Temporal erosion and sediment transport model for predicting water clarity in rivers

RA 1.3 - Modelling

John Dymond, Arman Haddadchi, Alex Herzig

Manaaki Whenua
Landcare Research

Overview

- Background
- Concept
- Erosion Model
  - Implementation
  - Calibration
- Sediment Transport Model
- Conclusion & Outlook

Background

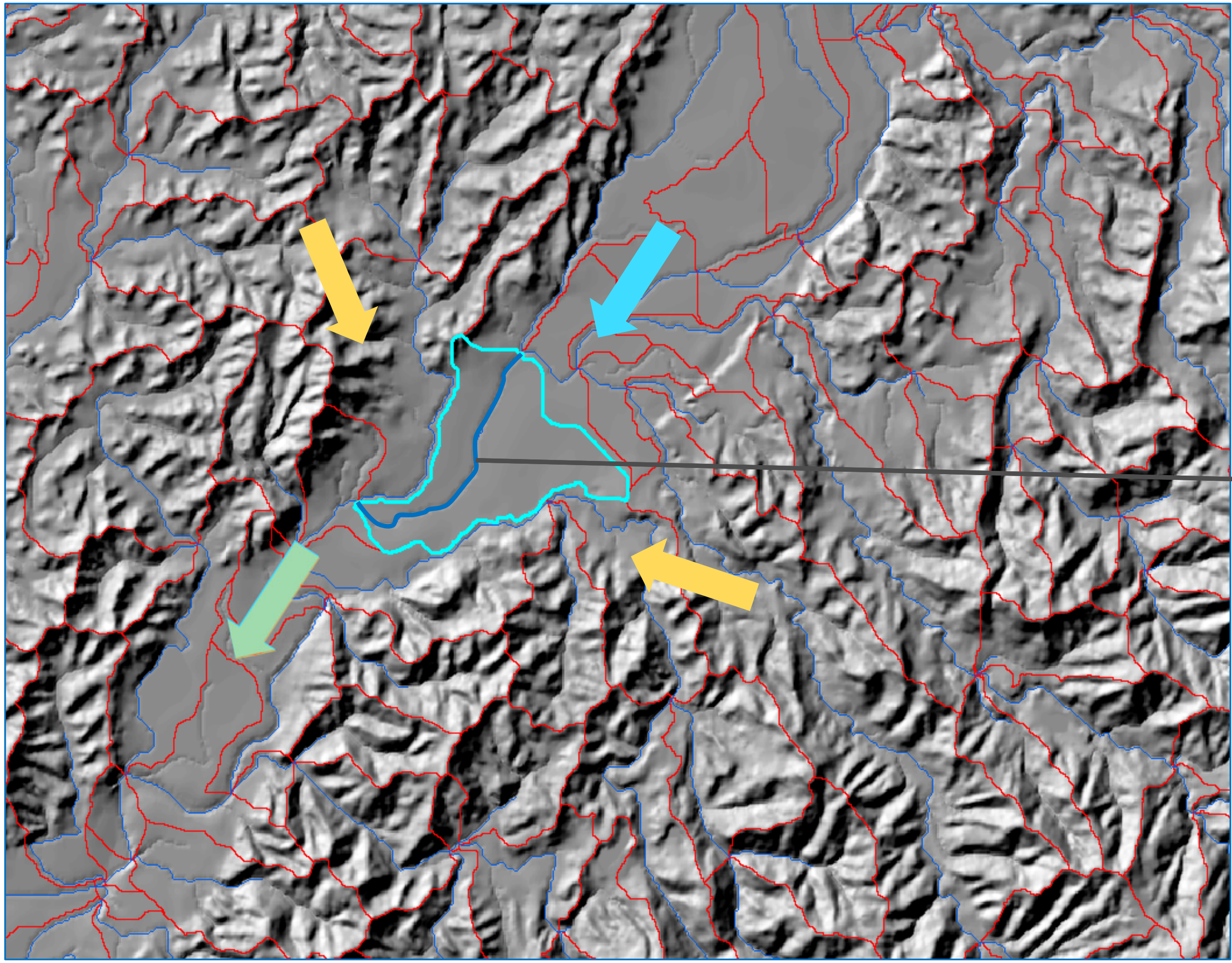
Motivation

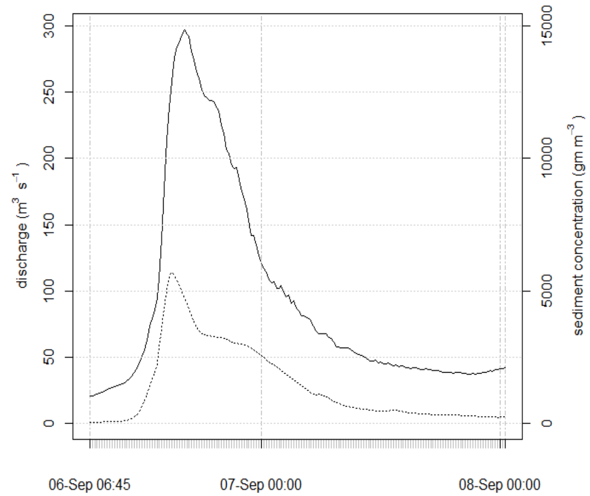
Sediment quantity and quality affects ecological integrity of rivers.

