Catchment scale simulations of fine sediment evacuation after widespread landsliding

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NERC SCIENCE OF THE ENVIRONMENT

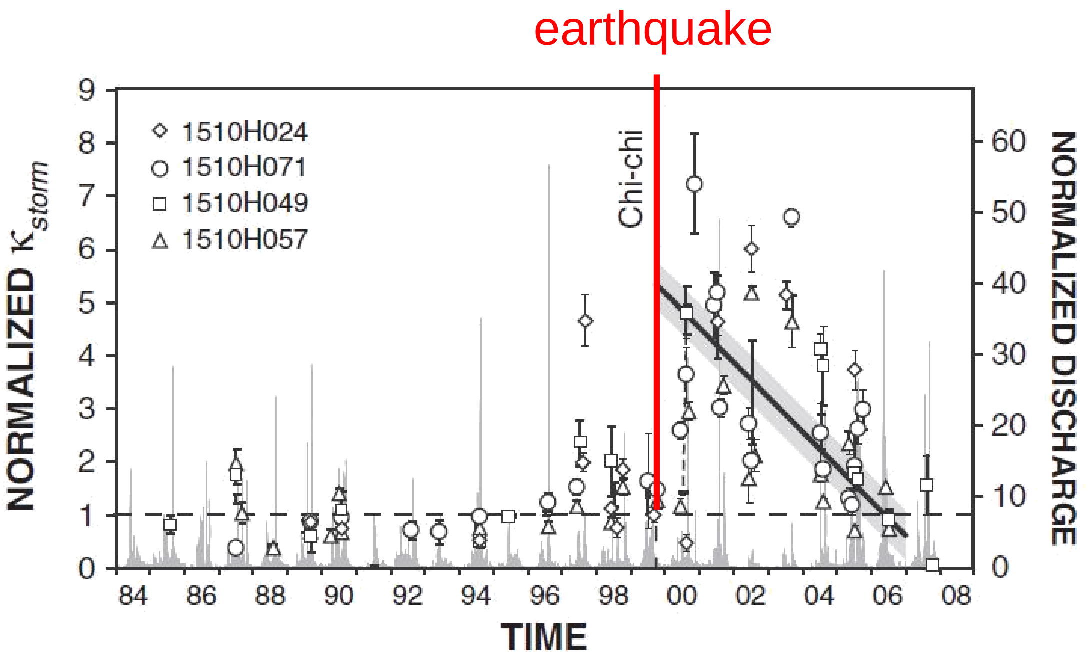
Introduction

Background and Motivation

1. Mass wasting associated to large earthquakes trigger mobilize a large quantity of sediment.

2008, Wenchuan earthquake

2. Several studies have shown that the finer sediment exported as suspended load experiences a phase of enhanced sediment transport during the 5 first years following the earthquake.



Hovius et al, 2011

Introduction

Background and Motivation

However, several questions persists on this matter:

1. What are the processes controlling the sediment evacuation in terms of sediment supply vs. fluvial transport capacity?

2. Is all the fine sediment being exhausted during the first decades or is there a significant amount of storage?

2D morphodynamic modelling – advantages for this problematic

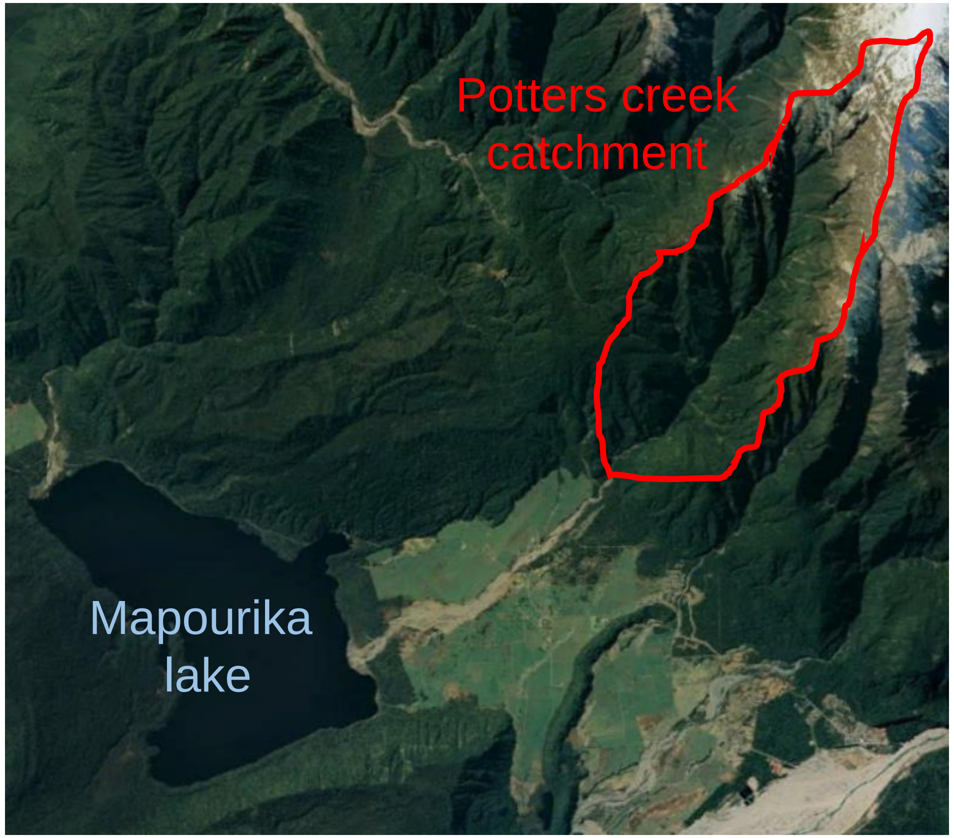
- Empirical data collection gives important insights on the dynamics of the fine sediment evacuation after a mass wasting. However, data from gauging station gives an integrative measure of all the processes acting in the catchment.
  - Using numerical models, we can ***track the evolution of landslide deposits within the catchment***.

- Natural observations are limited to the rare occurrence of mass wasting events (i.e. earthquakes, storms, …)
  - The flexibility of numerical modelling allows for an exploration of the impact of different landslide population properties such as ***landslide density*** and ***distribution***.

Study case – Potters Creek catchment, NZ

Southern Alps, West Coast of the South Island of New Zealand

Robinson and Davies, 2013



Area ~ 20 km^2

2D morphodynamic modelling

Introduction

- The evacuation of landslide deposits is investigated by using the 2D morphodynamic model Eros that is used at the catchment scale.

- This model has already been used in previous work aiming at understanding the processes controlling landslide evacuation at the reach scale and was focused on bedload transport.

- Eros hydrodynamic model is particularly resilient to local minima in the drainage network which can be introduced by several landslides reaching the river streams.

