1} \left\{ \frac{\cos(\lambda + \theta)}{\dfrac{(M + N)\sqrt{1 - a_\theta^2}}{N \eta_0 \tan \phi} + \sin(\lambda + \theta)} \right\}$$

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

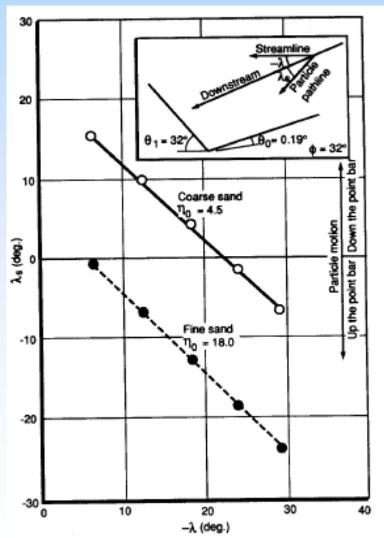


Fig. 2. Relation between λ_s and λ ($M/N = 1$).

from Kawai and Julien (IAHR-JHR, 1996)

Sediment Transport in Sharp Bends

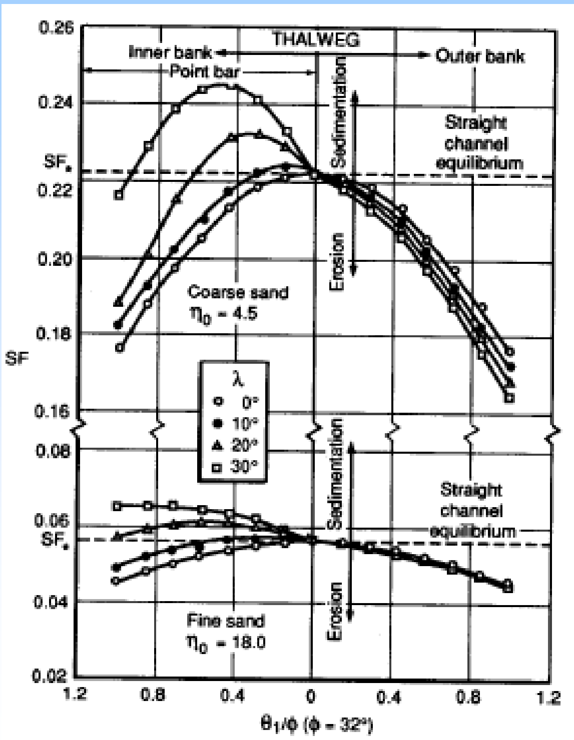


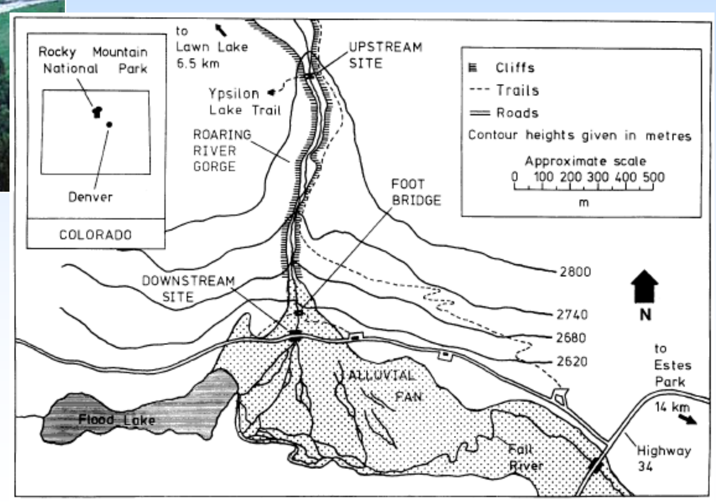
Fig. 3. Relation between SF and θ_1/ϕ ($M/N = 1$).

Laboratory experiments show that fine sand can deposit where coarse sand cannot, i.e. point bars

from Kawai and Julien (IAHR-JHR, 1996)

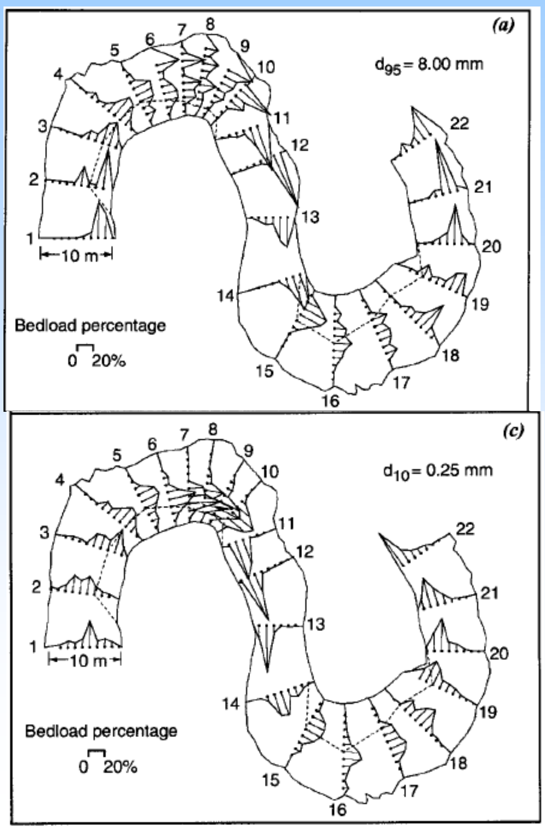
Roaring River Alluvial Fan:
Dramatic change in sediment supply

⬇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.

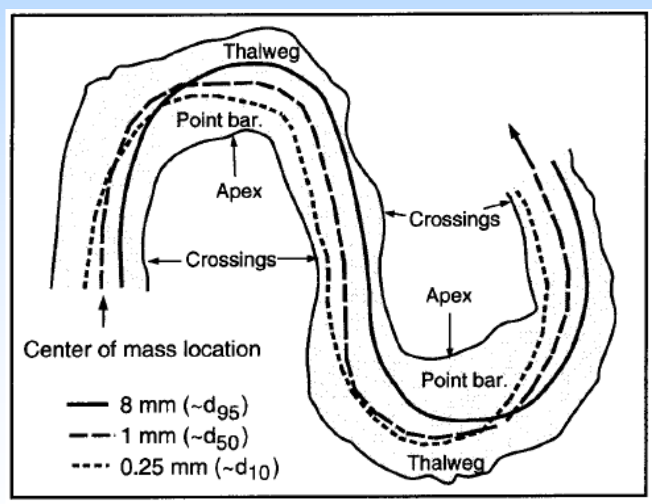


Fig. 5 Center of mass curves for three bedload size fractions

from Julien and Anthony (IAHR-JHR, 2002)

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Numerical modeling of meander migration

$$\frac{\partial(h\bar{u})}{\partial t} + \frac{\partial}{\partial x}(h\bar{u}^2) + \frac{\partial D_{uu}}{\partial x} + \frac{\partial}{\partial y}(h\bar{u}\bar{v}) + \frac{\partial D_{uv}}{\partial y} = -gh\frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}(h\tau_{xy}) - \tau_{bx} \qquad (1)$$

$$\frac{\partial(h\bar{v})}{\partial t} + \frac{\partial}{\partial x}(h\bar{u}\bar{v}) + \frac{\partial D_{uv}}{\partial x} + \frac{\partial}{\partial y}(h\bar{v}^2) + \frac{\partial D_{vv}}{\partial y} = -gh\frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial x}(h\tau_{yx}) + \frac{\partial}{\partial y}(h\tau_{yy}) - \tau_{by} \qquad (2)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(h\bar{u}) + \frac{\partial}{\partial y}(h\bar{v}) = 0 \qquad (3)$$

where $\bar{u}$ and $\bar{v}$ are depth-averaged velocity components in x and y directions, respectively; t is time; ζ is surface elevation; h is flow depth; g is acceleration due to gravity; τ_{bx} and τ_{by} are friction shear stress terms at the bottom in x and y directions, respectively, written as

$$\tau_{bx} = \frac{n^2 g}{h^{\frac{1}{3}}}\bar{u}U \quad \text{and} \quad \tau_{by} = \frac{n^2 g}{h^{\frac{1}{3}}}\bar{v}U$$

Model from Duan and Julien (ESPL, 2005)

Sediment Transport

$$q_b = C_m[(s-1)g]^{0.5} d_{50}^{1.5}(\mu'\tau_* - \tau_{*c})^{1.5} \quad (17)$$

where q_b is the total bedload transport rate per unit width; $\tau_* = (\rho u_*^2)/[(\rho_s - \rho)gd_{50}]$ is the effective particle mobility parameter; $\tau_{*c} = \tau_c/[(\rho_s - \rho)gd_{50}]$ is the critical value of τ_* for incipient motion depending on particle Reynolds number ($R_e^* = (u_* d_{50})/\nu$), and $\tau_{*c} = 0{\cdot}047$ when $R_e^* > 100$; constant coefficient $C_m = 8{\cdot}0$; and the bed-form effect was ignored so that the factor μ' was omitted in this model; d_{50} is the mean particle diameter; $s = \rho_s/\rho$, where ρ_s and ρ are densities of sand and water, respectively.

$$\frac{C}{C_a} = \left(\frac{h-z}{z}\frac{a}{h-a}\right)^Z \quad (25)$$

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

$$Z = \frac{\omega}{\kappa\beta' u_*} \quad (26)$$

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

$$(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial(q_{bx} + q_{sx})}{\partial x} + \frac{\partial(q_{by} + q_{sy})}{\partial y} = 0 \quad (33)$$

where p 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

$$q_{br}^{b} = \frac{\bar{\xi}(1-p)h_b}{\sin\bar{\beta}} \tag{35}$$

where q_{br}^{b} 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 $\bar{\xi}=0$, the riverbank is not undergoing erosion, so the near-bank, suspended sediment concentration reaches the value of equilibrium. The term $\sin\bar{\beta}$ converts the distance of bank erosion to the volumetric net bank material from basal erosion.