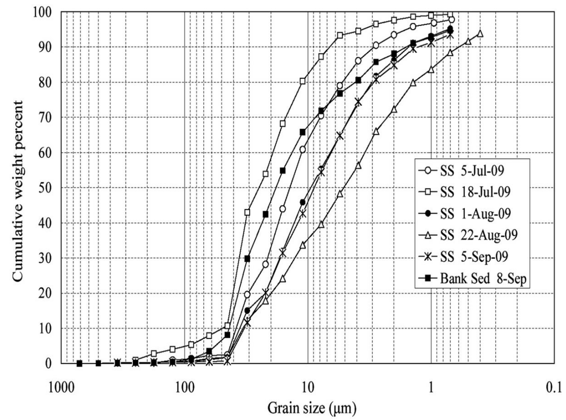
Objective

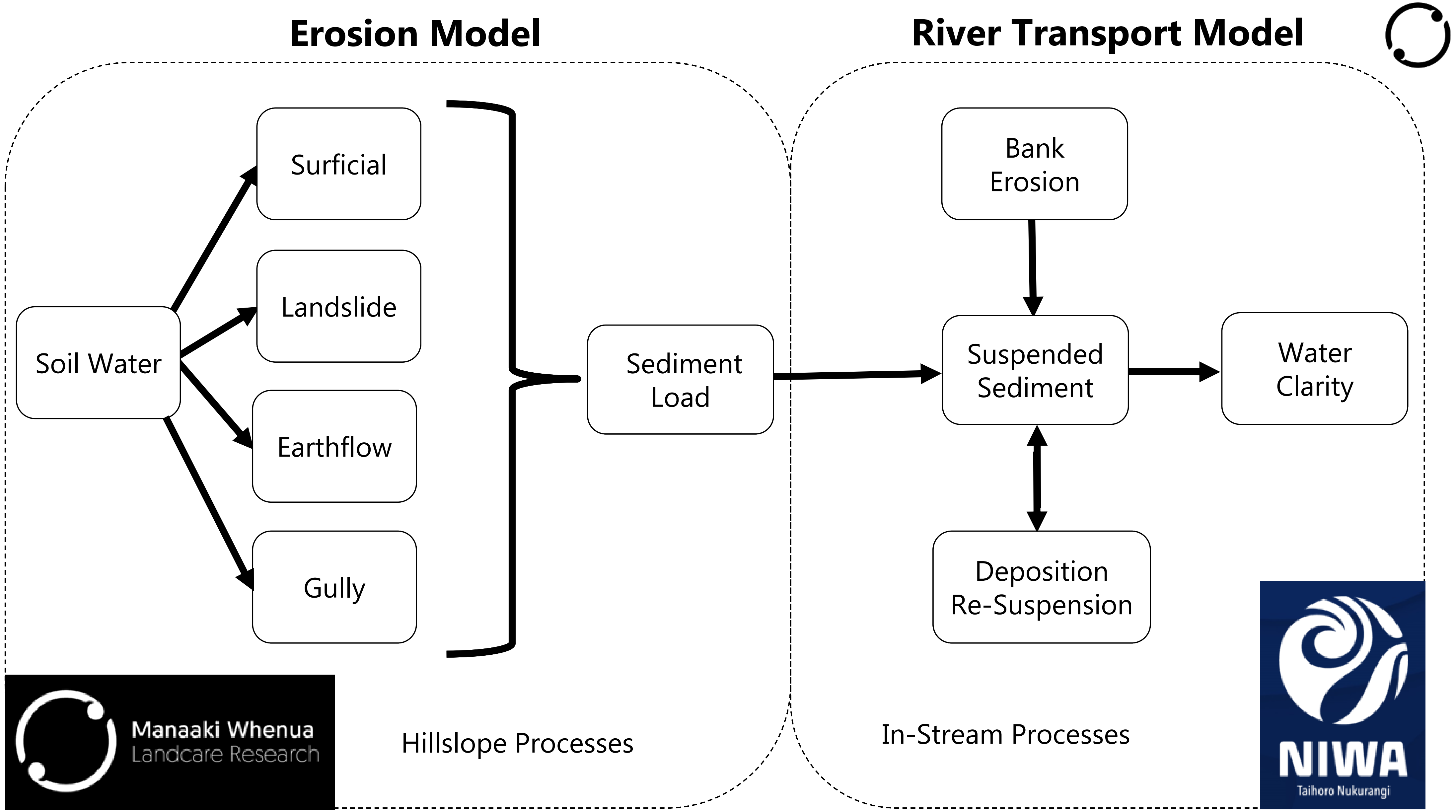
Predict sediment concentration in rivers at low flow.

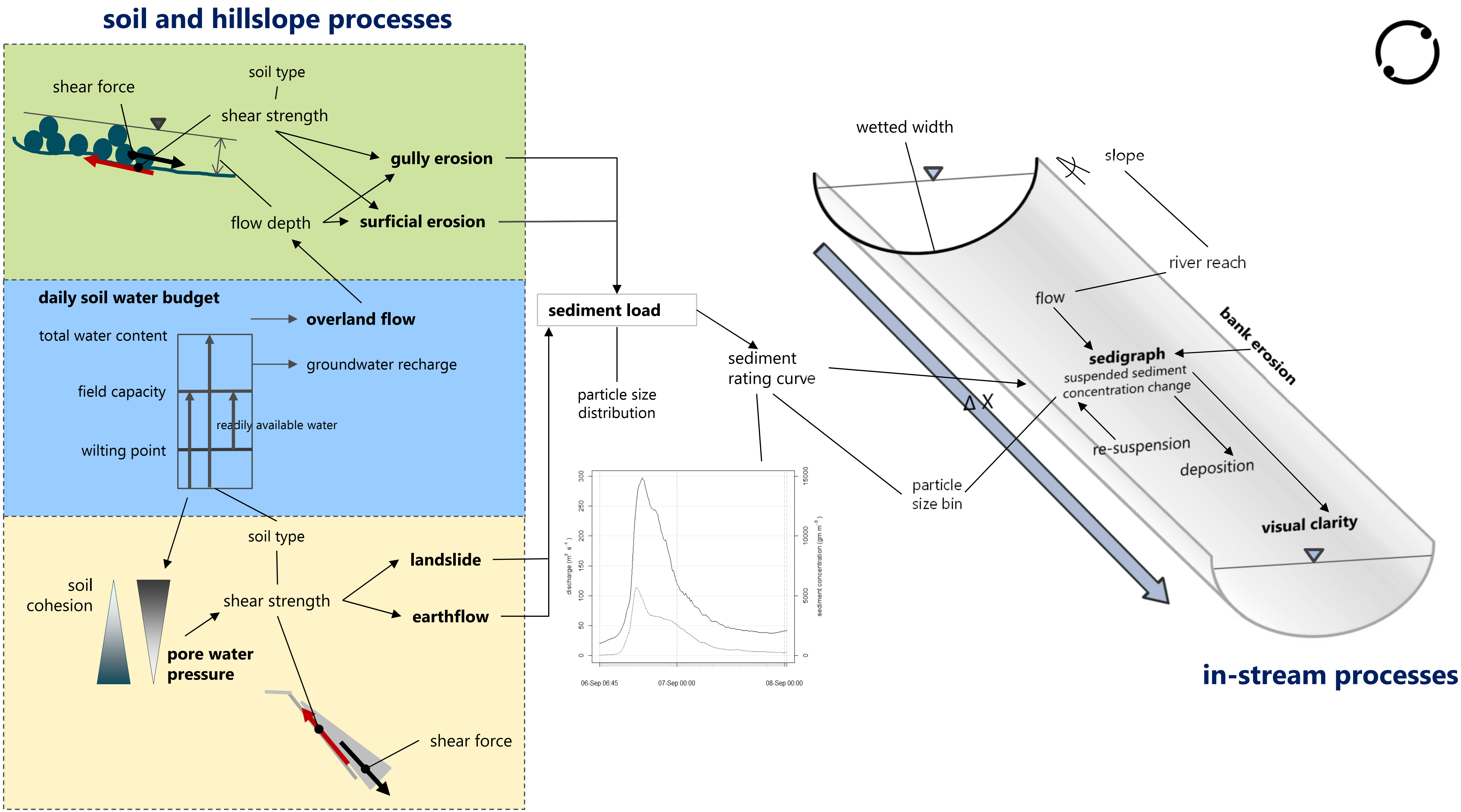
Concept




discharge (m^3 s^-1)
0
50
100
150
200
250
300
sediment concentration (gm m^-3)
0
5000
10000
15000
06-Sep 06:45
07-Sep 00:00
08-Sep 00:00


Cumulative weight percent
0
10
20
30
40
50
60
70
80
90
100
1000
100
10
1
0.1
Grain size (µm)
SS 5-Jul-09
SS 18-Jul-09
SS 1-Aug-09
SS 22-Aug-09
SS 5-Sep-09
Bank Sed 8-Sep


Erosion Model
River Transport Model
Surficial
Landslide
Soil Water
Earthflow
Gully
Sediment Load
Bank Erosion
Suspended Sediment
Water Clarity
Deposition Re-Suspension
Manaaki Whenua Landcare Research
Hillslope Processes
In-Stream Processes
NIWA
Taihoro Nukurangi


soil and hillslope processes
shear force
soil type
shear strength
gully erosion
flow depth
surficial erosion
daily soil water budget
overland flow
total water content
groundwater recharge
field capacity
readily available water
wilting point
soil type
soil cohesion
shear strength
landslide
earthflow
pore water pressure
shear force
sediment load
particle size distribution
sediment rating curve
06-Sep 06:45
07-Sep 00:00
08-Sep 00:00
wetted width
slope
river reach
flow
bank erosion
sedigraph
suspended sediment concentration change
ΔX
re-suspension
deposition
particle size bin
visual clarity
in-stream processes

