EGU General Assembly 2020

To slide or not to slide:
Explicit integration of landslides and sediment dynamics in a landscape evolution model

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fwo Research Foundation Flanders Opening new horizons

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The aim of this work

- We present HyLands, a hybrid landscape evolution model, to better understand interactions between landslide-derived sediment and river incision.

- The hybrid nature of the model lies in its capacity to simulate both erosion and deposition at any place in the landscape due to fluvial bedrock incision, sediment transport and rapid, stochastic mass wasting through landsliding.

Structure of this slideshow

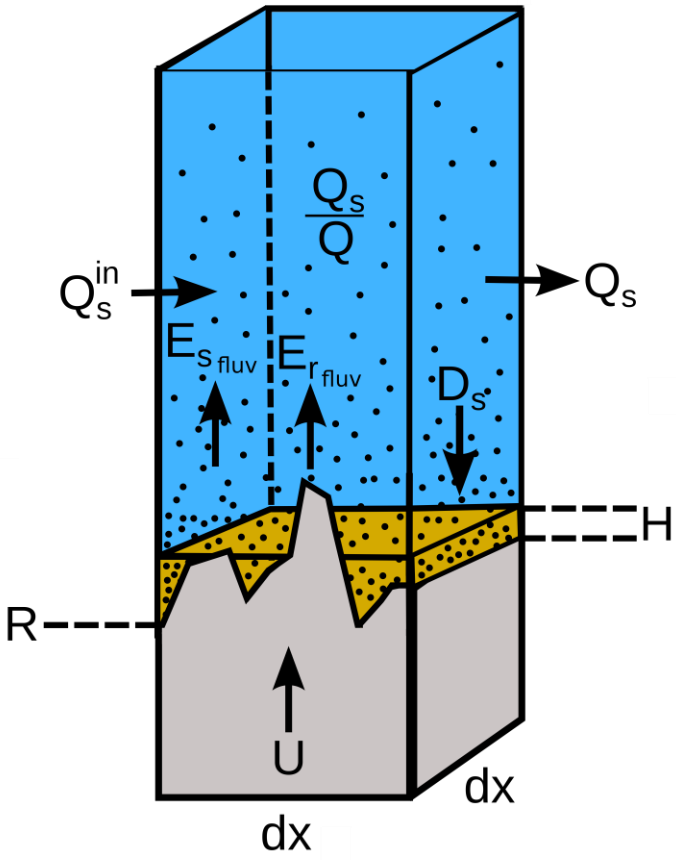
- Implementation
- Demonstration
- Application

HyLands: Implementation

The fluvial component

- Fluvial sediment transport and bedrock incision are calculated using the recently developed Stream Power with Alluvium Conservation and Entrainment (SPACE) model.
- Therefore, rivers in HyLands can dynamically transition from detachment-limited to transport-limited, and from bedrock to bedrock-alluvial to fully alluviated states.

cfr: Shobe et al. 2017: https://doi.org/10.5194/gmd-10-4577-2017



HyLands: Implementation

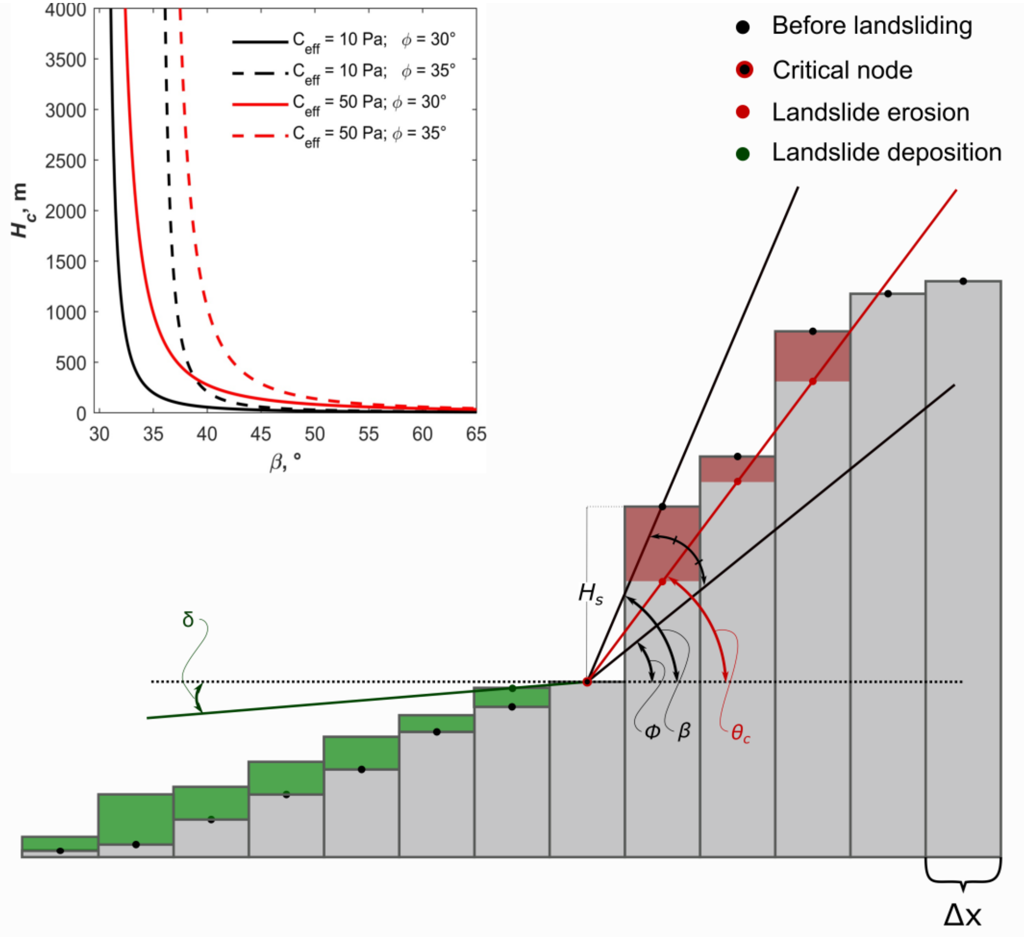
The landslide component

- Erosion and sediment production by landsliding is calculated using a Mohr-Coulomb stability analysis

  cfr: Densmore et al. 1998: https://doi.org/10.1029/98JB00510

- Landslide-derived sediment is routed and deposited using a multiple flow direction, non-linear deposition method

  cfr: Carretier et al. 2016: https://doi.org/10.5194/esurf-4-237-2016



HyLands: Implementation

The fluvial component

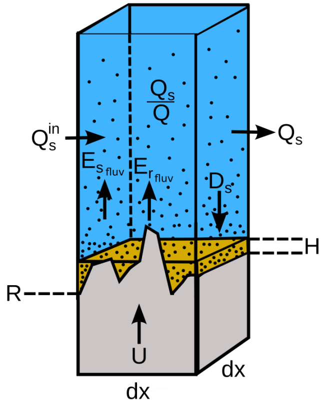


Figure 1. Sketch of fluvial SPACE component. Model setup and variable definitions for the SPACE bedrock-alluvial river erosion model. Reproduced from Shobe et al. (2017). Entrainment and deposition of sediment, as well as erosion of bedrock, can occur simultaneously. This approach allows channels to dynamically transition among bedrock, bedrock-alluvial, and fully alluviated states. At a given stream power, the relative rate of sediment entrainment $E_{s_{fluv}}$ and bedrock erosion $E_{r_{fluv}}$ is set by the ratio of sediment thickness H to the bedrock roughness height H_* (Fig. 2).

The landslide component

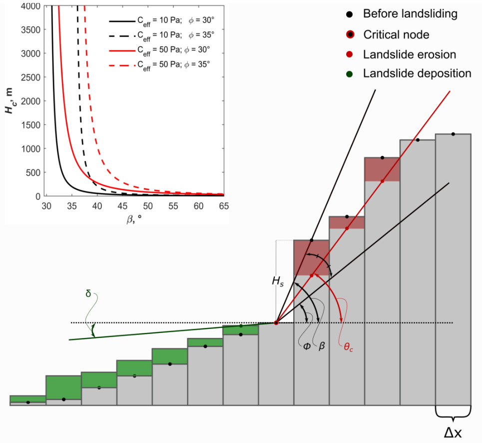
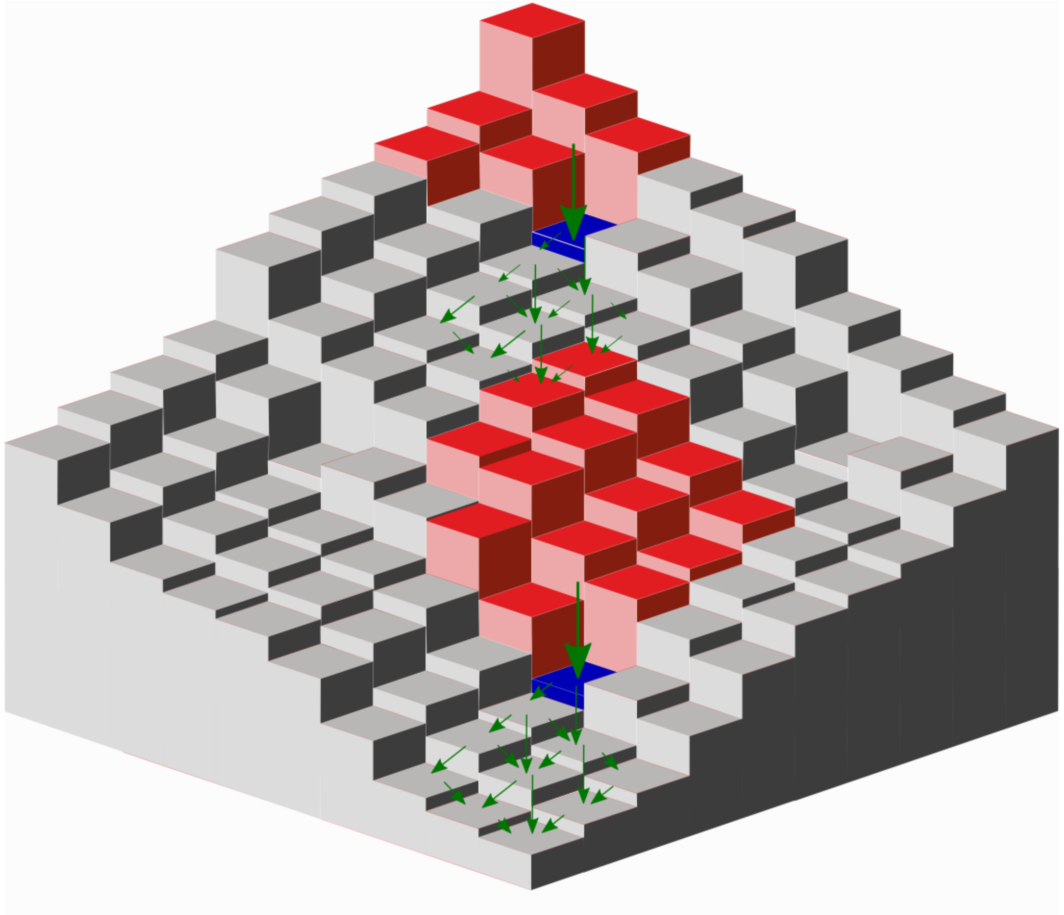


