Modeling the effects of in-stream sediment retention on rates of river incision and strath terrace formation

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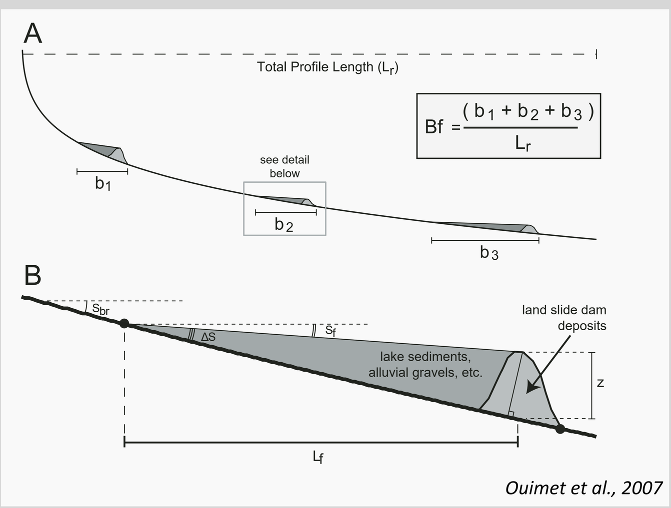
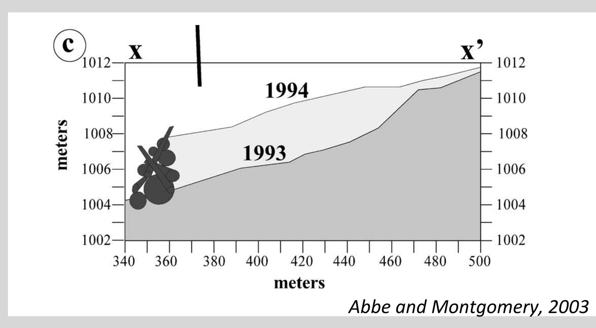
Introduction

River incision sets the pace of landscape response to perturbations through controlling the local base level. Incision is generally thought to depend on water discharge and sediment supply, and this framework leads us to interpret the relict landscape in terms of water and sediment *supply* fluctuations. However, we know that sediment does not always move smoothly through channels. Large woody debris, landslides, and rockfall can block the channel and impede the downstream transport of sediment.





A) Long profiles showing multiple landslides and the associated upstream alluvial wedge. B) Detailed view of the idealized geometry of landslide wedges. C) A field example from the Queets River, WA, of forced aggradation from a woody debris jam. Note the length scale of 140 m by 4 m.

