Backwater and River plume Controls on Scour Upstream of River Mouths: Morphodynamic Implications*

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Editor's note: Please refer to companion article by Chatanantavet and Lamb, entitled "Experimental Study of a Coupled River and River-plume System: Backwater Controls on Source-to-sink Sediment 75 Transfer," Search and Discovery Article #50712 (2012).

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Abstract

Sediment flux from rivers to oceans is the fundamental driver of fluvio-delatic morphodynamics and continental-margin sedimentation, yet sediment transport across the river-to-marine boundary is poorly understood. Coastal rivers typically are affected by backwater, a zone of spatially decelerating flow that is transitional between normal flow upstream and the offshore river plume. Flow deceleration in the backwater zone, as well as spreading of the offshore plume, should render rivers highly depositional near their mouths, leading to sedimentation and eventual elimination of the backwater zone at steady state. This reasoning is counter to observations of riverbed scour, erosional bedforms, and long-lived backwater zones near the mouths of some coastal rivers (e.g., Mississippi River). To explain these observations, we present a quasi-2D model of a coupled fluvial backwater and offshore river-plume system for the case of the Mississippi River. Results show that during high-discharge events the normal-flow depth can become larger than the water depth at the river mouth resulting in drawdown of the water surface, spatial acceleration of flow, and surprisingly erosion of the riverbed. Furthermore, it is the transient adjustment of the river to low flow and high flow events that allows a persistent backwater/drawdown zone. This zone in turn act as a filter on sediment transfer to marine environments whereby sediment flux from low-discharge events is muted and sediment flux from high-discharge events is enhanced from what would be expected from normal flow alone. Backwater dynamics and the potential for scour are rarely accounted for in fluvio-deltaic models, but they could have a significant impact morphodynamics and stratigraphy. For example, we show that backwater combined with variable discharges leads to a preferential deposition zone, which may explain why rivers tend to avulse about a persistent node setting the fundamental lengthscale of deltas. Furthermore, scour events in coastal rivers and distributary channels likely leave unconformities in fluvio-deltaic stratigraphy, which may appear similar to those previously interpreted to be a result of relative sea level changes or other allogenic forcings. Results are compared to flume experiments presented in a companion study by Chatanantavet et al. (2011).

References

Chatanantavet, P., K.X. Whipple, M.A. Adams, and M.P. Lamb, in review, Experimental study on coarse grain saltation dynamics in bedrock channels: Journal of Geophysical Research – Earth Surface.

Chatanantavet, P. and G. Parker, 2011, Quantitative testing of model of bedrock channel incision by plucking and macroabrasion: Journal of Hydraulic Engineering, v. 137/11, p. 1311-1317.

Hudson, P.F., R.H. Kesel, 2000, Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification: Geology, v. 28/6, p. 531-534.

Jerolmack, D.J., 2009, Conceptual framework for assessing the response of delta channel networks to Holocene sea-level rise, in B.P. Horton, and J.P. Donnelly, (eds.), Quaternary Science Reviews, v. 28/17-18, p. 1786-1800.

Lamb, M.P., J. Nittrouer, D. Mohrig, and J. Shaw, 2012, Backwater and river-plume controls on scour upstream of river mouths: Implications for fluvio-deltaic morphodynamics: Journal of Geophysical Research Earth Surface, v. 117, 15 p.

Lane, E.W., 1957, A study of the shape of channels formed by natural streams flowing in erodible material: Missouri River Division Sediment Series No. 9, US Army Engineer Division, Missouri River, Corps of Engineers, Omaha, Nebraska, 121 p.

Nittrouer, J.A., J. Shaw, M.P. Lamb, and D. Mohrig, 2011, Spatial and temporal trends for water-flow velocity and bed-material sediment transport in the lower Mississippi River: GSA Bulletin, v. 124/3-4, p. 400-414.

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47/1, p. 121-178.

Parker, G., J.A. Nittrouer, D.C. Mohrig, M.A. Allison, W.E. Dietrich, and V.R. Voller, 2009, Modeling the morphodynamics of the lower Mississippi River as a quasi-bedrock river: Eos Trans. AGU, 90/52, Fall Meeting Suppl. Abstract EP32A-01.

Parker, G., T. Muto, Y. Akamatsu, W.E. Dietrich, and J.W. Lauer, 2008b, Unravelling the conundrum of river response to rising sea-level from laboratory to field, Part I, Laboratory experiments: Sedimentology, v. 55/6, p. 1643-1655.

Parker, G., T. Muto, Y. Akamatsu, W.E. Dietrich, and J.W. Lauer, 2008a, Unravelling the conundrum of river response to rising sea-level from laboratory to field, Part II, The Fly0Strickland River system, Papua New Guinea: Sedimentology, v. 55/6, p. 1657-1686.

BACKWATER AND RIVER PLUME CONTROLS ON SCOUR UPSTREAM OF RIVER MOUTHS: MORPHODYNAMIC IMPLICATIONS

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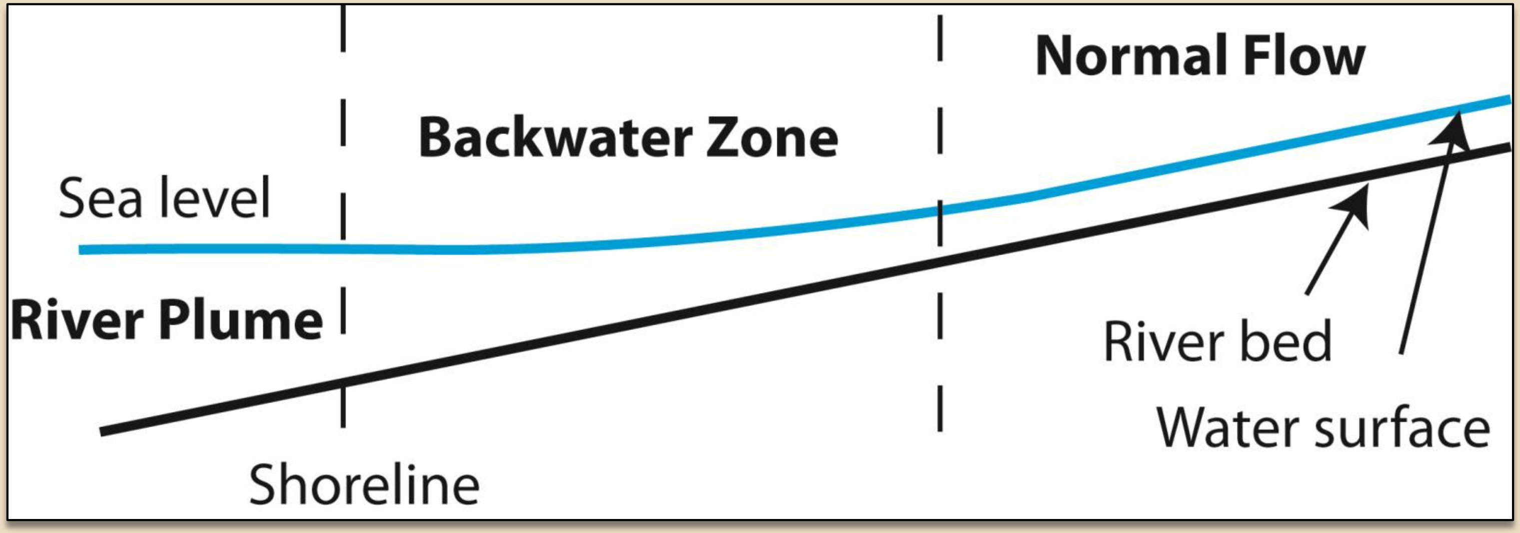
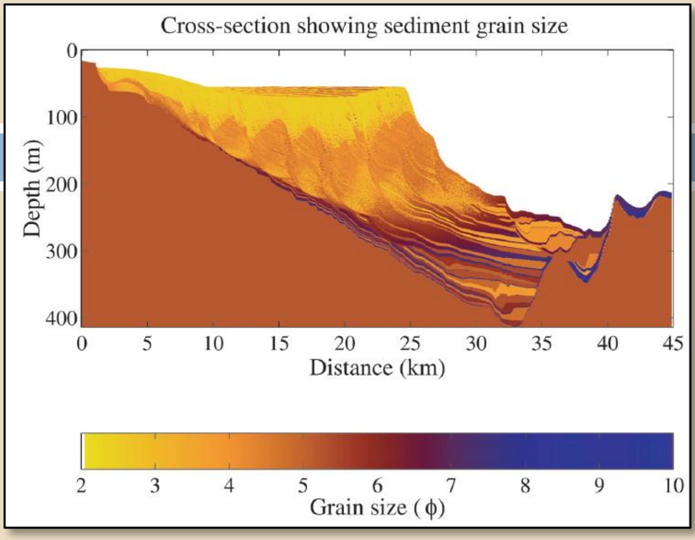
Rivers and oceans are connected by a zone of backwater