Figure 3. Sketch of landslide algorithm in two dimensions. Landslide erosion (red shaded area) is calculated using the Culmann approach (Culmann, 1875). β is the topographic slope, ϕ represents the angle of internal friction and θ is the inclination of the rupture plane. Deposition of landslide-derived sediment (green shaded area) is calculated using a non-local diffusion equation (Eq. 11, cfr. Carretier et al., 2016). δ is the minimal angle of the spreading slope under which landslide-derived sediment is distributed on the hillslope. This sketch illustrates a case where none of the landslide-derived sediment is in permanent suspension ($F_{f_{hill}} = 0$) and the amount of eroded sediment (red shaded area) equals the amount of deposited sediment (green shaded area). If the deposited volume creates a down-slope gradient which is lower than the minimum spreading angle, δ, the slope of deposited volume is adjusted so that the spreading slope equals δ. Probability for sliding is calculated as the ratio of the local hillslope height H_s to the maximum hillslope height H_c (Eq. 7, cfr. Densmore et al., 1998). The inset plot illustrates that H_c depends on the rock strength (cohesion C and internal friction angle ϕ) and the topographic slope β. The plotted lines are calculated using Eq. 8 with ρ is 2700 $\text{kg}\,\text{m}^{-3}$, and $g = 9.81$ m s^{-2}.

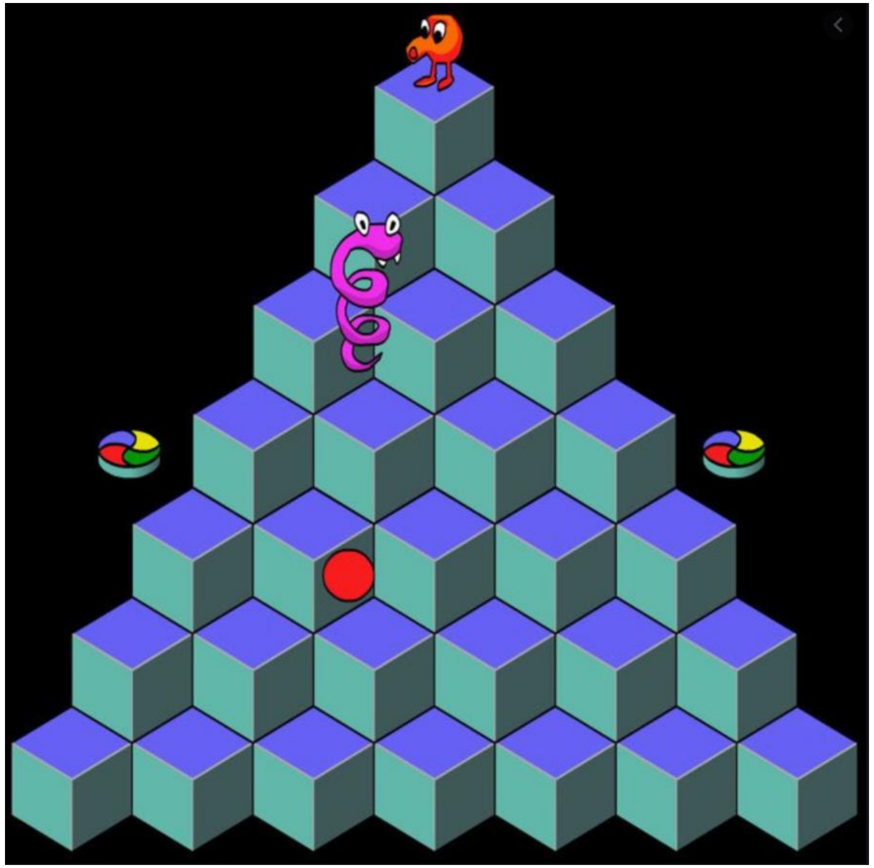
HyLands: Implementation

Landslide produced sediment routed in 3D



HyLands: Implementation

And no, this is not QBert



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HyLands: Implementation

Landslide produced sediment routed in 3D

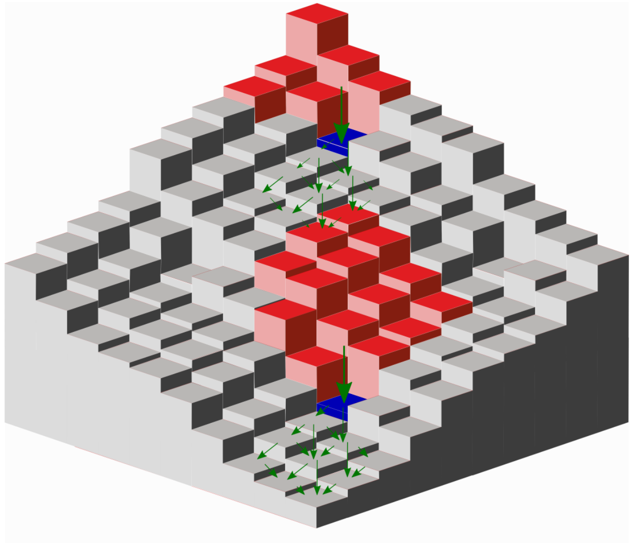


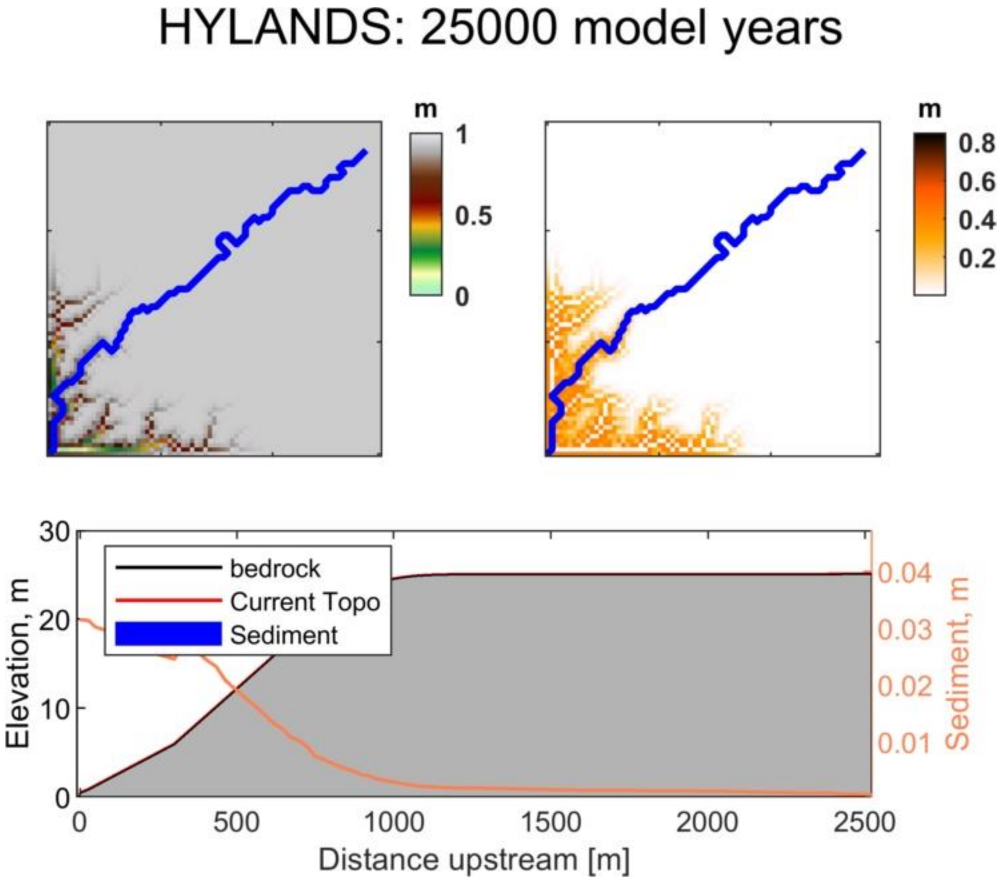
Figure 4. Sketch of landslide algorithm in three dimensions. Cells shaded in blue indicate the critical nodes where landslides initiate. Cells shaded in red represent the landslide source areas. After mass failing, sediment will be redistributed over the downslope cells using a multiple flow direction algorithm (indicated with green arrows). Sediment deposition rate depends on a transport distance L (cfr. Eqs. 11 and 12).

