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Supplementary Data for Snowmelt-Enhanced Late Cenozoic Incision in the Southern Rocky Mountains

Details of HydroTrendModeling

The HydroTrend model of Kettner and Syvitski (2008) was used to calculated the ratio of long-term bedload sediment flux for an elevated model basin to the same basin at 1 km elevation, $q_s(h)/q_s(1)$. For this calculation I choose a basin with an area of 100 km^2, a uniform elevation-area relationship, and a relief of 500 m. I varied the bedload rating exponent from 2 to 4. Empirical values for this exponent range between 2 and 5, but values higher than 4 are generally associated with armoring in steep, mountainous, coarse-grained channels (Emmett and Wolman, 2001). Daily precipitation values were sampled from a stretched Gaussian distribution with an exponent of 1.5 and a range equal to the mean value. These values were chosen based on analysis of intermediate-to-high elevation sites in Colorado. Monthly mean precipitation was assumed to be constant throughout the year for simplicity. For each 500 m of elevation increase, the temperature was decreased by 3ºC relative to the reference case, consistent with a 6ºC/km lapse rate. The annual temperature cycle for the reference case (outlet elevation of 1 km) was chosen to be

$$T = T_0 + T_{\mathrm{var}} \cos\left(\frac{2\pi t}{1yr}\right)$$

with T_0 and T_{var} were chosen to be 13ºC and 12ºC, respectively based on values appropriate for 1 km elevation sites in the Rocky Mountain region, based on PRISM monthly mean climate grids).

Values of $q_s(h)/q_s(1)$ predicted by the model vary from 1 at h = 1 km (by definition) to a maximum value that varies depending on the bedload rating exponent, n. If n = 2, snowmelt enhances the long-term sediment transport at h = 3.5 km elevation by only a factor of 1.6 (Figure DR1). If n = 3, snowmelt enhances the long-term sediment transport at high elevations by nearly a factor of 4. If n = 4, snowmelt enhances the long-term sediment transport at high elevations by nearly a factor of 8. Time series model predictions for rainfall at low and high-elevation sites are plotted in Figure DR2 and DR3 for the warm-climate/low elevation scenario of h = 1 km and the cold-climate/high-elevation scenario of h = 3 km, illustrating the effect that seasonally-pulsed runoff has on sediment transport rates. These results provide only a preliminary exploration of the controls on snowmelt-enhanced erosion, but they establish c = 4 as a reasonable reference value for the increase in long-term sediment transport at high elevations due to snowmelt-enhanced runoff. Sensitivity studies with the model showed that the ratio $q_s(h)/q_s(1)$ for high elevations increases with the bedload rating exponent (Figure DR1) and the magnitude of the annual temperature cycle, T_{var}. The ratio decreases as the range and skew of the frequency-intensity distribution of precipitation are increased Further work is needed to provide a more comprehensive mapping of snowmelt-enhanced erosion in the Rocky Mountain region using PRISM mean monthly datasets as a modern climate calibration.