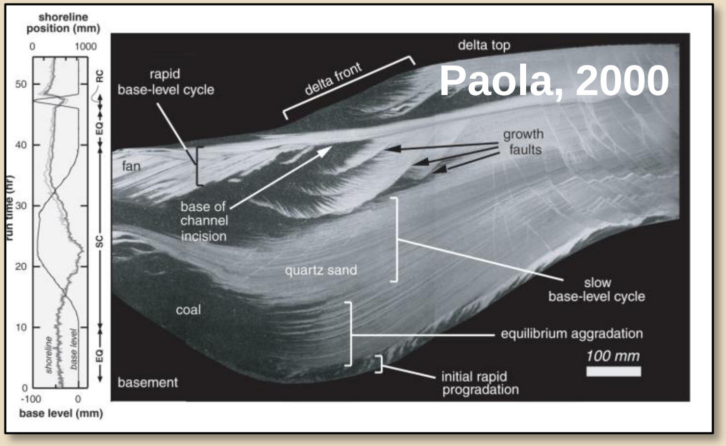
- Non-uniform flow that occurs in low Froude number flows near river mouths.
- The zone of backwater can be expansive on large low gradient rivers (e.g. 500 km on the Mississippi R.).
- It's spatial extent and deposition patterns are sensitive to river discharge *and* river mouth boundary conditions.

Most morphodynamic models neglect backwater

- Most numerical models route sediment by assuming $Q_s = f(S_b)$
  - Topographic diffusion
  - Steady-uniform flow
- Or models assume a single characteristic discharge, which does not allow a dynamic backwater zone
  - e.g., Parker et al., 2008
- Most flume experiments use high Froude numbers that minimize backwater effects.

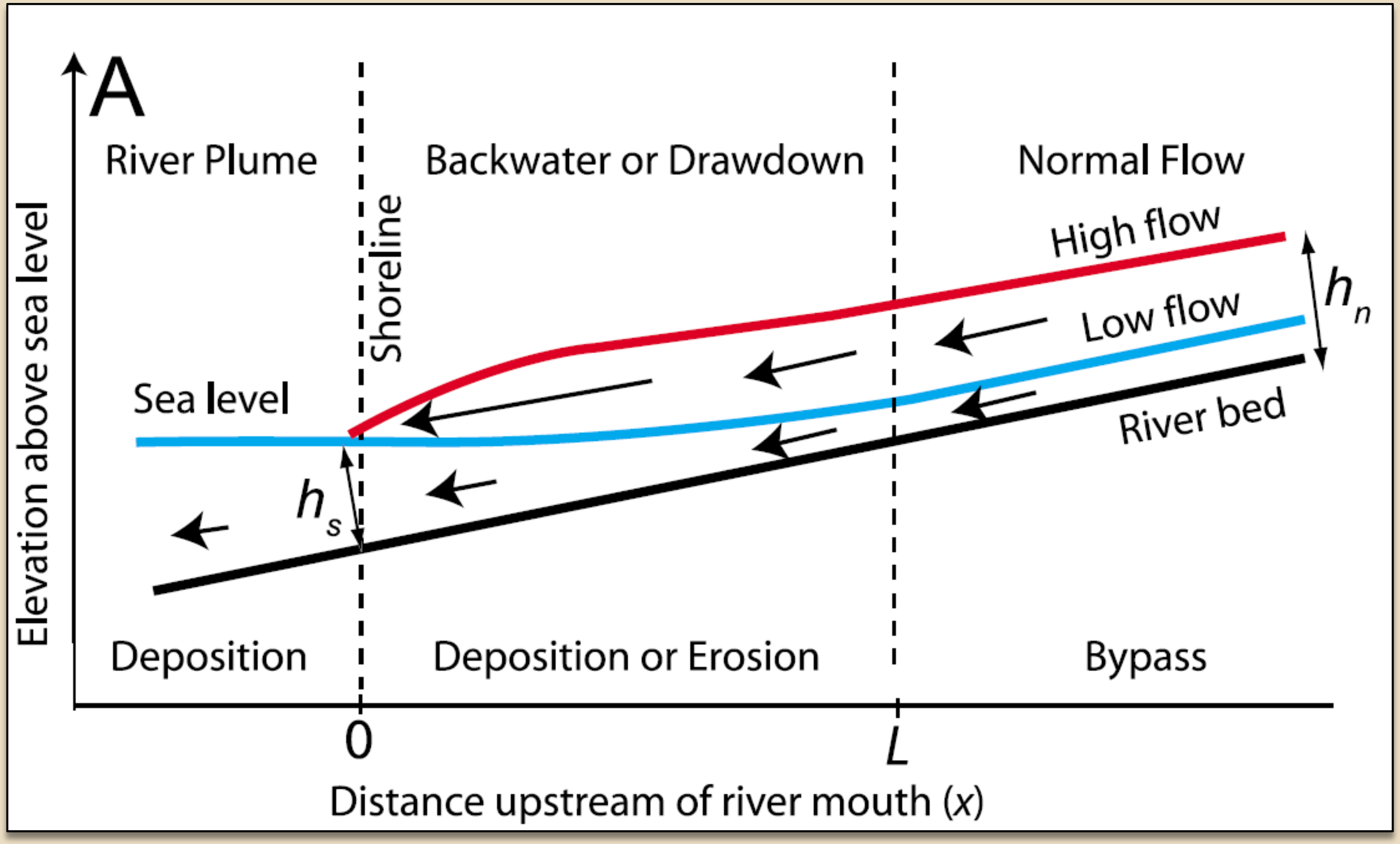


SEDFLUX Model, Syvitski and others



This results in rivers that always experience aggradation near their mouths.

Lane's [1957] hypothesis that rivers experience both erosion and deposition in the backwater zone