HyLands: Demonstration

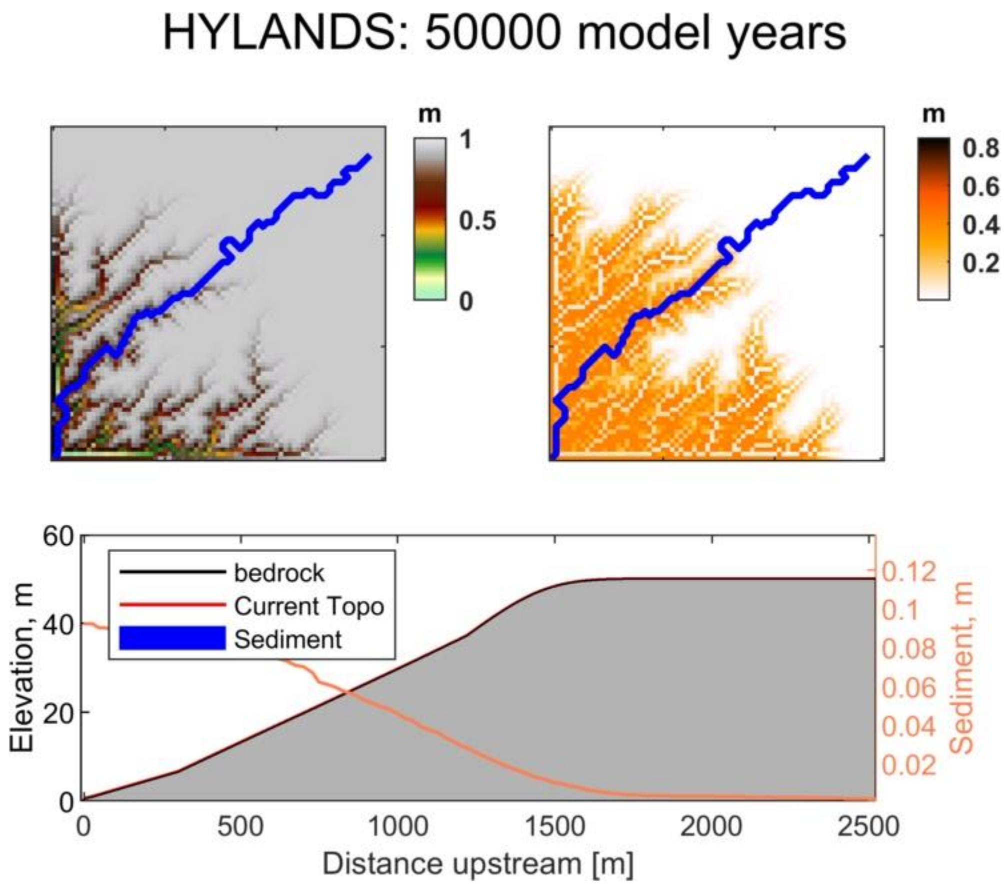
- Stage I: To steady state
- Stage II: 100-year period of intense landslide activity imposed on the steady state landscape
- Stage III: Back to steady state

