Responses of gravel-bed river networks to periodic climate change

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Background

- Environmental conditions influence surface processes
- Sedimentary & geomorphic archives may record past climate change
- Facies variations and terrace suites with orbital periodicities observed
- Can we use these records to quantitatively reconstruct past water and sediment supply?

Toro Basin terraces (e.g. Tofelde et al., 2017). Courtesy of S. Tofelde.

Modelling framework

- Long-profile evolution of transport-limited gravel-bed rivers (Wickert & Schildgen, 2019)
- Defined in terms of physical properties
- Includes channel-width adjustments
- Familiar diffusive form:

$$\frac{\partial z}{\partial t} = \frac{k_{Q_s} I Q_w}{\mathbb{S}^{7/6} B \left(1 - \lambda_p\right)} \frac{\partial}{\partial x} \left(\frac{\partial z}{\partial x} \left| \frac{\partial z}{\partial x} \right|^{1/6} \right) + U$$

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Water discharge

Modelling framework

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Valley width

Modelling framework

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- Defined in terms of physical properties
- Includes channel-width adjustments
- Familiar diffusive form:

$$\frac{\partial z}{\partial t} = \frac{k_{Q_s} I Q_w}{\mathbb{S}^{7/6} B \left(1 - \lambda_p\right)} \frac{\partial}{\partial x} \left(\frac{\partial z}{\partial x} \left| \frac{\partial z}{\partial x} \right|^{1/6} \right) + U$$

Slope (non-linear)

Perturbation analysis

e.g. Braun et al. (2015)

- Wish to quantify response to periodic forcing: challenging for non-linear systems
- Instead of solving full equation, solve for small perturbations

$$\frac{\partial z}{\partial t} = \frac{k_{Q_s} I Q_w}{\mathbb{S}^{7/6} B \left(1-\lambda_p\right)} \frac{\partial}{\partial x}\left(\frac{\partial z}{\partial x}\left|\frac{\partial z}{\partial x}\right|^{1/6}\right) + U$$

$$\frac{\partial\ \delta z}{\partial t} \approx \kappa \frac{\partial^2 \delta z}{\partial x^2}$$

$$\kappa = \frac{7}{6} \frac{k_{Q_s} I \bar{Q_w}}{\mathbb{S}^{7/6} B \left(1-\lambda_p\right)} \left|\frac{\partial \bar{z}}{\partial x}\right|^{1/6}$$

$$T_{eq} = L^2/\kappa$$

Response / Equilibration time
e.g. Paola et al. (1992)

Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = (A_{Q_s} - A_{Q_w})\ \bar{z}\ G_z\ \sin\left(\frac{2\pi}{P}(t - \varphi_z)\right)$$

Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = \boxed{(A_{Q_s} - A_{Q_w})\ \bar{z}}\, G_z\ \sin\left(\frac{2\pi}{P}(t-\varphi_z)\right)$$

Forcing amplitude

Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = (A_{Q_s} - A_{Q_w})\ \bar{z}\ G_z\ \sin\left(\frac{2\pi}{\boxed{P}}(t - \varphi_z)\right)$$

Forcing period

Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = (A_{Q_s} - A_{Q_w})\ \bar{z}\ \boxed{G_z}\ \sin\left(\frac{2\pi}{P}(t - \varphi_z)\right)$$

"Gain"

$$\frac{\textbf{Response Amplitude}}{\textbf{Forcing Amplitude}}$$

e.g. Braun et al. (2015)
e.g. Godard & Tucker (2022)

Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = (A_{Q_s} - A_{Q_w})\ \bar{z}\ G_z\ \sin\left(\frac{2\pi}{P}(t - \varphi_z)\right)$$