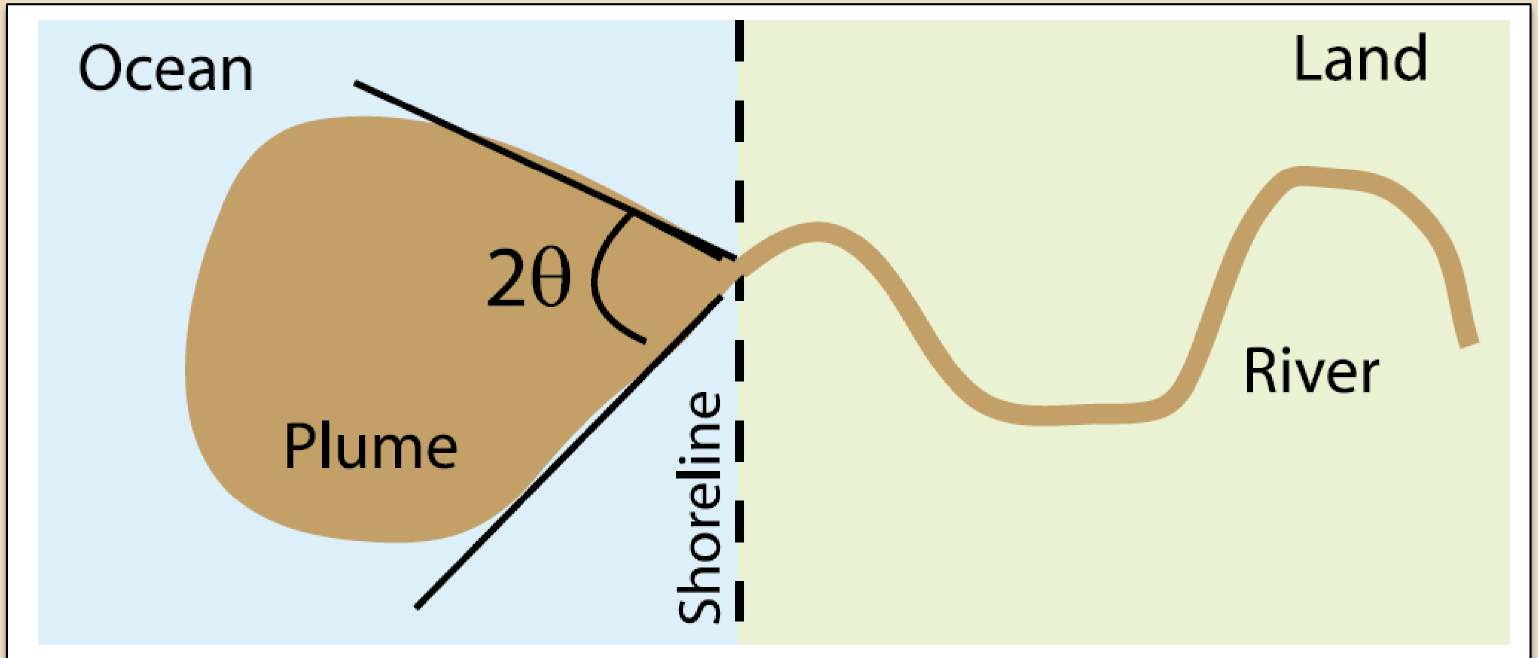


Low flow results in backwater and deposition.
High flow results in drawdown and scour.

Outline

- Numerical model of backwater dynamics and comparison to the Mississippi River
- Five morphodynamics / stratigraphic implications

Numerical Formulation



1. 1D Layer averaged equations of motion (St. Venant)
2. Conservation of fluid mass and momentum
3. Upstream of shoreline: backwater equation
4. Offshore – plume spreads at fixed angle

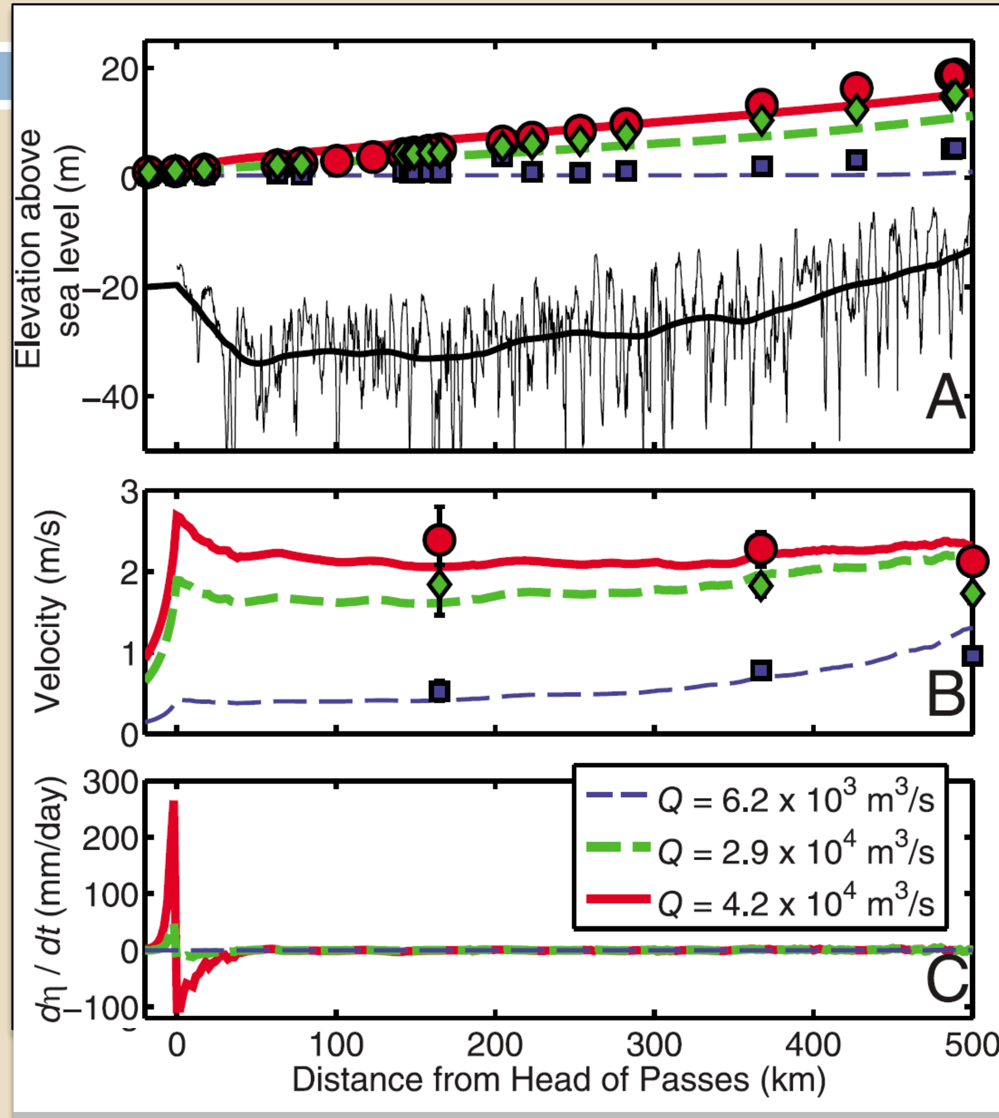
$$\frac{dh}{dx} = \frac{S_b - C_f F^2}{1 - F^2}$$

Application to Mississippi River

- Focus on lower 500 km
- Available data: bathymetry, stage height and flow velocity