HyLands: Demonstration

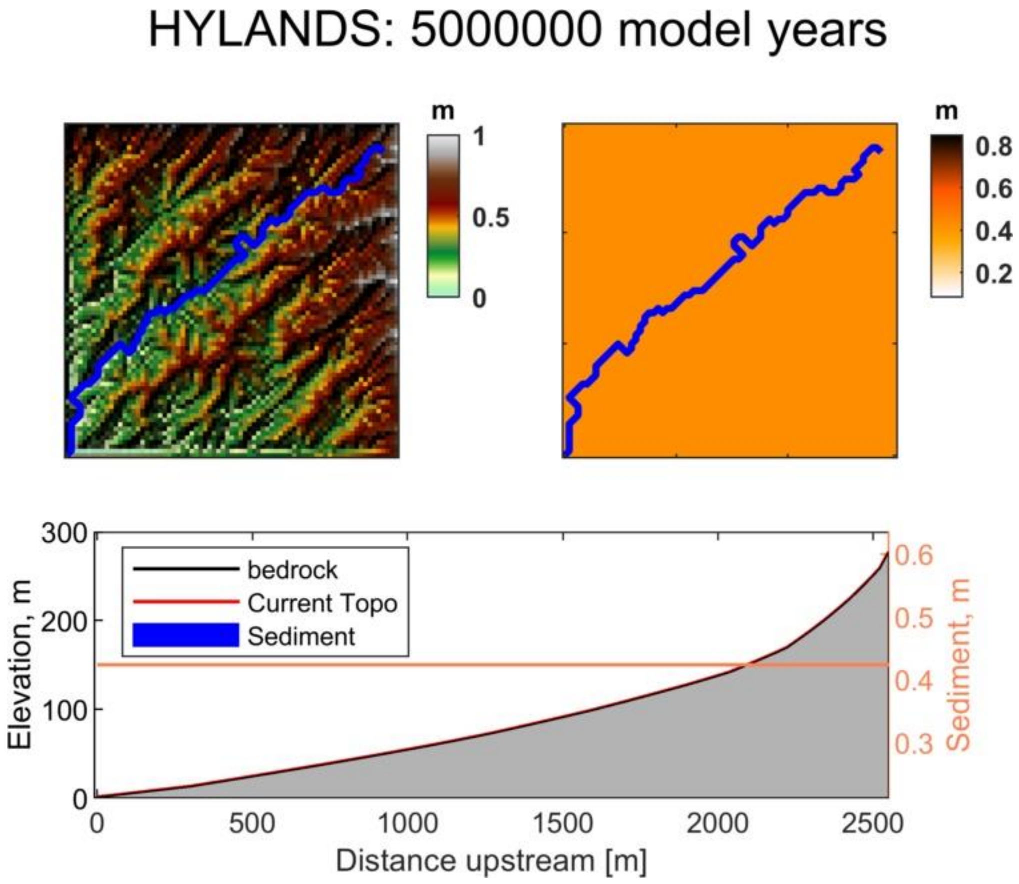
Stage I: To steady state



HyLands: Demonstration
Stage I: To steady state

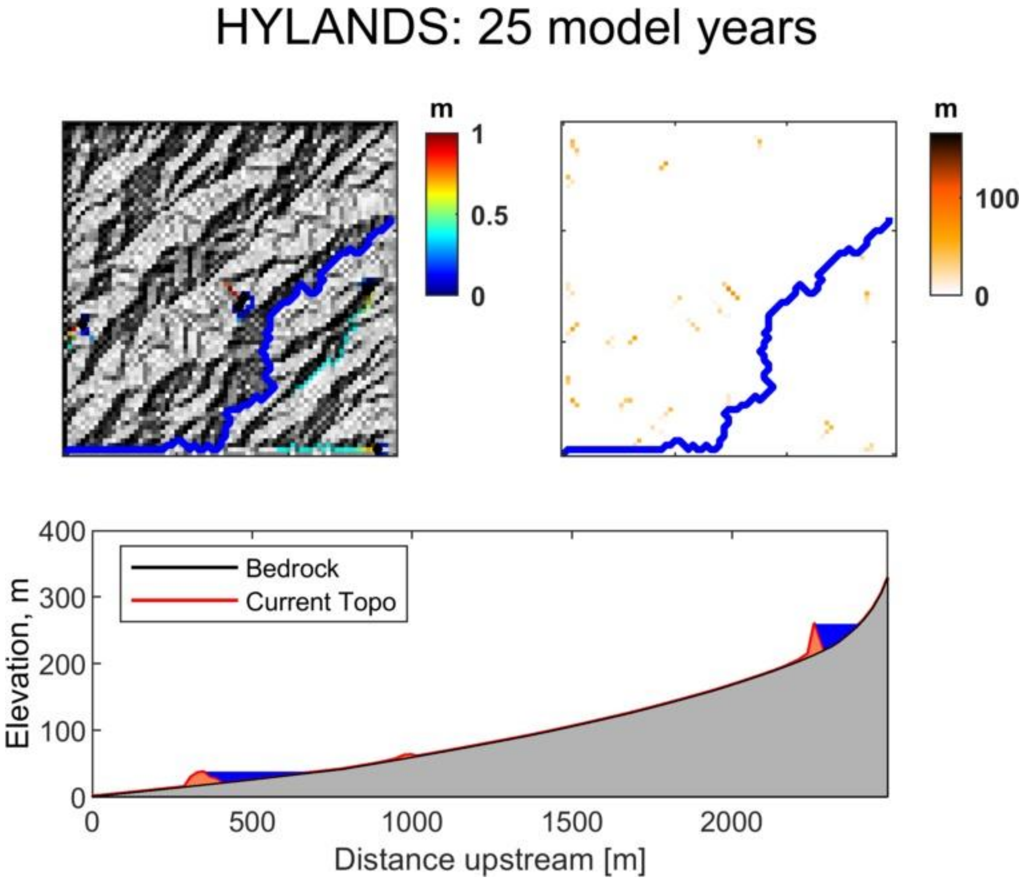


HyLands: Demonstration
Stage I: To steady state



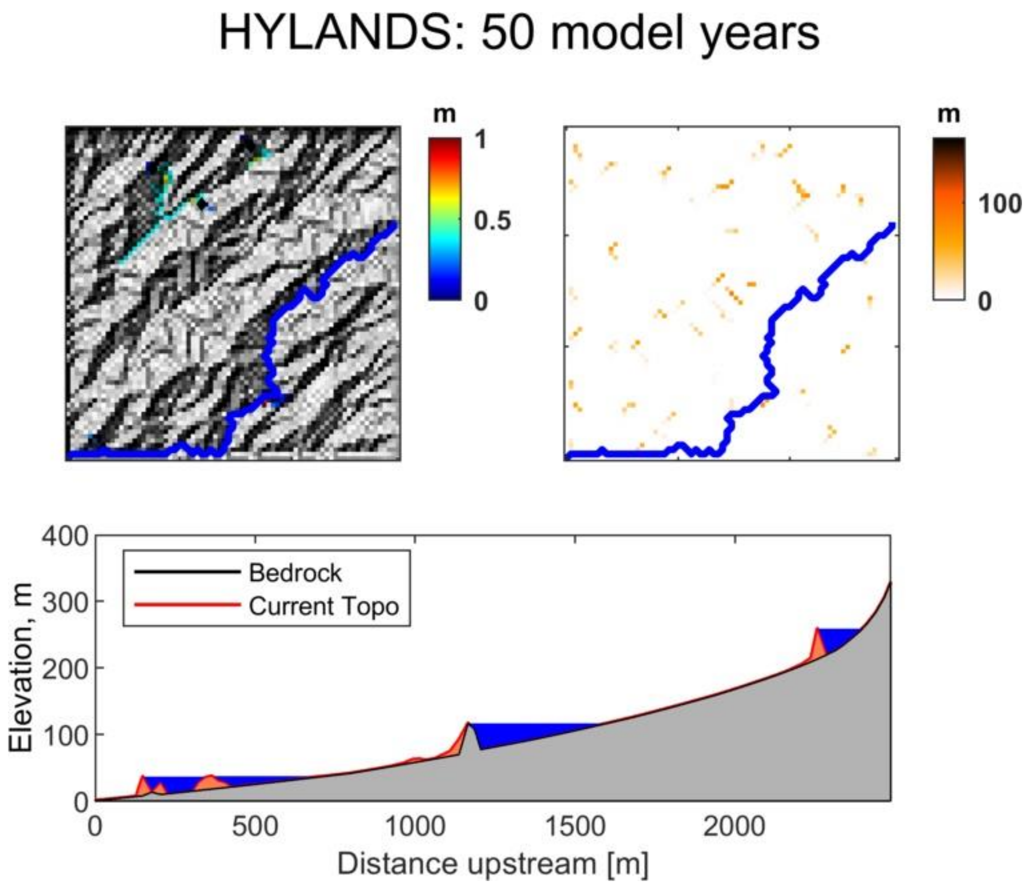
HyLands: Demonstration

Stage II: 100 years of intense landslide activity



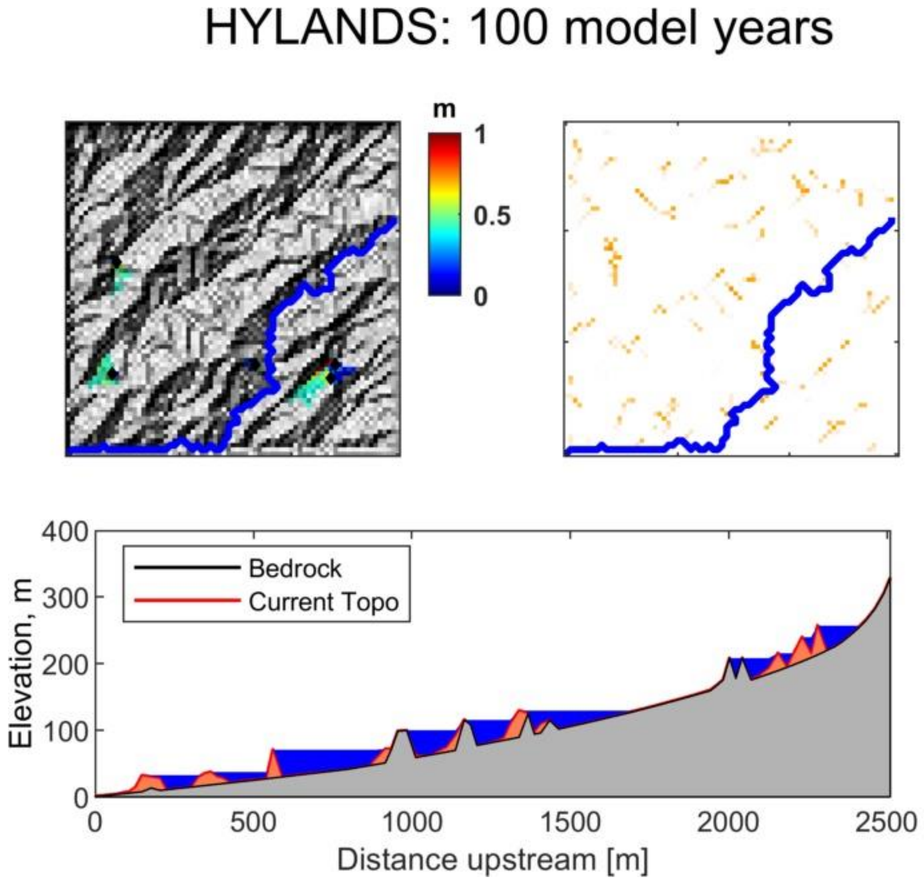
HyLands: Demonstration

Stage II: 100 years of intense landslide activity



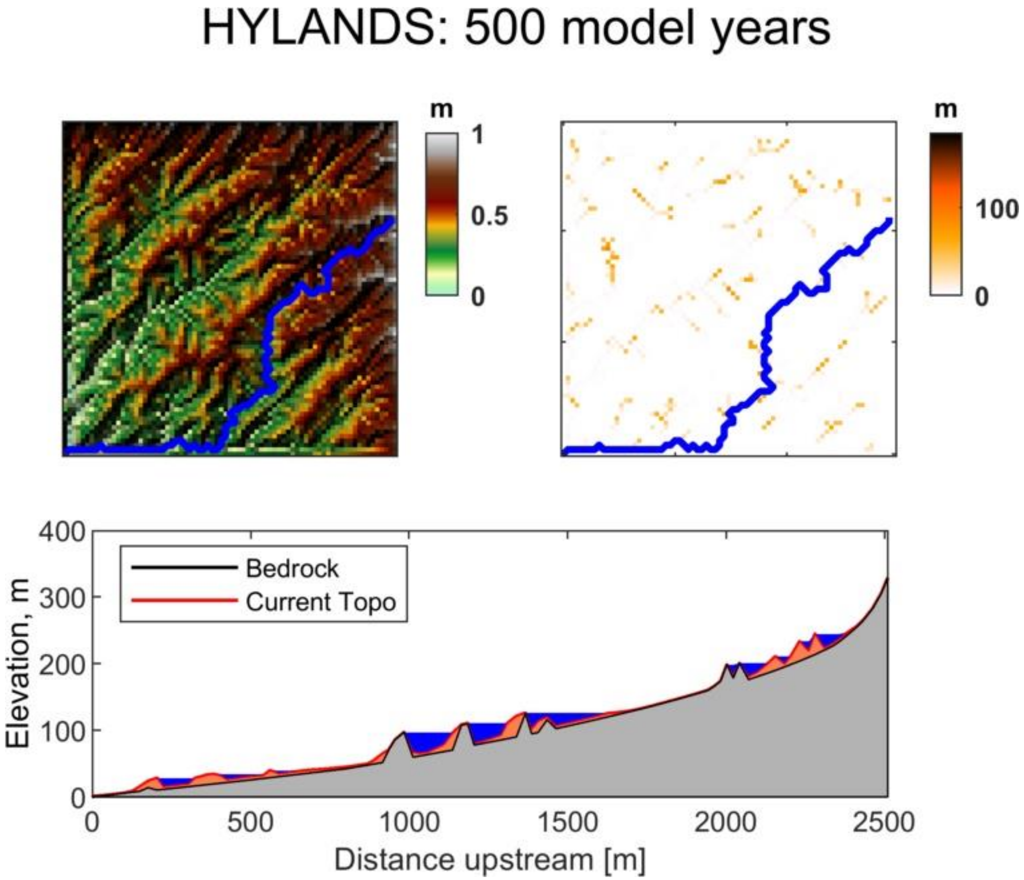
HyLands: Demonstration

Stage II: 100 years of intense landslide activity



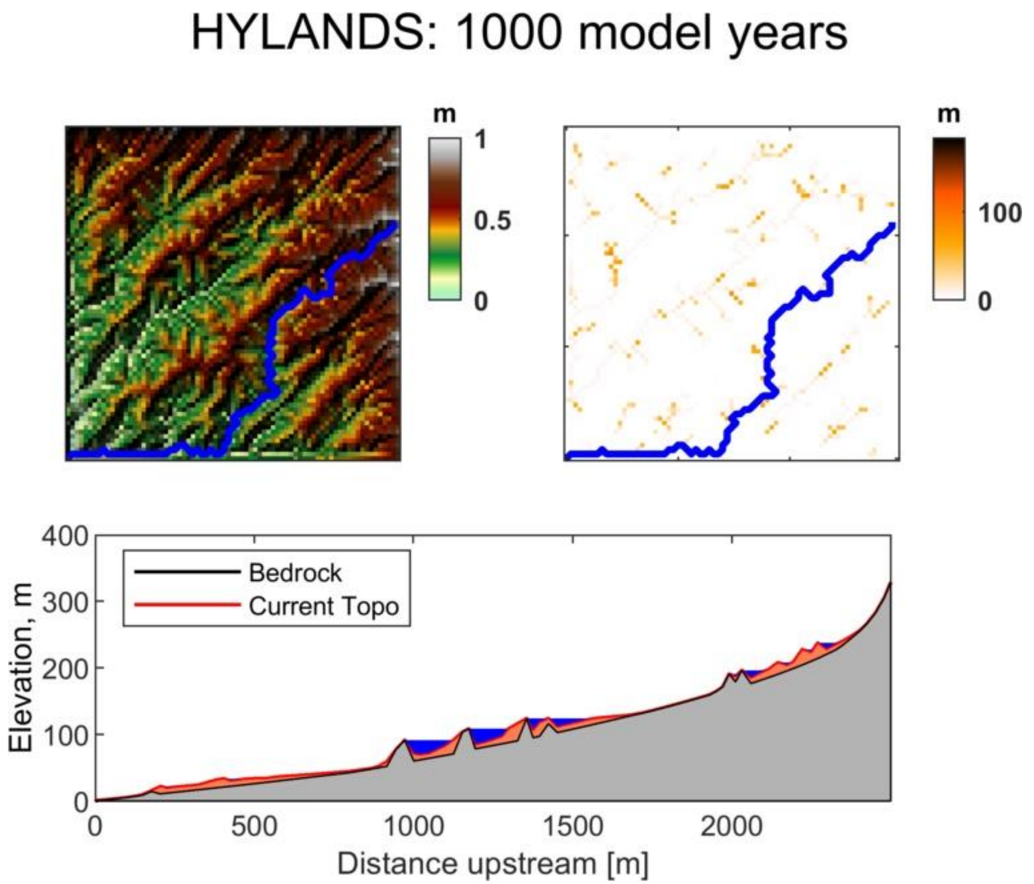
HyLands: Demonstration

Stage III: Back to steady state



