EP31A-0797: Backwater Controls on Source-to-sink Sediment Transport near Deltas: Connecting Morphodynamic, Numerical Modeling and Flume Experiments

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ABSTRACT: Sediment transfer from rivers to the ocean is the fundamental driver of continental sedimentation with implications for carbon burial, land use dynamics, and unraveling global climate change and Earth history from sedimentary strata. Despite the important role of source-to-sink sediment transfer, substantial uncertainty exists about the behavior of rivers near their mouths and sediment routing from rivers to their offshore plumes. Here we aim to better understand the morphodynamics and sediment transport in the transitional river-to-river-plume zone that is characterized by backwater hydrodynamics. We developed a quasi-2D morphodynamic, numerical model of a coupled river and river plume system. We also conducted flume experiments to test the numerical model results to directly observe morphodynamics near the river mouth. Our experiments were performed in a 7.5-m flume where a 10-cm wide river channel was connected to a 76-cm wide "ocean basin" allowing for offshore spreading of the river plume. Experiments were conducted in both transient and steady states for low discharge (M1) and high discharge (M2) conditions. Both the numerical model and the flume results demonstrate that (1) during low flows backwater hydrodynamics cause spatial flow deceleration and sediment deposition in the river channel and the offshore plume area, and (2) during high flows the backwater zone becomes a region of water-surface drawdown, spatial flow acceleration and bed scour. The results show that with a suite of flood events with different discharges and durations, a persistent backwater/drawdown zone exists and controls the patterns of deposition and erosion, which cannot be reproduced using a single characteristic discharge (as is often assumed). We also found channel levee formation offshore generated under bedload transport during the low flow condition, and a large scour hole offshore from the river mouth that is deeper than anywhere else in the river-plume system. Our study highlights the need to include coupled river and river plume system with a suite of flow discharges to accurately predict fluvio-deltaic morphodynamics and connectivity between fluvial sediment sources and marine sediment sinks.

Governing Equations in the Model

Fluid continuity equation

$$\frac{d(Uhw)}{dx} = 0$$

Fluid momentum equation

$$U\frac{dU}{dx} = -g\frac{dh}{dx} + gS - C_f\frac{U^2}{h}$$

Backwater equation for gradually-varied flow

$$\frac{dh}{dx} = \frac{S + Fr^2\left(\frac{h}{w}\frac{dw}{dx} - C_f\right)}{1 - Fr^2}$$