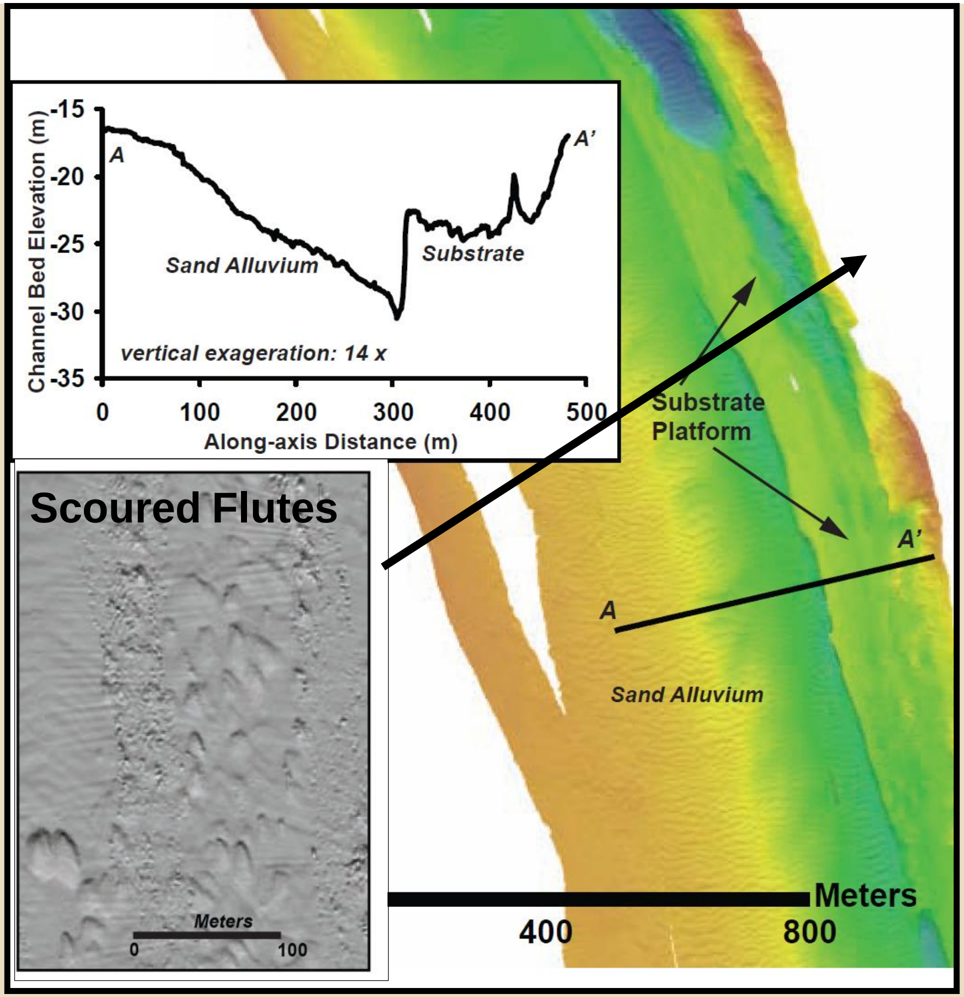
Model Results

- Events: Low flow, 1.9-yr flood, 27-yr flood.
- Spatial deceleration and deposition at low flow
- Acceleration and erosion at high flow
- Water surface at the river mouth is ~fixed at sea level due to plume spreading



(Lamb et al., 2012)

Lower Mississippi River shows evidence for erosion

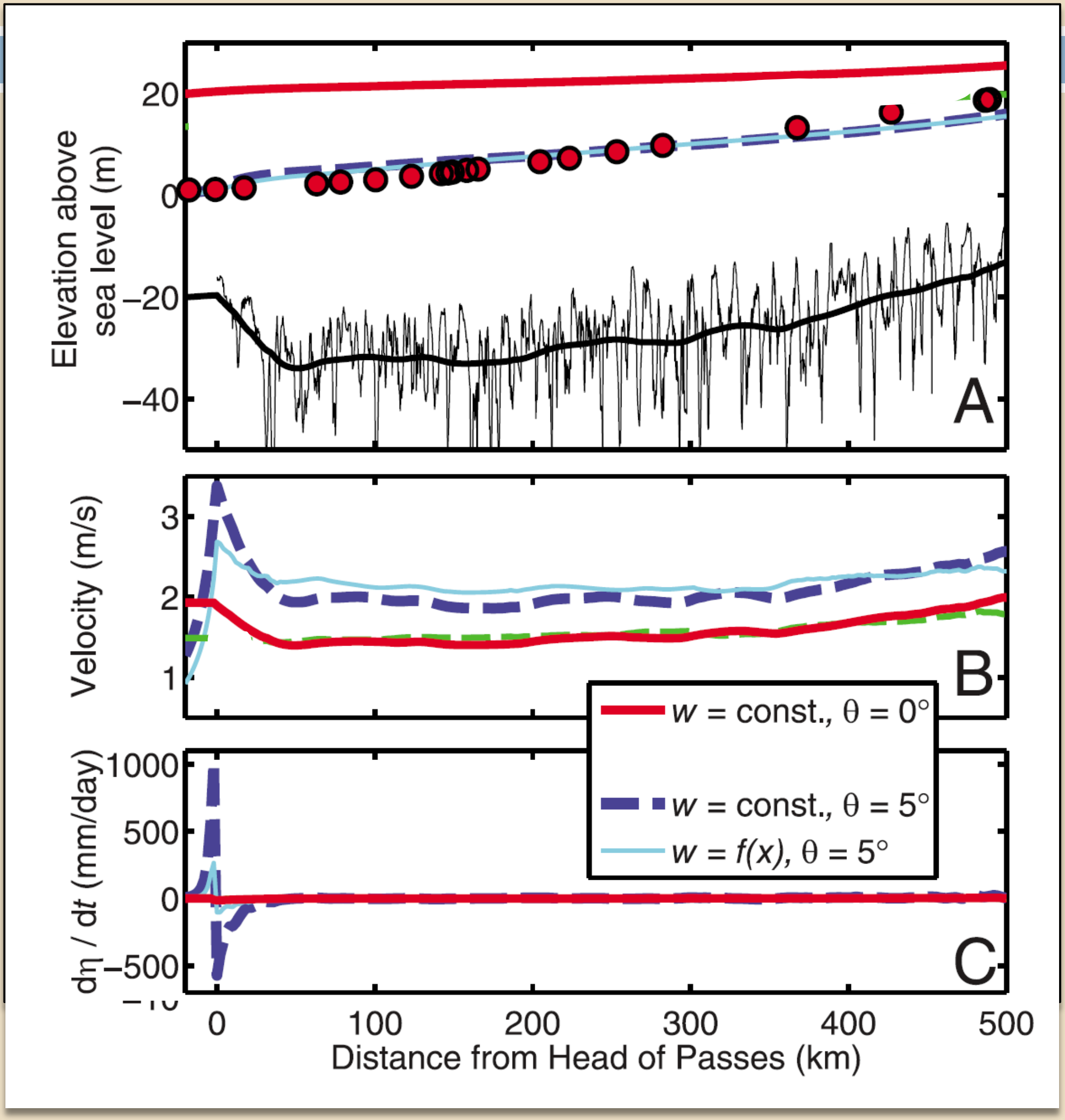


(Nittrouer et al., 2011)

40% of bed is scoured into "rock"