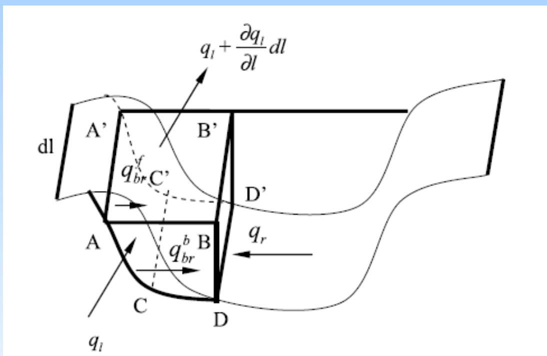
In natural environments, vegetation, heterogeneity in bank material and pore water pressure will add an apparent cohesion to the original non-cohesive material. The planar bank-failure model (Osman and Thorne, 1988; Darby and Thorne, 1996) is more appropriate as compared to the slumping model. In this 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

$$q_{br}^{f} = \bar{\xi}\Delta h_{bank}(1-p) \tag{36}$$

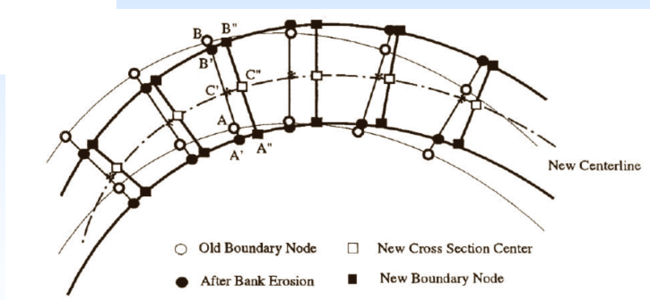
where q_{br}^{f} is the sediment material eroded per unit channel width from bank failure, and Δh_{bank} is the bank height above the water surface.

Model from Duan and Julien (ESPL, 2005)

Lateral Migration



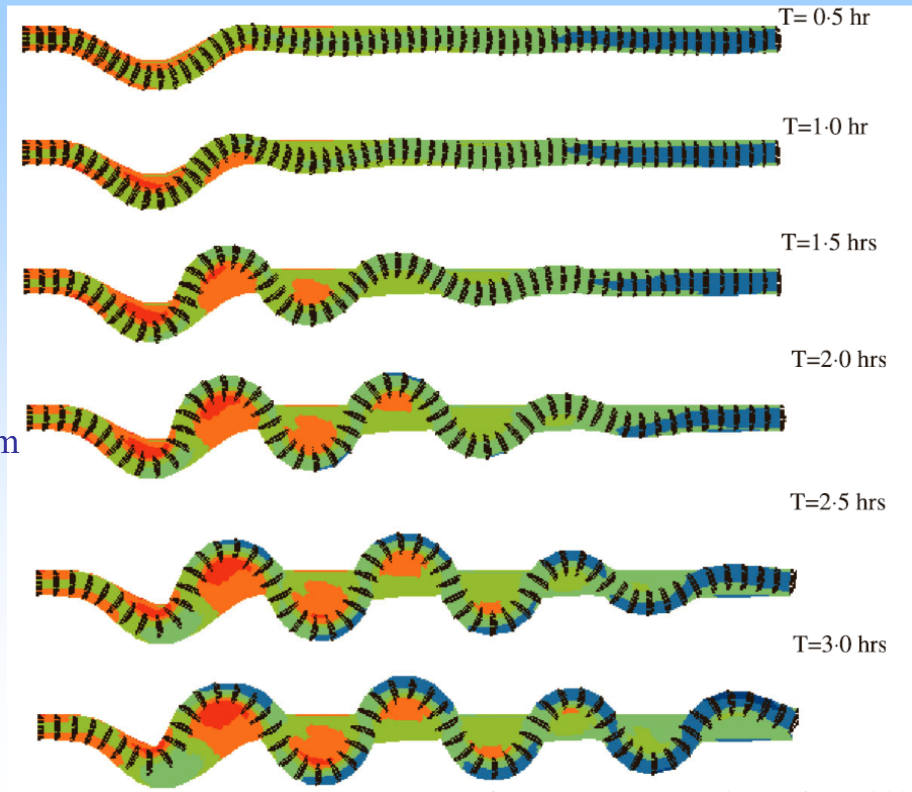
$$\varepsilon = -\frac{\left(\dfrac{\partial q_l}{\partial l}\dfrac{dr}{2} + q_r - q_{br}\right)}{h_b}$$



Model from Duan and Julien (ESPL, 2005)

Meandering Simulations

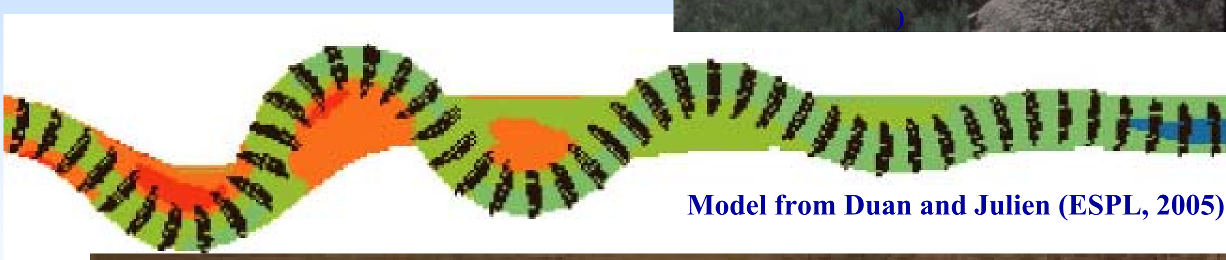
Initial Conditions
• sine-generated
• deflection angle 30°
• discharge 2.1 *l*/s
• width 0.4 m
• length 13.2 m
• sediment size 0.45 mm

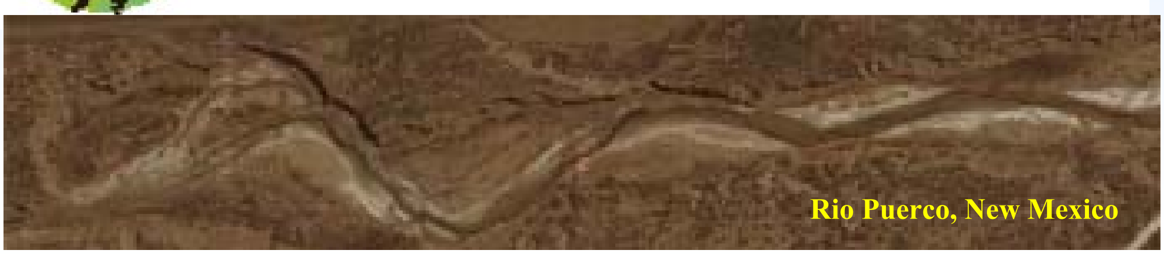


Model from Duan and Julien (ESPL, 2005)