Implementation

- low-code
- interoperable
- high performance

LUMASS modelling & optimisation

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An Interoperable Low-Code Modelling Framework for Integrated Spatial Modelling

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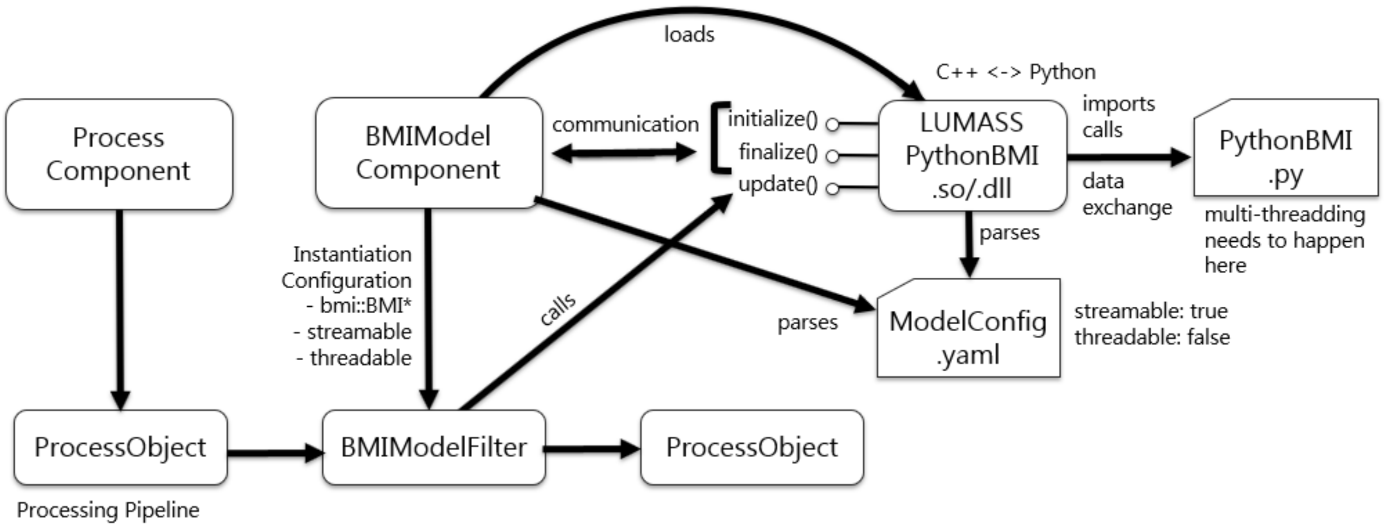
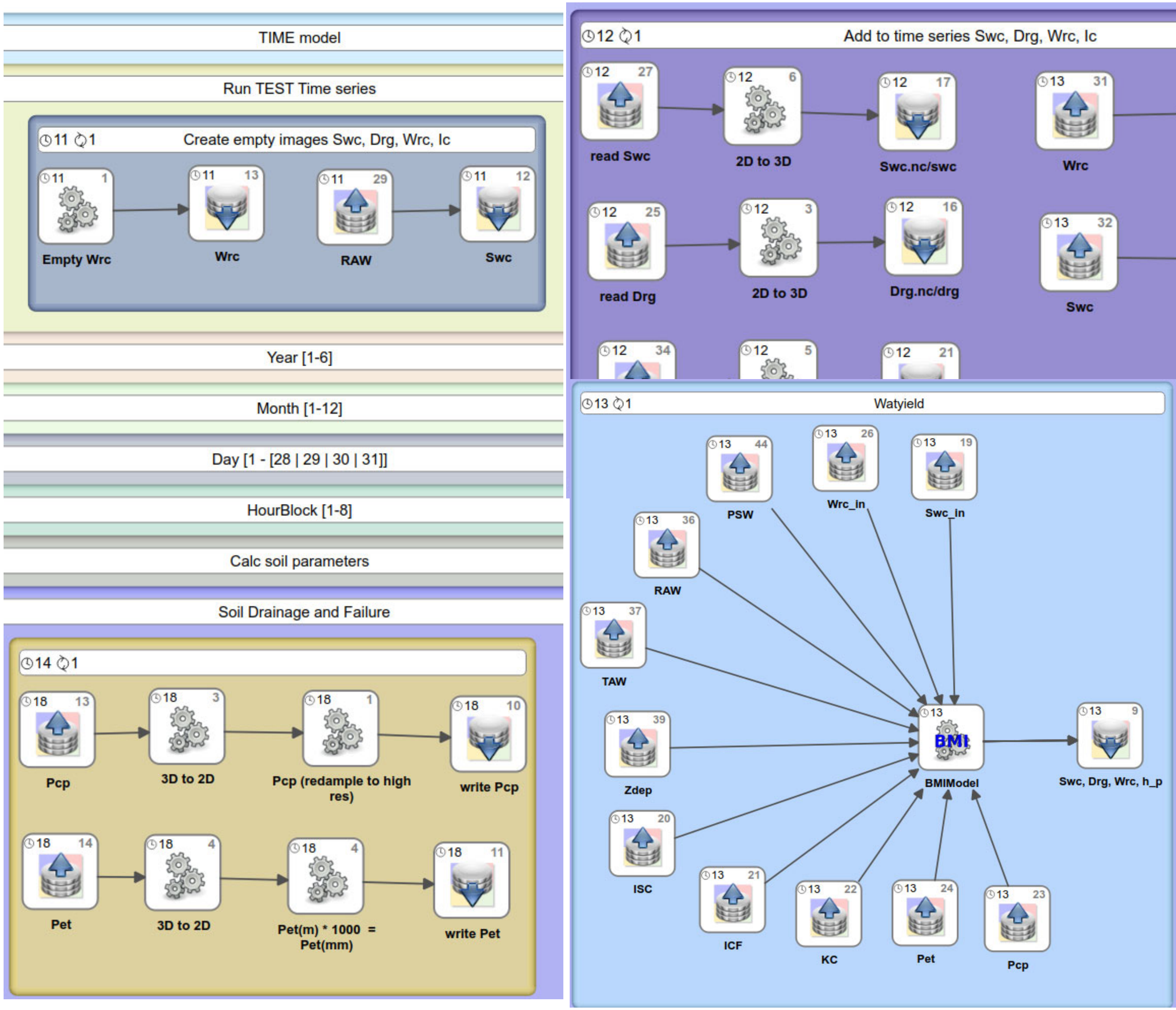
An Interoperable Low-Code Modelling Framework for Integrated Spatial Modelling