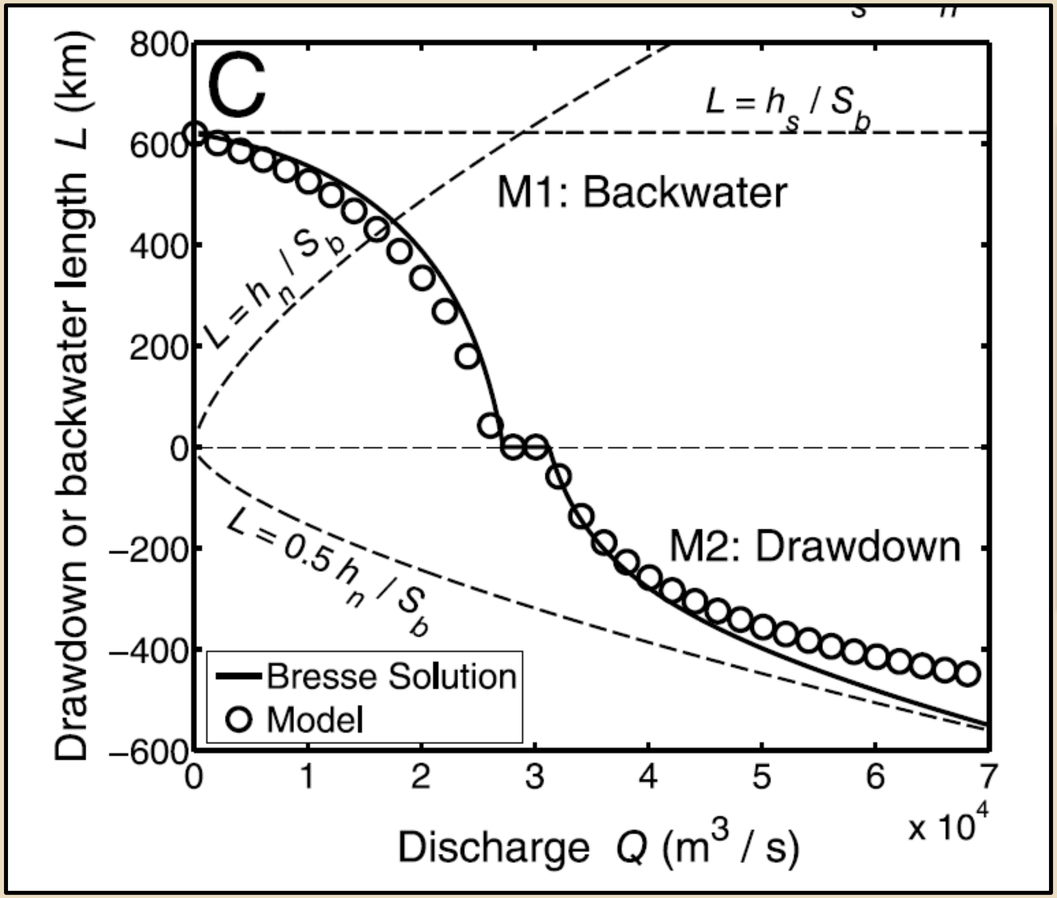
Model sensitivity at high flow

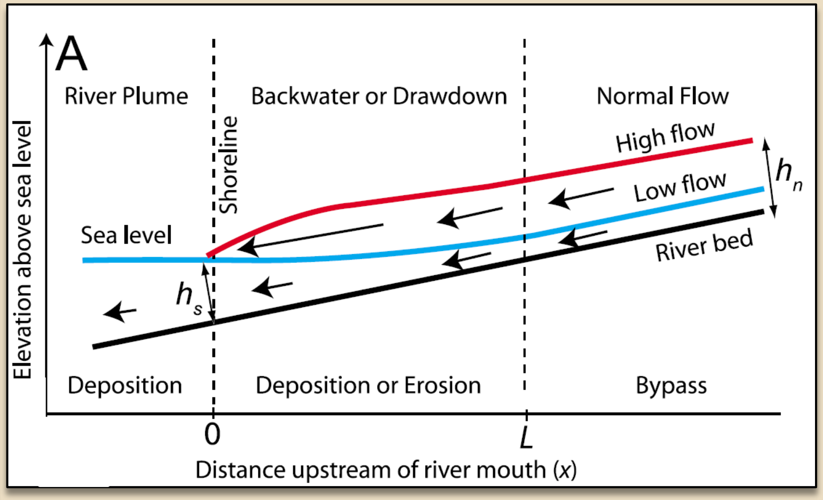
- Results are not sensitive to channel width variations (c.f., Parker et al., 2009).
- A finite plume spreading angle (> ~ 1 degree) is needed to reproduced measurements.



(Lamb et al., 2012)

How often does erosion occur on the lower Mississippi?

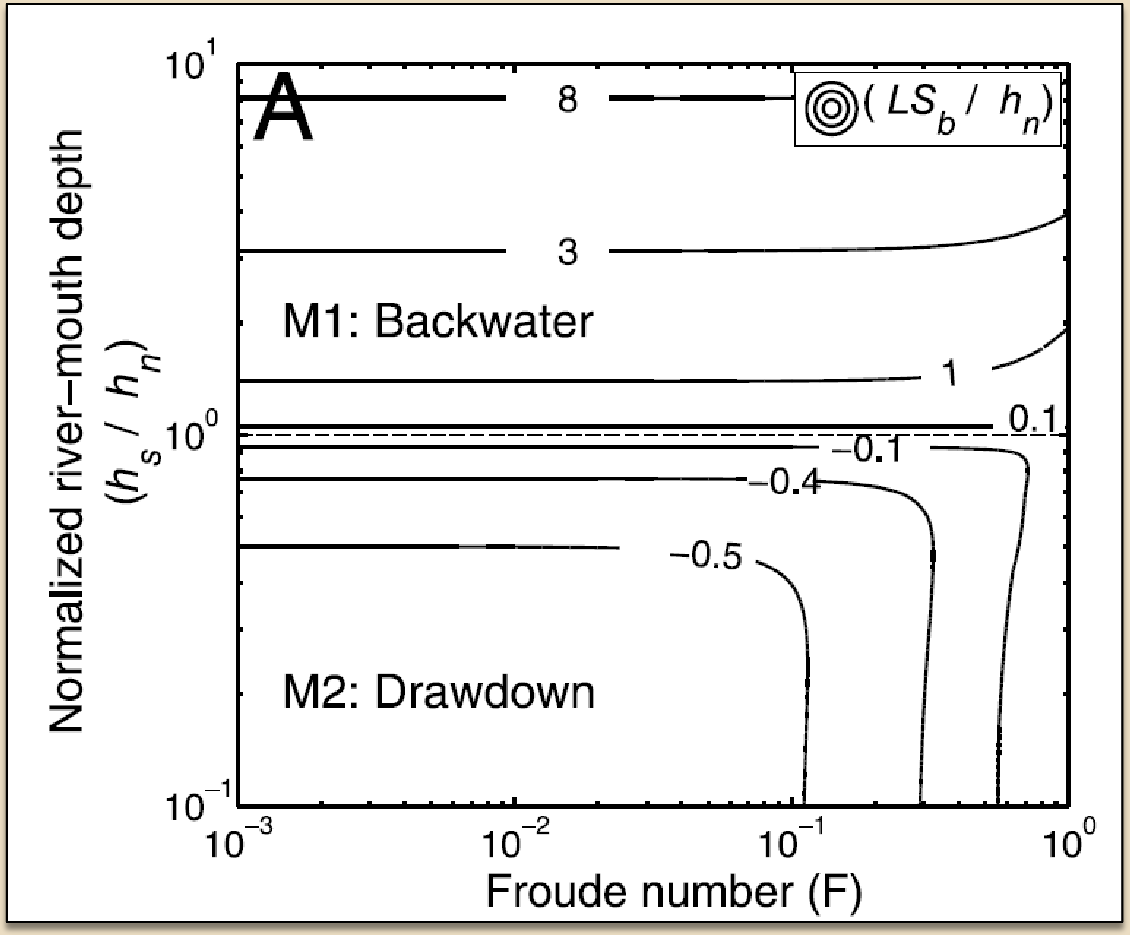




(Lamb et al., 2012)

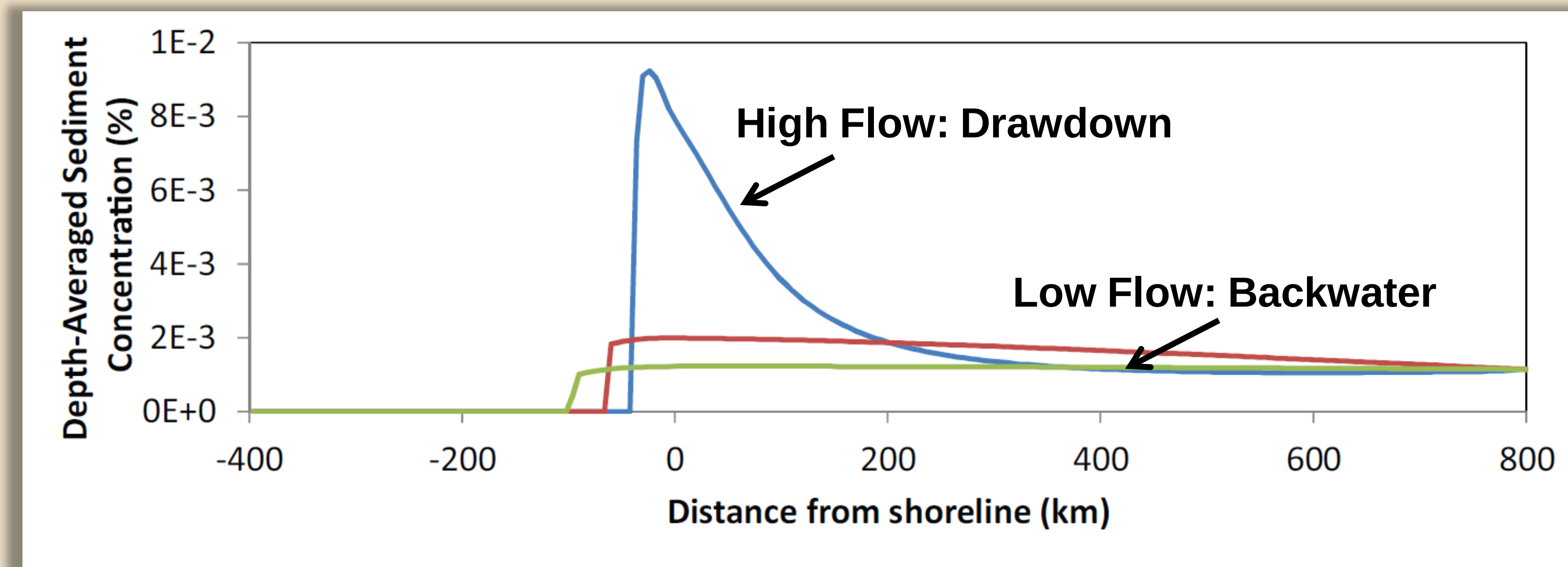
Transition from deposition to erosion occurs at 3 x 10^4 m^3/s; two-yr flood.