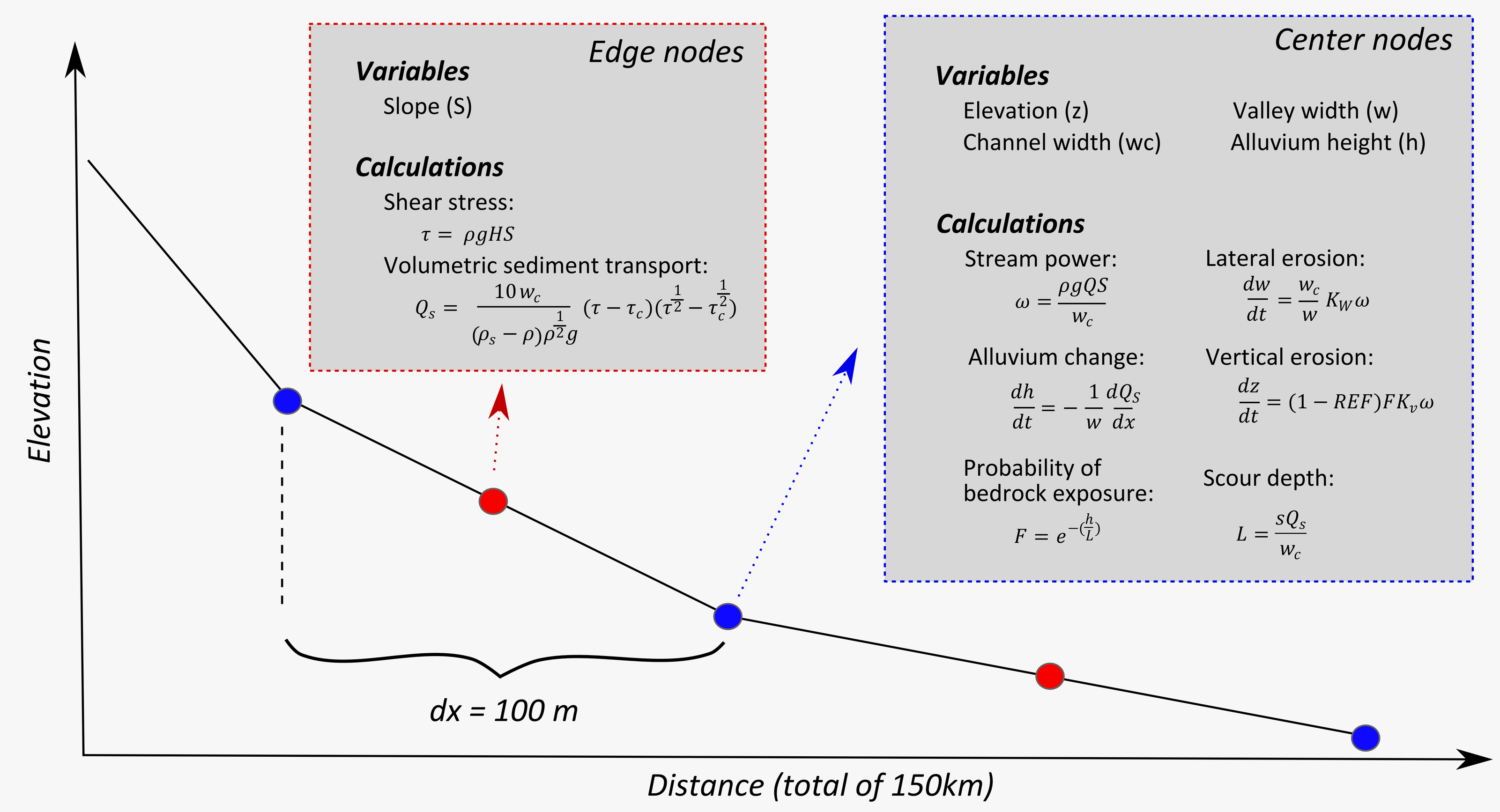
These blockages force sediment to remain on the bed and increase the **sediment retention**. Here, we investigate the role of sediment retention on river incision through these guiding questions:

1. Can sudden changes in sediment retention result in river incision?
2. If so, is the resulting river incision significant and persistent enough to leave a morphologic signature in river profiles over 1000s to 100,000s of years?
3. And finally, can strath terraces result from changes to sediment retention?

Model set up

The building block: a 1-D finite difference model from Hancock and Anderson (2002)

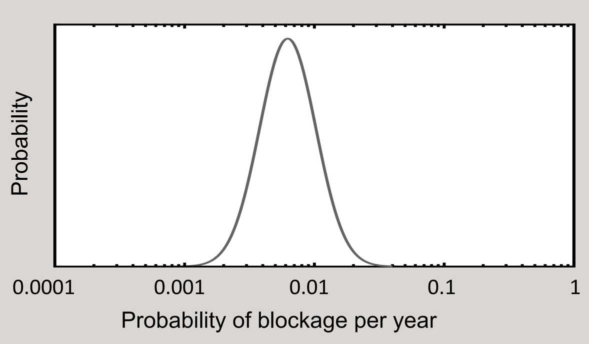
Erosion is driven by stream power and modified by the scour depth through the alluvium, which determines a probability of bedrock exposure. Alluvium builds up and erodes depending on the sediment flux. The vertical and lateral erosion rates are tracked to reconstruct the valley profile.



Retention efficiency factor (REF)

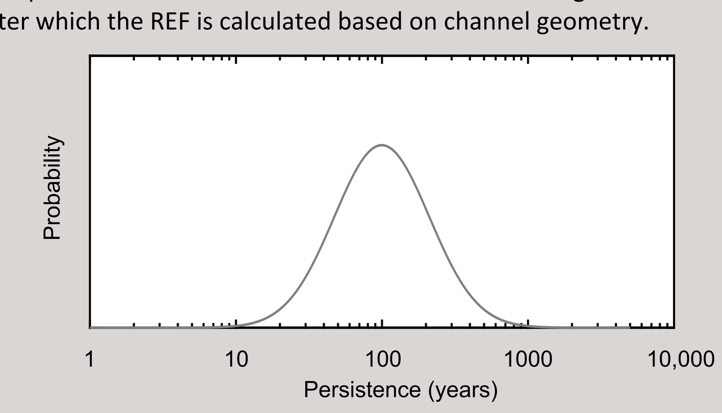
1. Is a blockage seeded?

