Reach-scale bed material sediment routing with off-channel sediment storage

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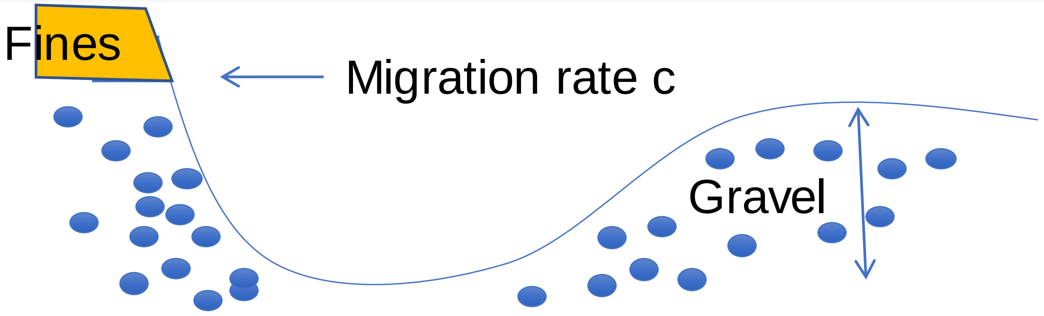
With thanks to Katie De Rego, Marwan Hassan, Brett Eaton, Hervé Piégay, Gary Parker, Enrica Viparelli, and many others

Overview

- Why is lateral exchange important in gravel-bed rivers?
- Modeling case studies
  - Walker River/Toy Model
  - Minnesota River/2 Size Fraction Model
  - Elwha River/MAST-1D
- What may this mean for Skagit River system?

Google Earth Engine Animation of Skagit River upstream from Sedro Wooley

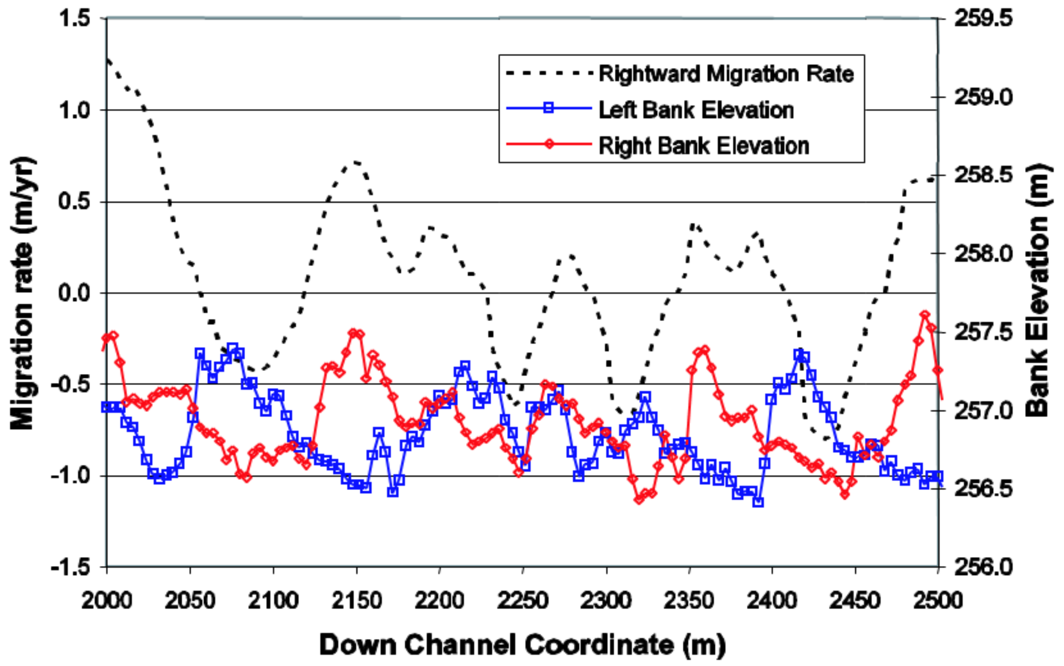
Sediment Mass Balance during Erosion



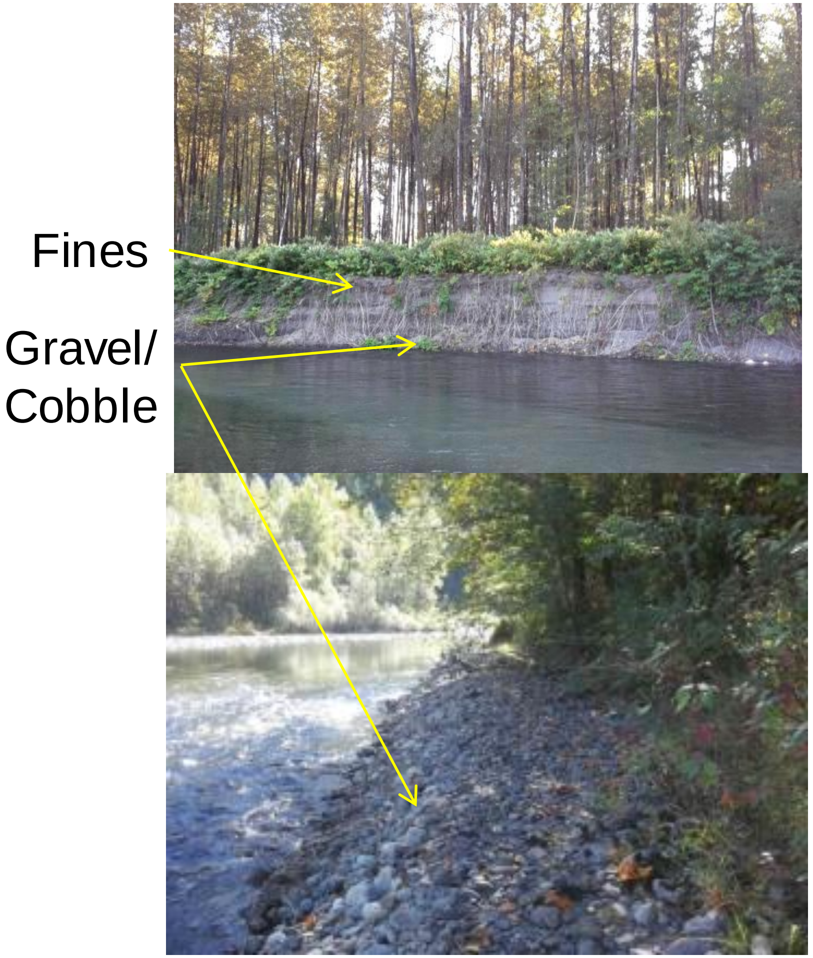
Points:

Migration can lead to net supply of sediment where channel migrates into high banks (or thick gravel).

In gravel-bed rivers, distance to exchange the majority of gravel between channel bed and adjacent bars may be just a few bends.