Scaling the backwater length to other rivers



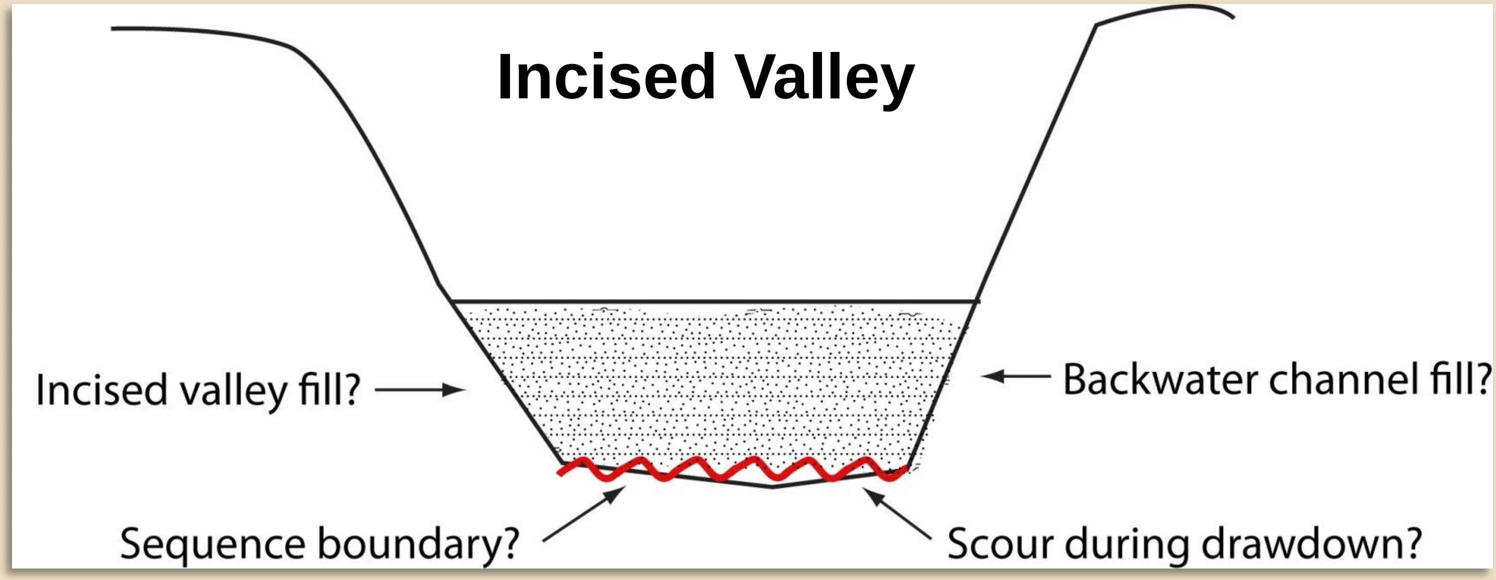
- $L \propto h_n / S_b$ is a key parameter for the maximum drawdown length.
- Backwater length can be infinitely large depending on the river mouth depth.
- Scour effects will be more pronounced in low gradient ($S_b < 0.005$) rivers.

Implication 1: Backwater as a filter on source to sink (bed-material) sediment flux



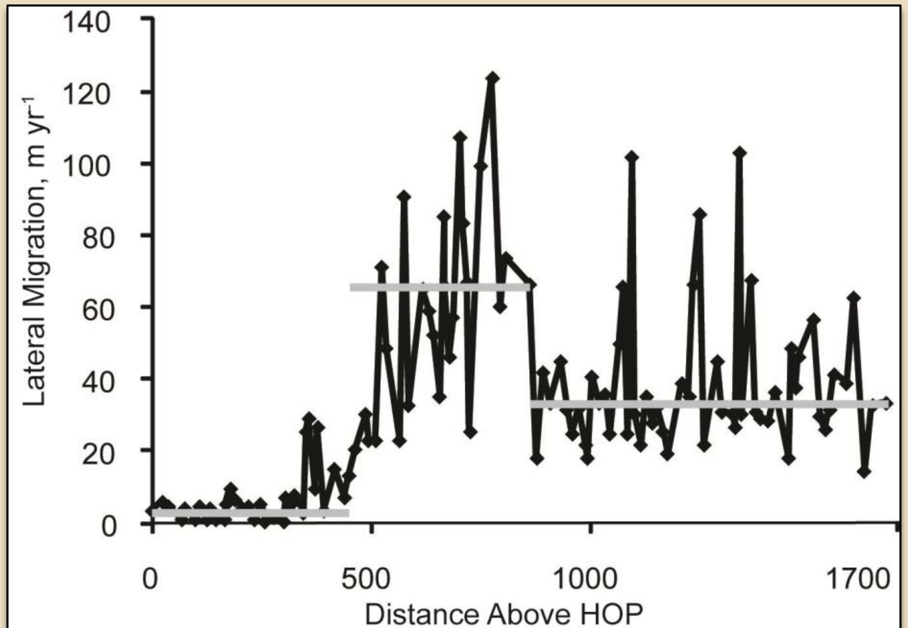
- Reduced bed-material load (sand) during low flows due to deposition in the backwater zone.
- Enhanced bed-material load during high flows due to scour in the backwater zone.

Implication 2: Backwater as an autogenic sequence boundary generator



- Backwater dynamics can create large-scale channel-bed scour near river mouths and in the absence of allogenic forcing (e.g., base level fall)
- Potential erosional zones are large (100s km) exceeding the width of the shelf in most cases.