Soil Processes

sequential processing

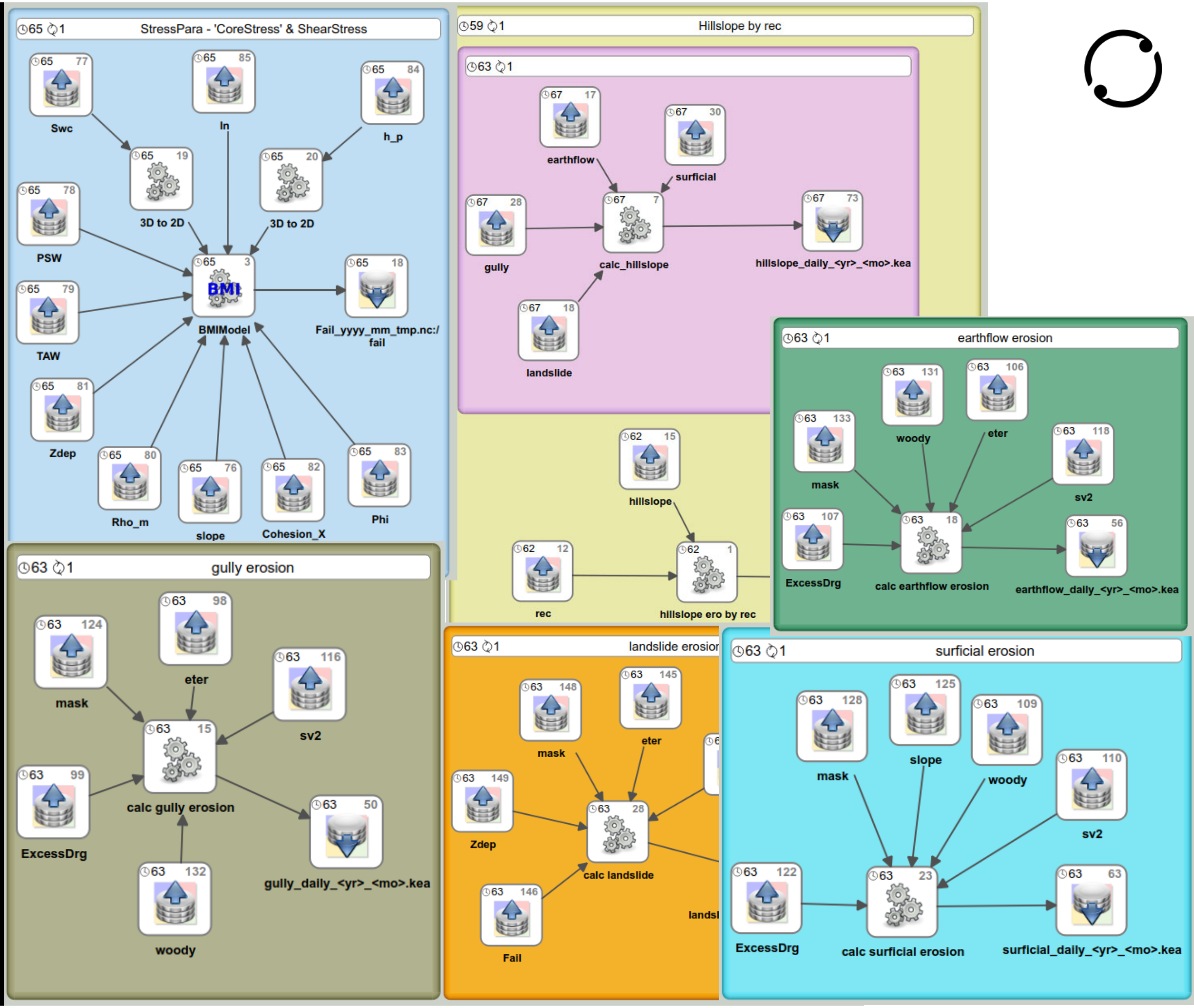
- extract rainfall input
- calc soil water budget
- calc depth of saturated water in soil profile



Erosion Processes

parallel processing

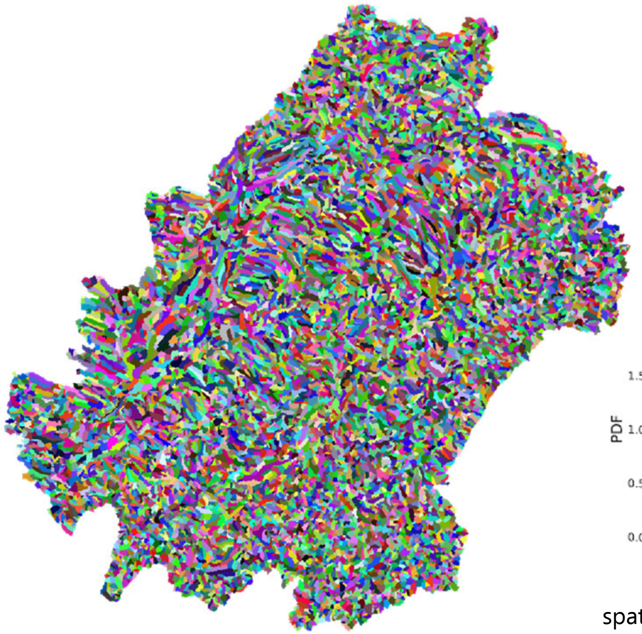
- calc soil stress
- calc erosion by process
- summarise by REC



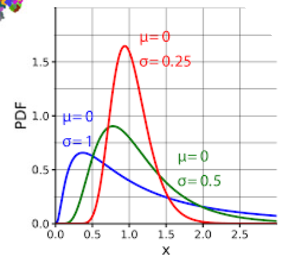
Calibration

SedNetNZ = $\sum_{1}^{REC} \sum_{1}^{t\_steps} (\ldots$

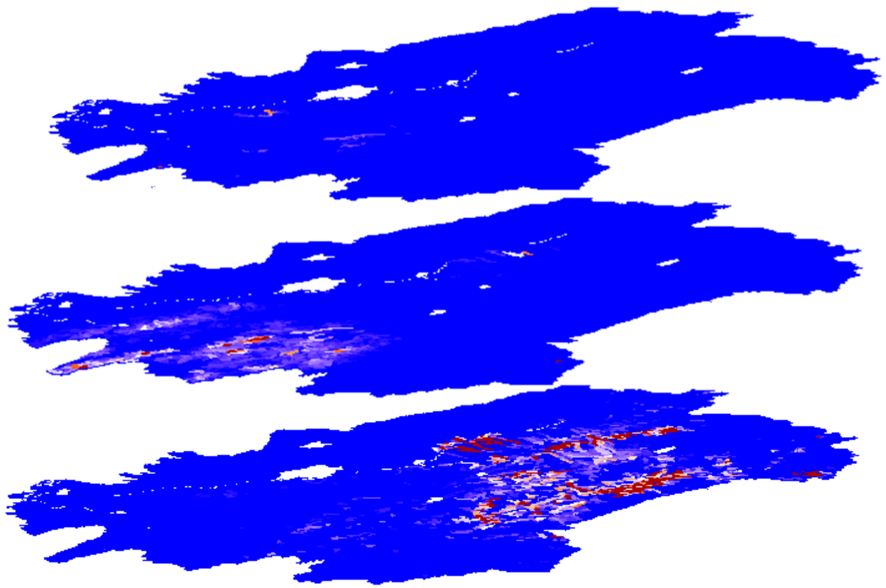
… landslide(cohesion) + surficial(k(shear stress)) + earthflow(speed) + gully(density) …