$$\frac{dw}{dx} = 2\tan\theta$$

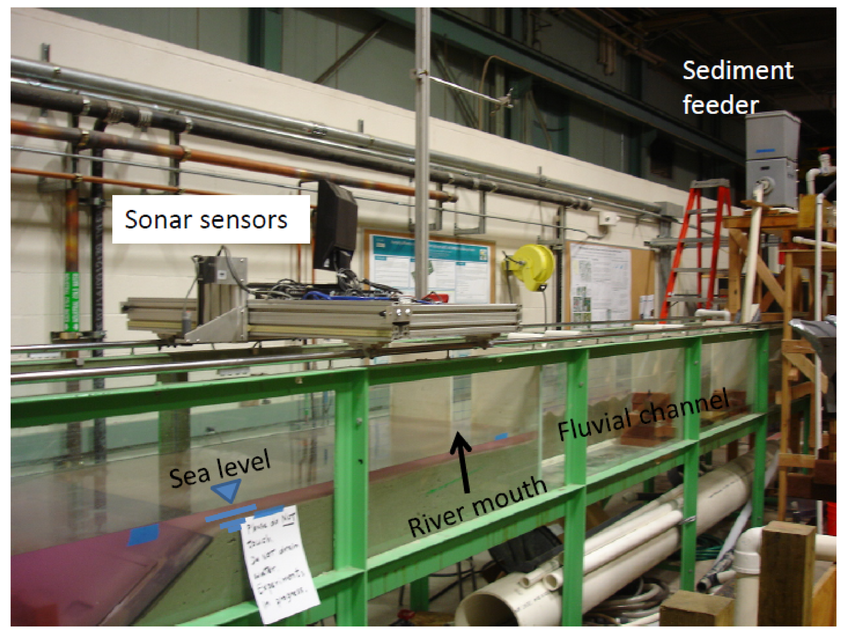
Bedload transport rate

$$Q_s = 3.97 * w(RgD_{50}^3)^{1/2}(\tau^* - \tau^*_c)^{3/2}$$

Evolution of the bed by continuity for dilute flow

$$(1 - \lambda_p)\left(\frac{\partial\eta}{\partial t} + \sigma\right) = -\frac{1}{w_s}\frac{\partial Q_s}{\partial x}$$

Note for Parameters :
U = streamwise velocity, h = water depth, S = bed slope, C_f = friction coef., w = width of water jet, D_{50} = grain size, τ^* = dimensionless bed shear stress , λ_p = bed porosity, η = bed elevation, σ = land subsidence rate, w_s = width of sediment depositional zone, Q_s = sediment transport rate, Fr = Froude number, x = down-channel distance, t = time, θ = plume spreading angle



- Experimental plan; run to equilibrium for both low and high flows; use numerical results as a guide, run transient cases
- Using walnut shell, D = 700 microns, R = 0.3
- Low flow (1.5 l/s), Q_s = 1.1 g/s, H = 6.4 cm, S = 0.0015 (equil.)
- High flow (3.4 l/s), Q_s = 1.9 g/s, H = 12.3 cm, S = 0.0015 (equil.)

Figure 1. Caltech experimental flume studying backwater dynamics

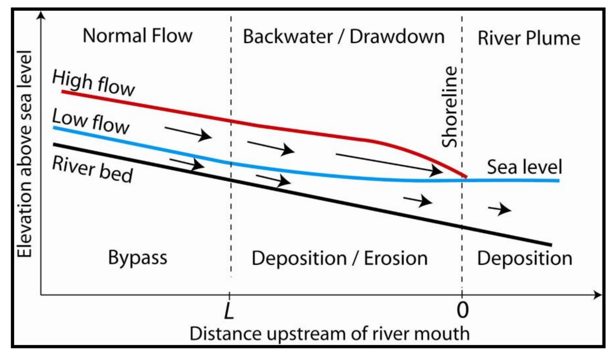


Figure 2. Schematic of backwater dynamics; M1 regime (blue line) and M2 regime (red line)