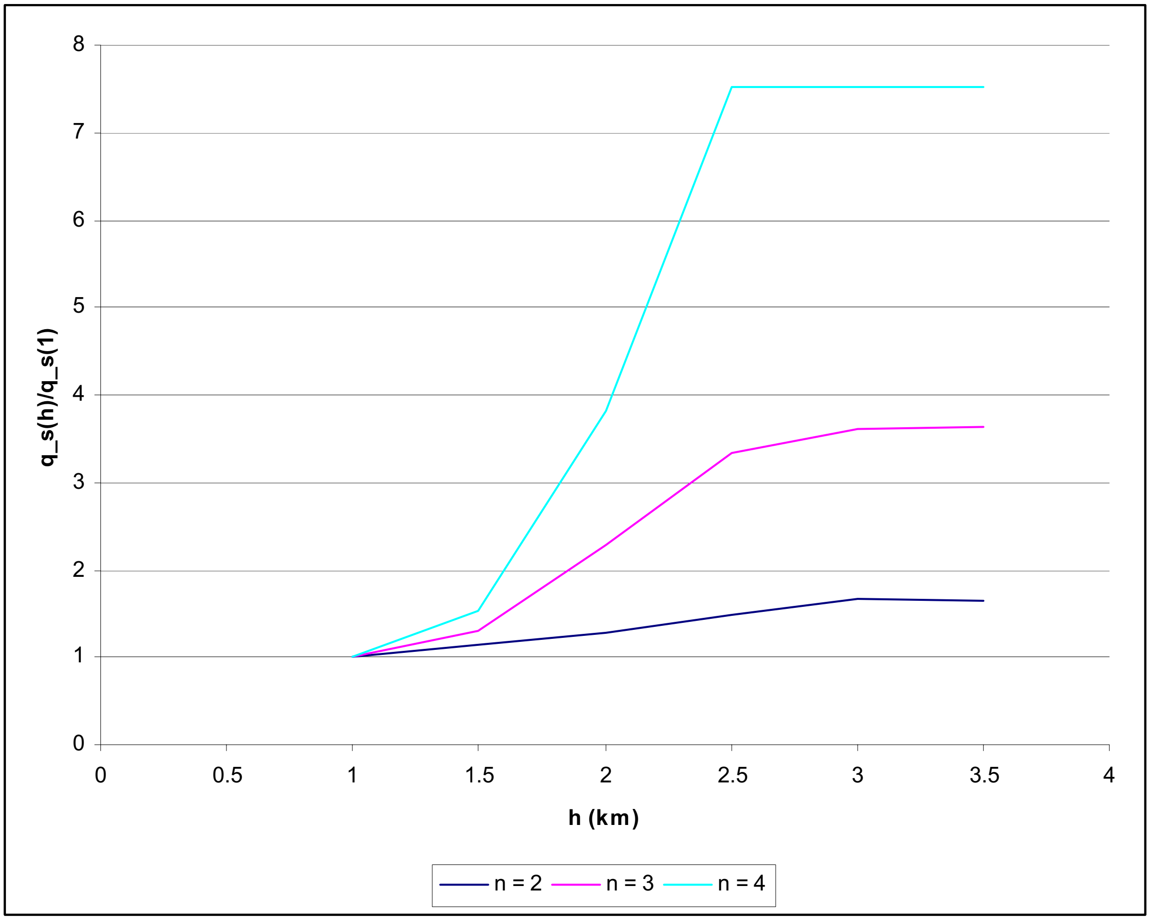

Figure DR1. Plot of $q_s(h)/q_s(1)$ as a function of elevation h and bedload rating exponent n predicted for the model basin according to the HydroTrend model of Kettner and Syvitski (2008).