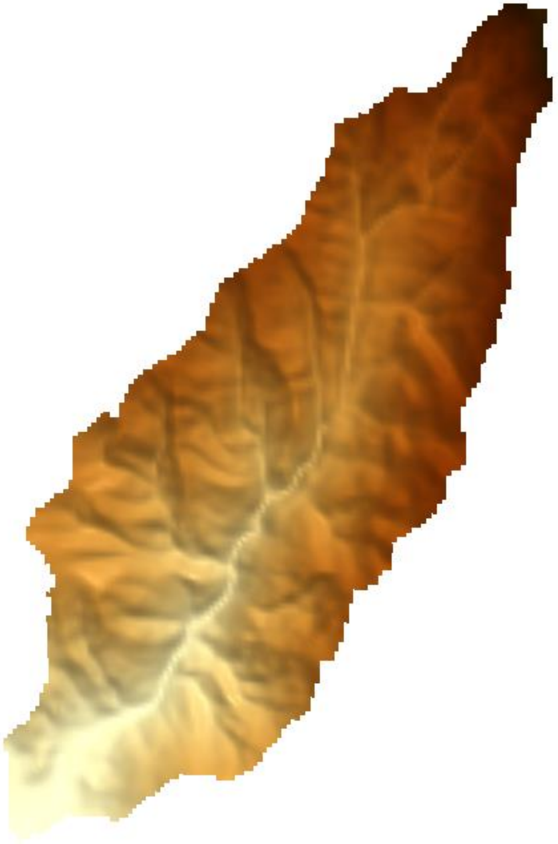
- Landslide-derived sediment connectivity to the river network emerges naturally from landslides introduction in the catchment.

- In the next slides, we present:
  1. the parameterization of the Eros model
  2. the initial topography on which computations are made
  3. the boundary conditions of the model that are divided into the landslides generation and the water discharge series.

2D morphodynamic modelling

Eros parameterization and models

Initial topography
Potters Creek catchment



DEM grid size = 32 m

Model components

- **Hydrodynamic model:**

Eros predicts the local discharge on every cell of the DEM.

- **Sediment entrainment model:**

$$\dot{e} = k_e q^{1.5} s$$

with k_e the entrainment constant, q the local discharge, s the local gradient

- **Deposition model:**

$$\dot{d} = \frac{q_s}{\xi}$$

with q_s, the sediment specific discharge and ξ transport length (ξ = 100 m).

2D morphodynamic modelling

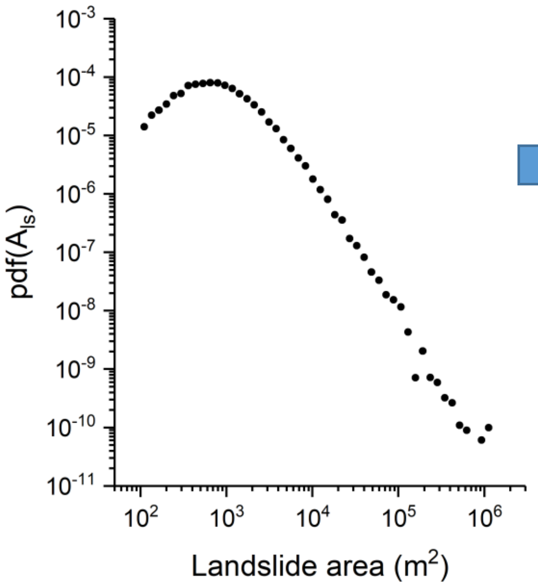
Initial topography and boundary conditions

Landslides generation

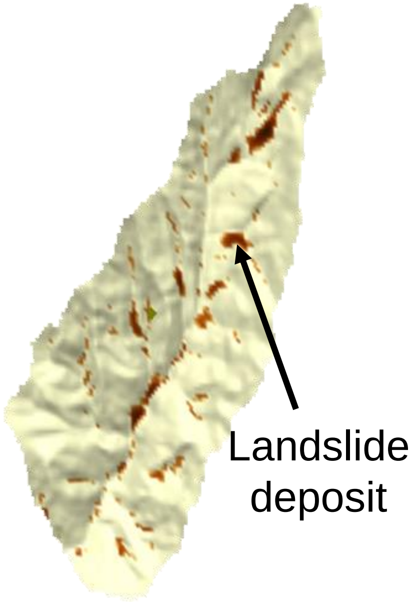
To generate landslides in the catchment we proceed as follows:

1. We set a landslide areal density (d_{ls}) that evolved between 2% and 10% of the total area of the catchment.
2. We define a pdf of landslide area ($pdf(A_{ls})$) using parameters from the literature (Hovius et al, 1997) that we randomly sample this until the sum of sampled landslide areas = d_{ls} $A_{catchment}$.
3. Landslide areas are converted to volumes with $V_{ls} = 0.01A_{ls}^{1.5}$ (Larsen et al, 2010).
4. We assign a location to each landslide of the population within the catchment by preferentially selecting DEM cells presenting the highest slopes.
5. The landslide-derived sediment is introduced in the catchment using a runout algorithm described in Lague, 2013 (AGU).

landslide density
set to 2 to 10%
+
Random sampling of pdf(A_{ls})



Landslide runout
algorithm

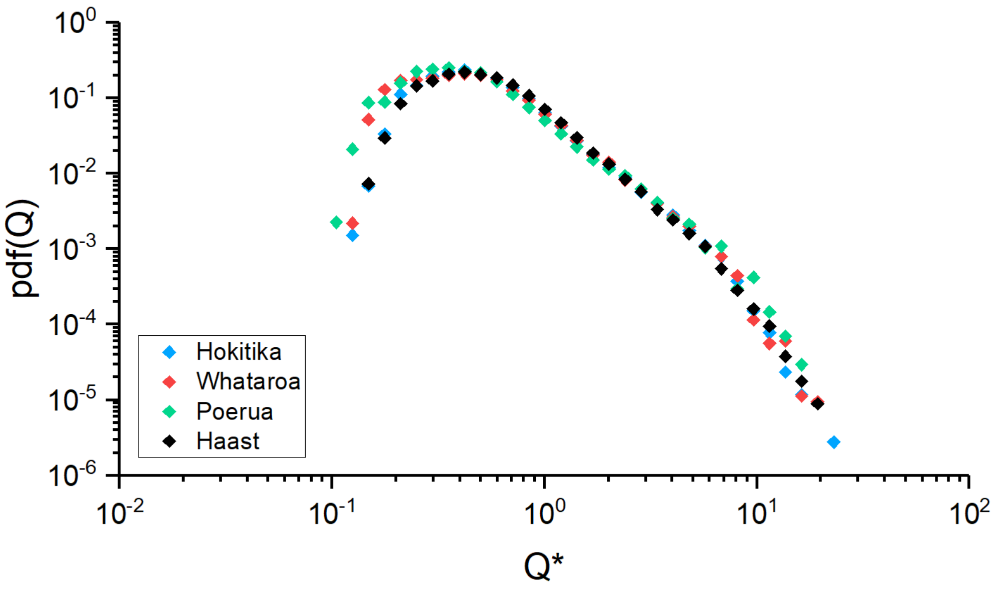


2D morphodynamic modelling

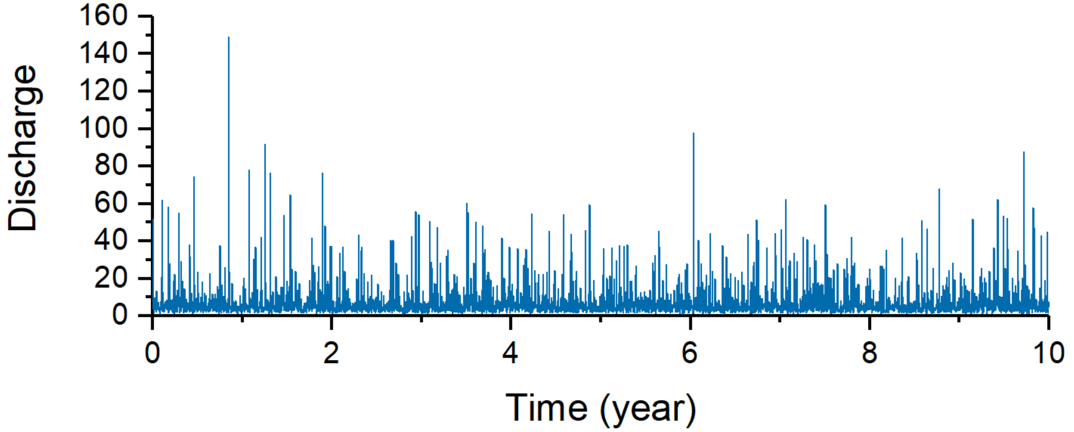
Initial topography and boundary conditions