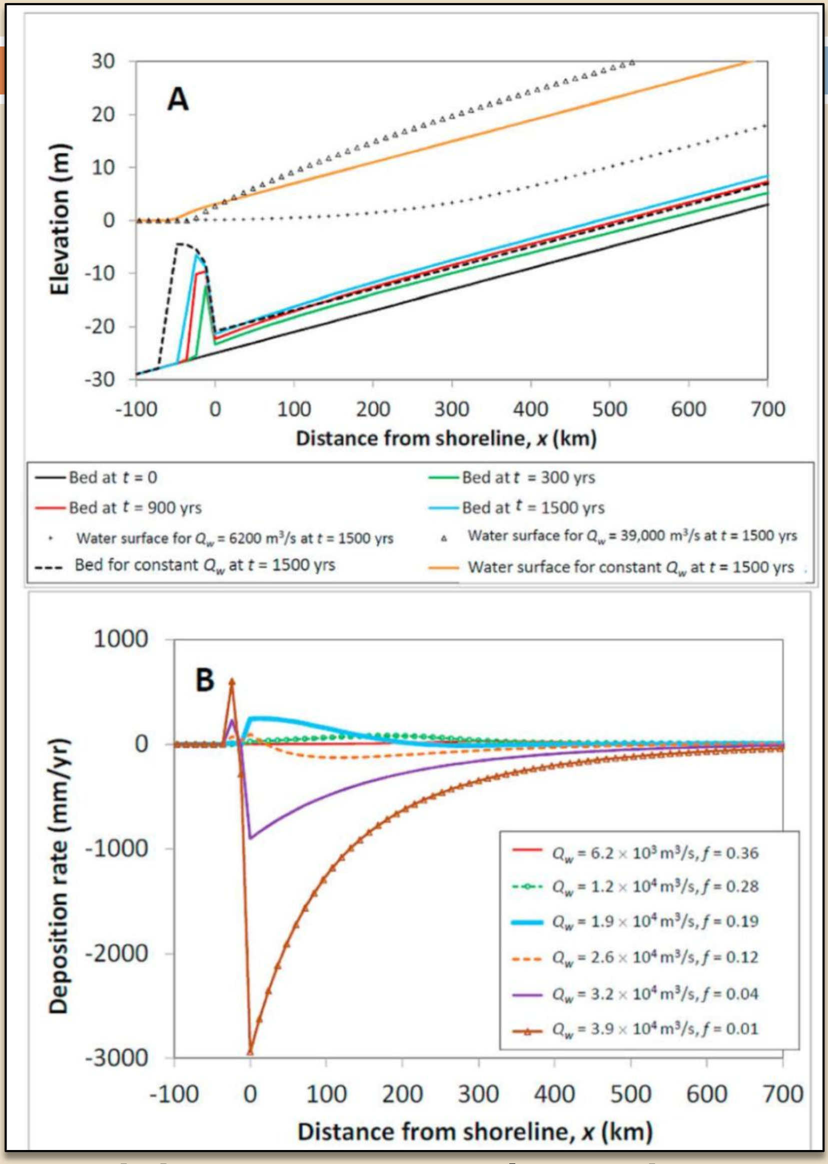
Implication 3: Reduced channel sinuosity in the backwater zone



(Hudson and Kesel, 2000)

- Lateral migration and channel sinuosity are substantially reduced in backwater zone

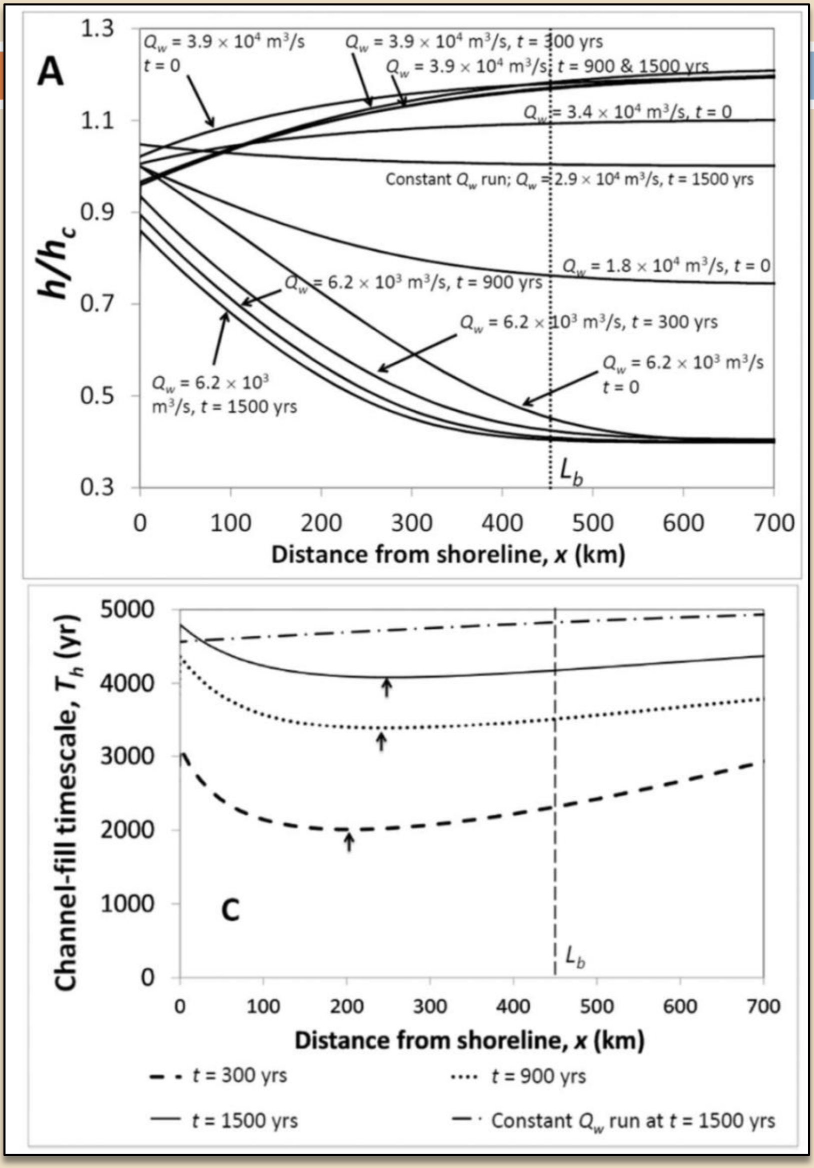
Implication 4: Backwater dynamics set the avulsion node location



(Chatanantavet et al., 2012)

- Morphodynamic simulation with multiple discharge events
- Low flow events cause deposition, high flow events cause scour.
- Cumulative effect is different than a model with a single discharge

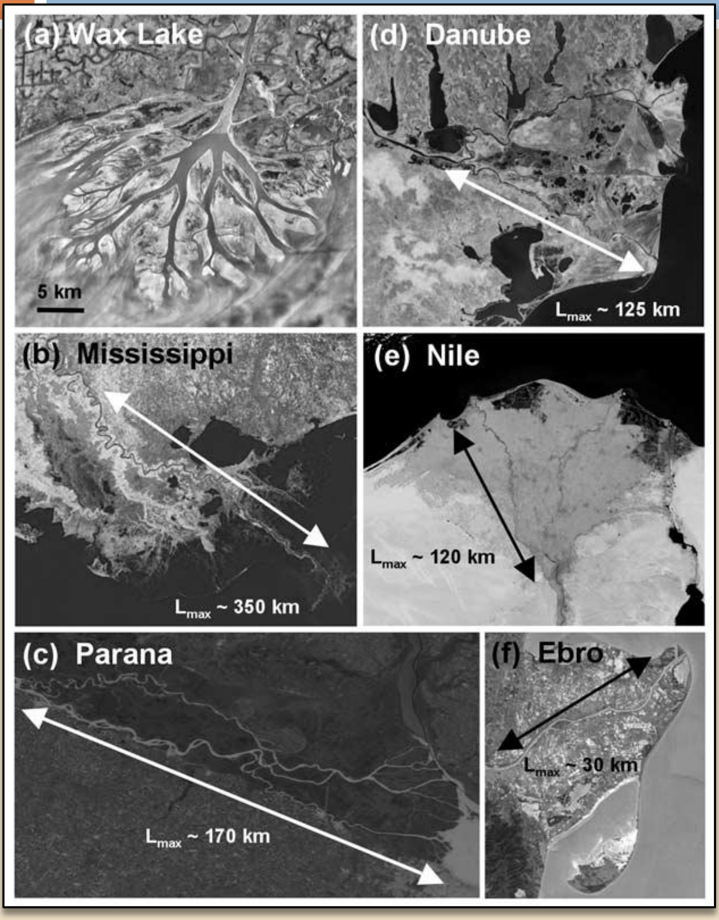
Implication 4: Backwater dynamics set the avulsion node location