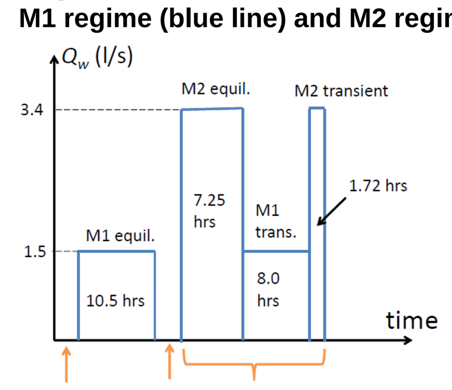


Figure 3. Plan for experimental runs

Numerical Model Results

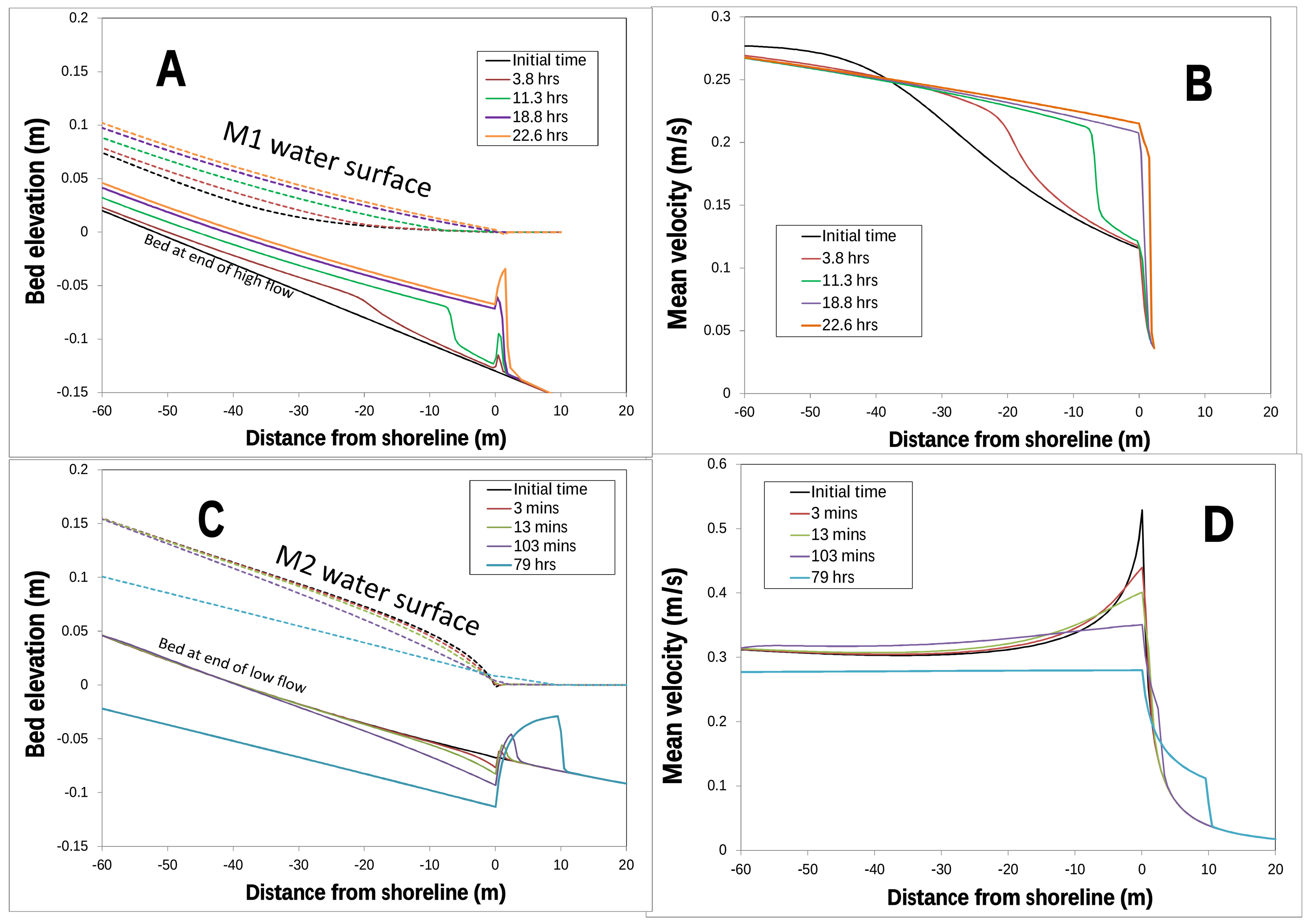


Figure 4. Numerical model results for channel bed evolution and flow velocity for our lab scale; (A) and (B) are for low flow (M1) condition of 1.5 l/s, and (C) and (D) are for high flow (M2) condition of 3.4 l/s. The spatial deceleration of flow for the case of M1 leads to bed deposition starting from upstream, while the spatial acceleration of flow for the case of M2 leads to bed scour starting from the channel downstream end (river mouth).