Water discharge

In this work, we use stochastic discharge series derived from the sampling of a discharge pdf of several New Zealand rivers from the west Coast of the Southern Alps.



discharge series used in the numerical modelling

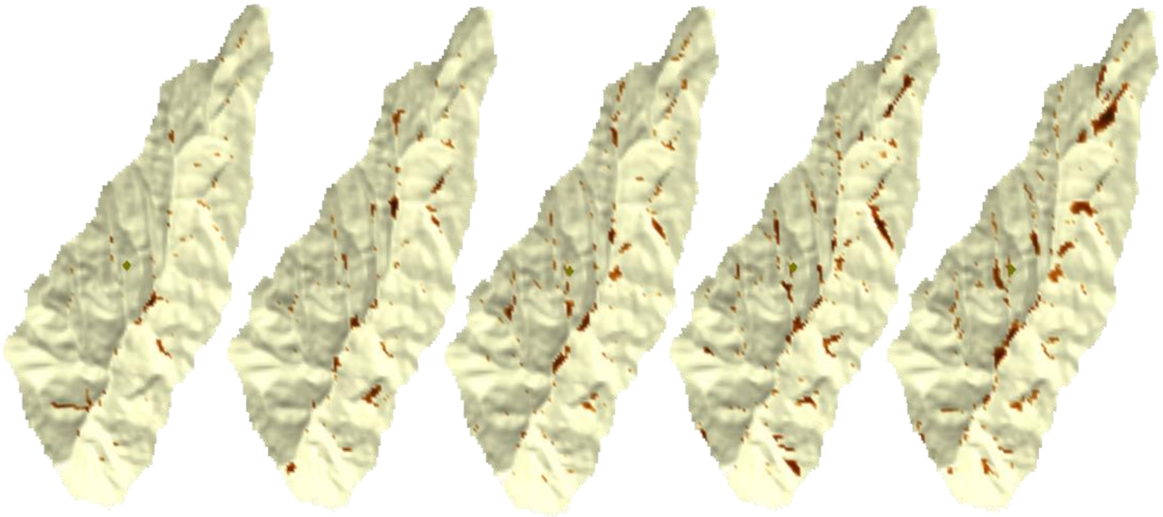


2D morphodynamic modelling

Simulation summary

In the following slides, we explore the impact of landslide density and landslide locations on the post-seismic sediment evacuation.

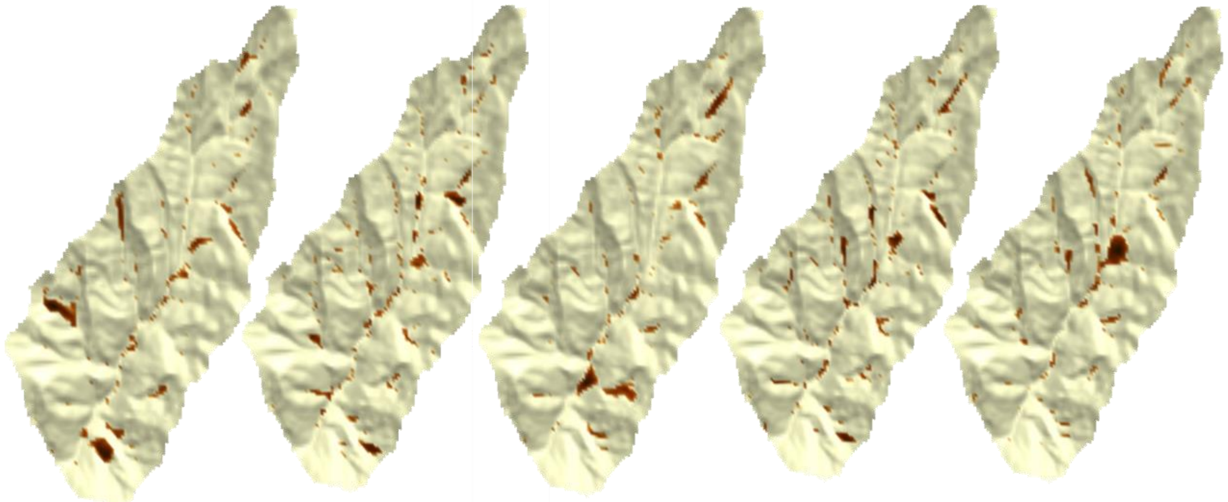
Landslide density



2% 4% 6% 8% 10%

- Landslide density ranges from 2% to 10%
- For each simulations, a landslide population is generated and introduced in the catchment
- Sediment volumes range from 0.94 to 6.9 10^6 m^3
- Landslides number ranges from 67 to 223.

Landslide locations

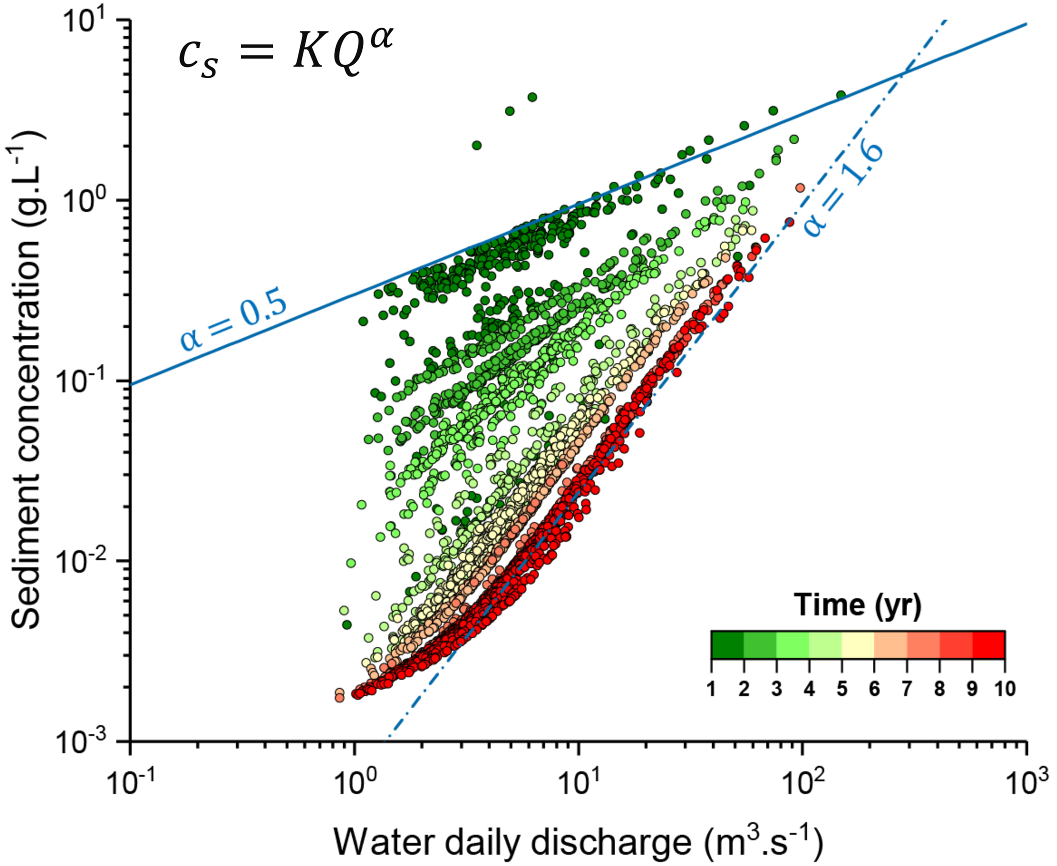


A B C D E

- Landslide density is set at 6%
- For each simulations, a landslide population is generated and introduced in the catchment
- Sediment volumes range from 2.7 to 5.2 10^6 m^3
- Landslides number ranges from 135 to 185.