Phase shift

Lag time

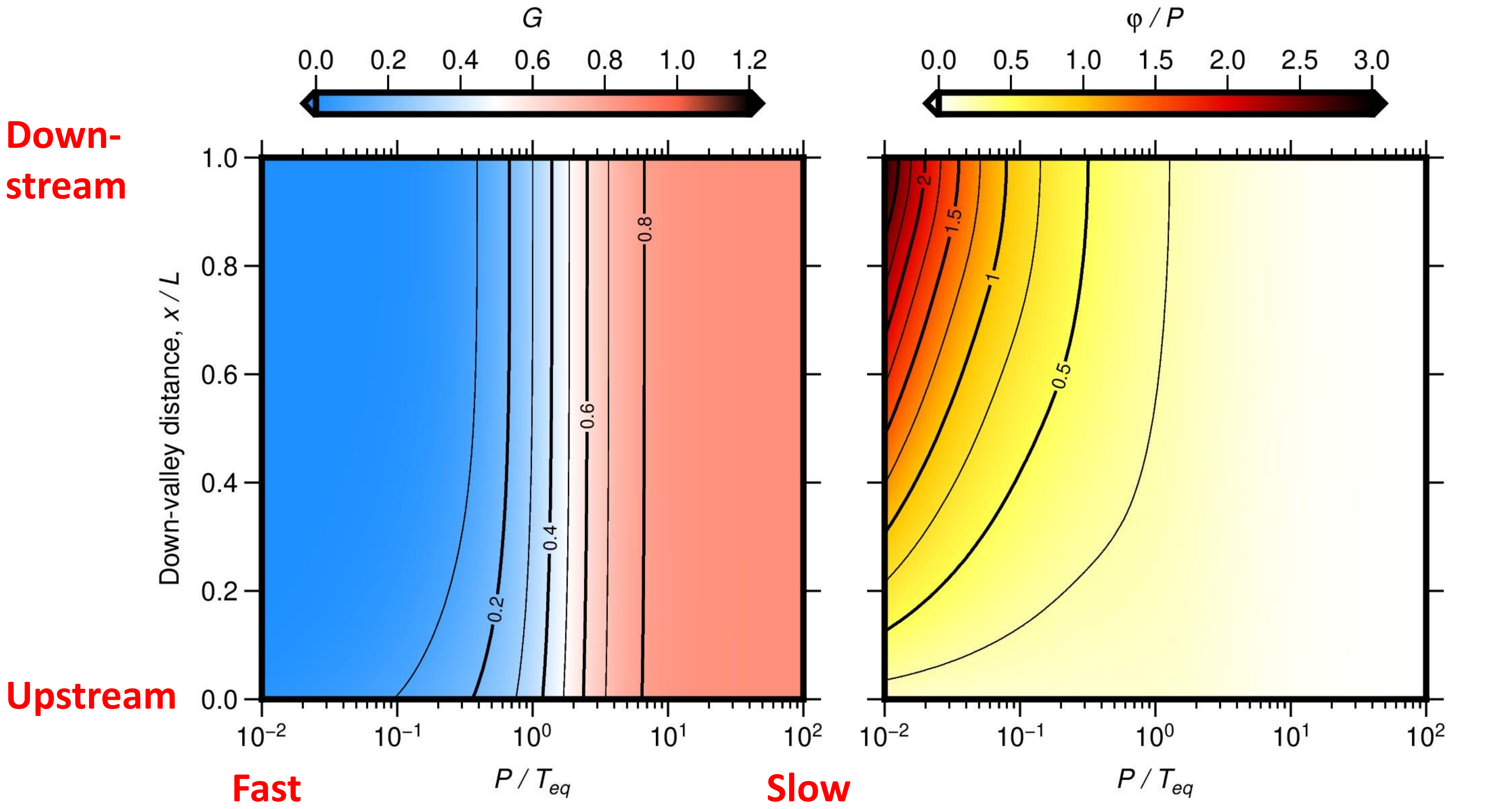
Results

- Impose sinusoidal variation in sediment & water supply

$$\delta z(x,t) = (A_{Q_s} - A_{Q_w})\ \bar{z}\ G_z\ \sin\left(\frac{2\pi}{P}(t-\varphi_z)\right)$$

$$\boxed{G_z,\ \varphi_z\ \ \left({}^{x}/_{L},\ {}^{P}/_{T_{eq}}\right)}$$

Response amplitude and lag depend on position and frequency of forcing


Down-
stream
Upstream
G
0.0
0.2
0.4
0.6
0.8
1.0
1.2
φ / P
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Down-valley distance, x / L
P / T_eq
P / T_eq
Fast
Slow