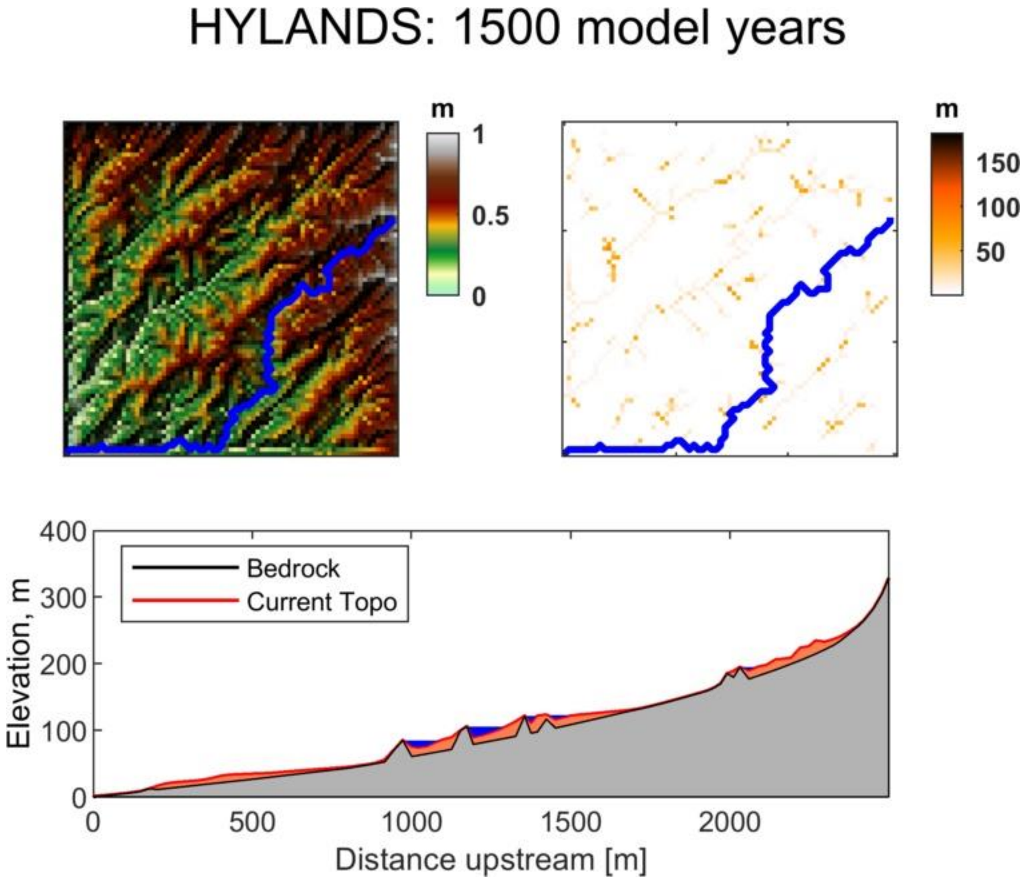
HyLands: Demonstration

Stage III: Back to steady state



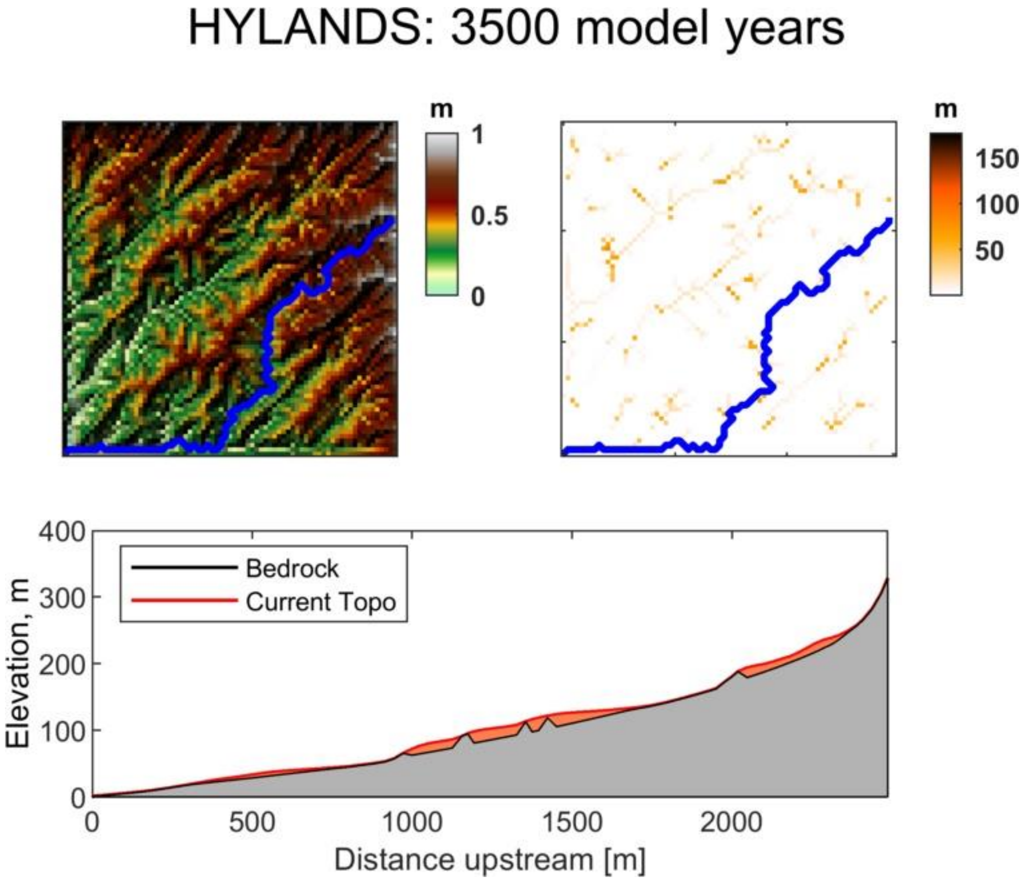
HyLands: Demonstration

Stage III: Back to steady state



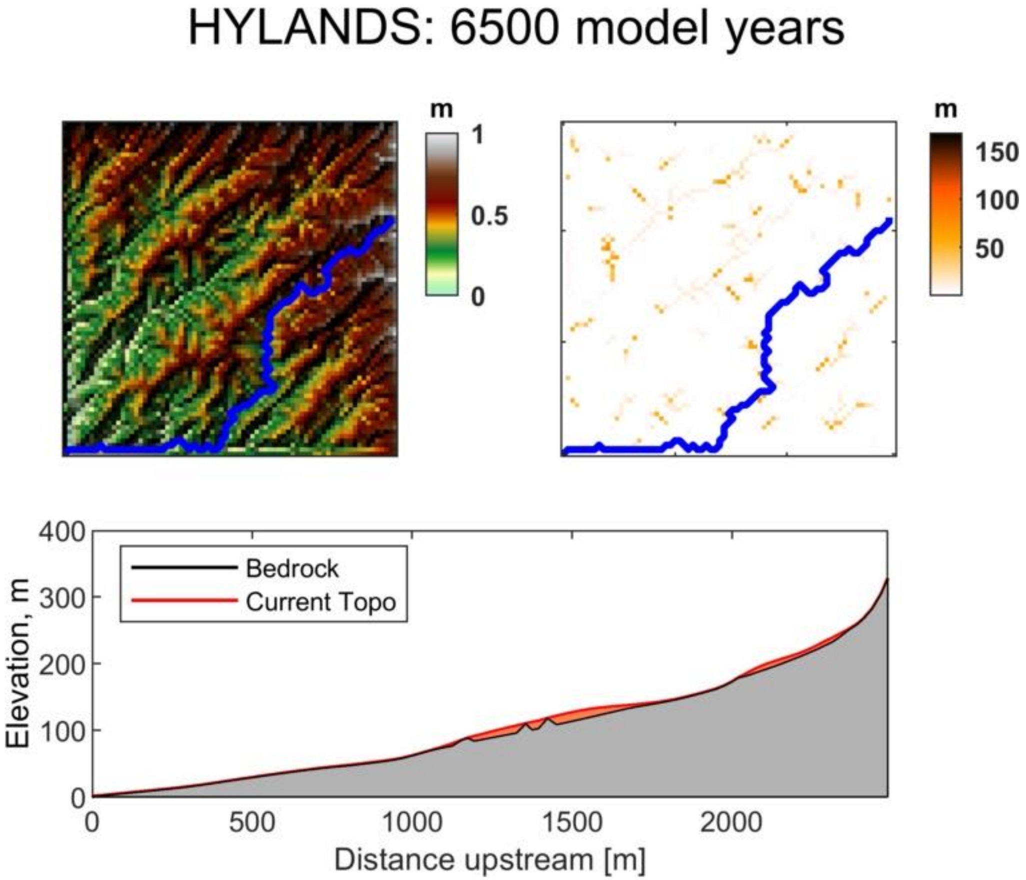
HyLands: Demonstration

Stage III: Back to steady state



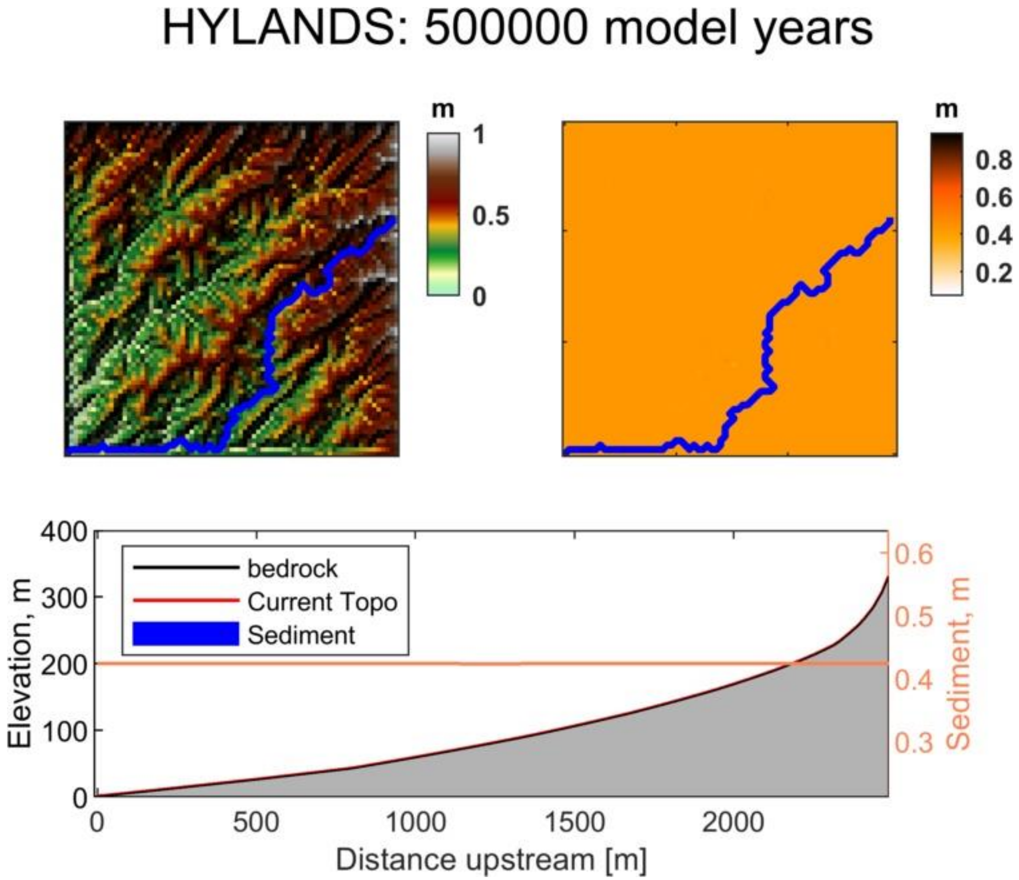
HyLands: Demonstration

Stage III: Back to steady state



HyLands: Demonstration

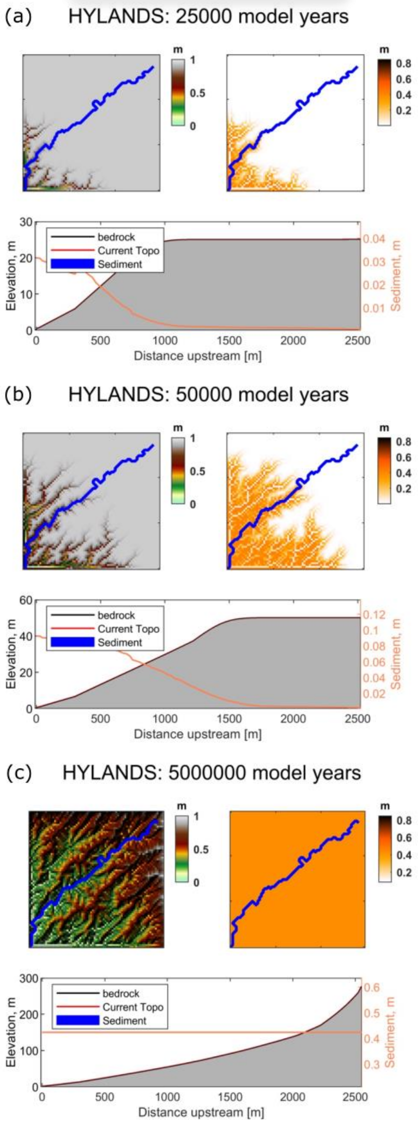
Stage III: Back to steady state



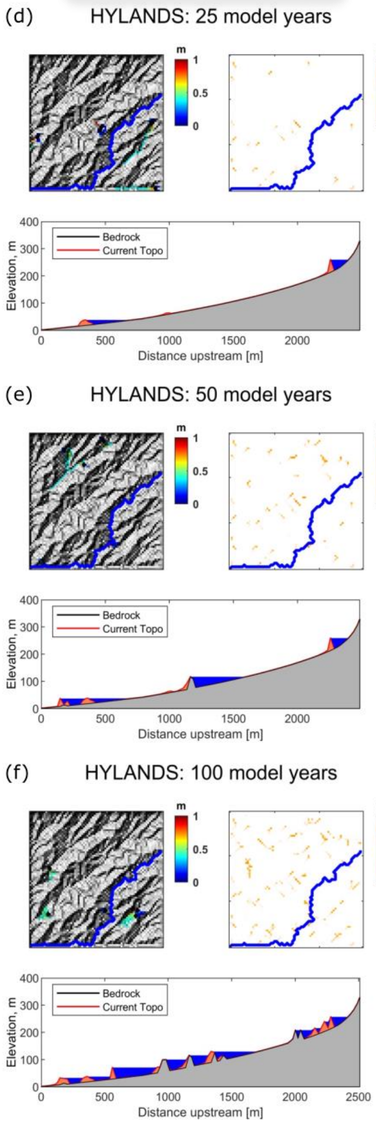
HyLands: Demonstration

An overview

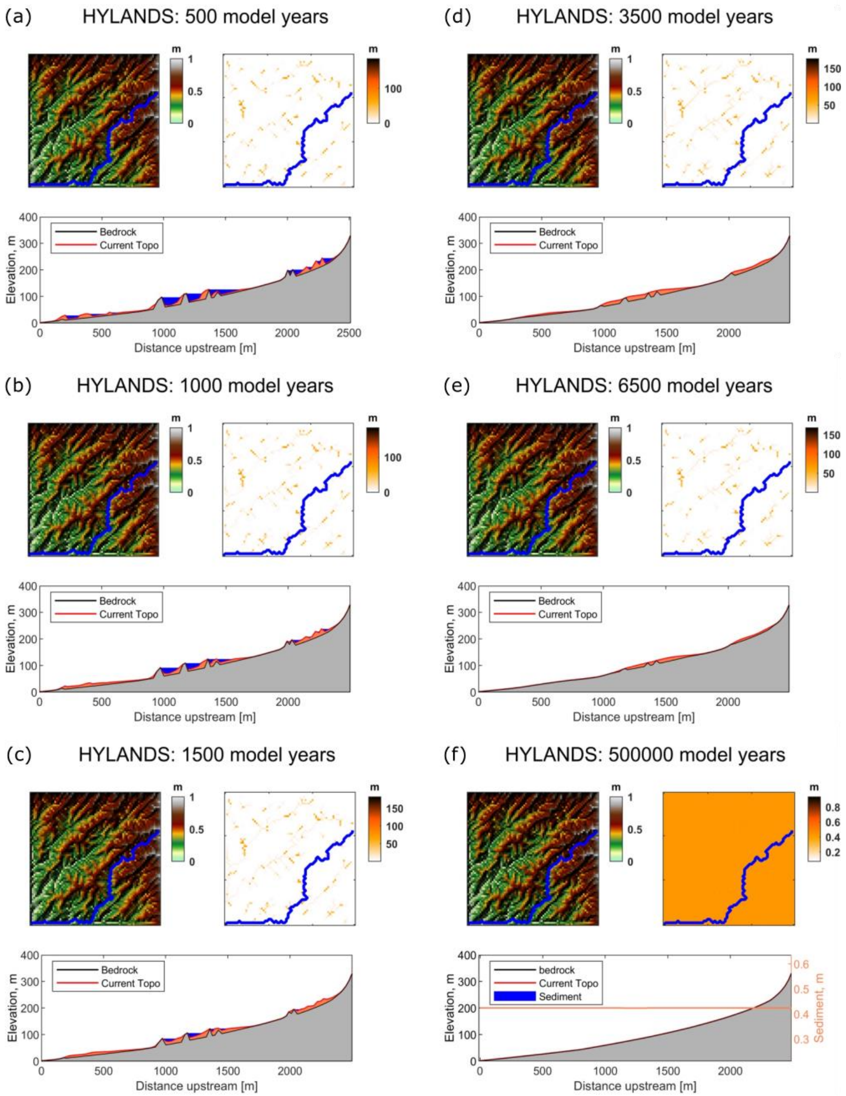
To steady state



100 years of LS events