Sediment concentration vs. water daily discharge

Here, we show an example (simulation d_{ls} = 4%) of the response of the sediment concentration as a function of discharge during the first 10 years following the earthquake.



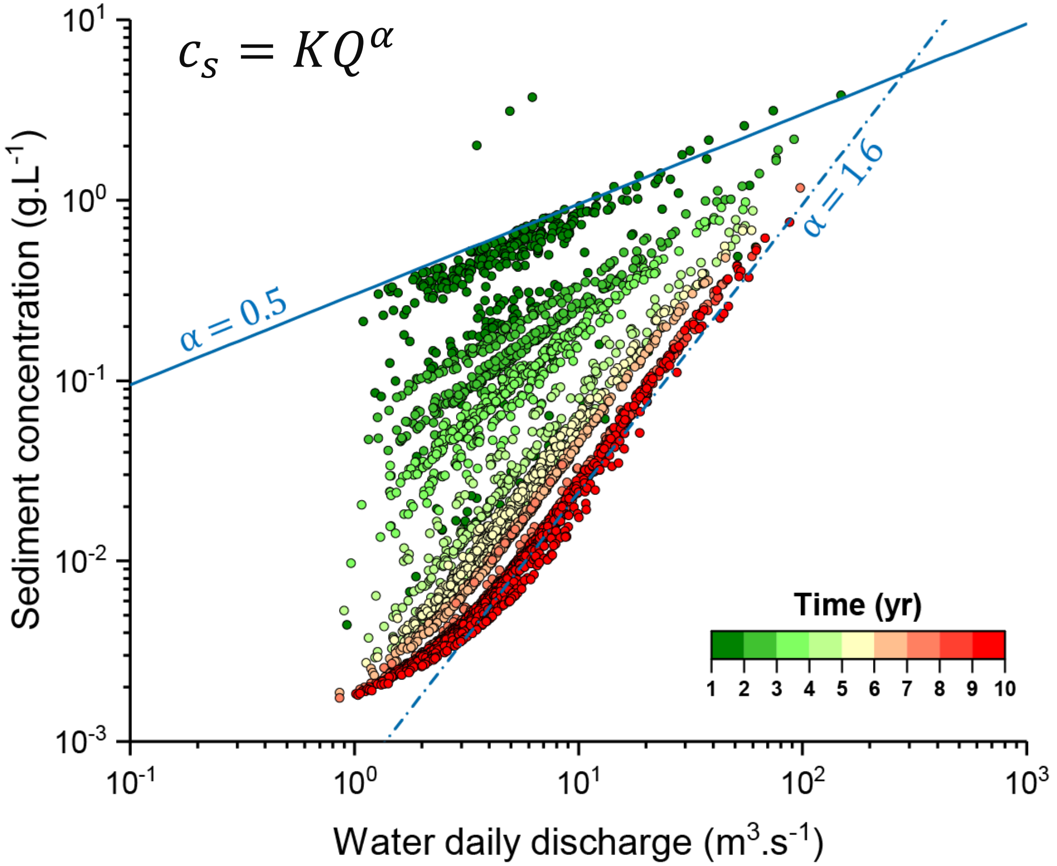
The sediment rating curve parameters evolve through time:

- From year 1 to 10: K (sediment concentration at unit discharge) **decreases** and $\boldsymbol{\alpha}$ **increases.**
- K **decreases** reflects the sediment supply exhaustion as more and more landslide deposits are being evacuated.
- $\boldsymbol{\alpha}$ **increases** is due to the fact that fluvial erosive power becomes less efficient with time.

The co-evolution of K and α has also been documented on natural cases such as after the Morakot typhoon in Taiwan (Huang and Montgomery, 2013) and after the Maule EQ in Chile (Tolorza et al, 2019).

Sediment concentration vs. water daily discharge

Here, we show an example (simulation d_{ls} = 4%) of the response of the sediment concentration as a function of discharge during the first 10 years following the earthquake.



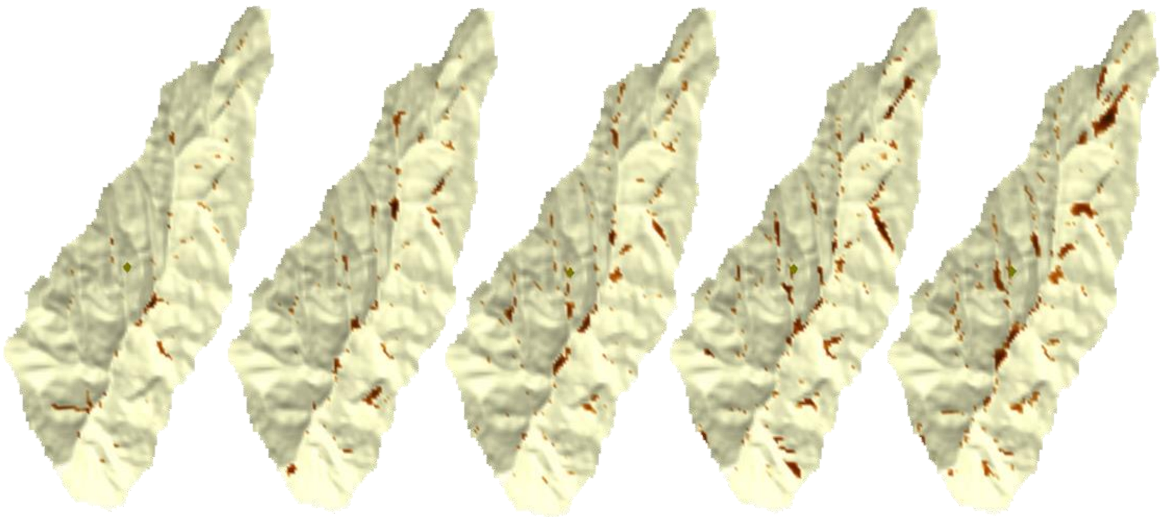
The sediment rating curve parameters evolve through time:

- During the first years, a high K and a low α ensure a higher transport efficiency of the low water discharge events
- However, the six highest discharge events are responsible for the export of ~45/50% of the total sediment volume during year 1.
- α = 1.6 is also the scaling of c_s-Q relationship of West Coast rivers when they are not disturbed by intense mass wasting.