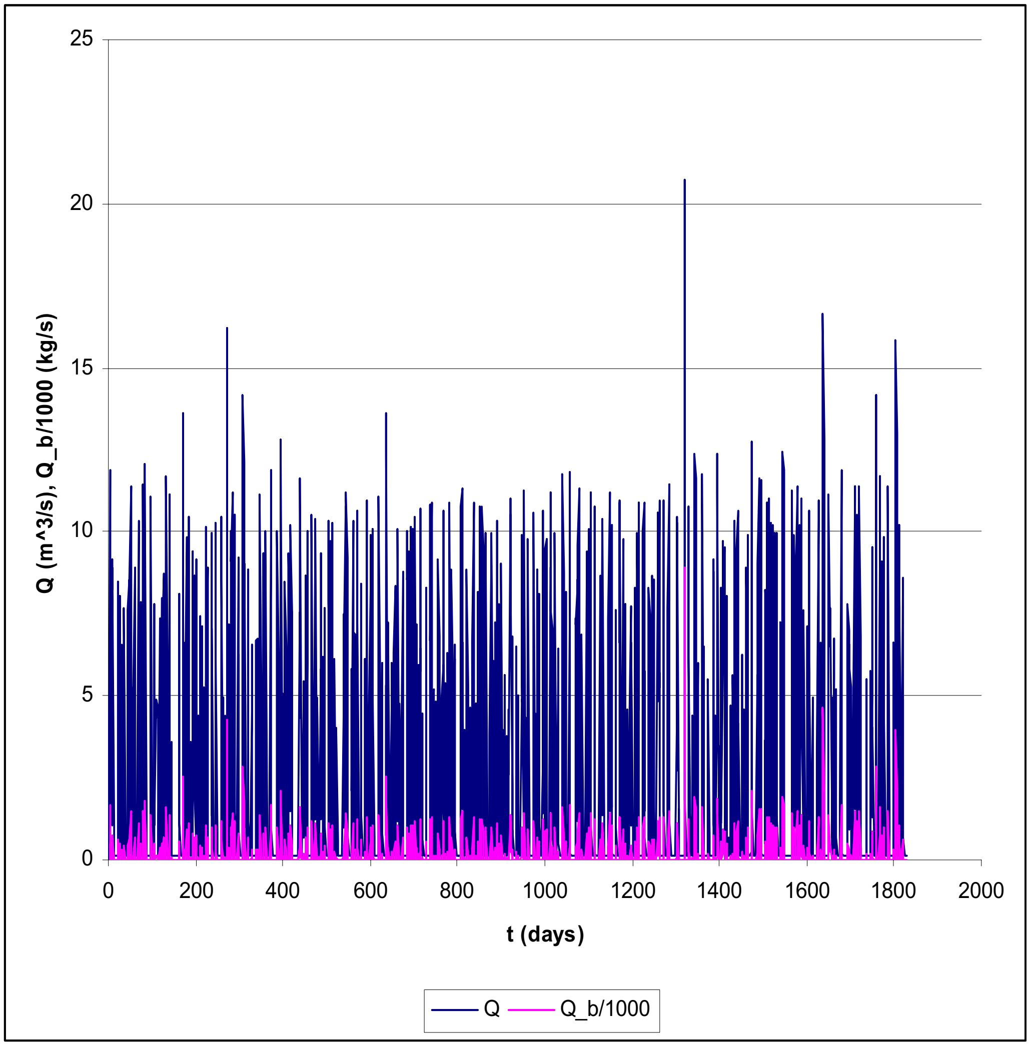

Figure DR2. Plot of discharge Q and bedload sediment flux Q_b (for $n = 3$; scaled down by a factor of 1000 to plot on the same scale as Q) for the model drainage basin with $h = 1$ km.