Whether a blockage is initiated in a given model year depends on the probability distribution of blockages. For large wood, we assume the 100-year flood causes most blockages, but smaller and larger events could also do it. Each node is given a probability of seeding based on the curve below. A random number generator then determines if the probability of seeding is met or not. If seeded, the blockage then gets a persistence.



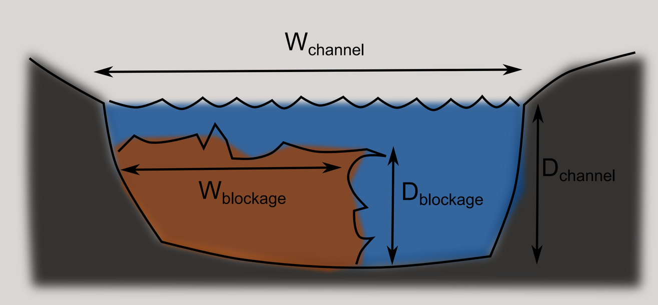
2. How long does it last?

The persistence, or longevity of the blockage can be customized to represent wood jams, rockfall, or other obstructions. Shown below is wood jams, which have been dated to last over 1000 years (*Abbe and Montgomery, 2003*), but likely usually last 100 years following large floods. The persistence is calculated for each node with a generated blockage, after which the REF is calculated based on channel geometry.



3. What is the REF?

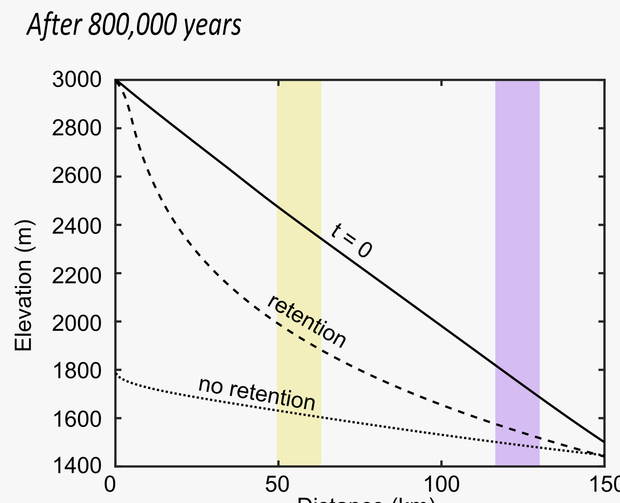
Erosion is actually modified by the **Retention Efficiency Factor**, which is the ratio of blockage size to channel size. We model it simply as a rectangular blockage and a rectangular channel cross section. The blockage size is the same for the entire channel, but can vary through time to simulate changes to wood size. Small channels will have a higher REF than large channels, which substantiates field observations on the efficacy of woody debris on varying channel sizes (*Abbe and Montgomery, 2003*).