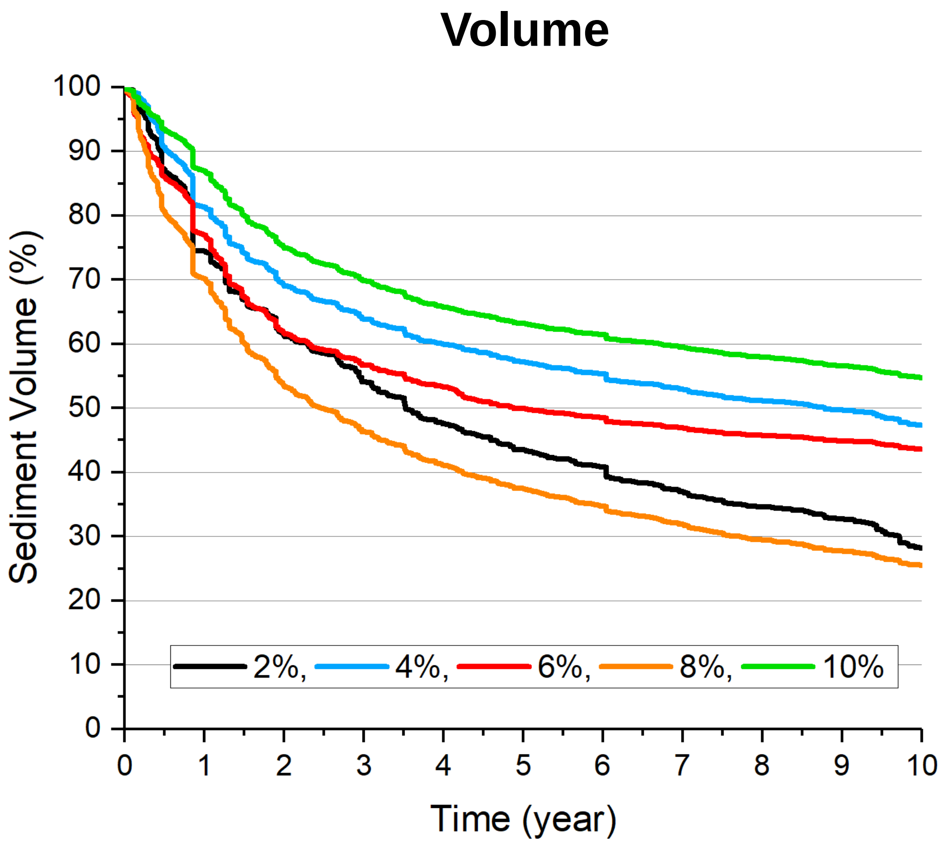
This response of the sediment concentration through time is observed systematically on all the simulations.

Impact of landslide density – d_{ls} ranges from 2 to 10%

Model initial setup for the different landslide density values explored



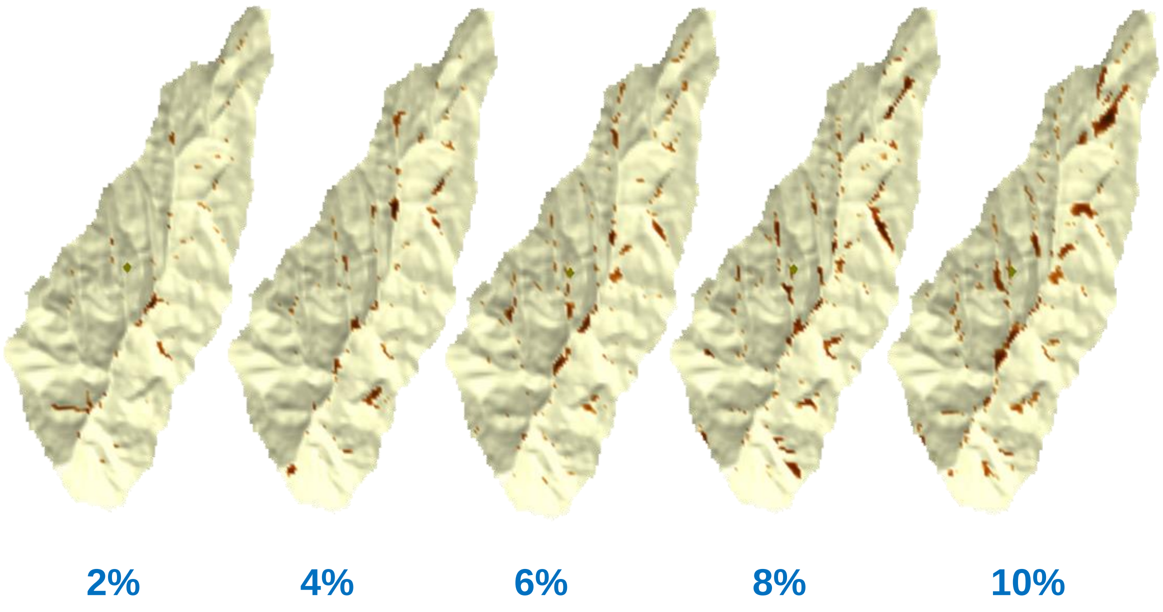
2% **4%** **6%** **8%** **10%**

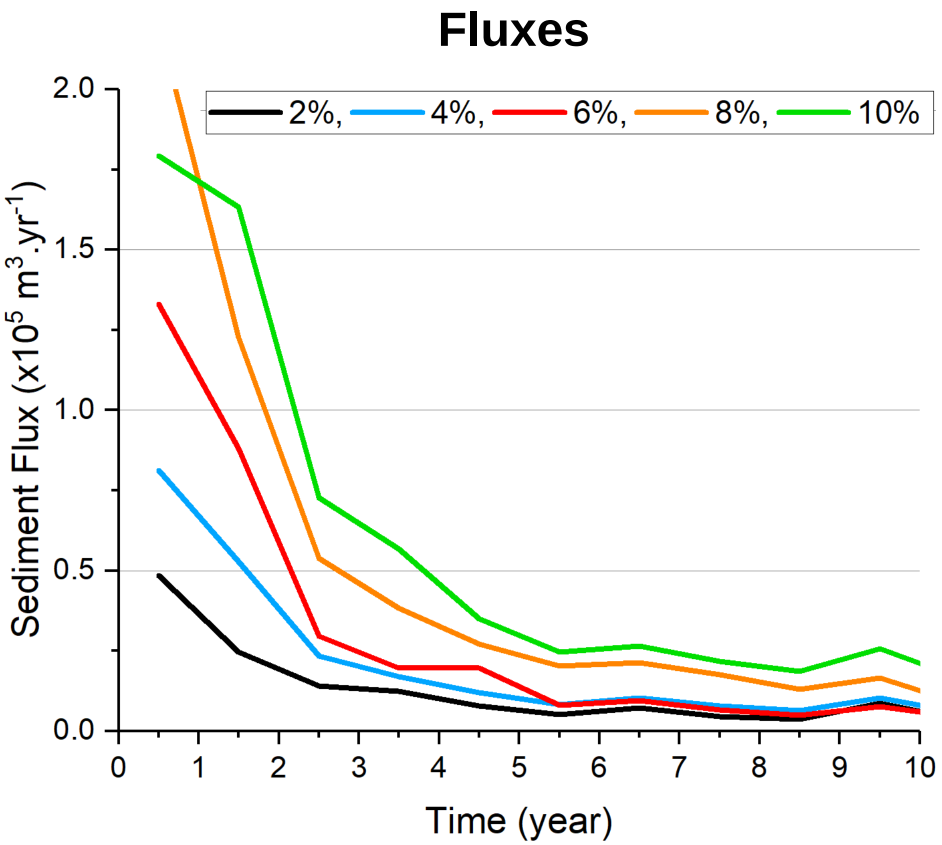


- **Year 1 to 5:** The total volume of the landslide population decreases fast with 40 to 65% of the deposits being transported out of the catchment.
- **Year 5 to 10:** the sediment evacuation slows down with only 5 to 10% of sediment evacuation.