Results from Flume Experiments

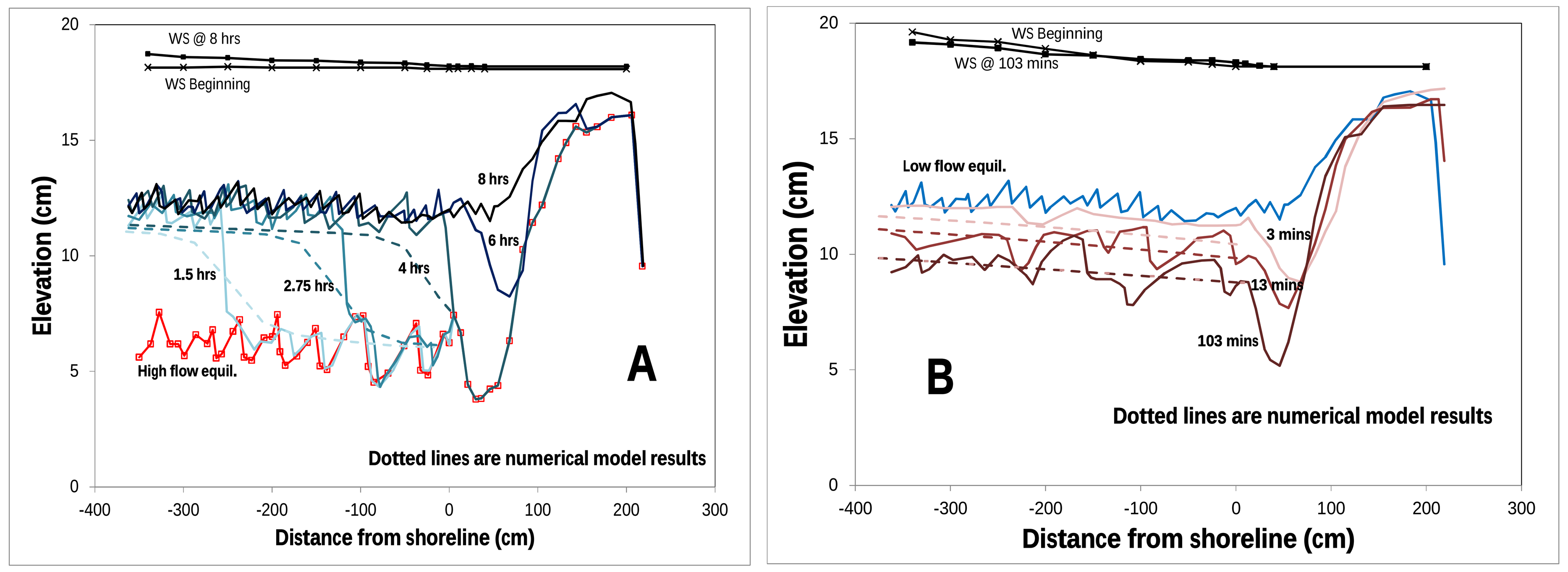
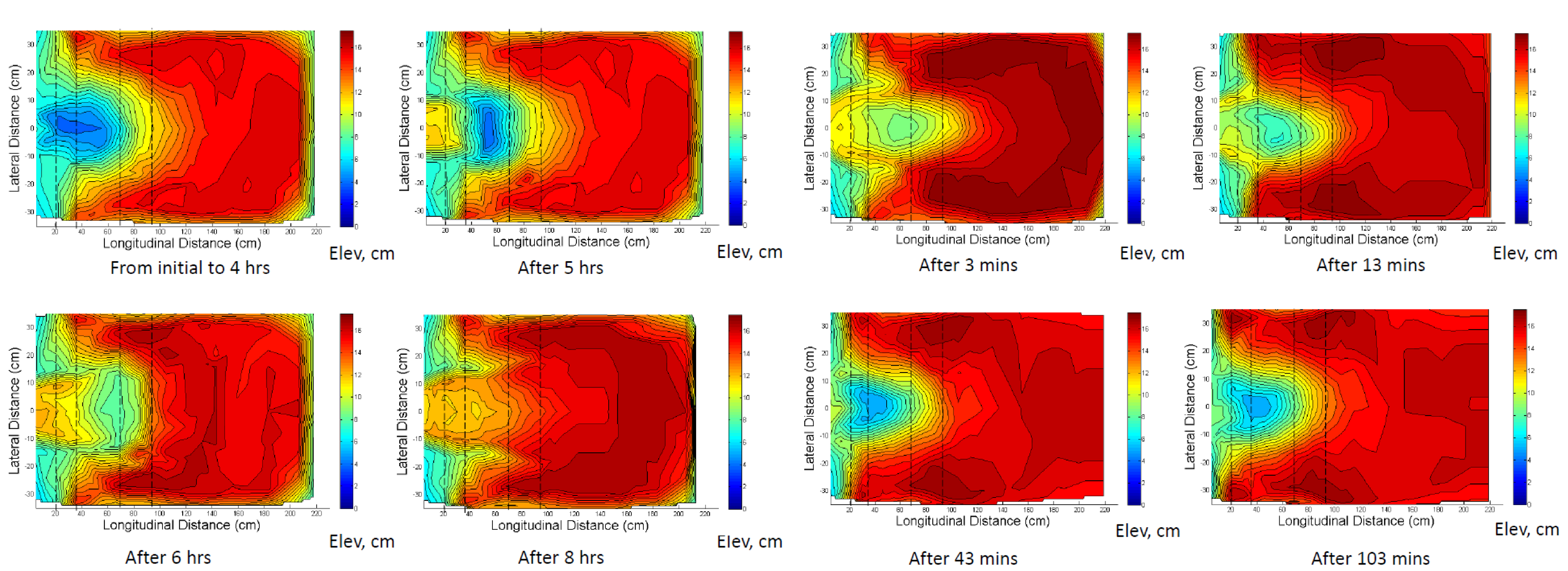