Post landslide events



HyLands: Demonstration

An overview

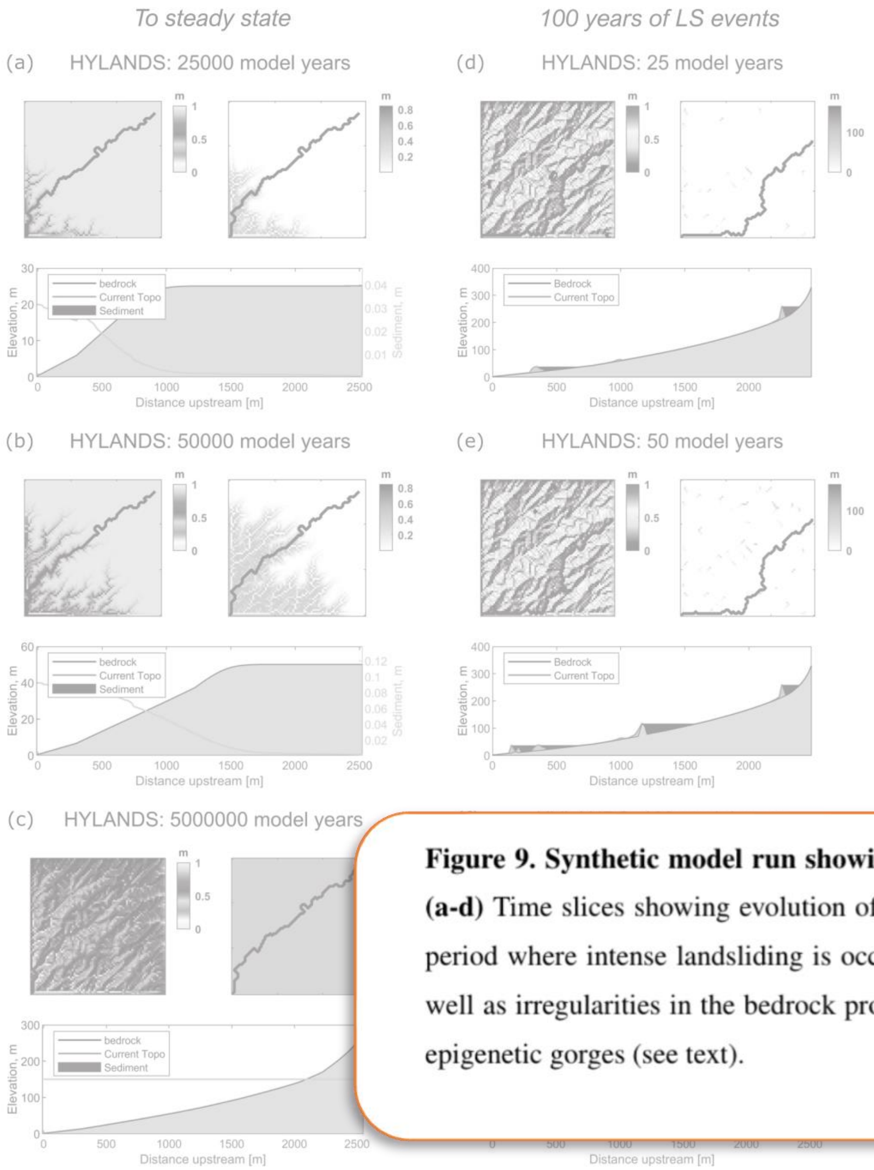


Figure 9. Synthetic model run showing landscape evolution to steady state followed by an intense landsliding period of 100 years. (a-d) Time slices showing evolution of the landscape to steady state, before the landslide period. **(e-h)** Time slices showing the landslide period where intense landsliding is occurring over a period of 100 years. Note that, during landsliding, both pure landslide dams arise as well as irregularities in the bedrock profile (the grey bumps). The latter originate from the river being redirected after landsliding forming epigenetic gorges (see text).