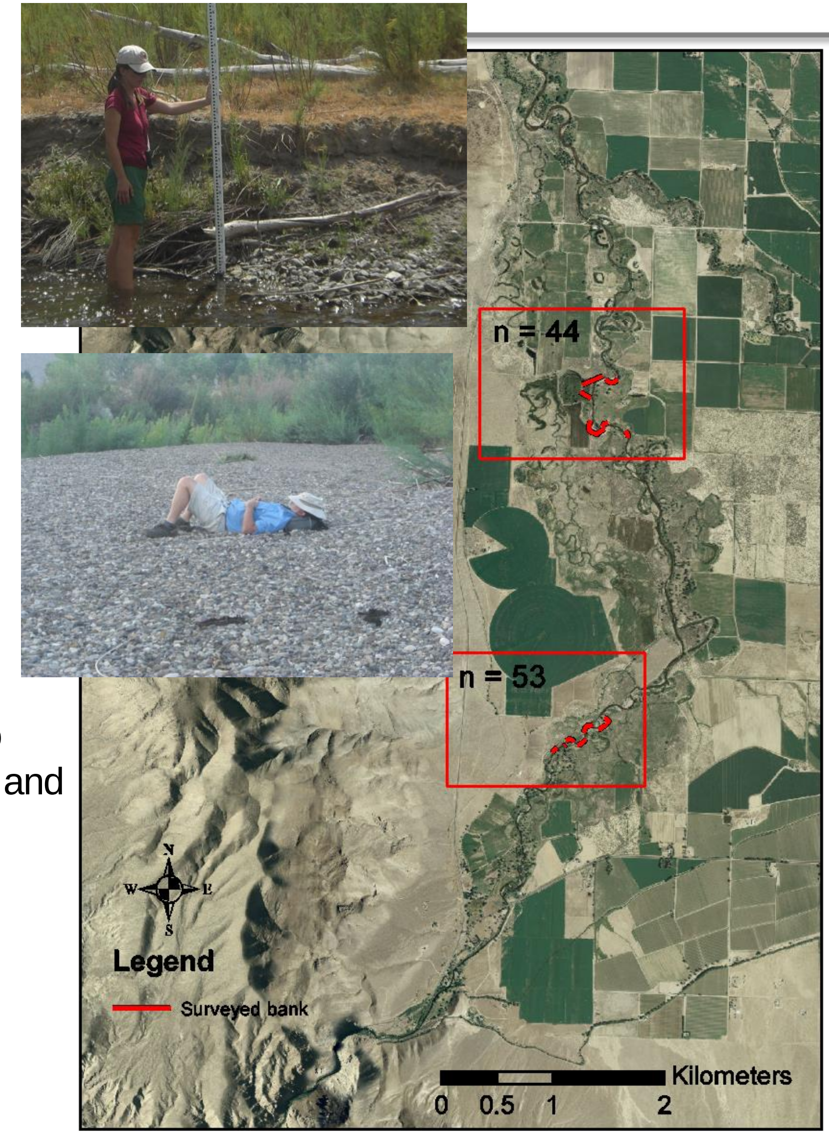


Lauer and Parker, 2008, Geomorphology

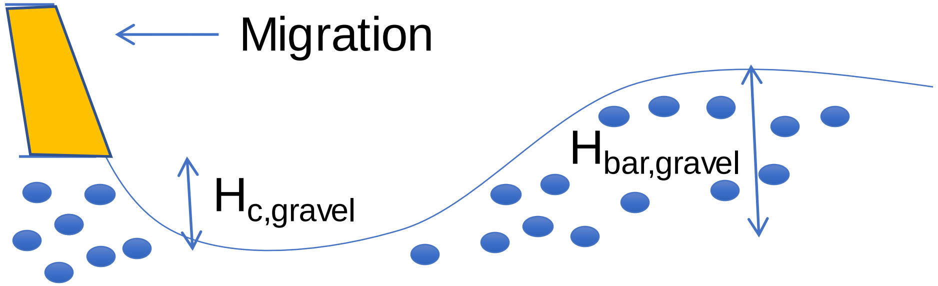


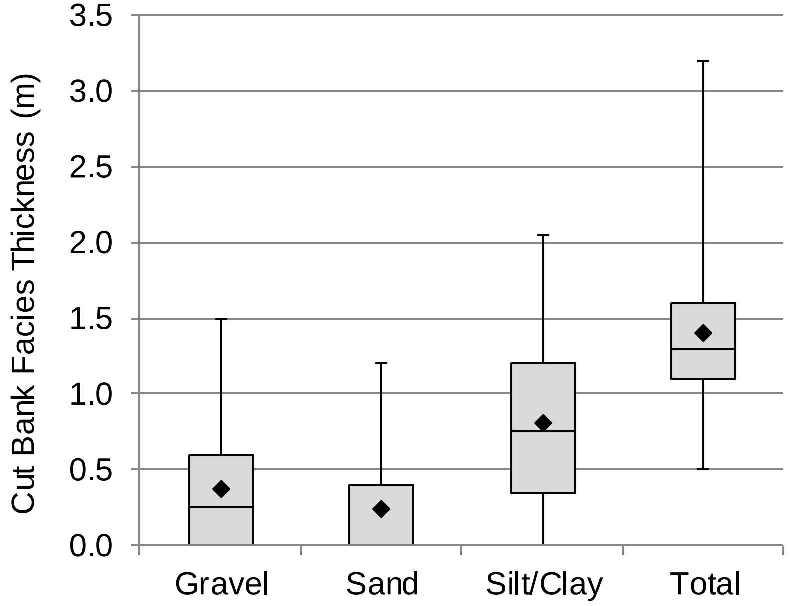
Middle Fork Snoqualmie R.

Uneven sediment exchange? West Walker River, NV



Special thanks to Milada Majerova and Peter Wilcock



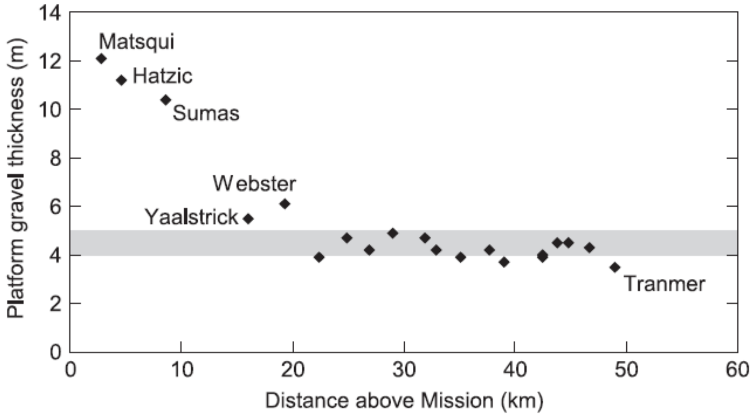


System may lose gravel to bars as channel migrates. Plausible rates of exchange allow channel to deplete itself of coarse gravel over ~10 km.

Simple Model for Morphology (all gravel, one size, constant width)

Hypothesis: Constant Point Bar Thickness

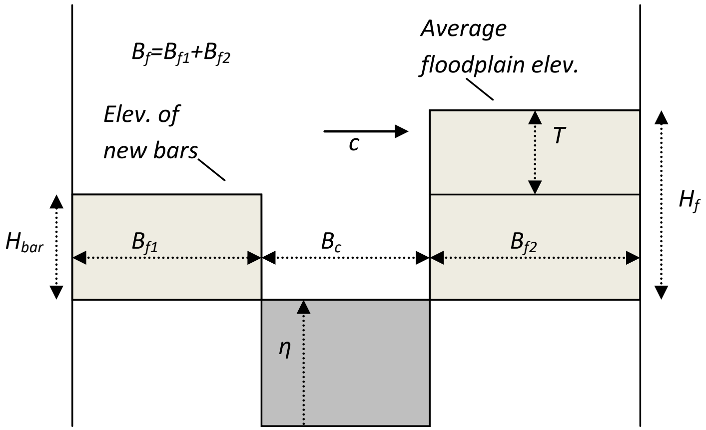
(see Church and Rice, 2009, ESPL 34: 1422-1432. Braudrick et al., 2009, PNAS).