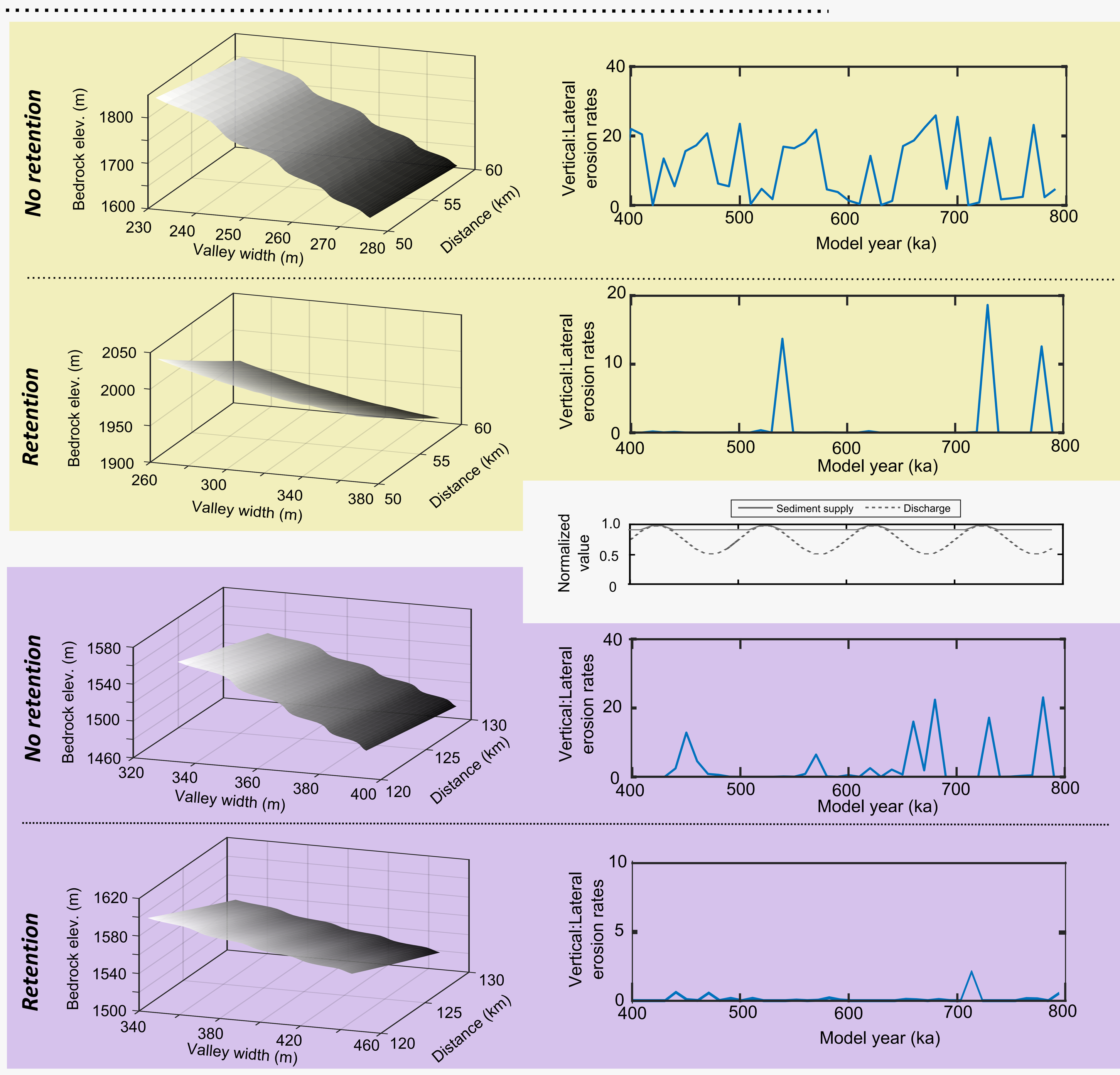
Results

Blockage size was set at 20 m by 0.5 m and the model was run for 800,000 years, starting from a linear profile of slope 0.01. Only the last 400,000 years are shown in the results since the first 400,000 years are spent rapidly incising to get an equilibrium profile. The reconstructed bedrock valley wall and ratio of erosion rates are shown at 55 and 125 kilometers for scenarios without blockages and with blockages.

After 800,000 years

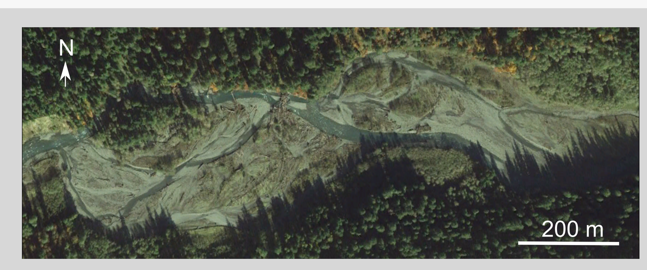


The longitudinal profile at the end of the model runs (above) indicates overall less incision occurs when there are blockages, and the profile concavity appears steepened. In the case without retention structures, the river continues to incise with an overall relief of <400 meters over 150 kilometers.