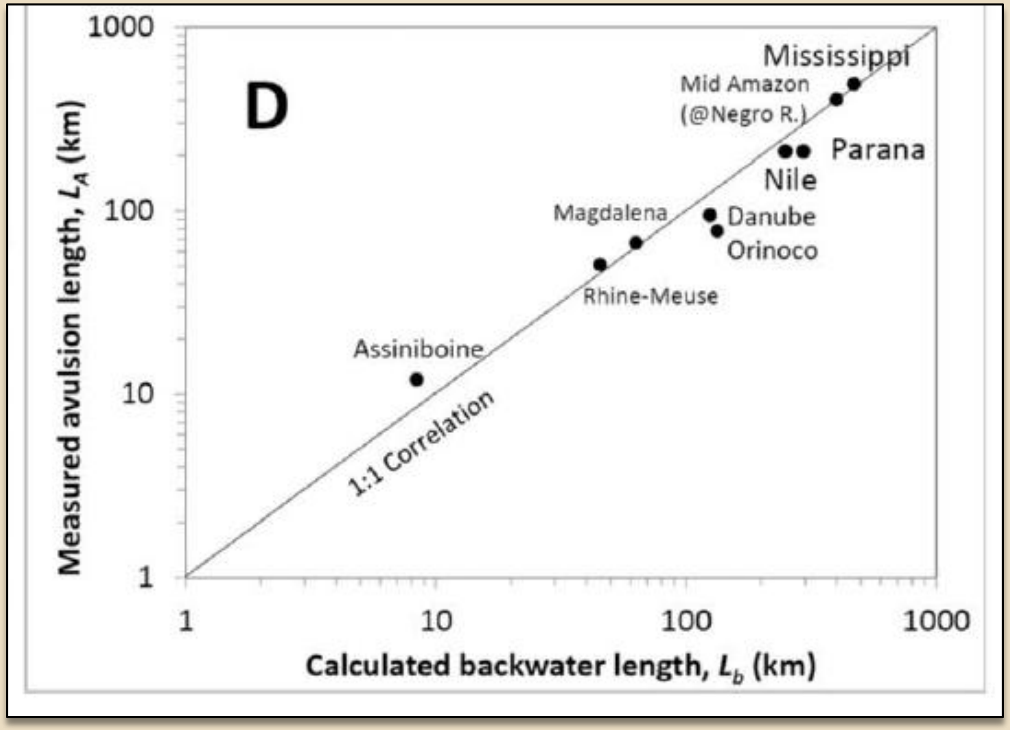
(Chatanantavet et al., 2012)

- Stage heights during floods are reduced within the backwater zone.
- Deposition rates are greater in upstream part of backwater zone.
- Channel fill timescale (Mohrig et al., 2000) has a minimum within the backwater zone.
- Avulsion is more likely in the upstream part of the backwater zone.

Implication 5: Backwater dynamics determine the size of deltas



(Jerolmack, 2009)

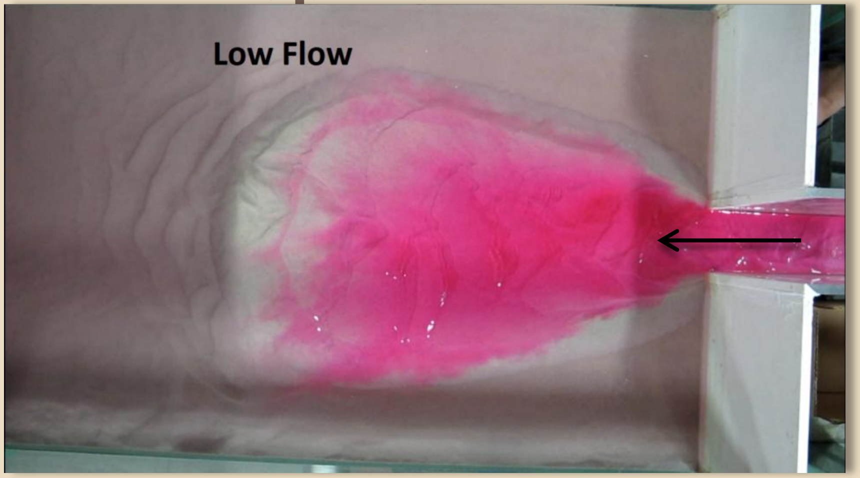


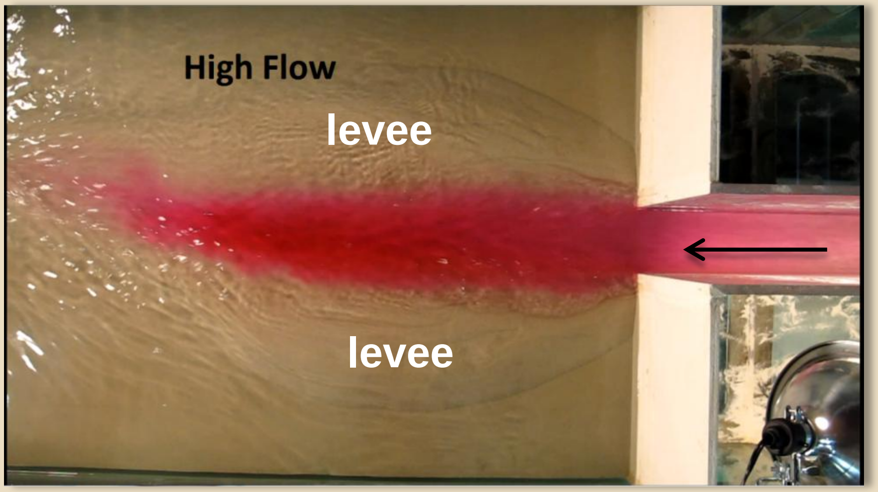
(Chatanantavet et al., 2012)

Avulsion length correlates with the backwater length

Implication 6: Backwater dynamics controls self-channelization

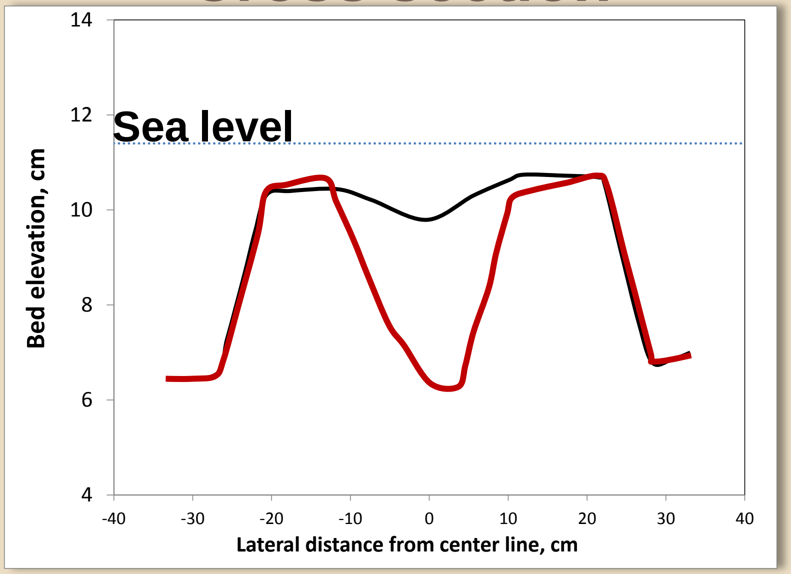
Top View





(Chatanantavet and Lamb, in prep.)

Cross section



- Backwater zone extends onto the proto-channel.
- Alternating between high and low flows is necessary for building depth-scale levees.

Conclusions

- Backwater zones act as a filter by muting sediment flux at low flows and enhancing sediment flux at high flows
- Large flood events can produce substantial channel-bed erosion near river mouths due to water-surface drawdown, in the absence of allogenic controls (sea level, climate, …)
- Backwater dynamics may determine the size of deltas by setting the location of the avulsion node.
- Backwater dynamics and variable river discharge are key in producing incipient channelization and depth-scale levees.