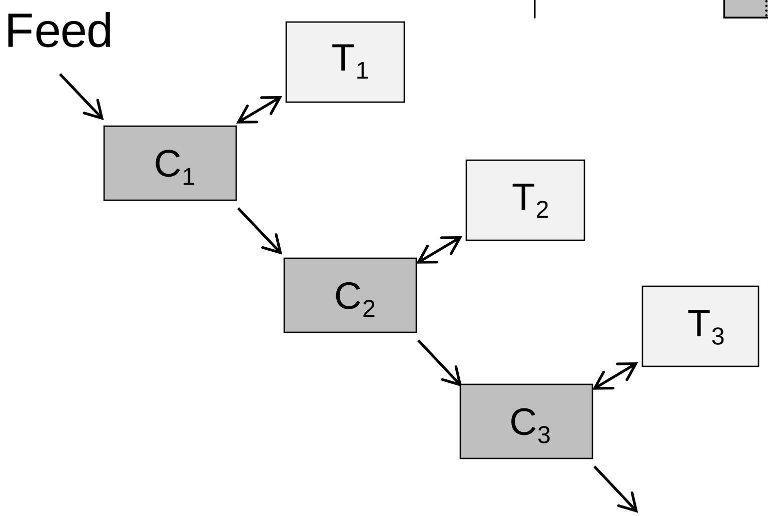


Terrace change rate	=	Bed degradation rate	-	Average height eroded from terrace
Bed change rate	=	Net sediment transported downstream	+	Sediment supplied from terrace

Mechanism for "Terrace" Reservoir T to Change Volume

(Lauer, 2012, *Gravel Bed Rivers* 7)

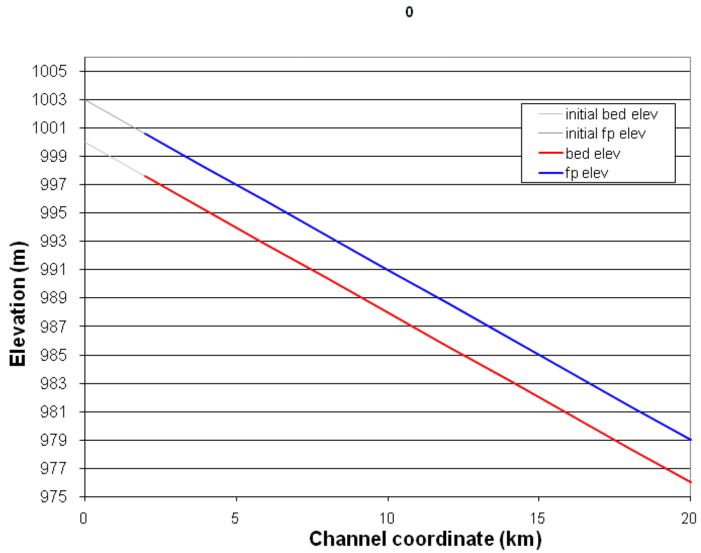


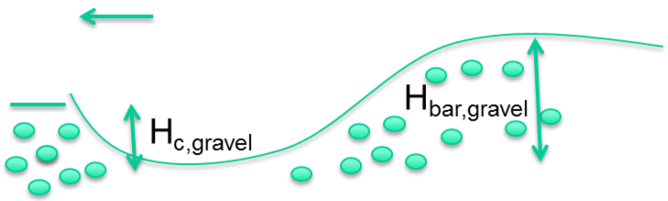


Results (Gravel Bed, Gravel Bars, Constant Width)

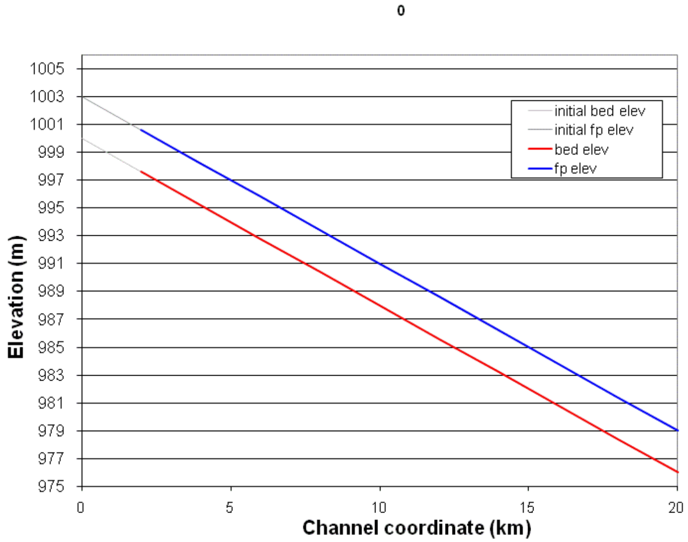
Flow partition between channel/terrace is driven by range of flows (including floods). As T increases, flow becomes focused in channel, causing further incision.

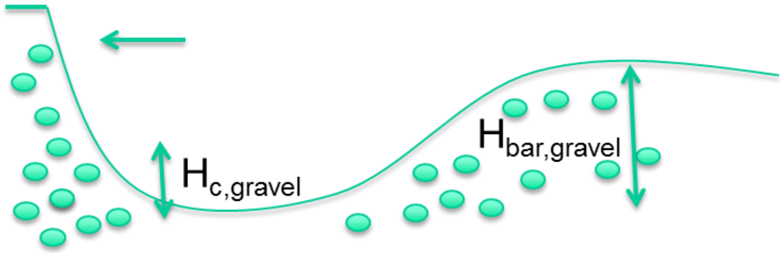
Increase load from initial equilibrium "graded" condition





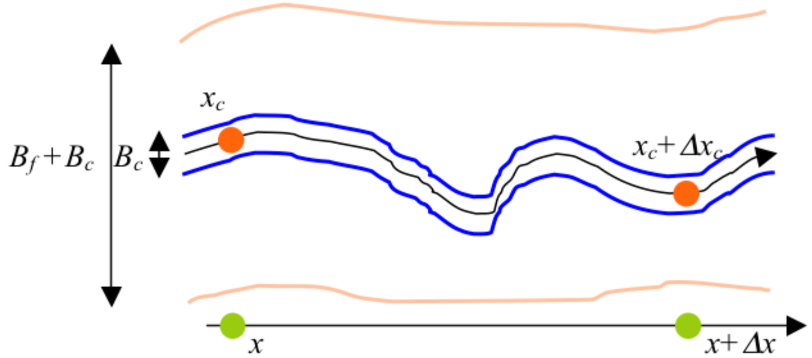
Reduce load from initial equilibrium "graded" condition