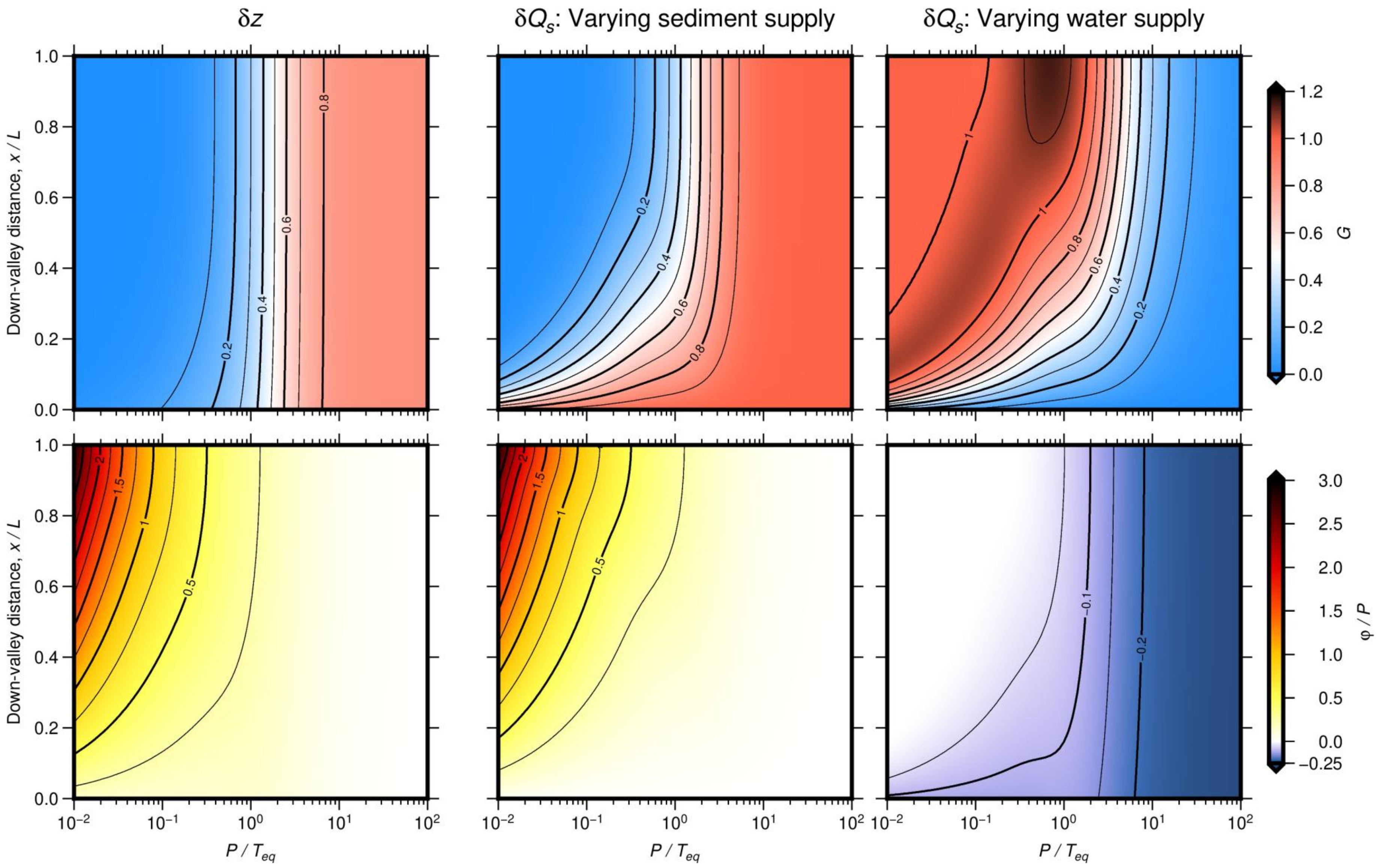
Conclusions & Implications

- Amplitudes of aggradation-incision cycles depend on basin geometry and hydrology
- Aggradation-incision cycles lag behind environmental change – interpreting terrace ages requires care
- Can also predict variation in sediment discharge – some similarities, some differences
- General behaviour also applies to more complicated modelling domain (though details differ)