REC catchments: n=13232

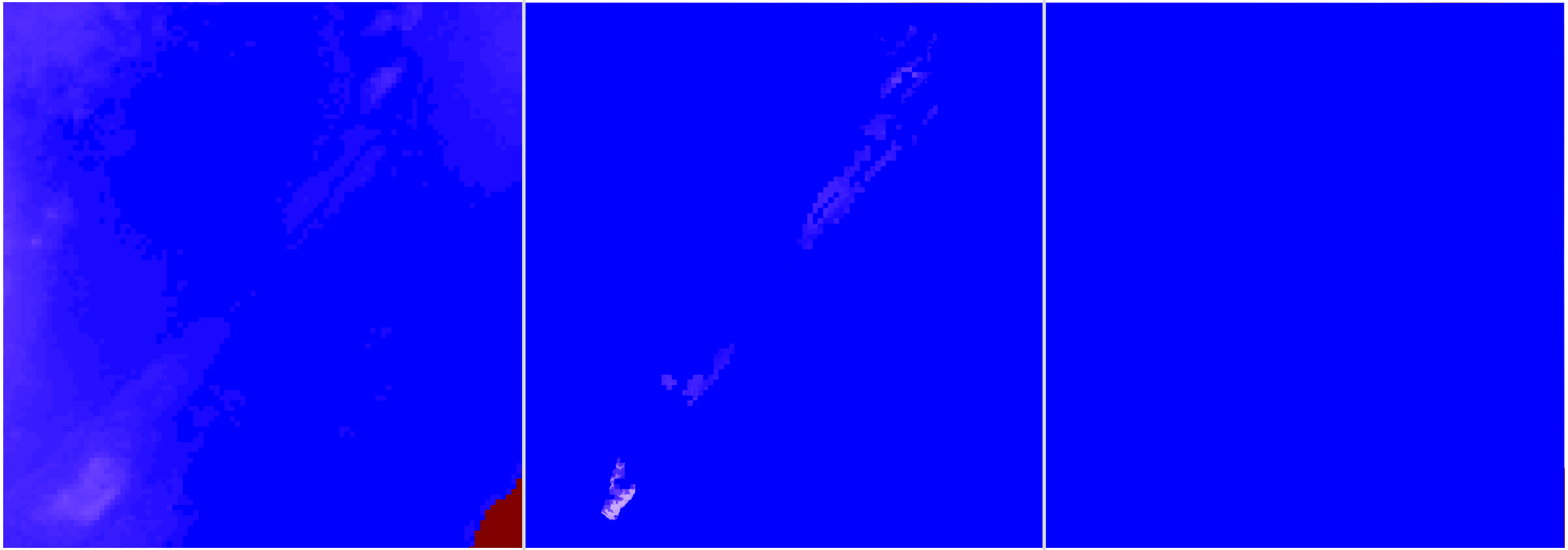


log-normal
spatiotemporal stochasticity



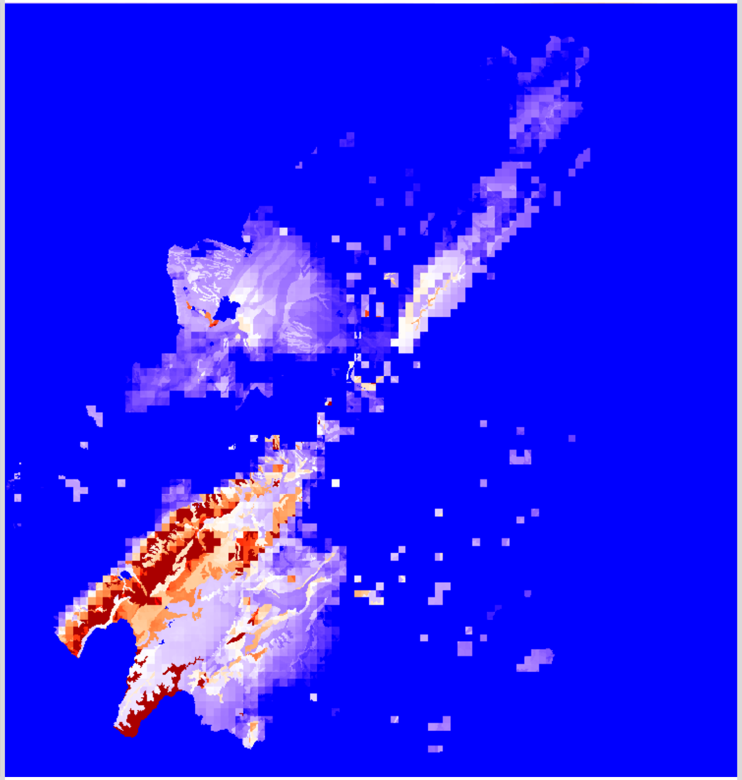
Time steps per year: m=2922

…)