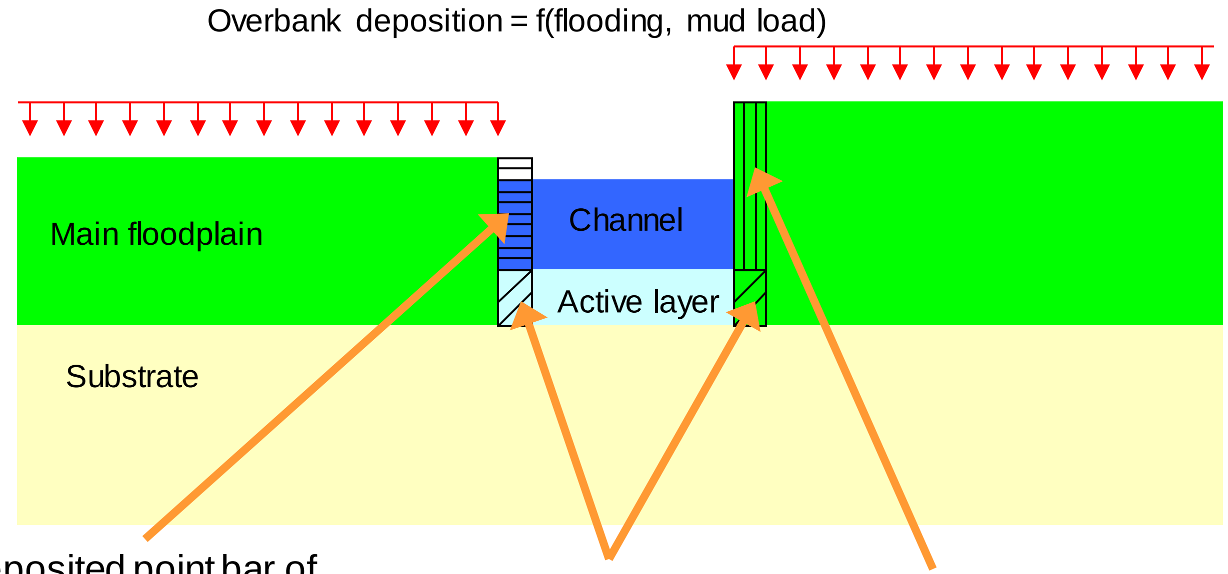


Two-fraction, three-reservoir model

Viparelli et al., 2013, *Computers and Geosciences.*



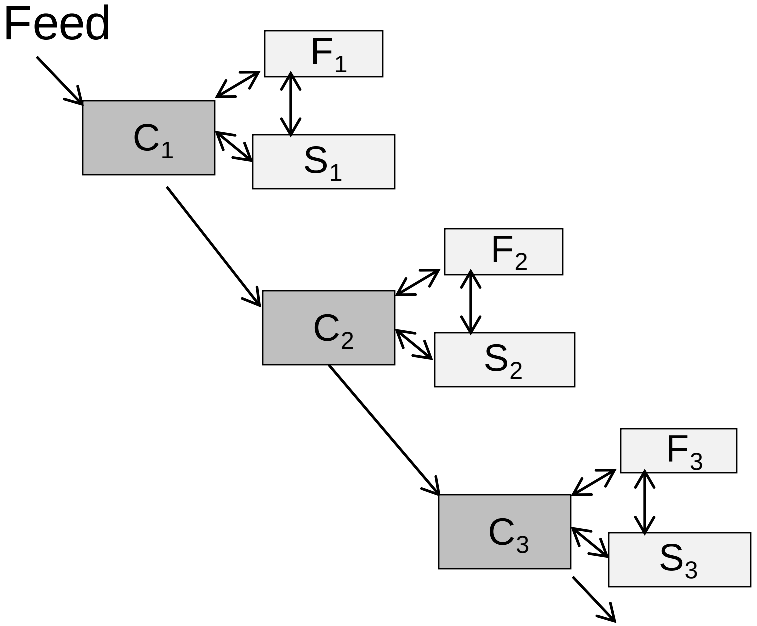
A second grain size (mud) is added and tracked in reservoirs representing channel, floodplain, or substrate. Material is moved to/from substrate as channel aggrades/degrades.



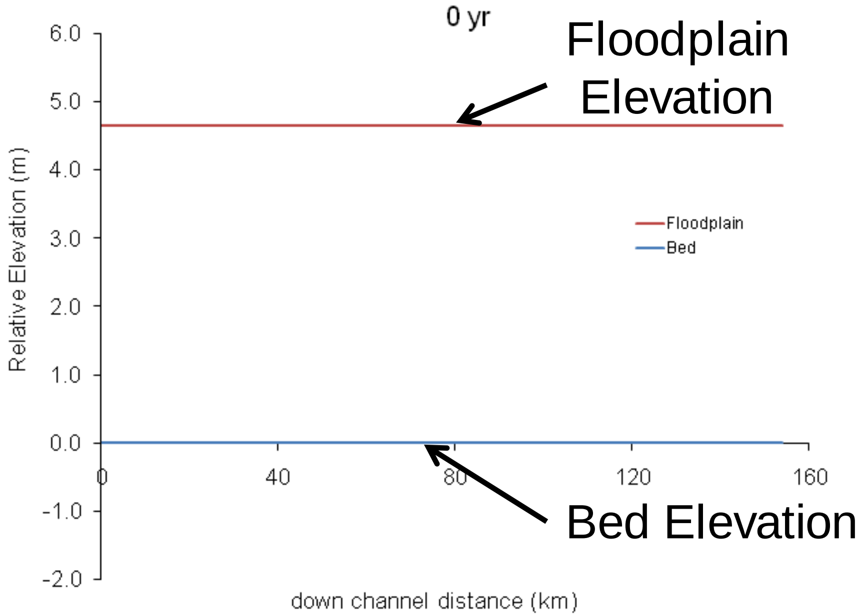
Newly deposited point bar of specified thickness. Mud fraction depends on mud in channel.

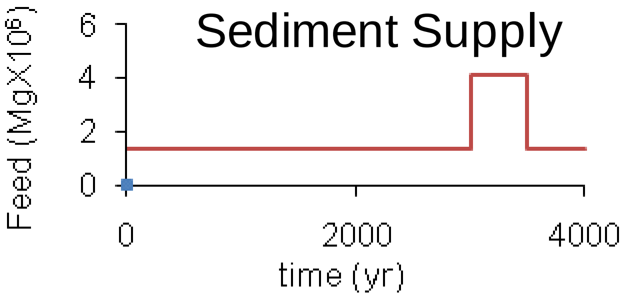
Sediment exchanged as channel migrates

Sediment eroded from the floodplain as channel migrates



Simulation of System Overloaded with Mud

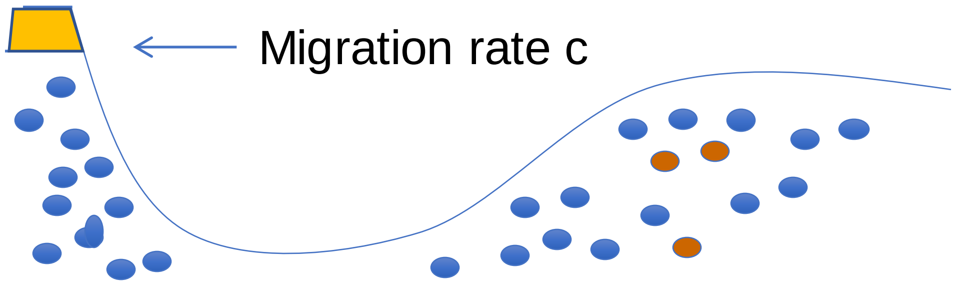




Key Points:

•Bed responds to an increase in mud because mud displaces sand from floodplain (muddier point bars)

•Final bed is lower because of focused overbank flow forced into channel due to floodplain deposition