Extra results: Sediment discharge

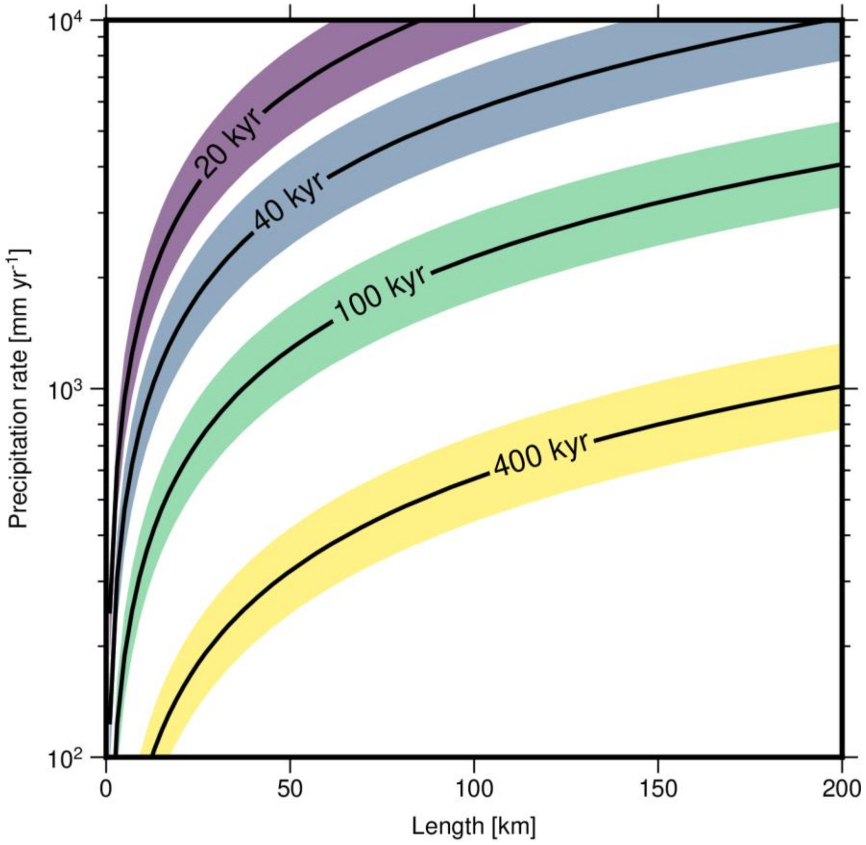
- We can also define gain and lag for sediment discharge
- Unlike variation in elevation, different behaviour predicted depending on whether sediment or water supply is varied
- When water supply is varied, high frequency variation in sediment discharge with negative lag predicted

$$\delta Q_s(x,t) = (A_{Q_s} - A_{Q_w})\ \overline{Q_s}\ G_{Q_s}\ \sin\left(\frac{2\pi}{P}(t - \varphi_{Q_s})\right)$$


δz
δQ_s: Varying sediment supply
δQ_s: Varying water supply
Down-valley distance, x / L
P / T_eq
G
φ / P
1.0
0.8
0.6
0.4
0.2
0.0
1.2
3.0
2.5
2.0
1.5
0.5
−0.25
−0.1
−0.2
10^−2
10^−1
10^0
10^1
10^2

Extra results: Predicting T_{eq}

- We can predict Teq using scaling laws for discharge and valley width
- Wide range predicted for natural rivers – wide range of responses possible



Equilibration time contours as functions of valley length and precipitation rate.

Upstream drainage area assumed to scale with Hack’s Law; valley width with scaling law described by Clubb et al. (2022).