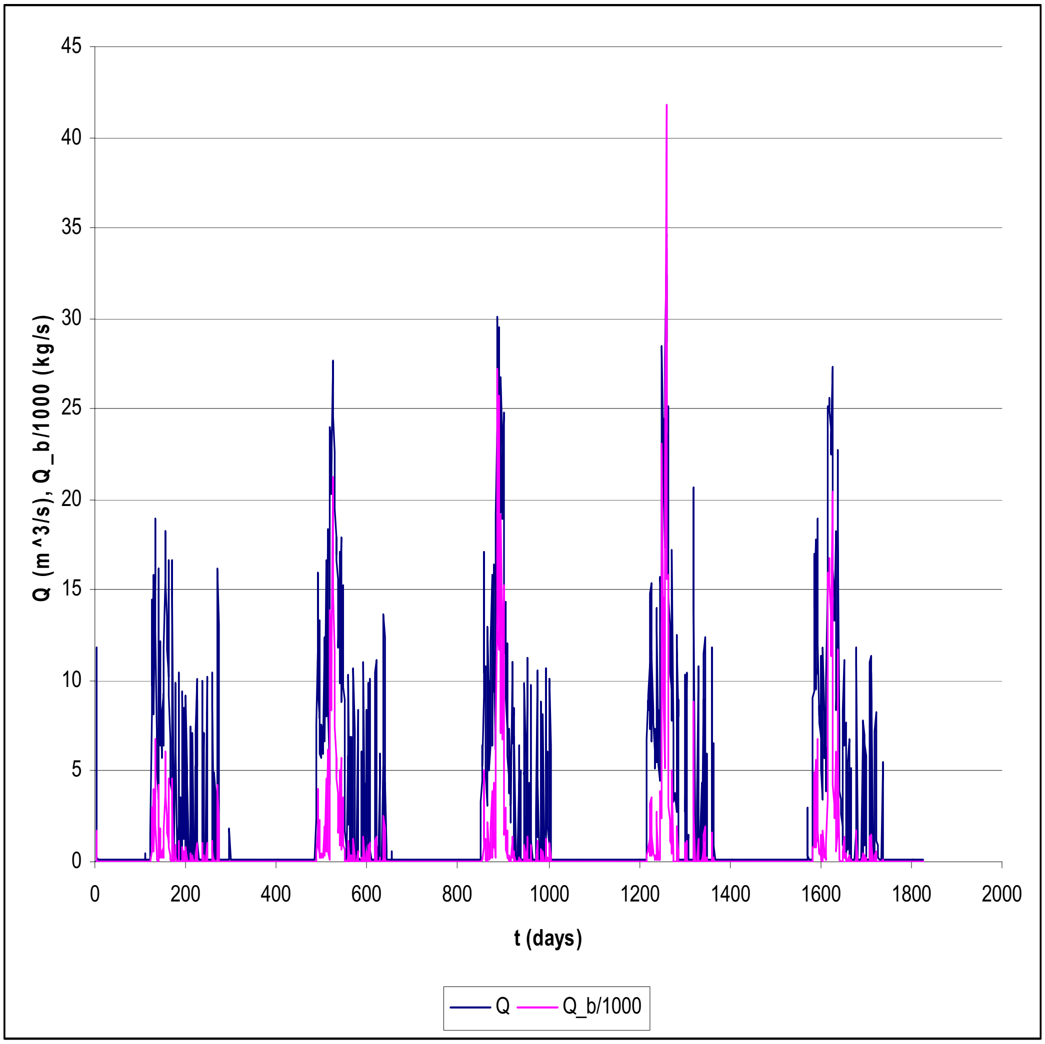

Figure DR3. Plot of discharge Q and bedload sediment flux Q_b (for $n = 3$; scaled down by a factor of 1000 to plot on the same scale as Q) for the model drainage basin with $h = 3$ km.

Further Discussion of Model-Predicted Incision Map

The model-predicted incision map in Figure 3 is broadly similar to the spatial distribution of incision as constrained by McMillan et al. (2006). Both maps have limitations that make it difficult to precisely compare the two maps for individual areas, however. The model is limited because it assumes that the modern drainage configuration is the same as the paleodrainage configuration. In intramontane basin areas, where only channel incision and lateral erosion have taken place, this is likely to be a reasonable assumption for at the large spatial scales of the analysis. At lower elevations, however, erosion of the intramontane basins upstream caused widespread deposition and channel avulsion, as shown in Figure 4. The incision model shown in Figure 3 does not incorporate the drainage reorganization that resulted from this widespread deposition and, as a result, the model does not correctly predict the details of incision in the western Great Plains. Specifically, the model predicts relatively low values of incision in the incised valleys of western Great Plains (e.g. the North and South Platte and Arkansas and Canadian Rivers), while the actual amount of incision is actually greater in these areas than in adjacent interfluves (McMillan et al., 2006). The map of McMillan et al. (2006) also has limitations that make precise comparisons difficult. Most importantly, McMillan et al.'s map is a minimum estimate for incision. Also, the results are sensitive to the accuracy and density of marker beds used in the analysis as well as the assumptions used. Pederson et al. (2002), for example, used broadly similar techniques to infer incision in the upper Colorado River drainage basin but used a higher density of dated marker beds and corrected for isostatic adjustments to incision. Pederson et al.'s analysis produced broadly similar results but locally there are differences between the two studies. Nevertheless, the model-predicted map shown in Figure 3 is in broad agreement with the map of McMillan et al. (2006) and supports the hypothesis that snowmelt-enhanced runoff was an important mechanism for driving late Cenozoic exhumation of these basins.

Further Discussion of 2D Dynamic Model

The results of the 2D dynamic model shown in Figure 4 also have limitations. Deposition of the Ogallala formation from approximately 17 to 5 Ma (Izett, 1975; Naeser et al., 1980) was followed by incision throughout the Great Plains to form the incised valleys of the North and South Platte and Canadian and Arkansas Rivers (Figure 3). In the 2D model, the river incises only into the proximal portion of its downstream deposit and hence underestimates the degree of actual incision that followed deposition. There are two likely reasons for this discrepancy. First, incision into the proximal deposits of the Ogallala Formation would have caused a positive feedback process in which channel narrowing, focusing of stream power, and channel incision worked in a positive feedback. As a 2D model, the model illustrated in Figure 4 cannot incorporate the role of channel narrowing in enhancing the incision process and therefore may underestimate the extent of incision. Wobus et al. (2008) recently argued that incision into the Ogallala sediments was driven by the 3D response of Great Plains rivers to Plio-Quaternary climate changes. Wobus et al., (2008) showed that Plio-Quaternary climatic changes could have caused hydrologic changes that could have triggered a positive feedback of channel incision and narrowing consistent with the planform geometry of the incised river valleys of the Great Plains identified in Figure 3.

References Cited

Emmett, W.W., and Wolman, M.G., 2001, Effective discharge and gravel-bed rivers: Earth Surface Processes and Landforms, v. 26, no. 13, p. 1369-1380.

Wobus, C., Tucker, G.E., and Anderson, R.S., 2008, Cenozoic Incision of the North American High Plains: Topographic Re-Analysis and the Possible Role of Climate Change: Geological Society of America Abstracts with Programs, abs. 178-8.