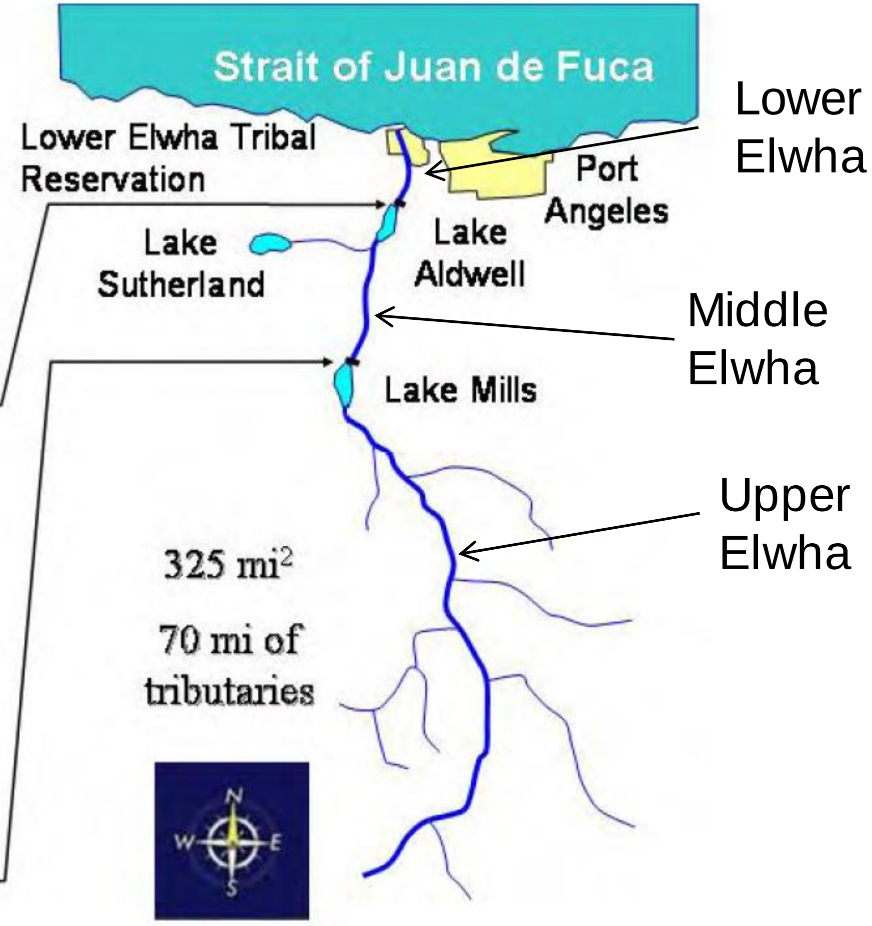
Elwha River, Washington: Size Specific Storage Rates

1911;
River Mile
4.9
(failed 1912, rebuilt 1914)

Elwha Dam

1927;
River Mile
13.4
(Now within Olympic National Park)

Glines Canyon Dam



From Randle and Bountry, 2010, Elwha River Restoration: Sediment Adaptive Management, U.S. Bureau of Reclamation

Exchange Distances on Elwha

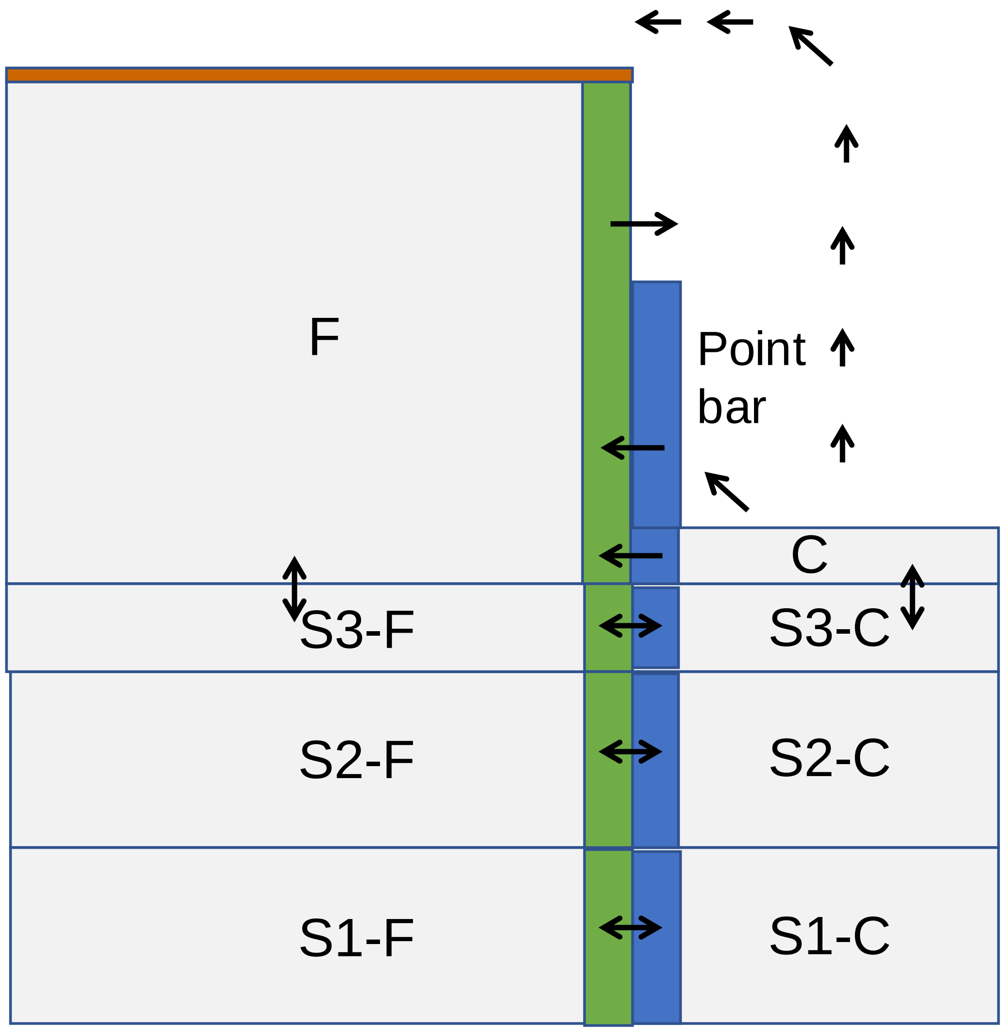
Exchange Distance = Down channel sediment flux / Rate at which sediment is exchanged per unit channel length

- Assumptions:
  - Pre-removal migration rates of 1.3 m/yr (Draut et al., 2008, USGS 2008-5127)
  - Bank height = 1.5 m
  - Fraction in banks crudely estimated from photo
  - Size fractions in load from 1994 drawdown experiment.
  - Long term load from Reservoir Accumulation: 340,000 Mg/yr (Magirl et al., 2015, Geomorphology)

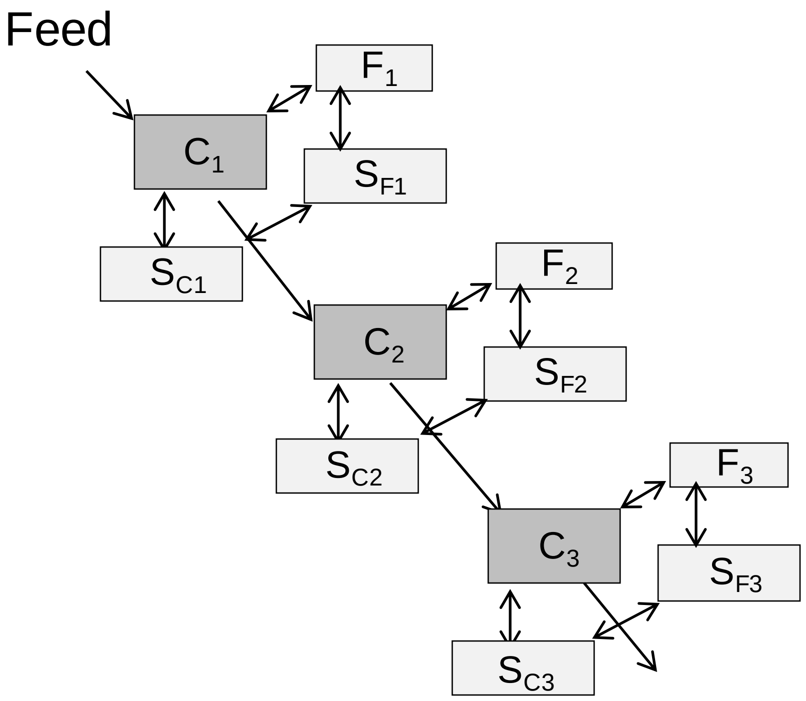
Size	Load Fraction	Flux (Mg/yr)	Assumed Exchange Fraction	Exchange Flux (Mg/m/yr)	Exchange Distance (km)
Silt/Clay	0.48	163,200	0.1	0.312	523
Sand	0.37	125,800	0.2	0.624	202
Gravel	0.13	44,200	0.3	0.936	47
Cobble	0.02	6,800	0.4	1.248	$\boxed{5}$