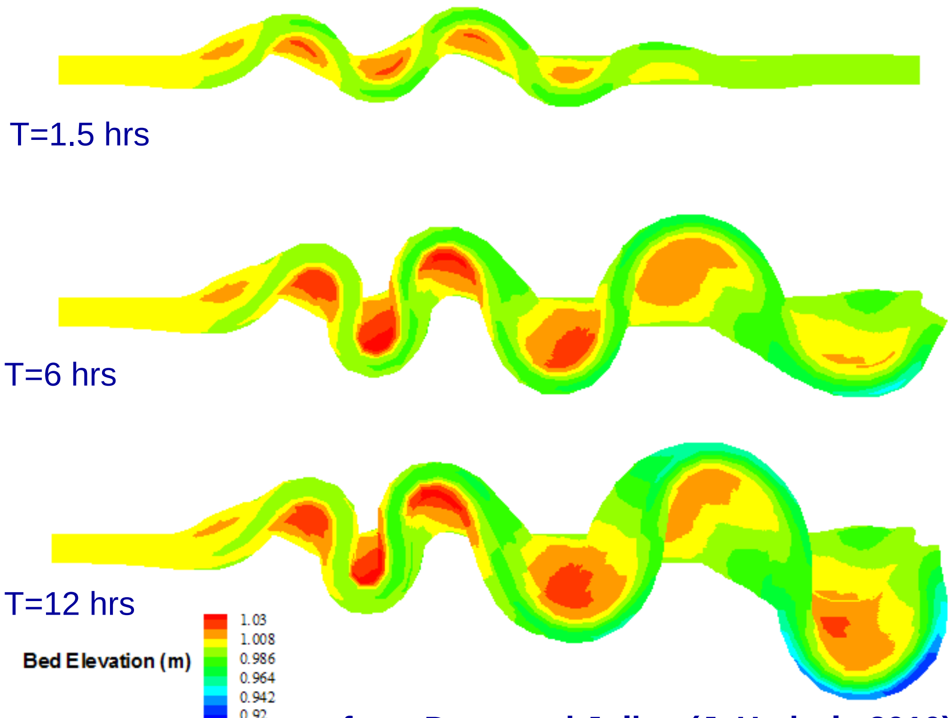
Meandering Evolution

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


Model from Duan and Julien (ESPL, 2005)

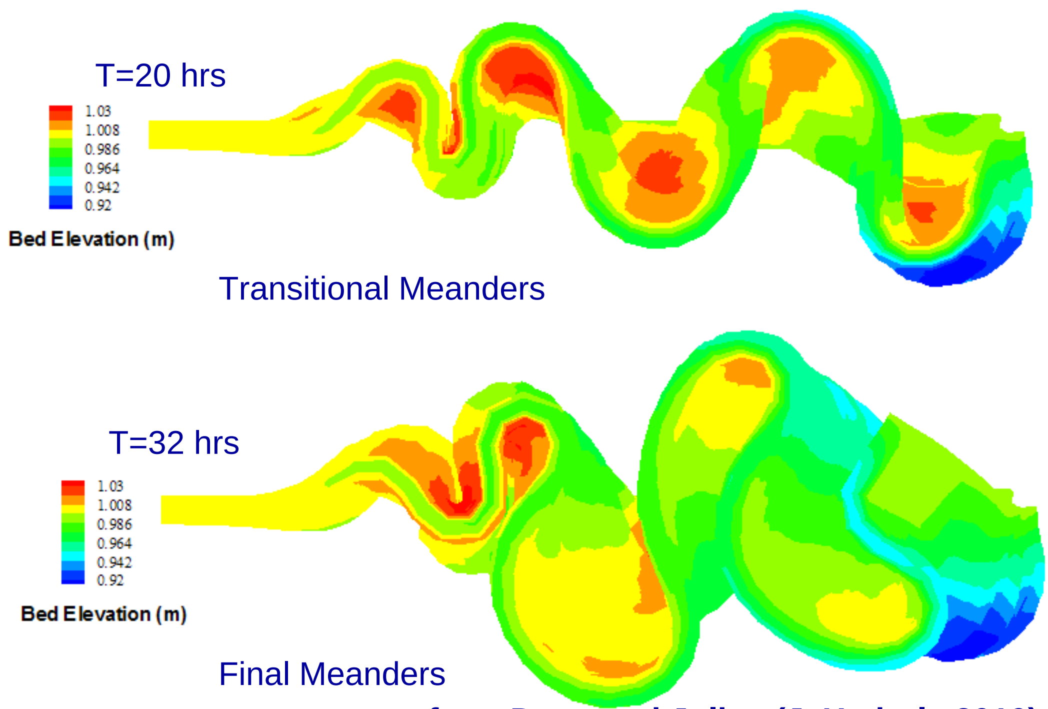


Meandering Simulations



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

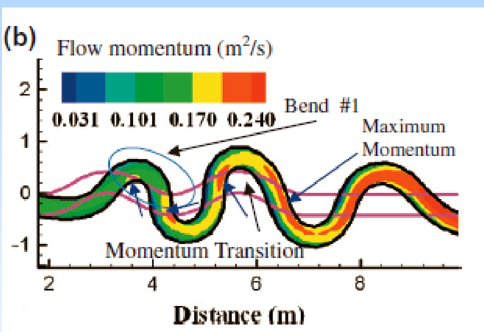
Meandering Simulations

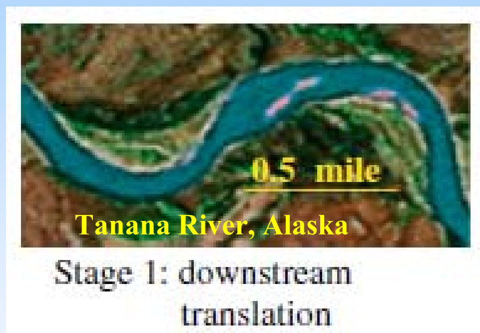


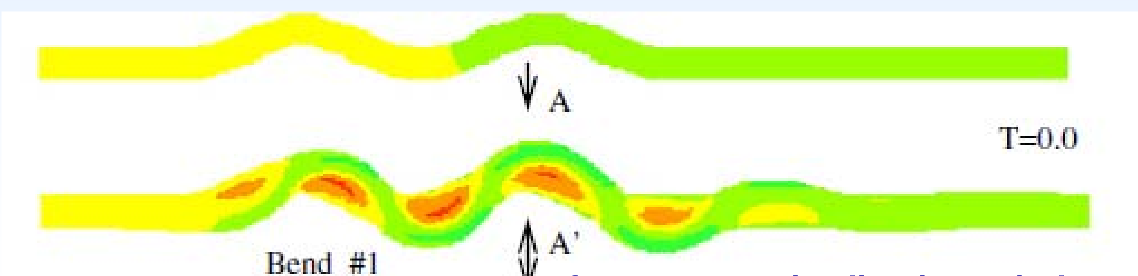
from Duan and Julien (J. Hydrol., 2010)

Meandering Evolution

Stage 1 - Downstream Extension



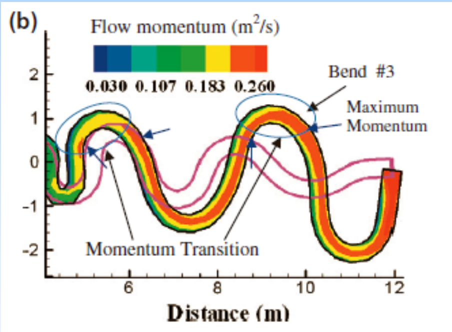


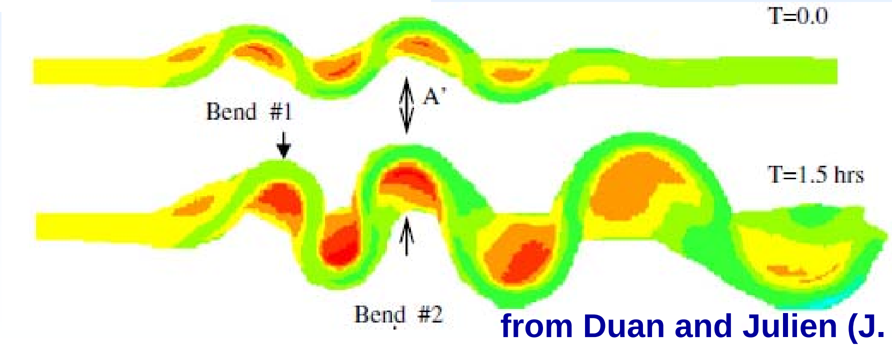


from Duan and Julien (J. Hydrol., 2010)