Impact of landslide density – d_{ls} ranges from 2 to 10%

Model initial setup for the different landslide density values explored

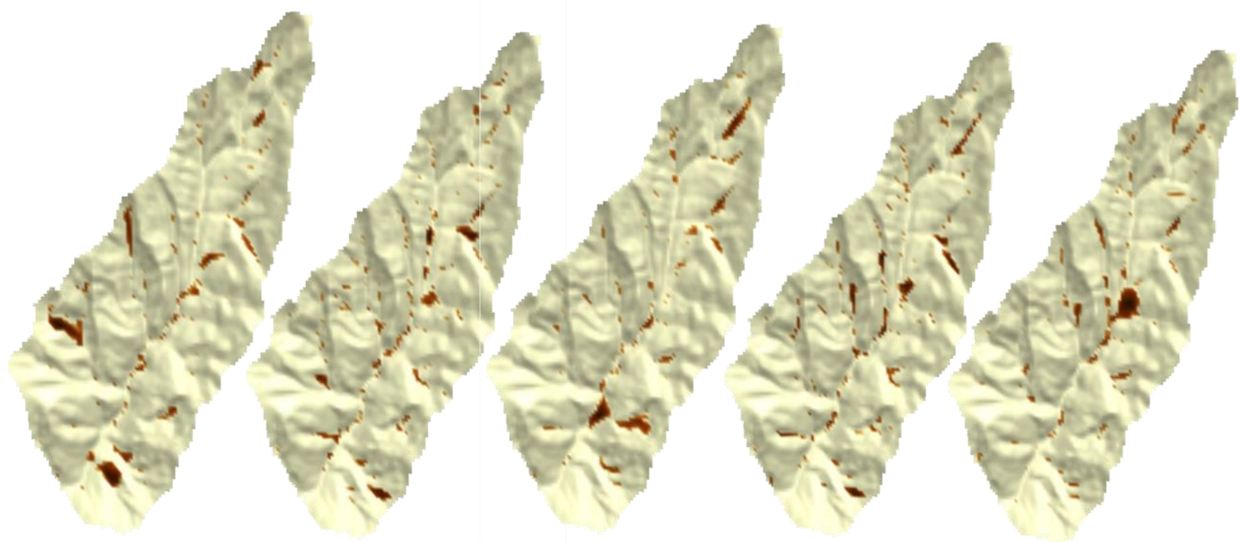




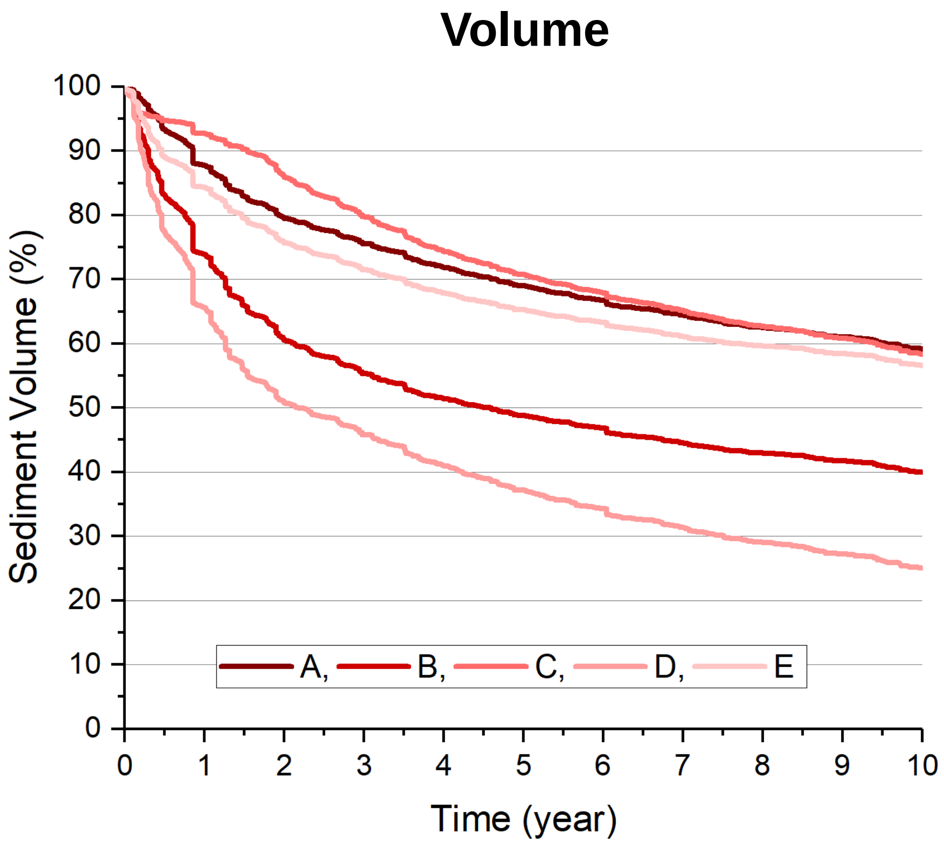
- **Year 1 to 5:** high sediment fluxes due to a fast sediment evacuation until they decrease to a more stable value during **year 5 to 10**.
- Landslide density controls the fluxes peak amplitude but not the period of time during which the fluxes are larger.