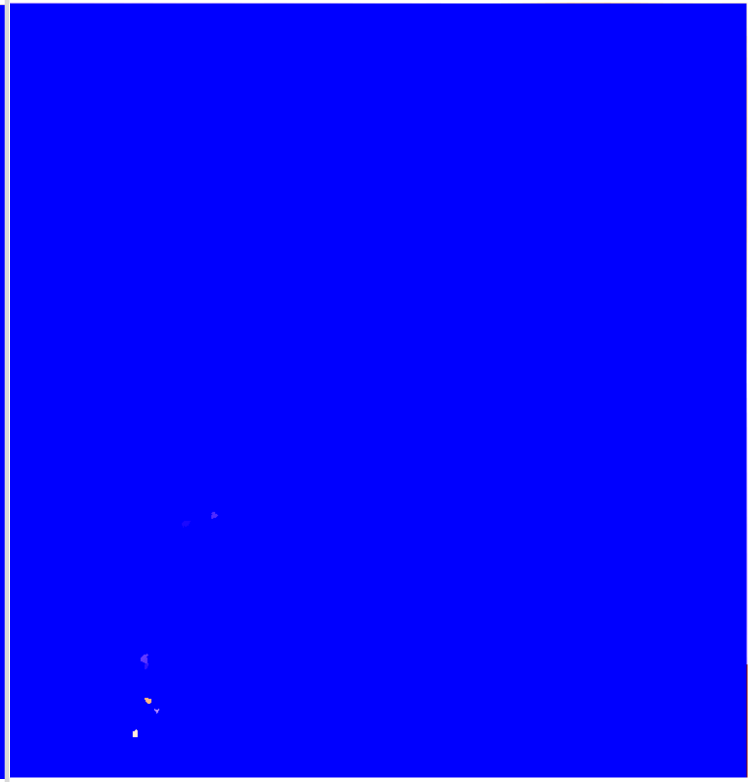


precipitation soil saturation erosion

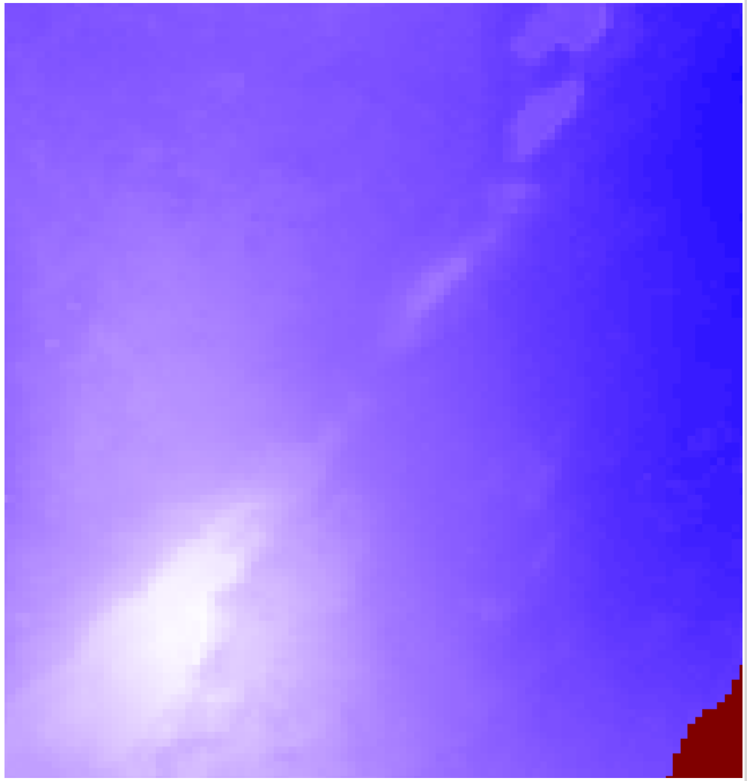
precipitation



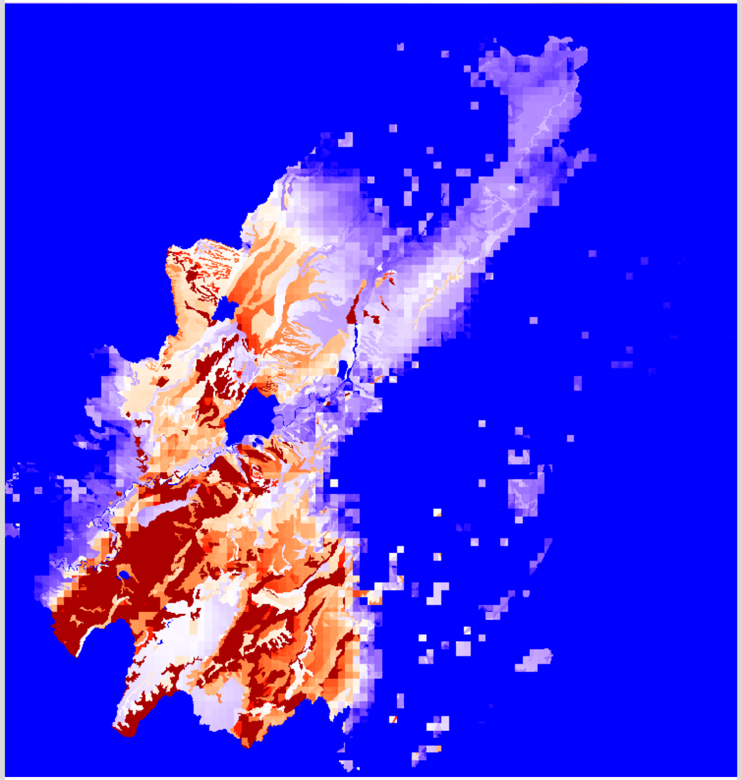
soil saturation



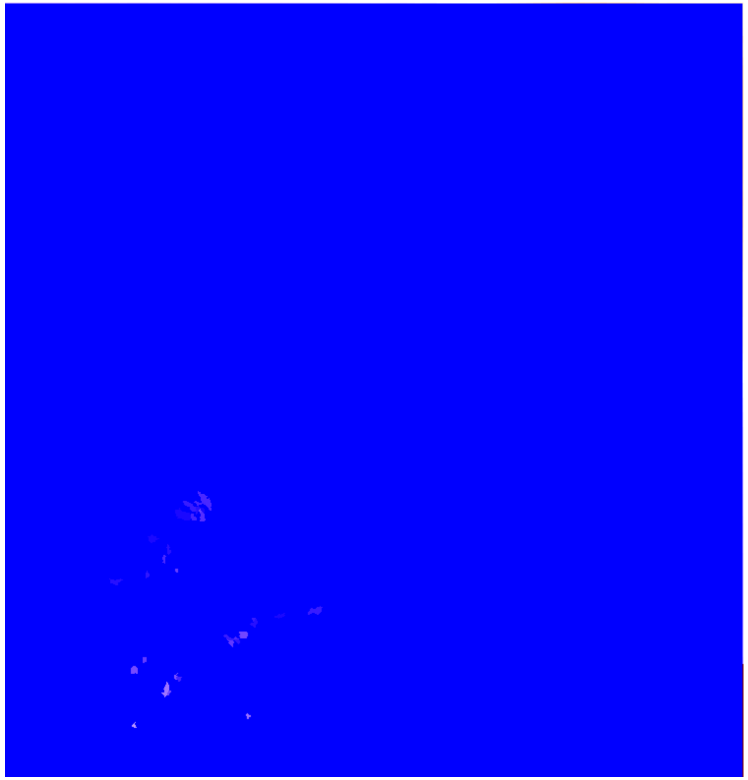
erosion



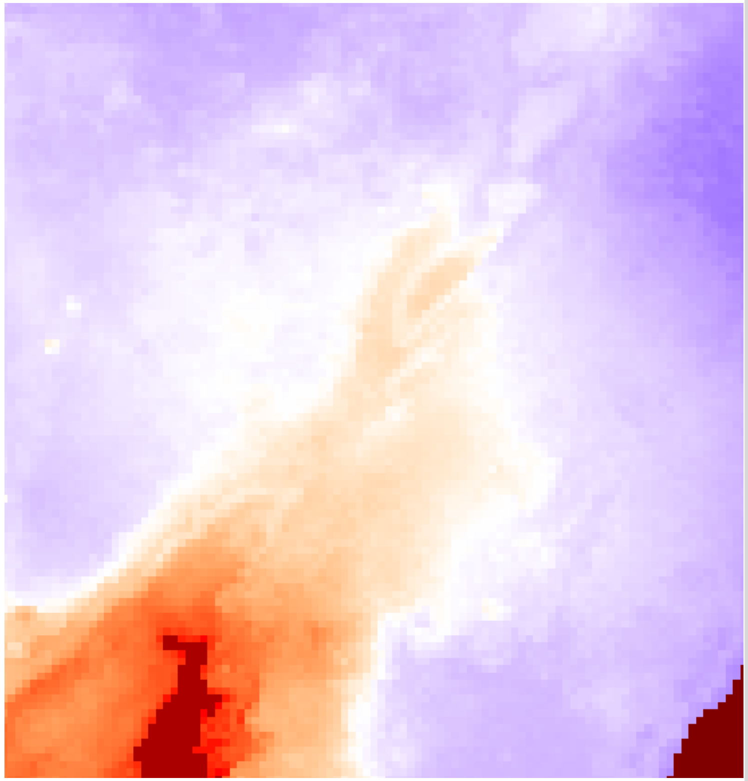
precipitation



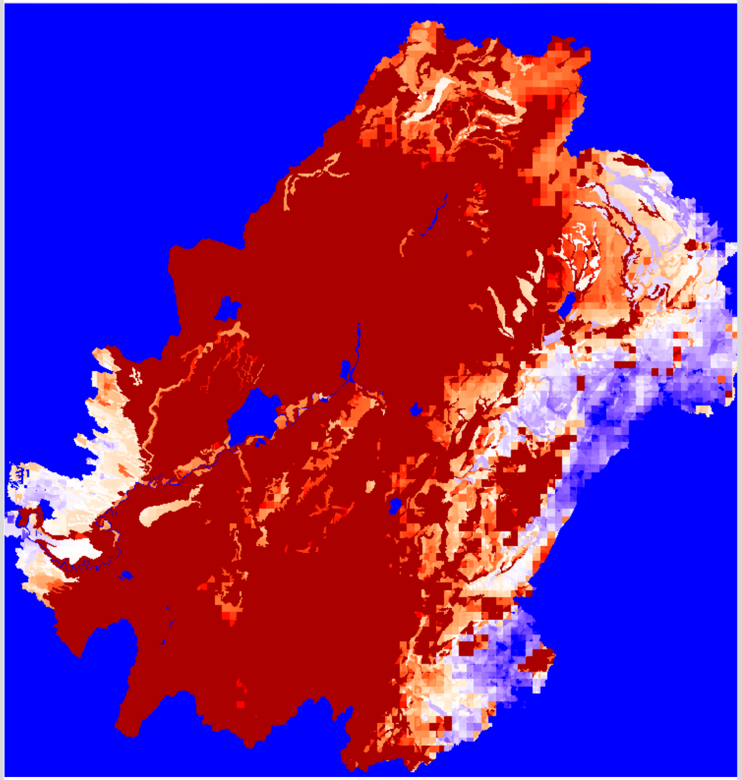
soil saturation