Meandering Evolution

Stage 2 - Lateral Extension

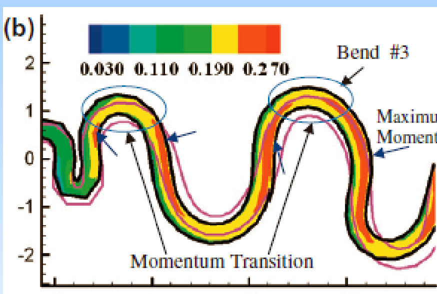


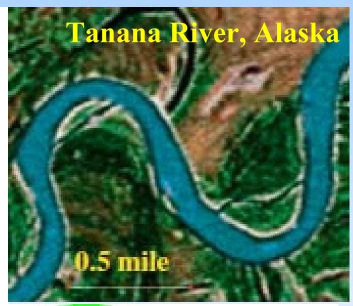


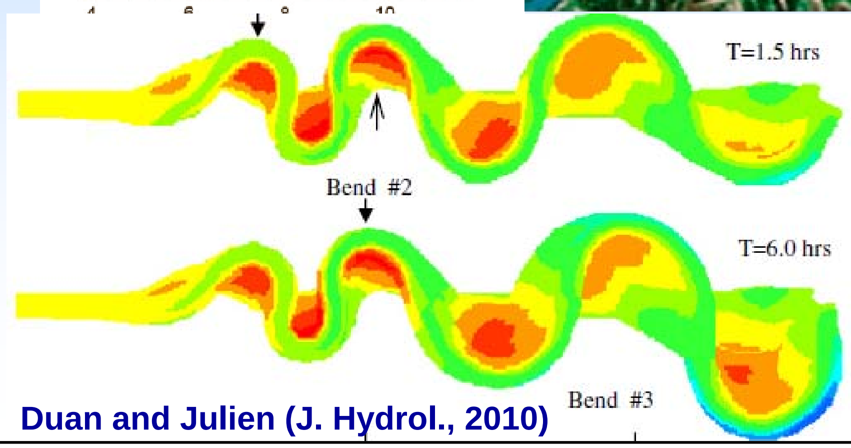
from Duan and Julien (J. Hydrol., 2010)

Meandering Evolution

Stage 3 – Near Equilibrium



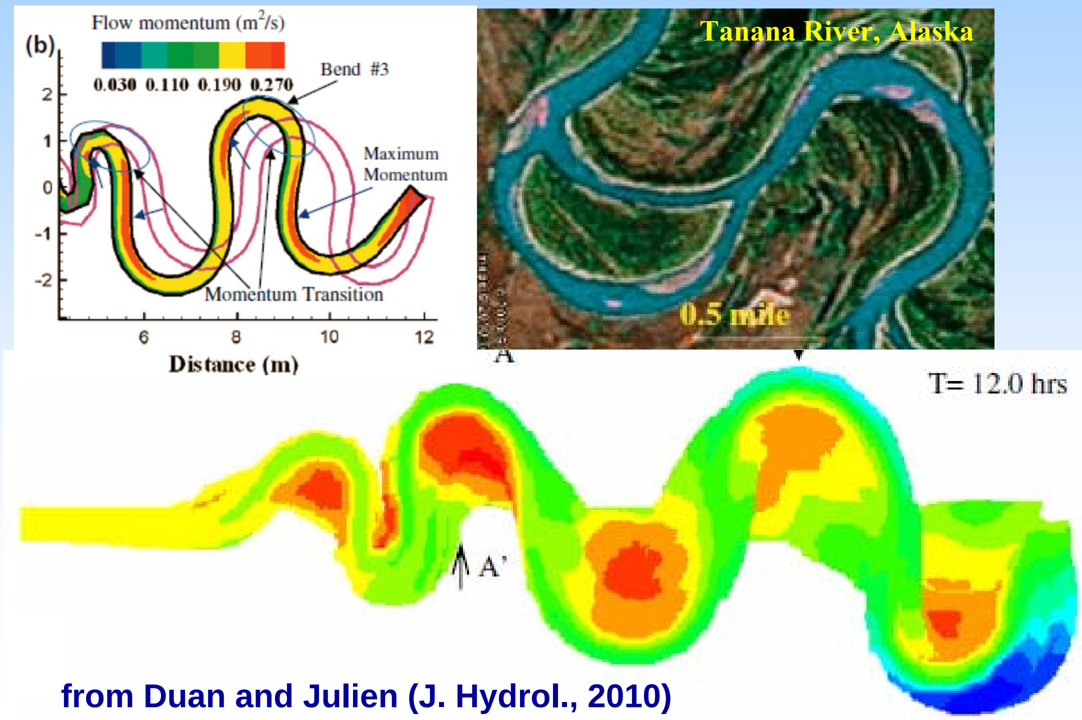




Duan and Julien (J. Hydrol., 2010)

Meandering Evolution

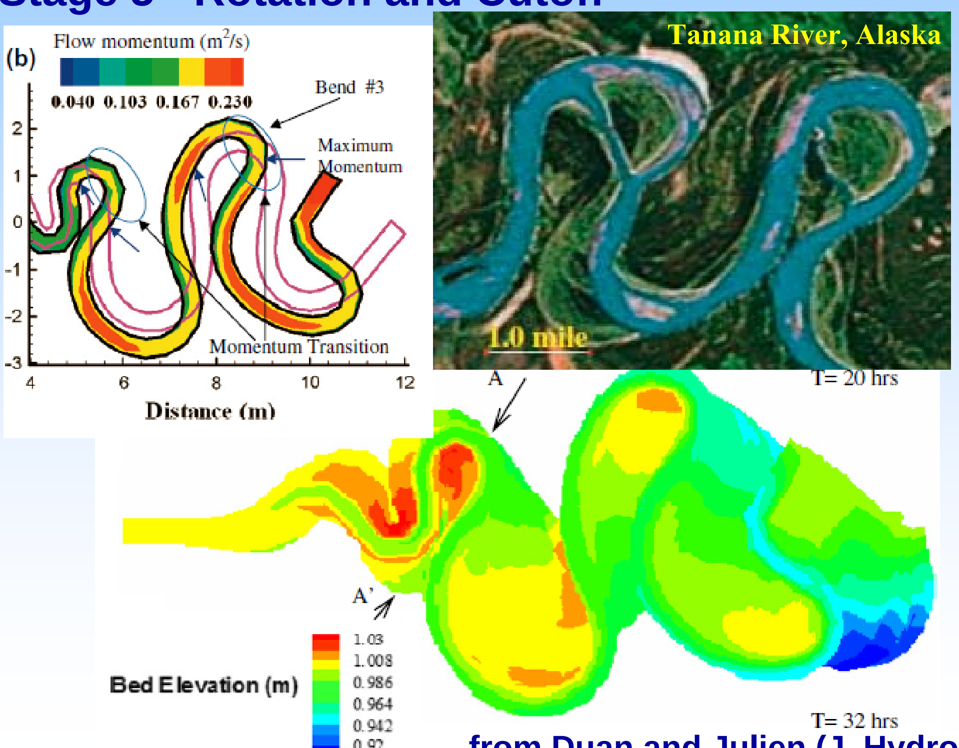
Stage 4 - Upstream Migration



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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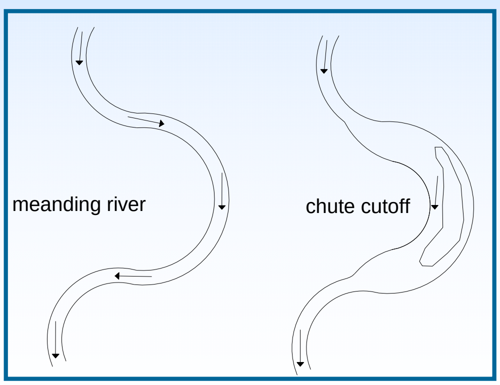
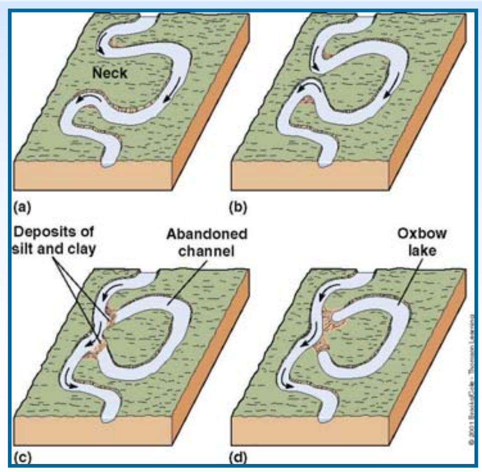
Morphology of chute and neck cutoffs

- **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.