Bed Material

Multiple Size Model: Morphodynamics and Sediment Tracers in 1-D (Lauer et al., 2016, Advances in Water Resources)



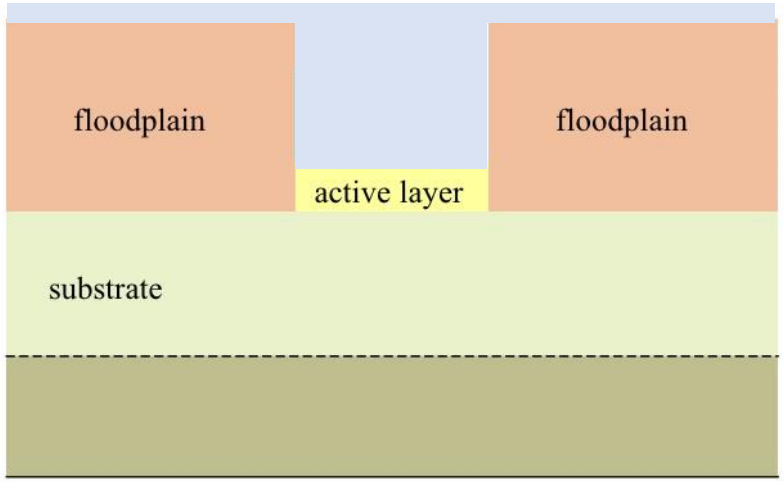
Now calculate size-specific down channel flux e.g. Wilcock & Crowe (2003) and keep track of how much volume of each size class is in each reservoir.



Multiple substrates needed to prevent unrealistic mixing from channel

Computational Procedure for MAST-1D

- **Hydraulics** (calculated for subset of flows river might experience or for daily flows)



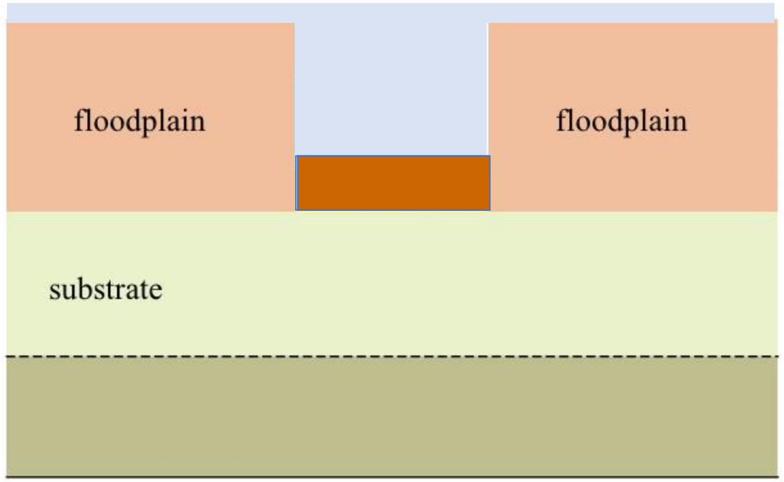
Computational Procedure for MAST-1D

- **Hydraulics** (calculated for several bins in flow duration curve or for daily flows)
- Compute **sediment transport capacity** in each sediment size

$$W_i^* = \frac{(s-1)gq_{si}}{F_i(\tau/\rho)^{3/2}} = f\left(\frac{\tau}{\tau_{ri}}, F_i\right)$$

$$\tau_{ri} = f(F_s) \quad \text{or} \quad \tau_{ri} = f\left(\frac{D_i}{D_g}\right)$$

Wilcock and Crowe, 2003 or Gaueman et al., 2009, WRR



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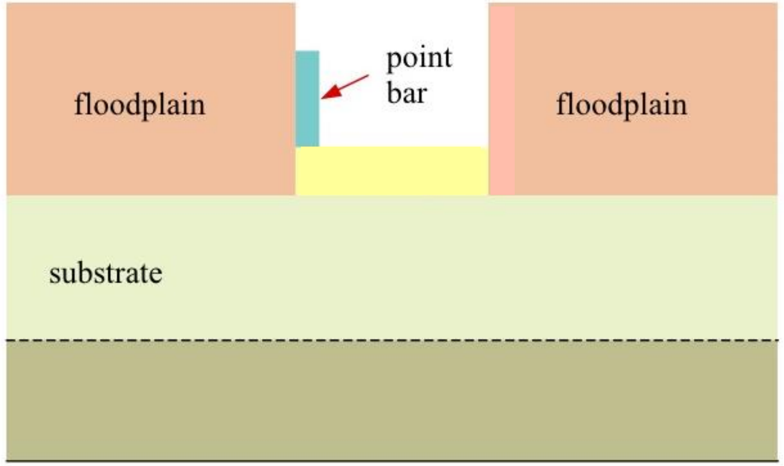

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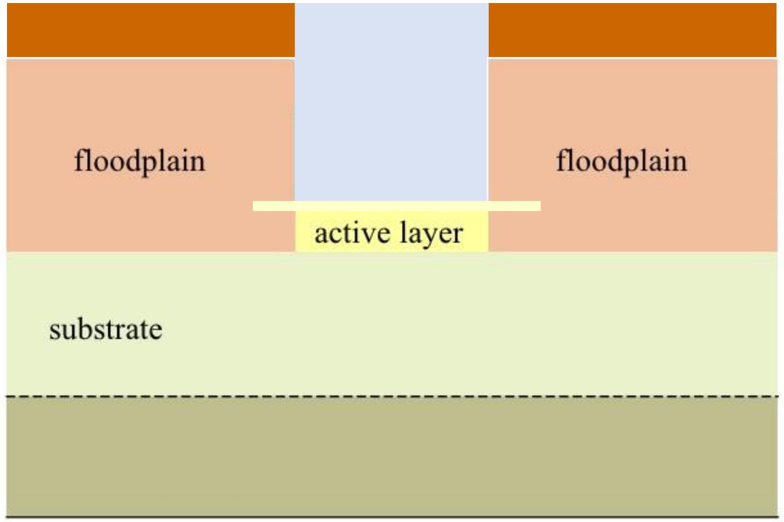

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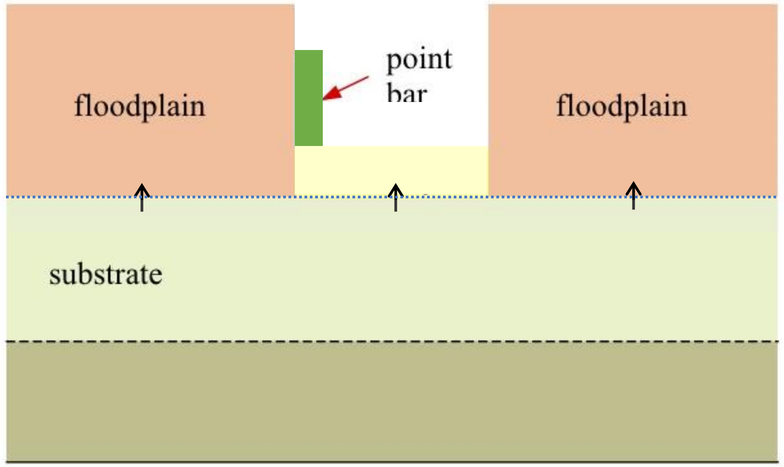
- Compute **bed change rate** by finding net gain/loss of sediment in "active layer"
- Compute **vertical exchange fluxes** and **update sediment size fractions** in all reservoirs