HyLands: Demonstration

An overview

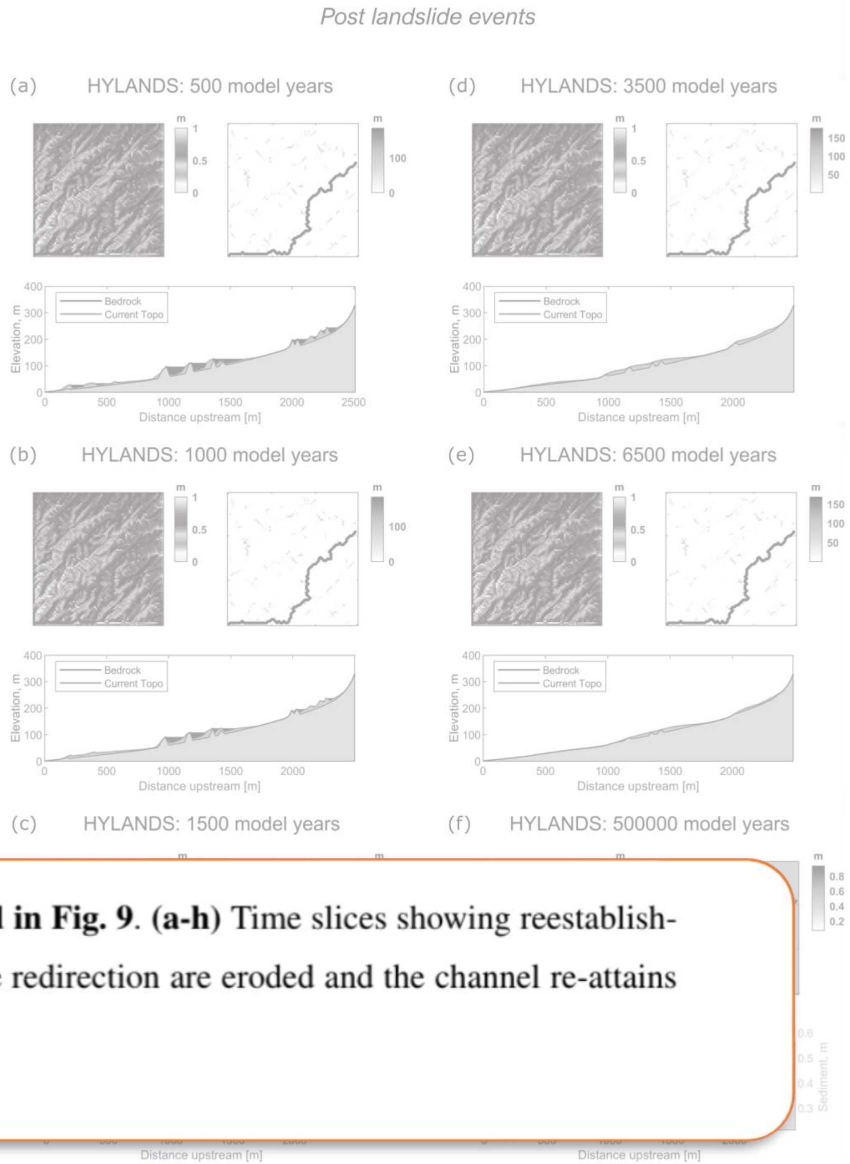


Figure 10. Synthetic model run showing recovery from intense landsliding illustrated in Fig. 9. (a-h) Time slices showing reestablishment of the landscape steady state. Bedrock bumps created by landslide-induced drainage redirection are eroded and the channel re-attains its smoothly concave-up, steady-state configuration.

HyLands: Demonstration

The movie

- Stage I: https://doi.org/10.5446/45970
- Stage II: https://doi.org/10.5446/45971
- Stage III: https://doi.org/10.5446/45972

HyLands: Application

Applying HyLands to the Namche Barwa-Gyala Peri massif

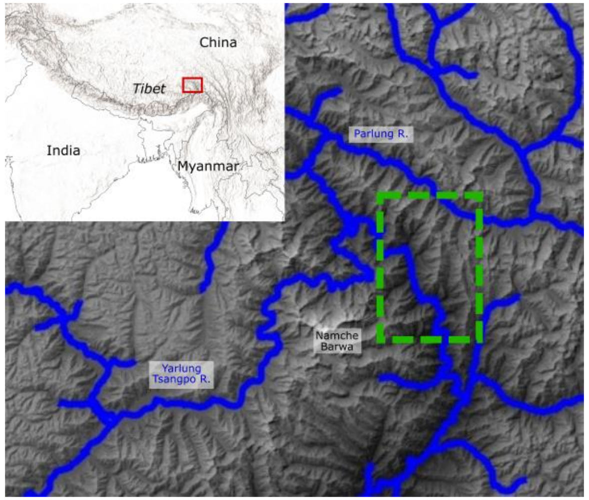
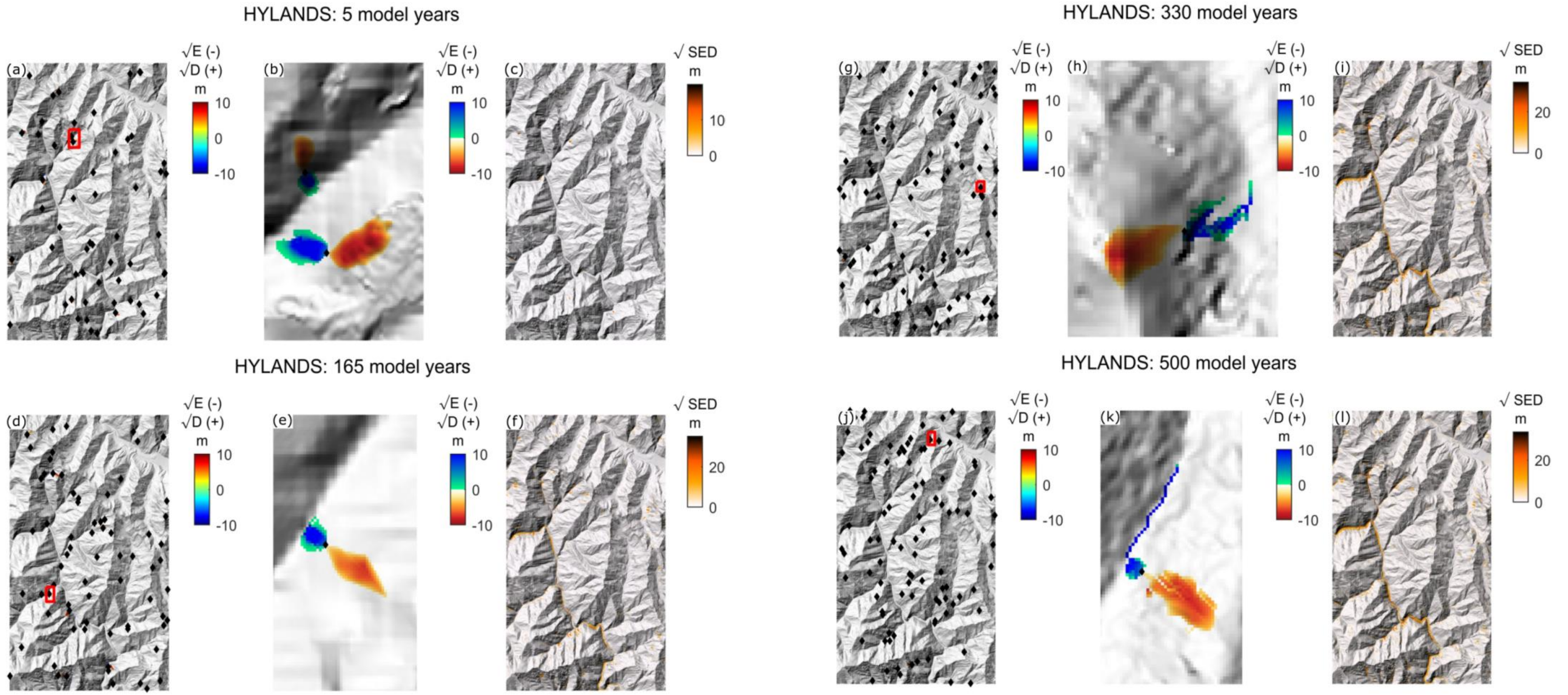


Figure 6. Namche Barwa-Gyala Peri massif used for model evaluation. The red rectangle on the inset figure indicates the geographical location of the study area. The green dashed rectangle indicates the part of the DEM used to evaluate HyLands. The shaded colours indicate elevations, which were derived from the 30 m SRTM v3 DEM (NASA JPL, 2013) and resampled to a higher resolution of 20 m using a bicubic interpolation method. Main map is produced with TopoToolbox (Schwanghart and Scherler, 2014). Inset map is made in QGis 3©, using Natural Earth vector and raster map data available at www.naturalearthdata.com.