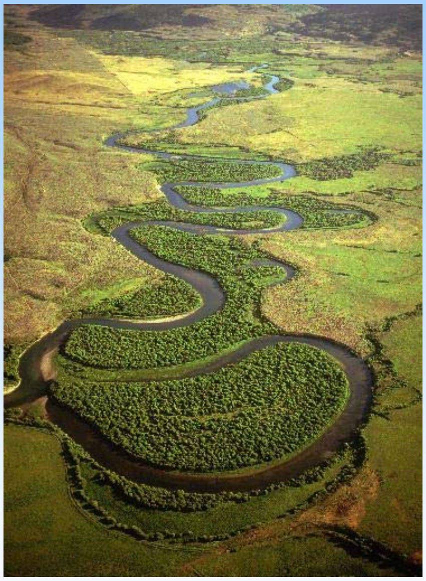


Natural Chute Cutoffs

- Often in response to an increase in sediment load

- Chute cutoffs on Williams River, AK
  (Photo by N.D. Smith)

Natural Neck Cutoffs



- Neck cutoff, Green River WY

(Photo by Michael Collier; American Geological Institute)

- Geologic cutoff, San Juan River, UT

(Photo by Roger Weller; Cochise College)

Oxbow Lake

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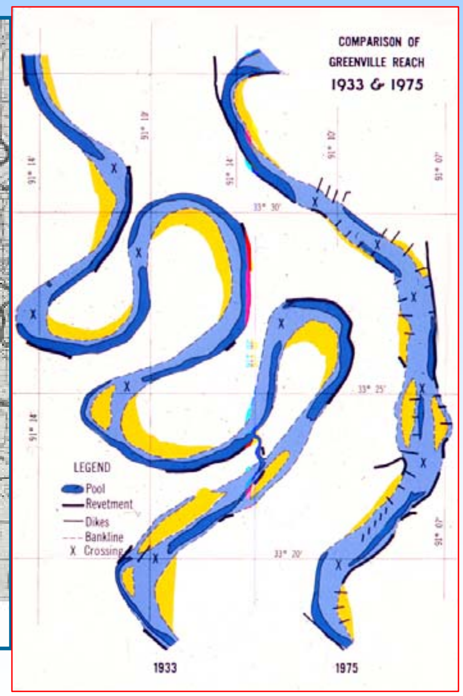
River engineering and management

- *River restoration and water quality*

River engineering and management

Mississippi River near Greenville, MS

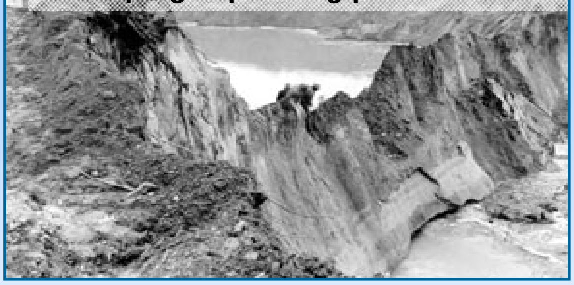
HISTORIC DEVELOPMENT OF THE GREENVILLE REACH



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

http://www.mvd.usace.army.mil/mrc/Upon_There_Shoulders/Chapter12.htm

Mississippi River

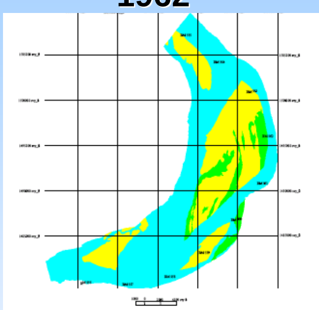
Leland and Tarpley Cutoffs

From Winkley (1977)