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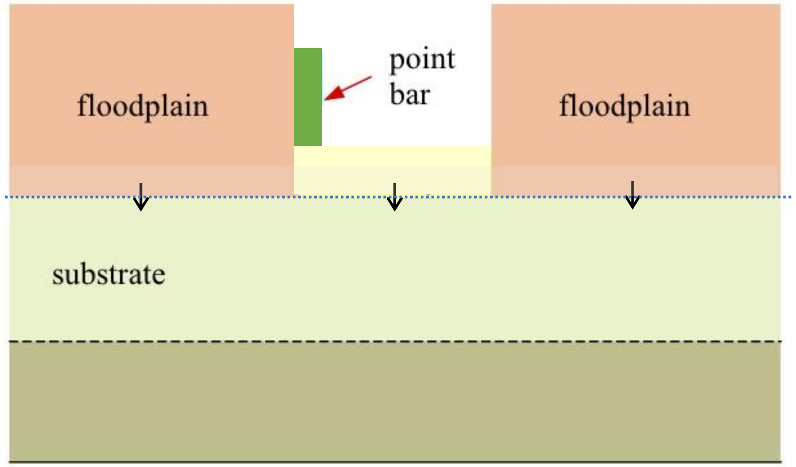
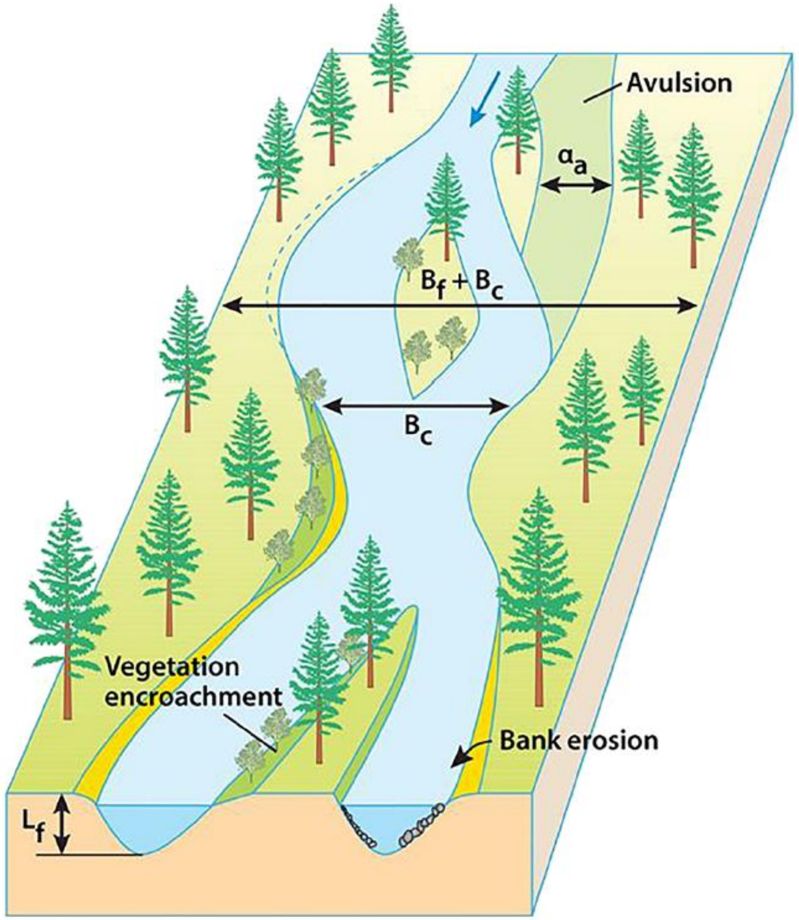


Additional features (see De Rego et al., 2020, *Geomorphology*)

Thanks to Katie De Rego, Marwan Hassan, and Brett Eaton

- Code adapted to timeseries input for flow
- Widening rate = f(mobility of bank material)

  See also Dunn and Jerolmack, 2020, *Science Advances*
- Narrowing rate = f(vegetation encroachment)
- Migration rate assumed half of sum of widening and narrowing rate (so narrowing occurs on point bar)
- Channel avulsions (at a node)
- Application to Elwha River
  - Animations: 100-year response to damming
    - Migration (constant rate) turned on
    - Migration (constant rate) turned off
  - Time Series of Entire Dammed/Removal Period
    - Assumes sediment in Lake Mills supplied at initially high but exponentially decreasing rate after removal



Simulation Results, 100 years of Sediment Starvation

Results with no migration

Results with migration

Total In-channel bed material load (m^3/s)

Conclusion: After damming but prior to removal, the banks were the main source of bed material

Simulation Results, 100 years of Sediment Starvation

Results with no migration

Results with migration

D_{50} (mm)

Conclusion: With or without lateral migration, the bed coarsens rapidly in response to dam construction.

Simulation Results, 100 years of Sediment Starvation

Results with no migration

Results with migration

Cumulative Bed Change (m)

Counterintuitively, the lateral migration allows for ADDITIONAL incision—probably because the coarse armor that forms gets transferred to the floodplain. In other words, the channel moves around the armor and incises into old floodplain material.

Flooding After Dam Removal
(Altair Campground, March 14, 2014)

Simulation Results: Middle Elwha

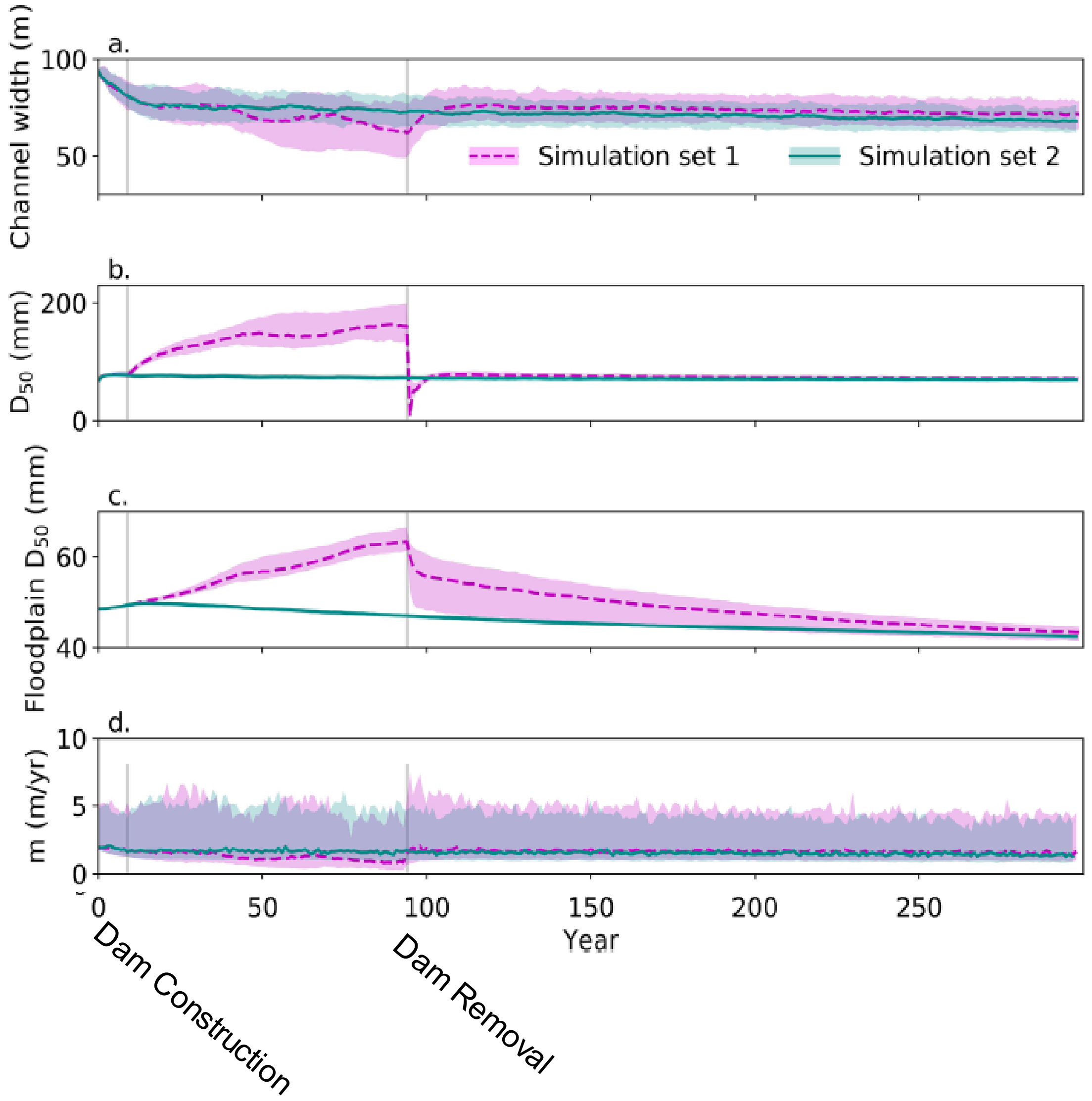
(De Rego et al., 2020, *Geomorphology*)