Implications

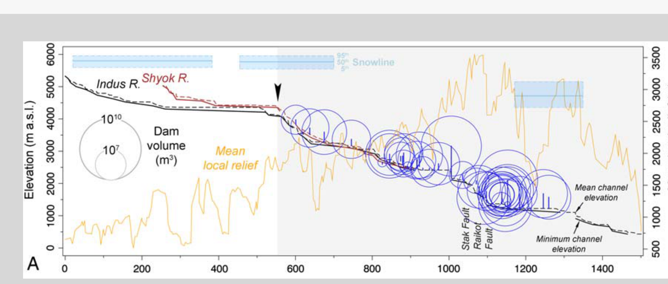
Valley character. Lateral erosion rates are amplified when blockages are present, resulting in wider valleys in model simulations with retention factors present. Rivers with simulated blockages are alluvial and prone to aggradation, while blockage-free rivers are bedrock with an alluvial cover in the lower 50 km. Although not accounted for in our model, rivers are likely more laterally mobile due to deflection and channel narrowing from the blockages. We theorize that rivers experiencing a high frequency of blockages would be braided, similar to the Queets River, WA, which contains numerous old-growth wood jams.



The Queets River, WA, is a braided river containing woody debris jams that is likely analagous to our simulated rivers. In the picture, water flow is right to left.

Vertical incision. Blockages inhibit vertical erosion, though occasionally the destruction of a blockage can result in short periods of enhanced incision. However, these periods are short, and distinct strath terraces do not form, especially in the upstream reaches. In the lower 50km, the short periods of incision leave behind diffuse strath terraces on the valley walls.

Multiple simulations with retention show the periods of rapid vertical incision vary depending on the blockage persistence and frequency, but may overall be influenced by climate. When sediment supply and water discharge are high, the water depth increases and gives the blockage a lower efficiency. During these times, vertical incision rates do increase above lateral erosion rates. However, vertical erosion rates are much lower than non-retention simulations and so we would expect real-world rivers with frequent blockages to experience less erosion at those blockage sites than elsewhere along the profile. This prediction is borne out in landslide-prone rivers in which a stepped profile results from the contrast of sediment retention and non-retention (e.g., Ouimet et al., 2007; Korup et al., 2010).

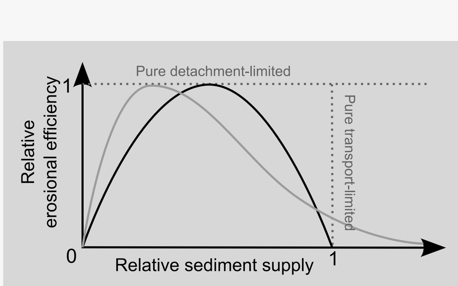


Longitudinal profile of the Indus River from Korup et al. (2010). Blue circles show the size and location of landslide dams, which retain sediment and increase the REF. Note that the landslide reach is stepped while the non-retention zones upstream and downstream are concave up.

Future work

Immediate to near future: Modeling will be transitioned to a 2-D framework - such as LandLab - to model additional complexities such as wildfire, and simulate climate change more accurately.

Using components such as SedDepEroder, we will incorporate the role of sediment supply more accurately by using erosional efficiency-sediment supply relationships such as the ones shown below. Sediment retention



Modified from Hobley et al., 2011

Further in the future: Future work will examine fluctuations to sediment retention over time, looking for where in the profile is most susceptible to changes, to what degree the profile changes, and how well this is preserved. This preliminary work indicates a high difference between rivers with no retention and those with retention, and suggests that if one system were to vary in retention structure size or competency, significant changes to erosion rates will result.

The model observations on changing retention will be linked to field studies of rivers where deforestation has decreased the sediment retention. We have observed that in rivers experiencing a near complete loss of sediment retaining structures, incision rates are cm-dm/yr and a historic strath terrace is emerging. Combining these observations with model simulations will help constrain the spatial and temporal persistence of incision from decreased sediment retention.

Acknowledgments

We thank Dr. Ed Waddington for guidance in developing and troubleshooting the numerical model, using equations from Hancock and Anderson (2002).

The basis for this project comes from field evidence of rapid erosion following wood removal, observed by the authors and others. For the field work, we thank T Hillebrand, A Pacubas, and R Schanz for their assistance.

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