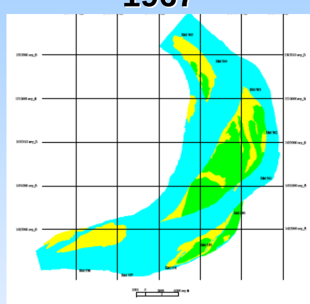
Engineered Chute Cutoff

Choctaw Bar, Mississippi River

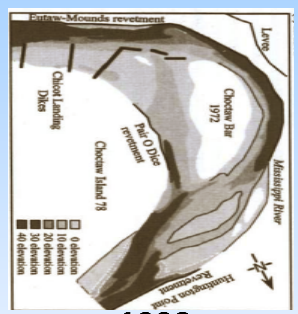
1962



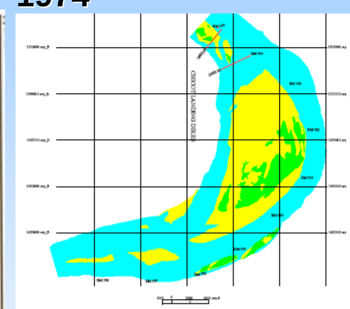
1967



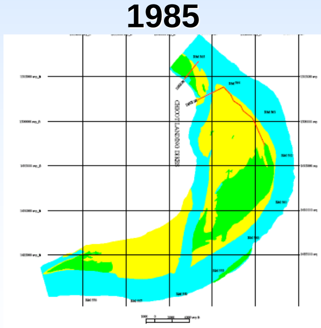
1972



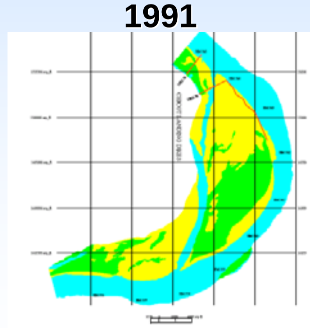
1974



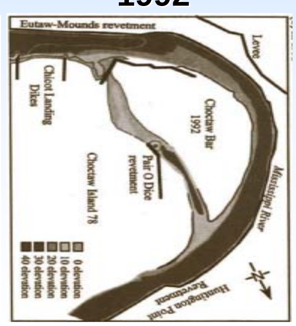
1985



1991



1992



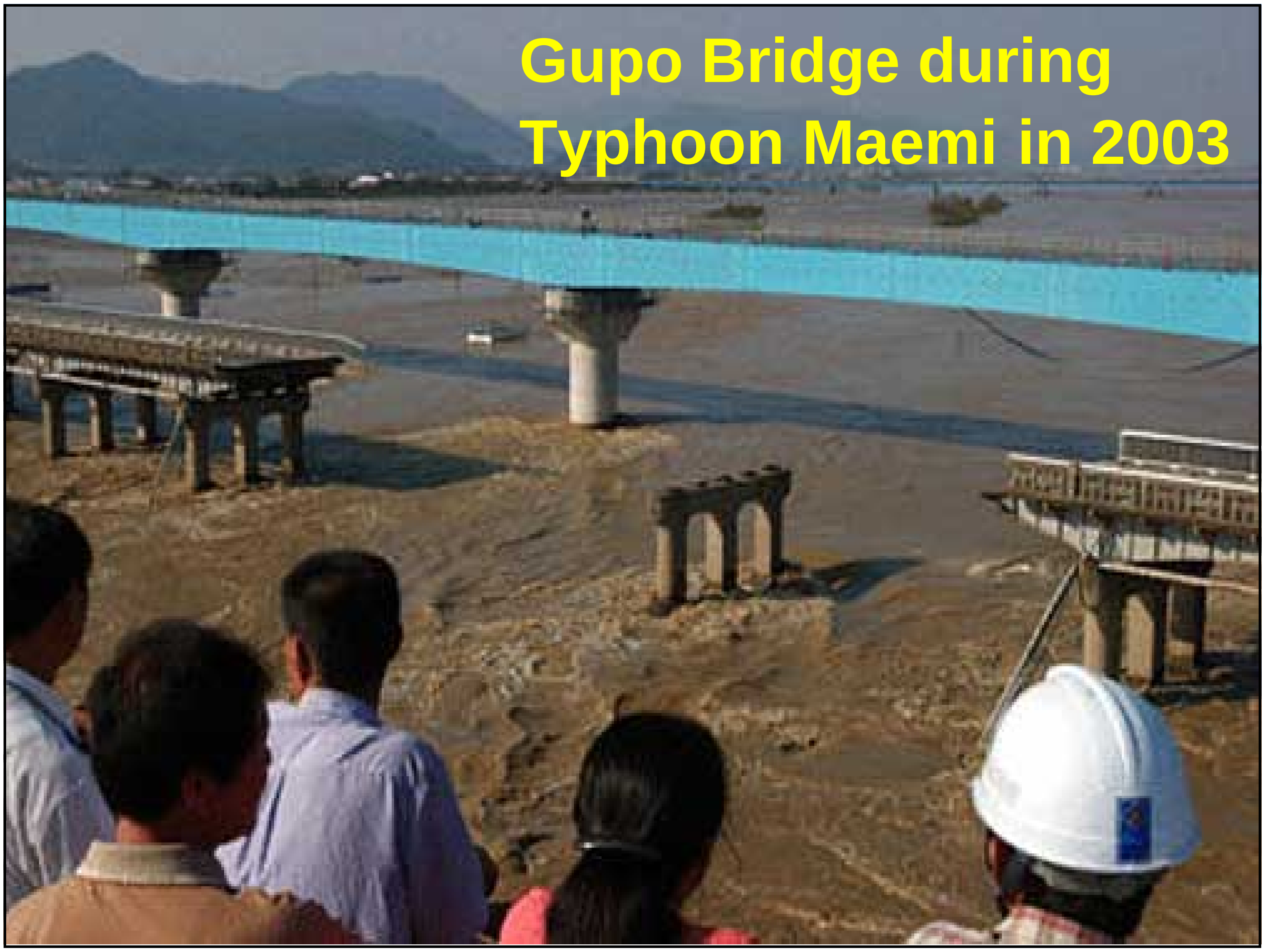
Current

(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

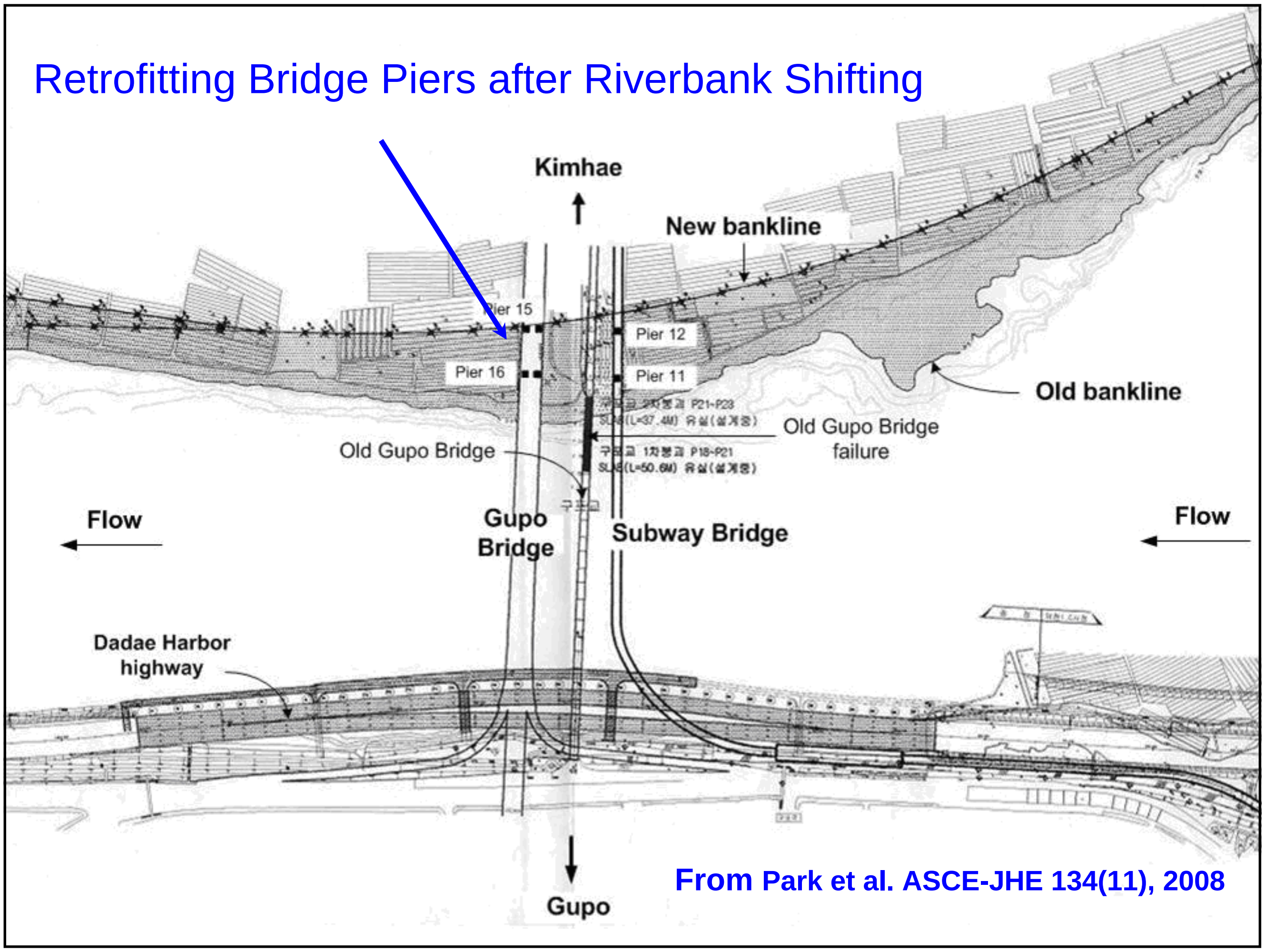
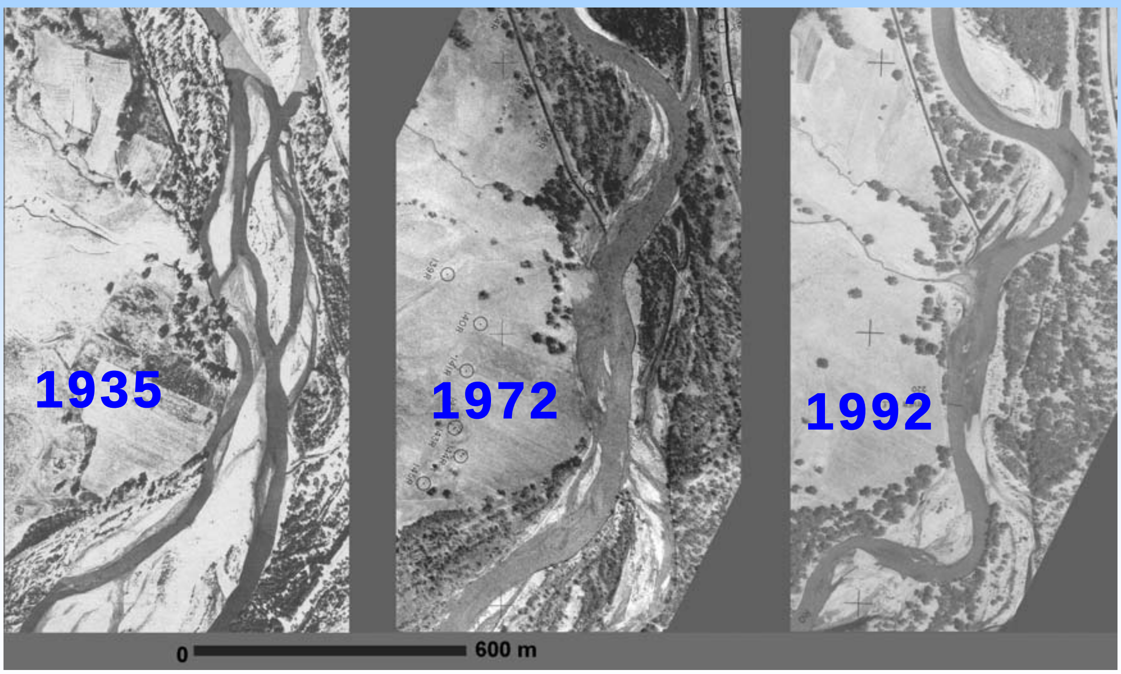

Retrofitting Bridge Piers after Riverbank Shifting
Kimhae
New bankline
Pier 15
Pier 12
Pier 16
Pier 11
Old bankline
Old Gupo Bridge
failure
Old Gupo Bridge
Flow
Gupo
Bridge
Subway Bridge
Flow
Dadae Harbor
highway
Gupo
From Park et al. ASCE-JHE 134(11), 2008

Figure 14. Gupo and Subway Bridge Piers before and after retrofitting construction

Park et al. ASCE-JHE 134(11), 2008.