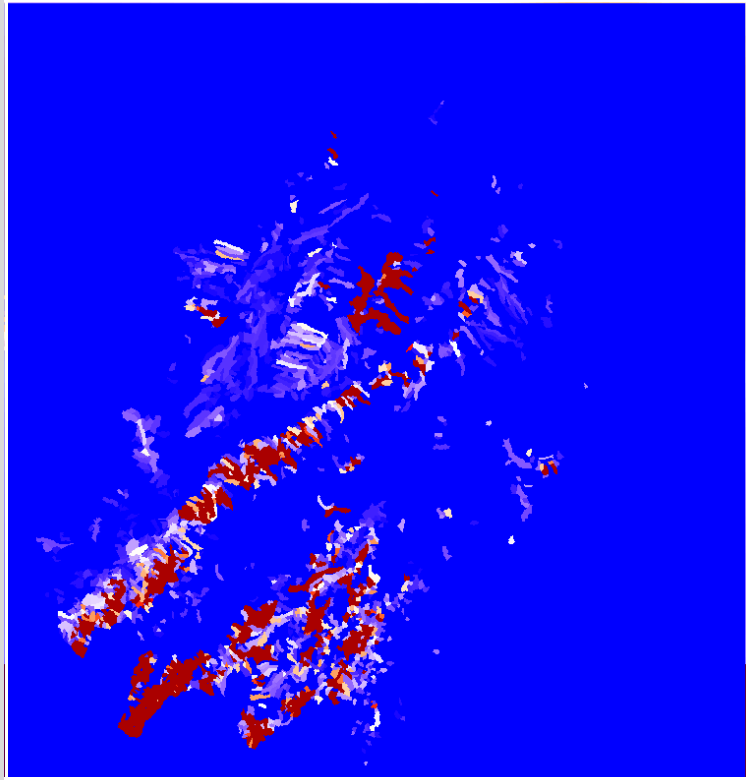
erosion



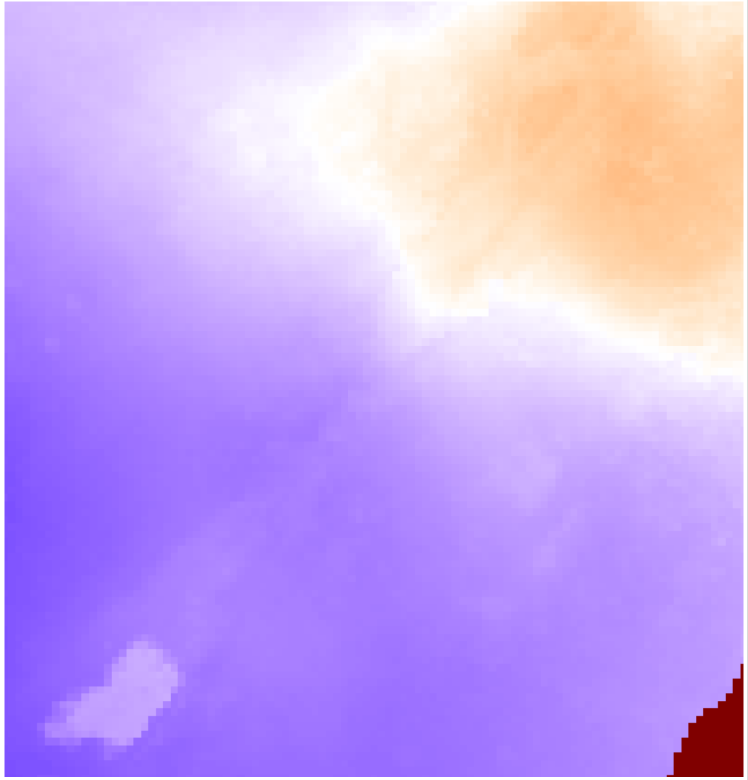
precipitation



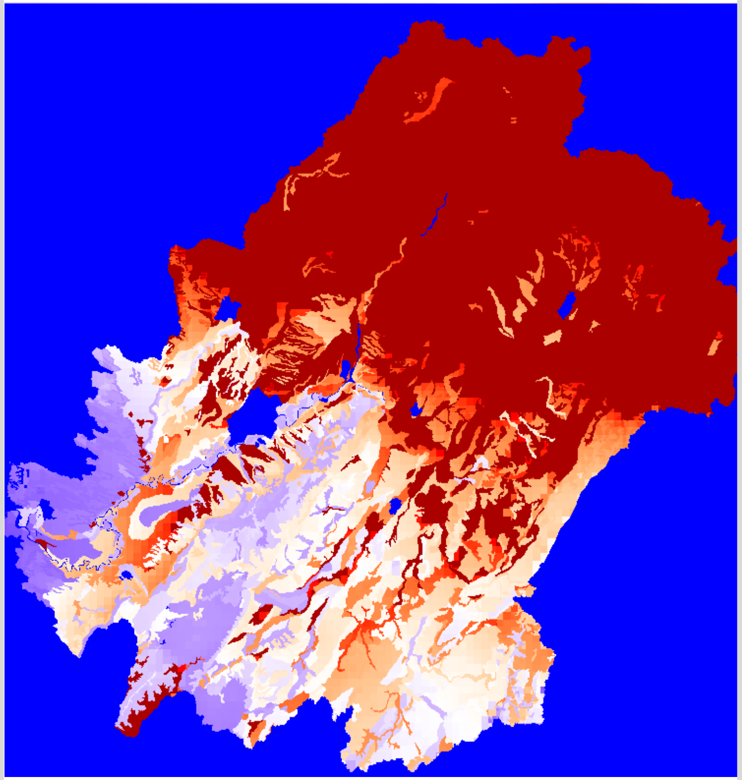
soil saturation



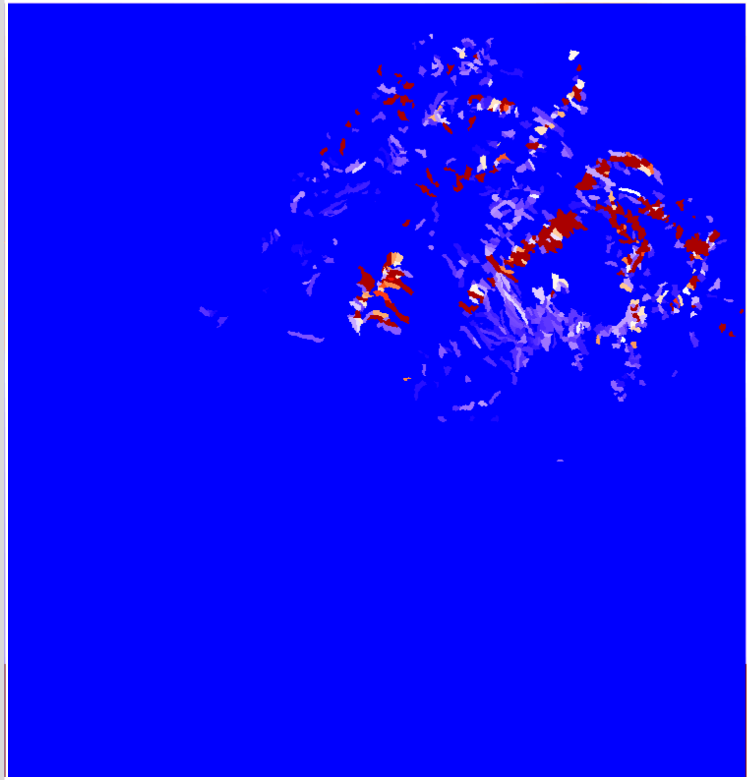
erosion



precipitation



soil saturation



erosion

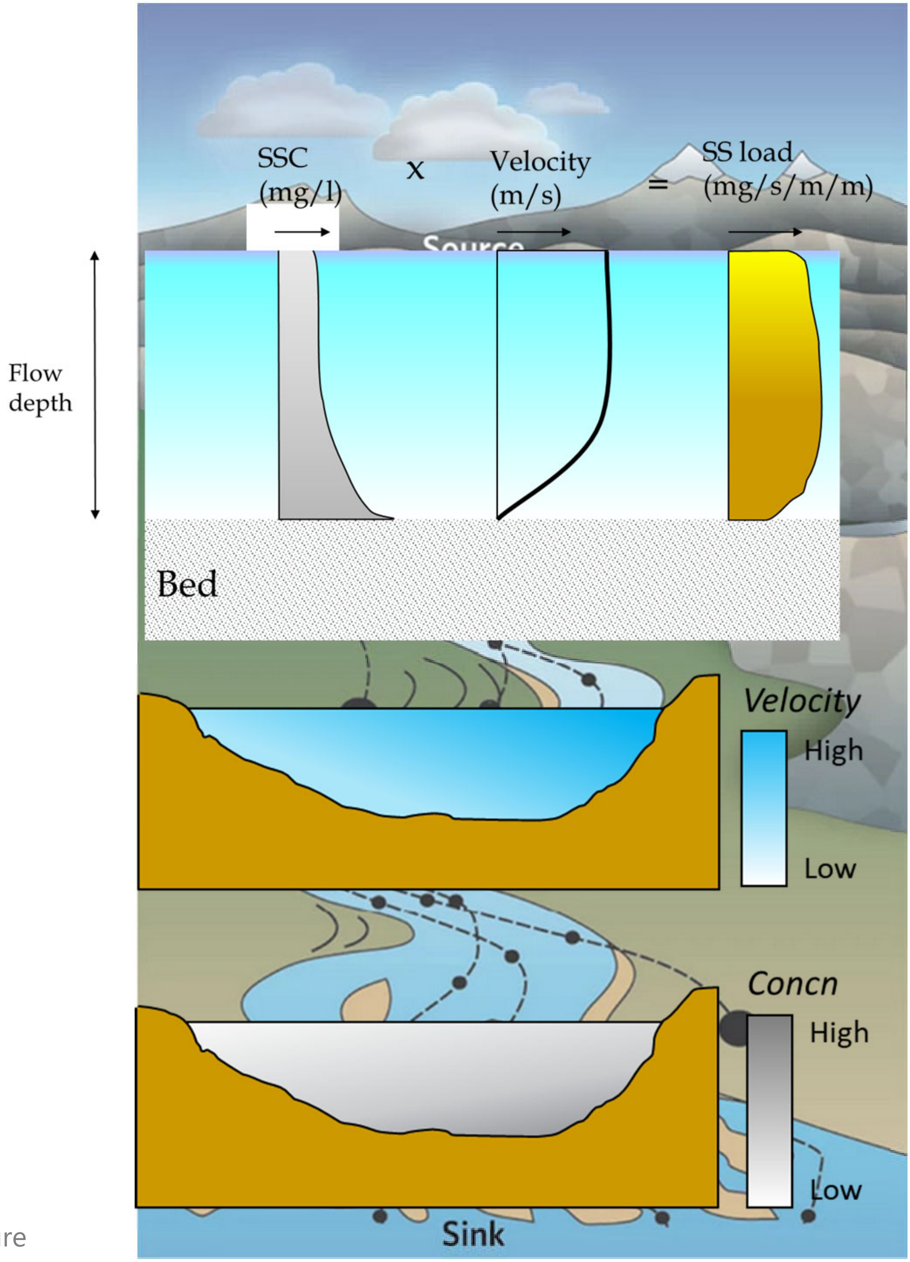
Sediment Transport Model

Sediment transport model (River model)