Impact of landslide locations

Model initial setup for the different landslide locations explored



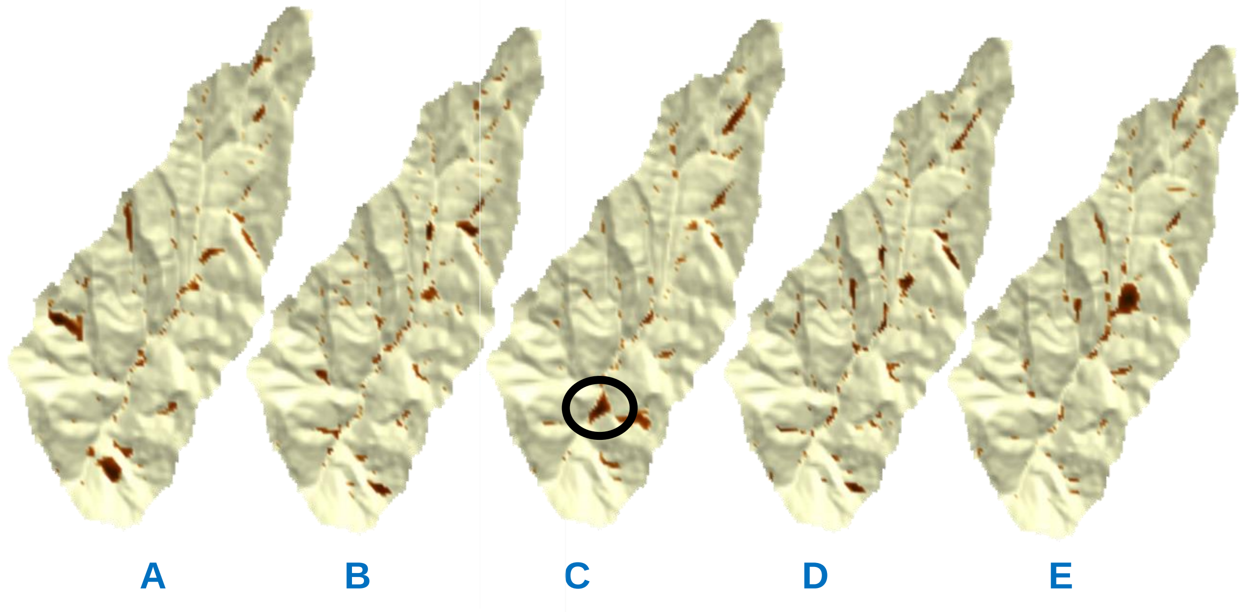
A B C D E

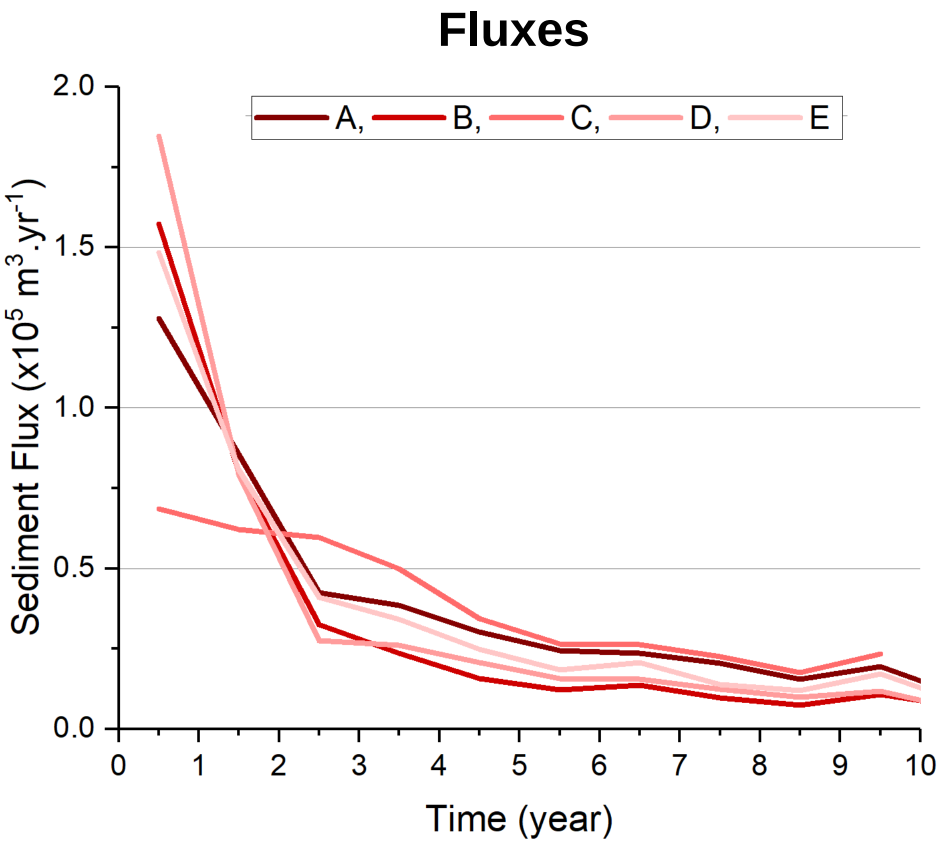


- The volume evolution share the same characteristics that previous simulations.
- However, three simulations (A,C,E) are less efficient to export sediment during the five first years.

Impact of landslide locations

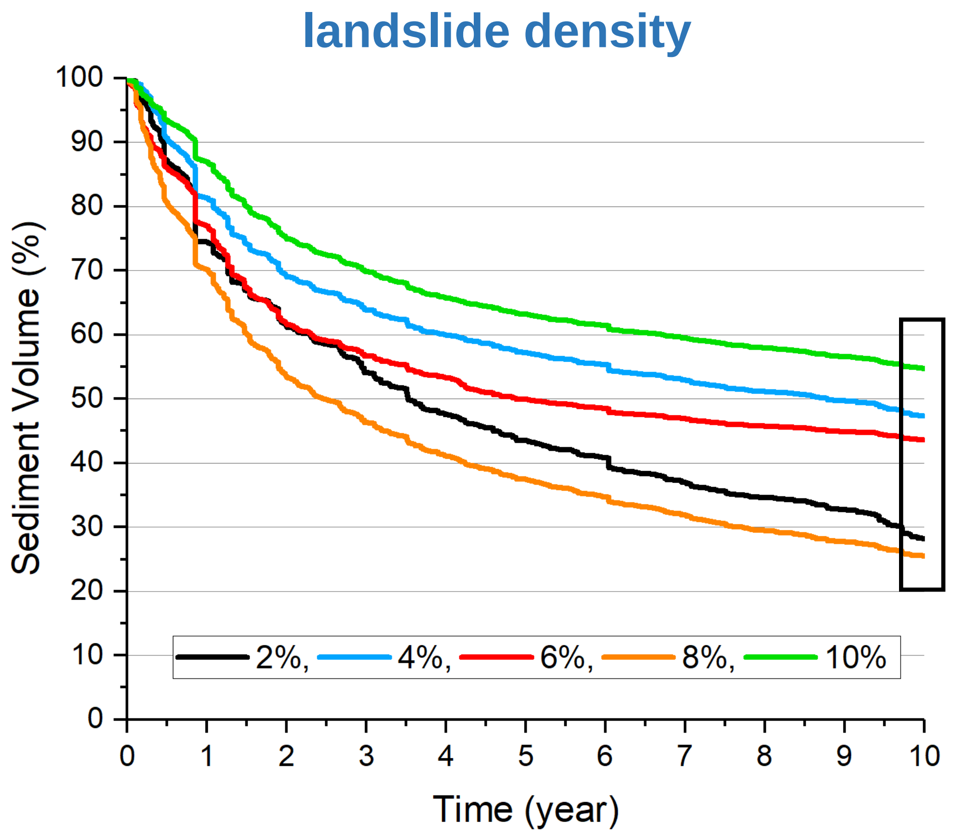
Model initial setup for the different landslide locations explored