River Management

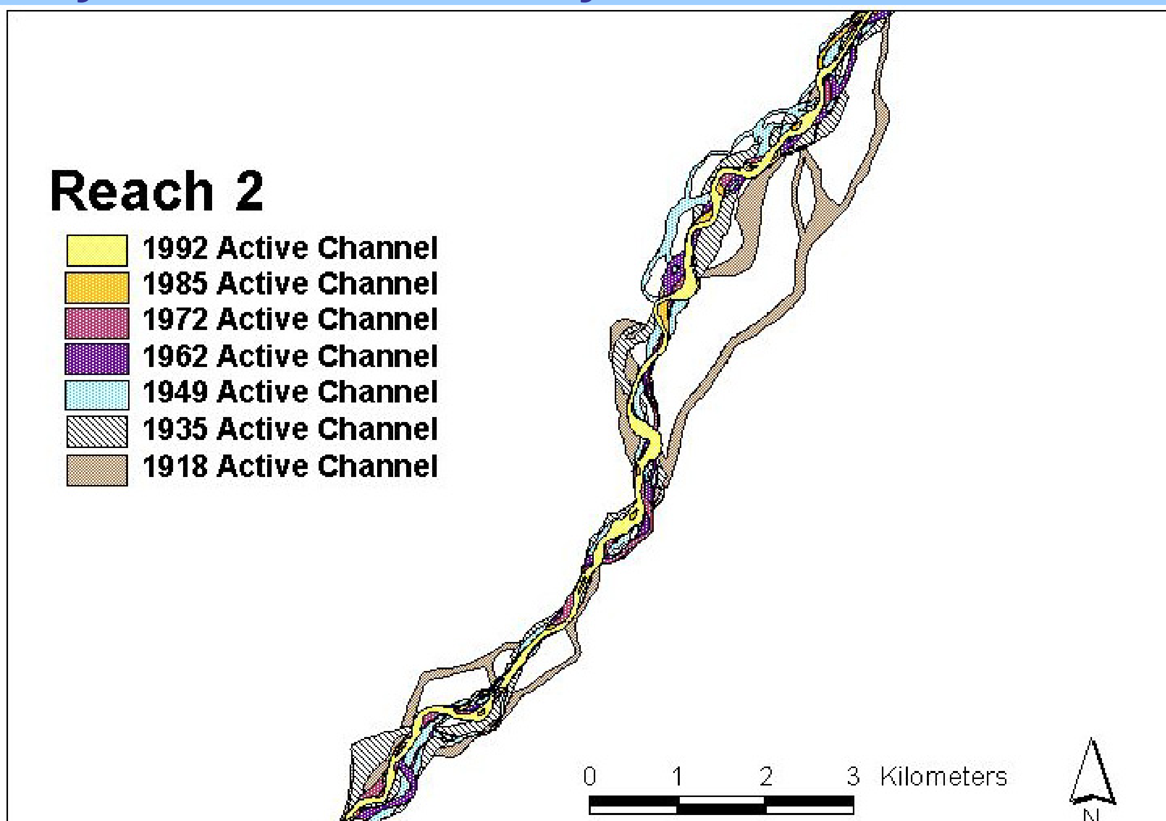
Rio Grande below Cochiti Dam, NM



Braiding **Transition** **Meandering**

From Richard et al. ASCE-JHE 131(11), 2005

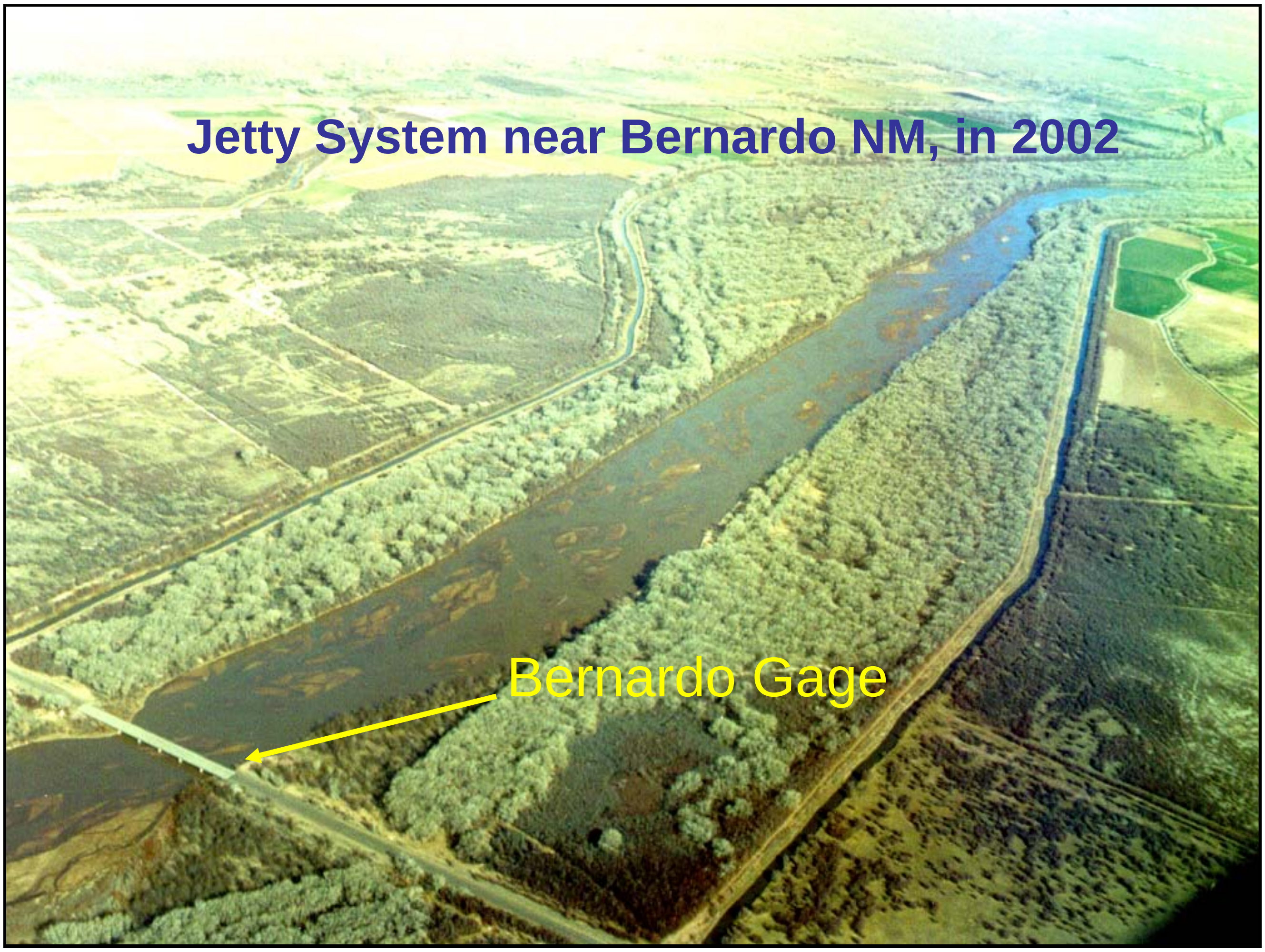
Hydraulic Geometry of the Rio Grande



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
Bernardo Gage

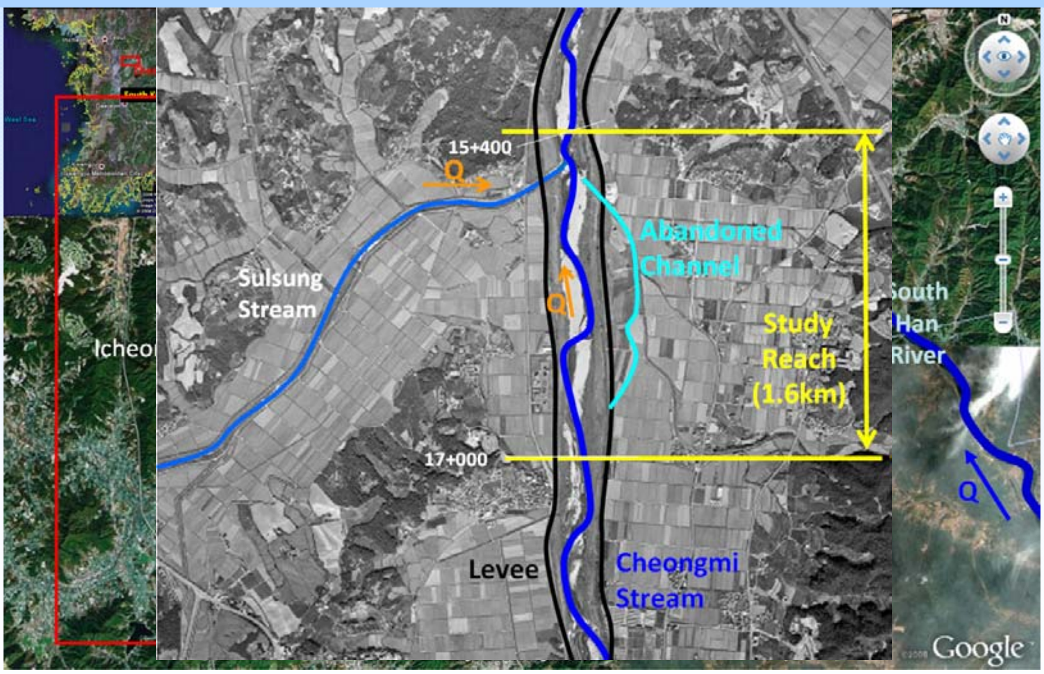
Sediment Plugs on the Rio Grande

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*

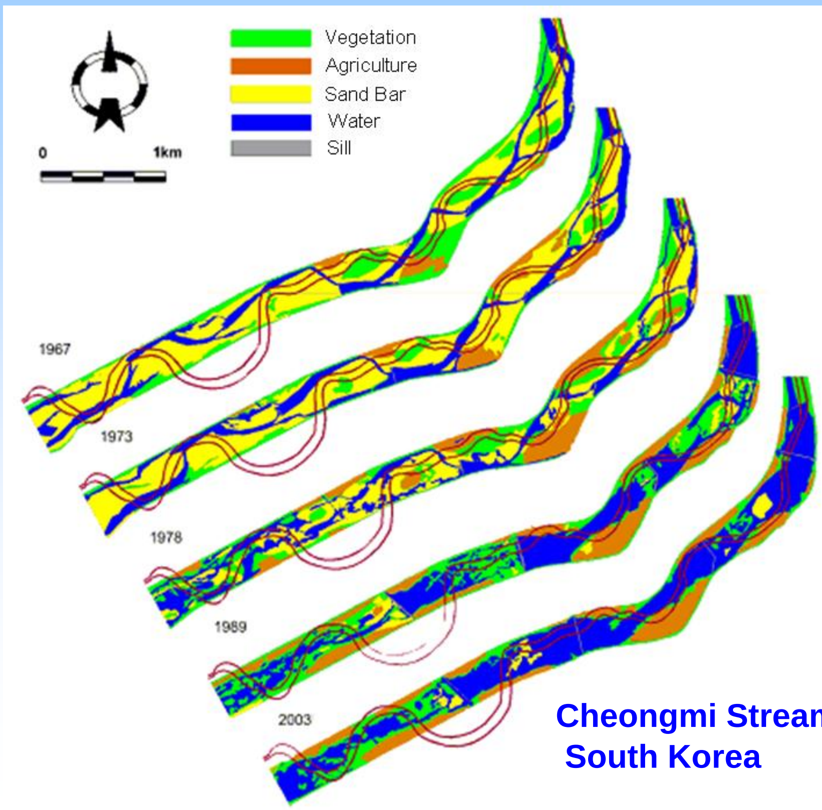
River restoration and water quality

River restoration and water quality