Figure 5. Comparisons of results of river longitudinal profiles from flume experiments (Figure 1) and numerical model for (A) M1 or depositional regime and (B) M2 or erosional regime. Dotted lines are from numerical model while solid lines are from flume experiments. The ripple size in the case of low flow is smaller than the one for high flow. Note that due to the limited flume length, we only study a 4-m channel subsection upstream from the river mouth in Figure 4.



(A) M1 transient run (M2-to-M1)

(B) M2 transient run (M1-to-M2)

Figure 6. Contour plots of bed evolutions in the offshore basin from flume experiments; (A) M1 transient run and (B) M2 transient run. In the case of M1 transient, for the first 4 hrs the morphodynamics only occur in the river-channel section (Fig. 5A); hence, the basin topography is the M2 equilibrium. After 4 hrs, the bed deposition occurs beyond the river mouth and fills the scour hole from previous M2 condition. In the M2 transient case, the bed changes occur faster; only after 3 mins, erosion re-creates the scour hole. After 103 mins, however, it does not yet reach equilibrium state. Dashed lines are the locations of the cross-sectional profiles in Figure 7.

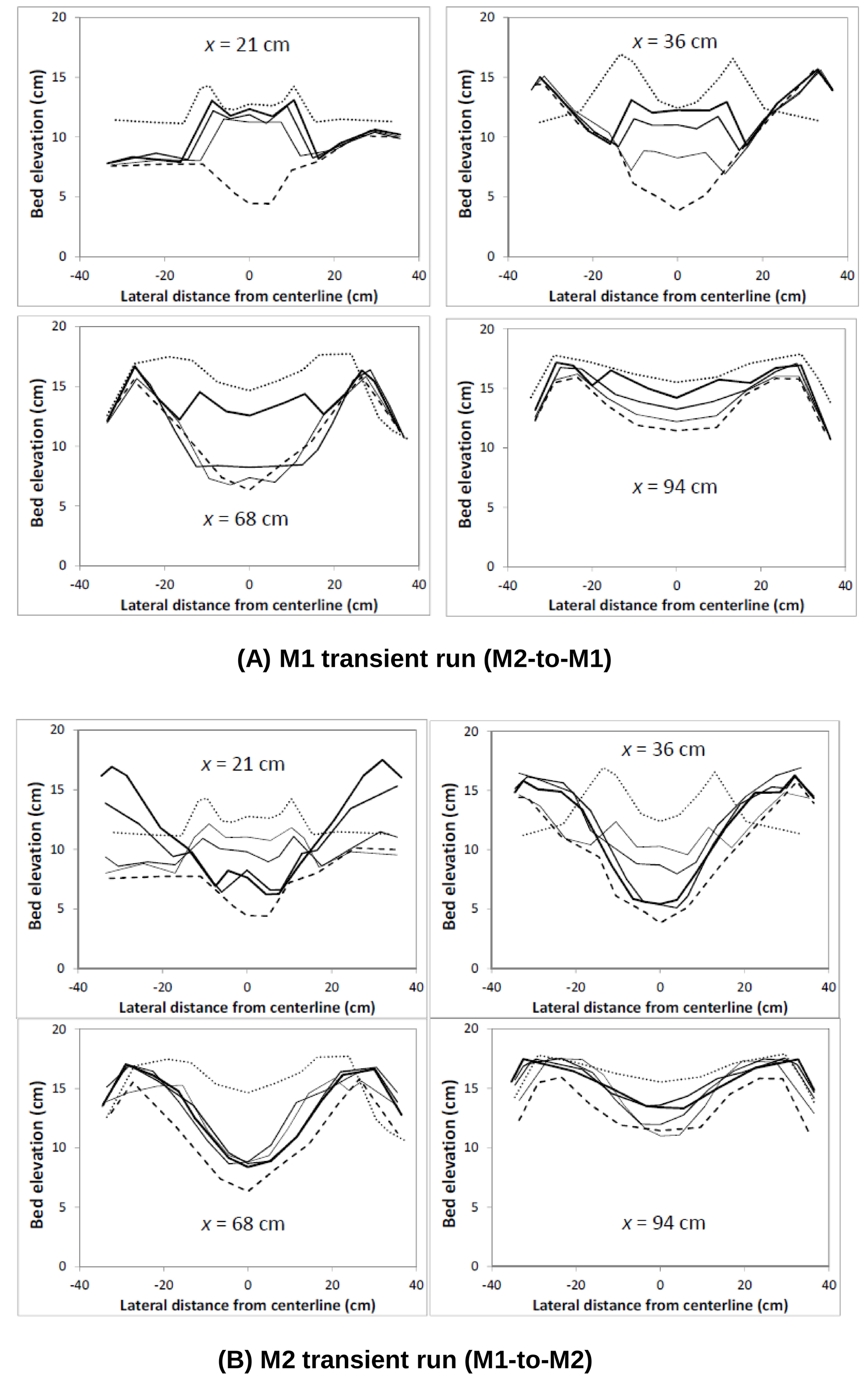


Figure 7. Evolutions of cross-sectional profiles at four longitudinal locations along the basin; (A) M1 transient run with time steps = 5, 6, and 8 hrs from thinnest line to thicker lines, and (B) M2 transient run with time steps = 3, 13, 43, and 103 mins from thinnest line to thicker lines. Dotted lines are M1 equilibrium case and dashed lines are M2 equilibrium case. Notice the levees formation in the case of M1 runs and the scour hole development in the case of M2 runs.

Conclusions

In natural deltaic rivers, normal (steady and uniform) flow is not expected near the river mouth due to the standing water level in the basin (ocean or lake), which creates a transitional or backwater zone. Both the numerical model and the flume results here demonstrate that (1) during low flows backwater hydrodynamics cause spatial flow deceleration and downstream-propagating wave of deposition, and (2) during high flows the backwater zone becomes a region of water-surface drawdown, spatial flow acceleration and bed scour in the river channel and the offshore plume areas. A flood hydrograph in natural rivers with different discharges can switch the hydrodynamic regimes from spatial acceleration to deceleration, and vice versa. Offshore levees formation during low flow is found to be an autogenic process and here occurs due to bedload, while during high flow there is an offshore, deep scour hole generated.