HyLands: Application

Namche Barwa-Gyala Peri massif



HyLands: Application

Namche Barwa-Gyala Peri massif

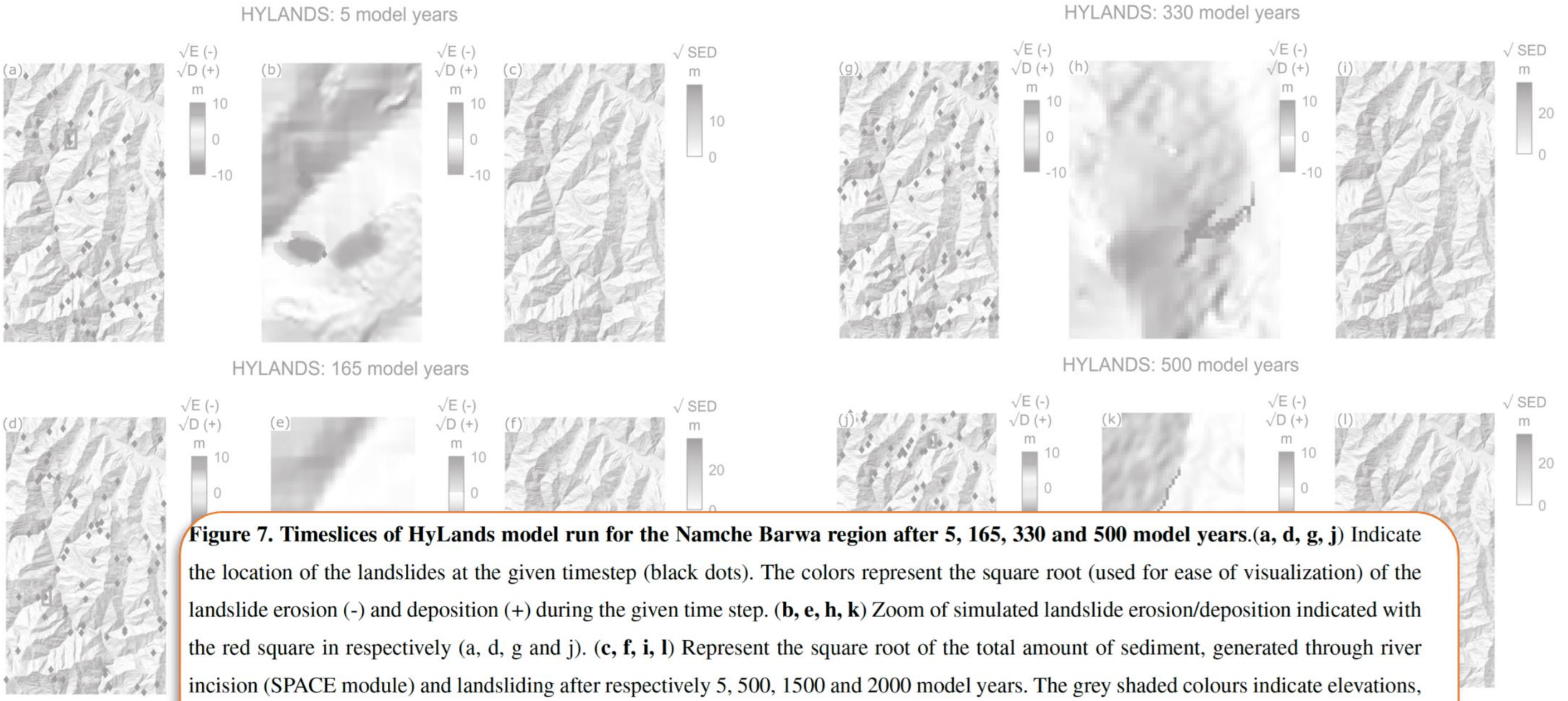


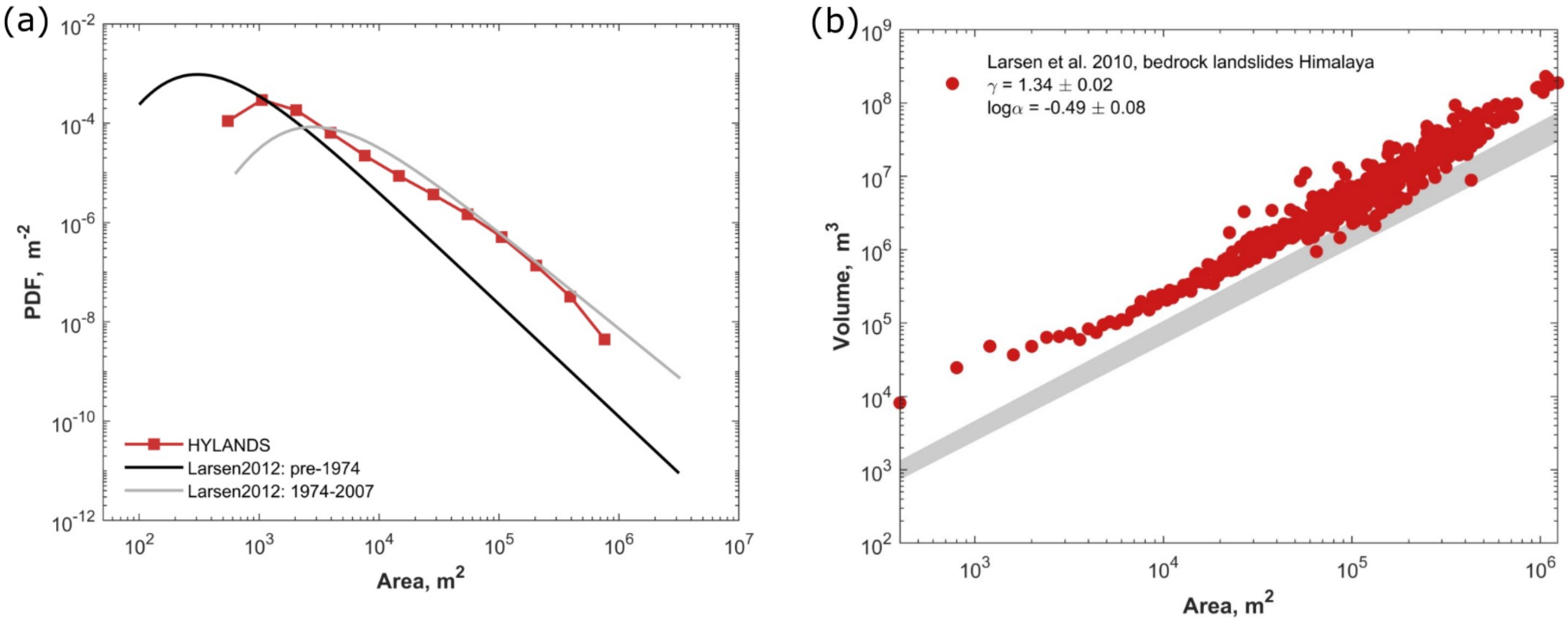
Figure 7. Timeslices of HyLands model run for the Namche Barwa region after 5, 165, 330 and 500 model years.(**a, d, g, j**) Indicate the location of the landslides at the given timestep (black dots). The colors represent the square root (used for ease of visualization) of the landslide erosion (-) and deposition (+) during the given time step. (**b, e, h, k**) Zoom of simulated landslide erosion/deposition indicated with the red square in respectively (a, d, g and j). (**c, f, i, l**) Represent the square root of the total amount of sediment, generated through river incision (SPACE module) and landsliding after respectively 5, 500, 1500 and 2000 model years. The grey shaded colours indicate elevations, which were derived from the 30 m SRTM v3 DEM (NASA JPL, 2013).

HyLands: Application

The movie

- Namche Barwa-Gyala Peri massif: https://doi.org/10.5446/45973

HyLands: Application
Namche Barwa-Gyala Peri massif



HyLands: Application

Namche Barwa-Gyala Peri massif

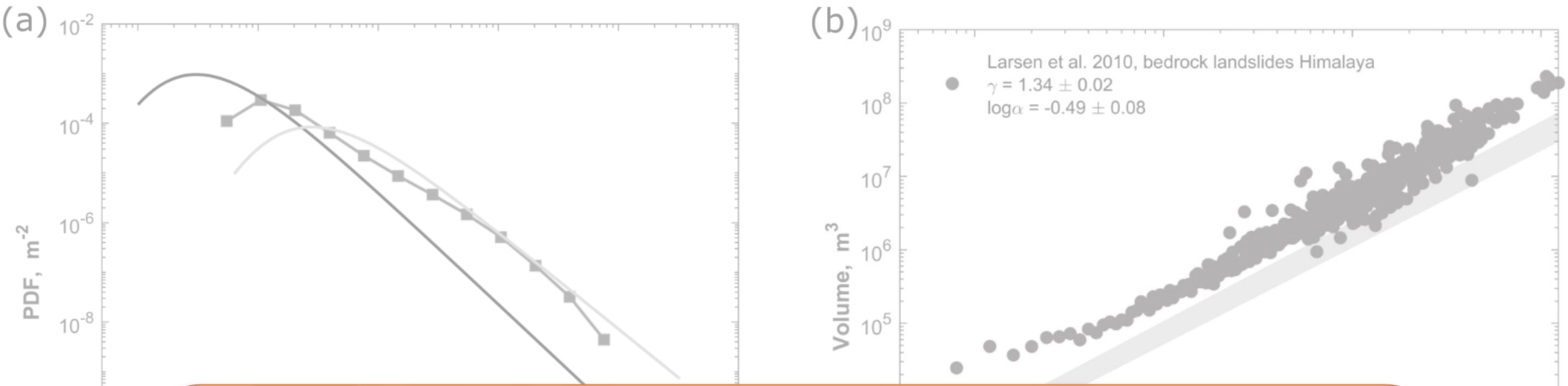


Figure 8. Comparison between modelled and observed characteristic landslide scaling relationships. (**a**) Magnitude frequency relationship. The grey and black line represent the best fitting inverse gamma distribution (Eq. 19) of the landslide activity mapped before 1974 and between 1974 - 2012, respectively (Larsen and Montgomery, 2012). The fitting parameters are respectively ($a_l = 768 \times 10^{-6}$, $s_l = -32.6 \times 10^{-6}$ and $\rho_l = 1.27$) and ($a_l = 6100 \times 10^{-6}$, $s_l = -311 \times 10^{-6}$ and $\rho_l = 0.96$)). The red dots represent the magnitude-frequency distribution simulated using HyLands. (**b**) Area-Volume relationship. The grey dashed zone represents the expected area-volume scaling relationship, observed for bedrock landslides in the Himalaya (Larsen et al., 2010). Fit is calculated using Eq. 20 with fitting parameters $\gamma = 1.32 \pm 0.02$ and ${}^{10}\log\alpha = -0.49 \pm 0.06$. The red dots represent the geometry of the data simulated with HyLands.

HyLands: potential applications

- HyLands provides a unique toolbox to explicitly simulate the interaction between fluvial dynamics and landslide triggering.
- HyLands can be used as an experimental environment to test how landslides influence landscape response to external perturbations.
- HyLands can be used to evaluate the response time of a landscape to a landslide event and to understand the timescales over which landslide-derived sediments are exported from the landscape.