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

Historical Planform



Cheongmi Stream,
South Korea

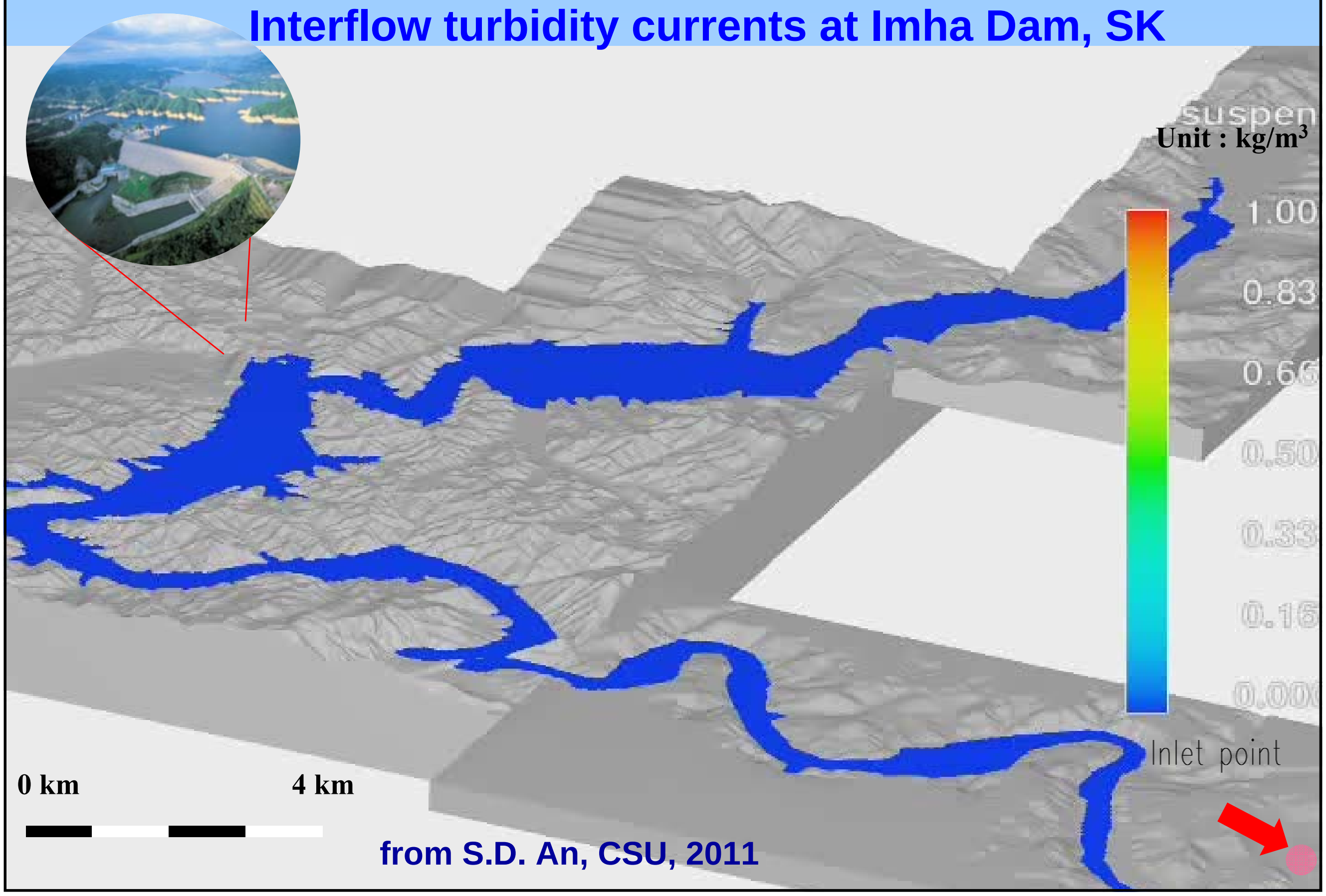
Water Quality Issues

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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- ***J. England,*** *USBR*
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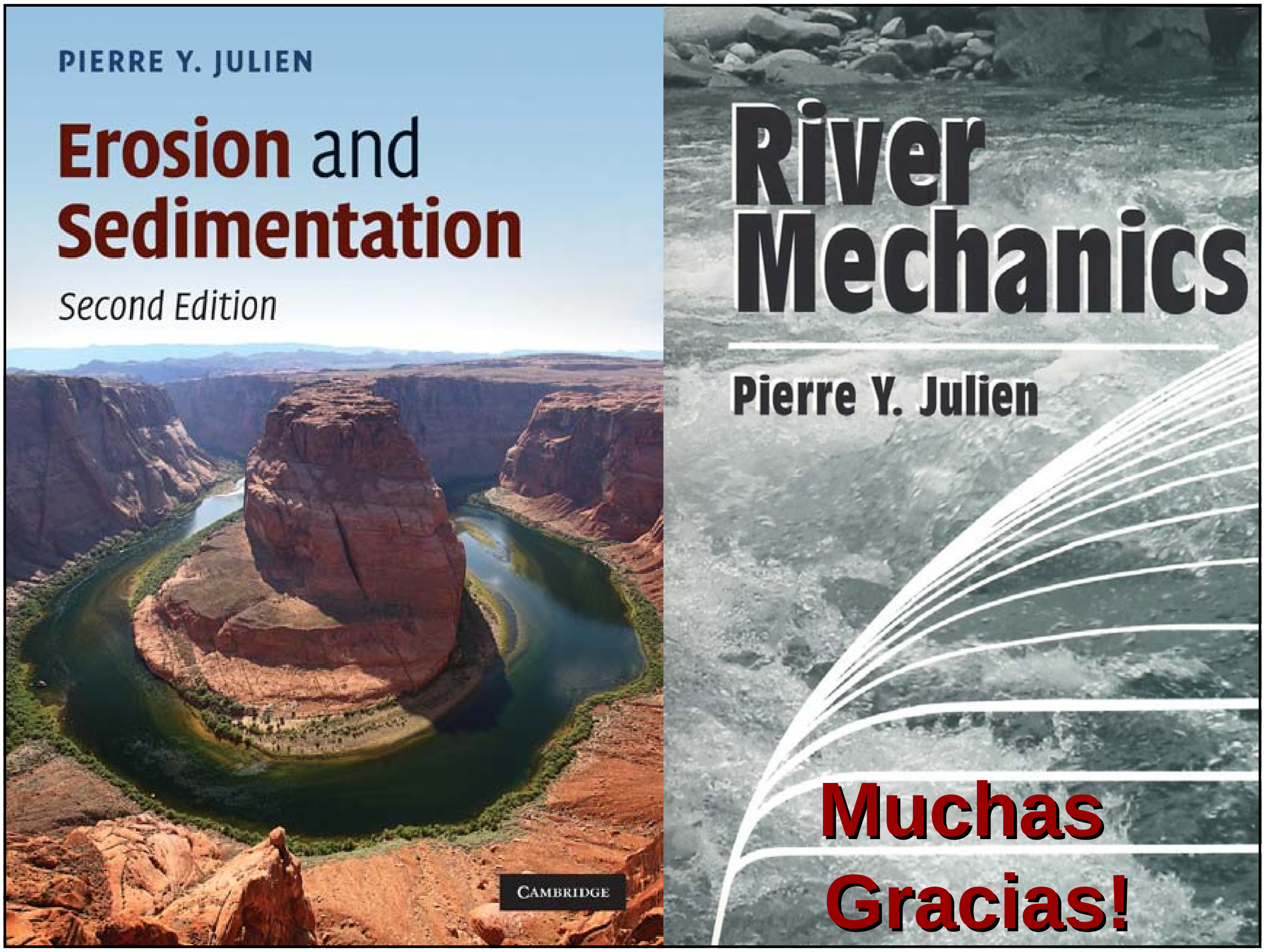
- ***H. Woo,*** *KICT, South Korea*
- ***S.K. Park,*** *PNU, South Korea*
- *So many others…*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Muchas Gracias!