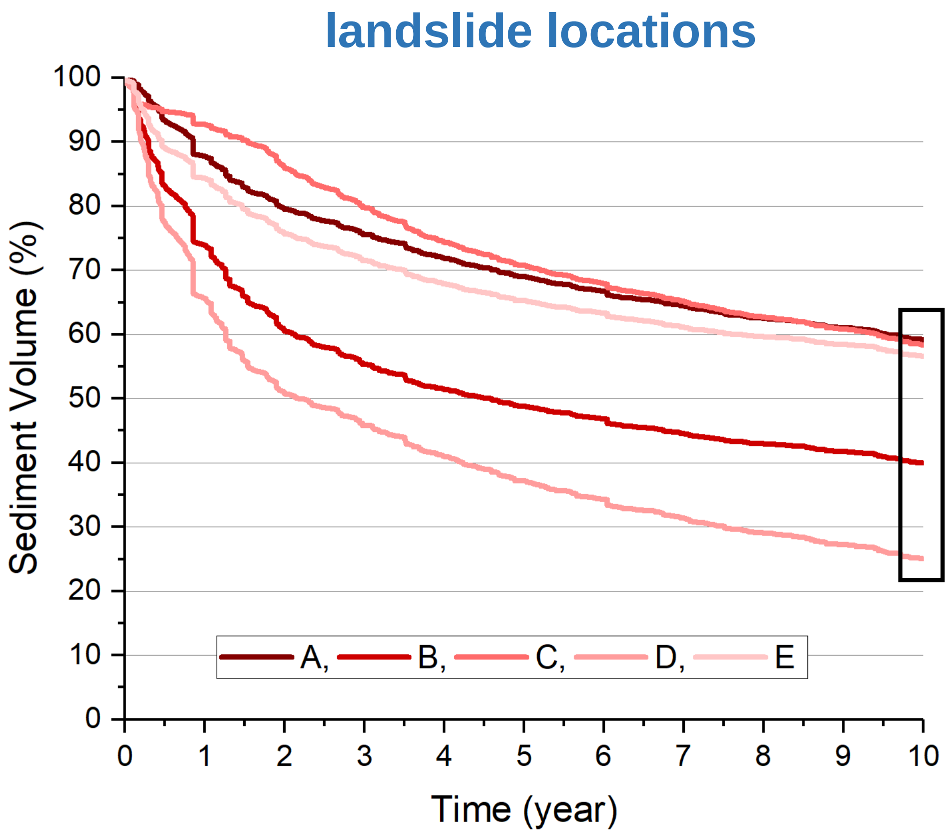




- All the simulations show the same decrease of sediment fluxes during the 5 first years but one (C) which presents lower sediment fluxes due to a landslide dam formation trapping most of the sediment coming from upstream.
- Landslide locations have an impact on the amplitude of peak fluxes.

Sediment storage

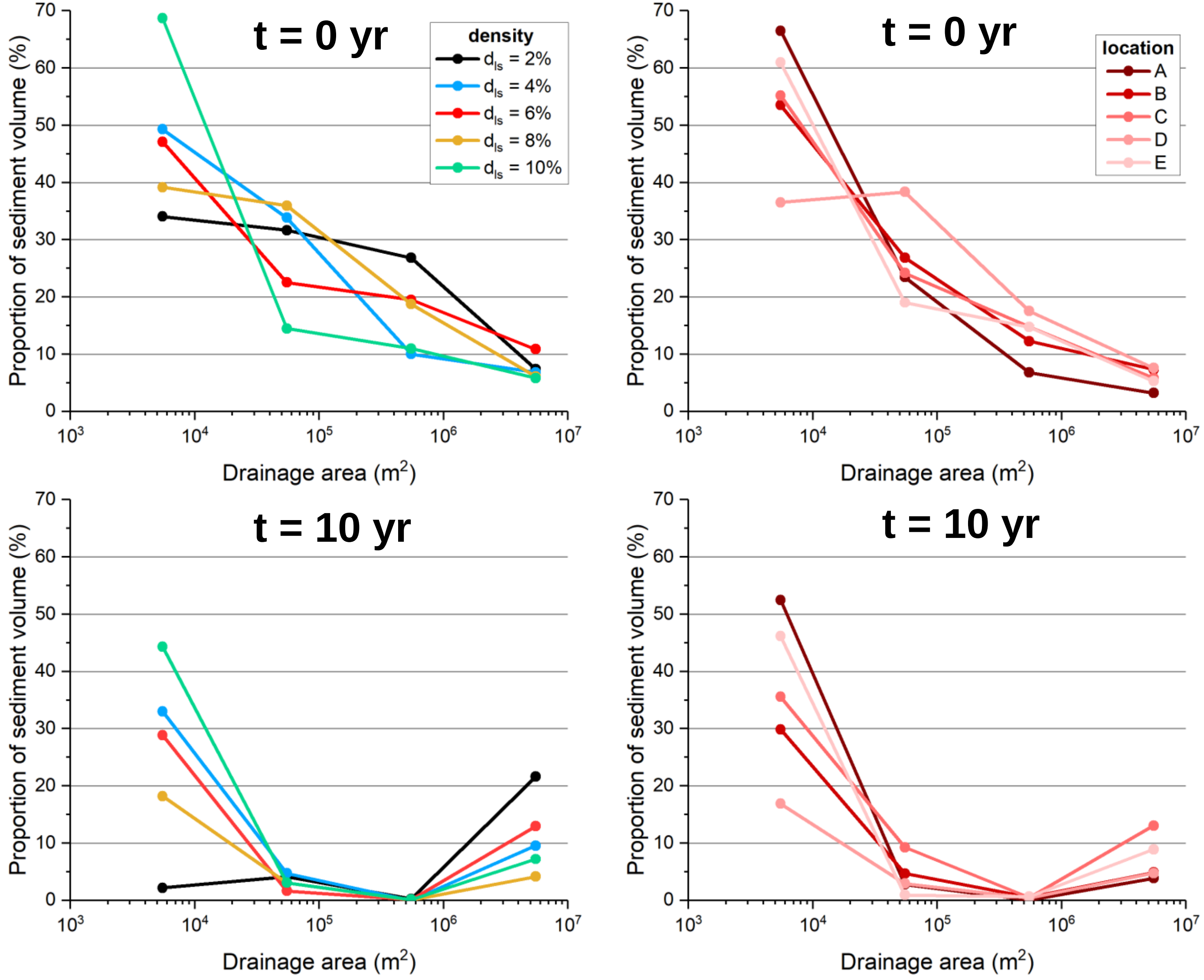




- All the simulations show that 10 years after the mass-wasting event, a large amount of sediment is stored within the catchment ranging from 25% to 60% of the initial volume of fine material mobilized by landslides.
- This proportion of sediment storage is not function of landslide density but is controlled by landslide locations (see after).

Sediment storage

landslide density | **landslide locations**



- At the initial stage, all the simulations present a higher proportion of sediment stored in low drainage areas.
- Simulations where the amount of sediment present in drainage areas < 10^4 m^2 is the lowest (2%, 8%, D and B) are the ones storing less sediment after 10 years.
- This proportion of sediment storage is not a function of landslide density but emerges from landslide locations.
- After 10 years, the sediment present in drainage areas > 10^4 m^2 and < 10^6 m^2 is mostly exhausted.
- Sediment storage is prominent in low drainage areas where sediment entrainment rates are the lowest and therefore where sediment transport is less efficient.
- Some sediment is also trapped upstream of landslide dams

Conclusions

- Use of a morphodynamic approach with a fully stochastic forcing on the discharge series and sediment production by mass wasting at the catchment scale and on short timescales (10 years).

- The model reproduces several features observed on natural cases:
  - Co-evolution of the c_s-Q relationship parameters (Huang and Montgomery, 2013; Tolorza et al, 2019)
  - Enhancement of the sediment fluxes during the first 5 years following the earthquakes (Hovius et al, 2011, Wang et al, 2015).
  - Important storage of landslide deposits on hillslopes at initial state (Dadson et al, 2004).

- The sediment evacuation dynamics and particularly the period of time in which the fluvial network is the most efficient to export fine sediment is controlled by the sediment supply located at the vicinity of channelized flow.

- Our simulations predicts residence times of a large proportion of the fine material > 10 years controlled by a large amount of sediment stocked on hillslopes. Questions remain about the fate of the stored sediments and the processes capable of exporting them out of the catchment (large storms, debris flows, …?).

- Future work: comparison of model output with lake Mapourika sedimentary records.