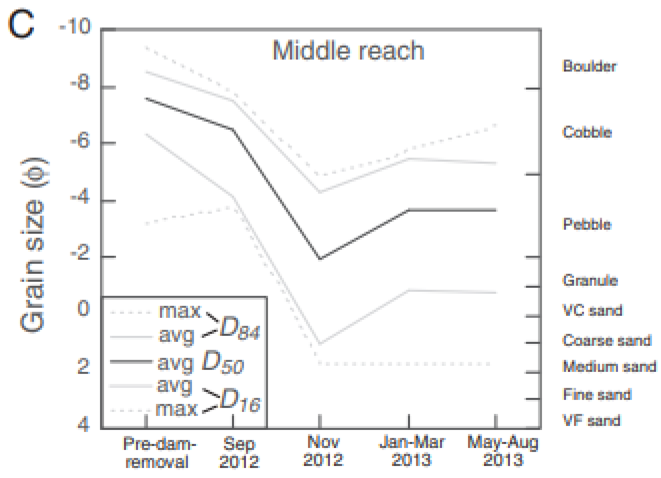
Channel narrows after damming, rapidly returns to original width after removal

Bed coarsens after damming, rapidly fines after removal

Floodplain material responds more slowly than bed

Channel migration rates increase immediately after removal





Observed post-removal fining, (East et al., 2015)

Needs/Challenges

- Data needs (in addition to hydrologic projections)
  - Size-specific upstream/tributary inputs
  - Size distributions in eroding banks, bars, substrate
  - Overbank deposition measurements
  - Initial conditions (i.e., how close to model “equilibrium” should one start?)
  - More validation experiments (but see also Lauer et al., 2016, Advances in Water Resources)
- Model development
  - Network Representation (MAST-1D written with simple network in mind, but untried)
  - Braiding/meandering
  - Abrasion/weathering
  - Code documentation
- Carefully developed management questions

Other Sediment Routing Approaches

Handle each “link” in hydrologic network discretely

- Conserve suspended load in channel only (e.g. SWAT)
- Size-specific off-channel storage w/ geomorphic feedbacks (not aware of any examples)

Conserve bed material in channel for one or more nodes in link, channel geometry = f(drainage area) (e.g. Czuba 2018; Landlab, CHILD)

1-D size-specific active bed routing in channel bed only, constant width (e.g., CCHE1D, SHR1D, HEC-RAS, TUGS, Konrad et al., 2009)

1-D size specific routing in multiple discrete reservoirs, solve for channel capacity (MAST-1D approach)

2-D Simulations such as CAESAR-LisFlood, IRIC

Increasing computational time →

Increasing scale (space and time) of published applications ←

Closing Thoughts

- Advantages of 1-D/off channel reservoir approach
  - Explicitly solves for channel capacity
  - Plausible variability in channel width
  - Plausible model for lateral migration (thanks to Katie!)
  - Appropriate trends in grain size
  - Equilibrium “graded” state possible
- Insight from simulations
  - Nature of sediment put into lateral storage can control bed evolution
  - Reduction in sediment load from damming reduces sediment size and may reduce lateral activity of channel—while replacing load re-invigorates lateral change
- Main conclusion: lateral channel change can a major decade-scale mechanism for storage or supply of bed material


Thank You!

References

Braudrick CA, Dietrich WE, Leverich GT, Sklar LS. 2009. Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. Proceedings of the National Academy of Sciences 106(40): 16936–16941.

Church, M. and Rice, S.P., 2009. Form and growth of bars in a wandering gravel-bed river. Earth Surface Processes and Landforms 34: 1422–1432.

Cui Y. 2007. The unified gravel-sand (TUGS) model: Simulating sediment transport and gravel/sand grain size distributions in gravel-bedded rivers. Water Resour Res 43.

Czuba JA. 2018. A Lagrangian framework for exploring complexities of mixed-size sediment transport ing ravel-bedded river networks. Geomorphology 321: 146-152.

De Rego K, Eaton B, Lauer JW, Hassan M, 2020, A decadal-scale numerical model for wandering, cobble-bedded rivers subject to disturbance. Earth Surface Processes and Landforms 45: 912-927.

Draut AE, Logan JB, McCoy RE, McHenry M, Warrick JA, 2008. Channel Evolution on the Lower Elwha River, Washington, 1939-2006

East EE, Pess GB, Bountry JA, Magirl CS, Ritchie AC, Logan JB, Randle TJ, Mastin MC, Minear JT, Duda JJ, Liermann MC, McHenry ML, Beechie TJ, Shafroth PB. 2015. Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. Geomorphology 228: 765-786

Dunn KBJ, Jerolmack DJ. 2020. What sets river width? Science Advances 6(41): eabc1505.

Gaeuman D, Andrews ED, Kraus A, Smith W. Predicting fractional bed load transport rates: application of the Wilcock-Crowe equations to a regu- lated gravel bed river. Water Resour Res 2009;45.

Konrad CP. 2009. Simulating the recovery of suspended sediment transport and river-bed stability in response to dam removal on the Elwha River, Washington. Ecological Engineering 35(7): 1104–1115.

Lauer JW, Parker G. 2008. Net local removal of floodplain sediment by river me- ander migration. Geomorphology 96:123–49.

Lauer JW. 2012. The importance of off-channel sediment storage in 1-D morphodynamic modeling. In: Church, M., P. Biron, and A. Roy, eds., Gravel Bed Rivers: Processes, Tools, Environments, Wiley, Chichester.

Lauer JW, Viparelli E, Piégay H. 2016. Morphodynamics and sediment tracers in 1-D (MAST-1D): 1-D sediment transport that includes exchange with an off-channel sediment reservoir. Advances in Water Resources 93: 135–149.

Magirl CS, Hilldale RC, Curran CA, Duda JJ, Straub TD, Domanski M, Foreman JR. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Fluvial sediment load. Geomorphology 246: 669-686.

Randle and Bountry, 2010, Elwha River Restoration: Sediment Adaptive Management, 2nd. Joint Federal Interagency Conference, Las Vegas. U.S. Bureau of Reclamation

Viparelli E, Lauer JW, Belmont P, Parker G. 2013. A numerical model to develop long-term sediment budgets using isotopic sediment fingerprints. Comput Geosci 53:114–22.

Wilcock PR, Crowe JC. Surface-based transport model for mixed-size sediment. J Hydraul Eng 2003;129:120–8.