- **Suspended sediment routing model**
- **Coupled with dynamic erosion process model**

Link eroded materials from sources to sinks through the river network

- It is **1-D model**:
  - ❖ Depth-averaged SSC
  - ❖ Cross section-averaged SSC

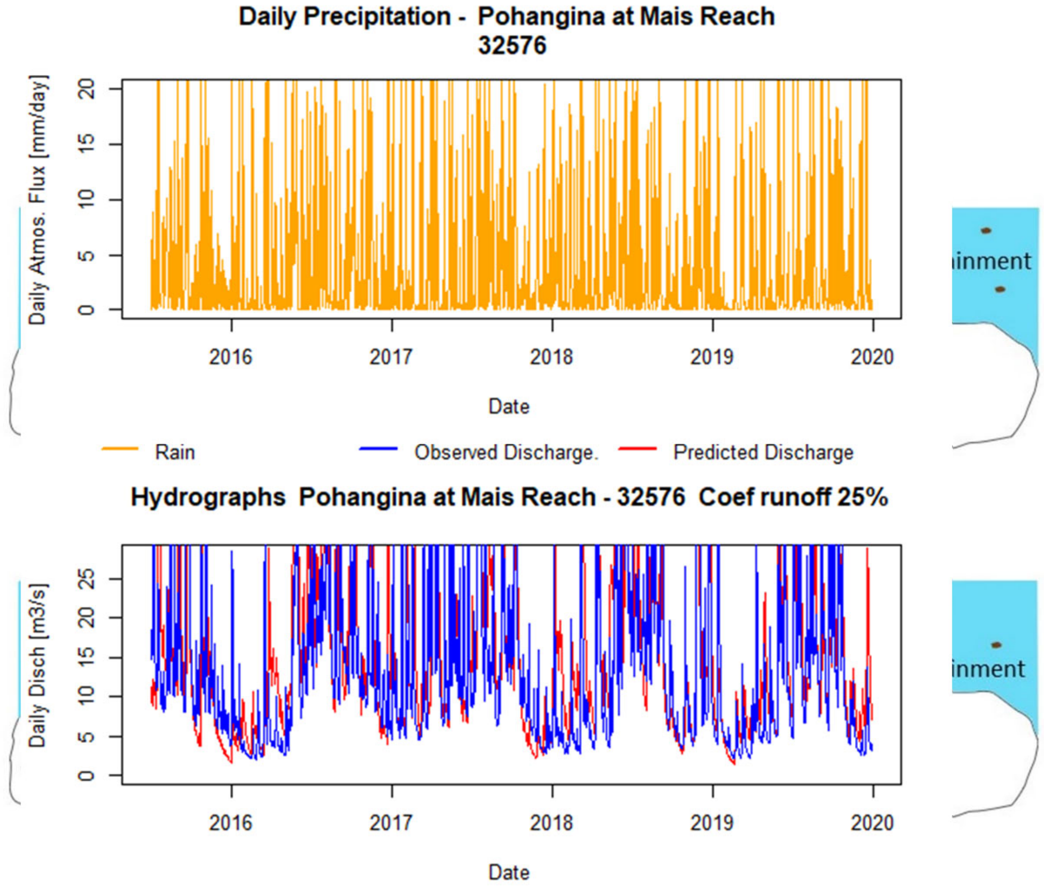


From: Allen PA (2008) From landscapes into geological history. Nature

Sediment routing model

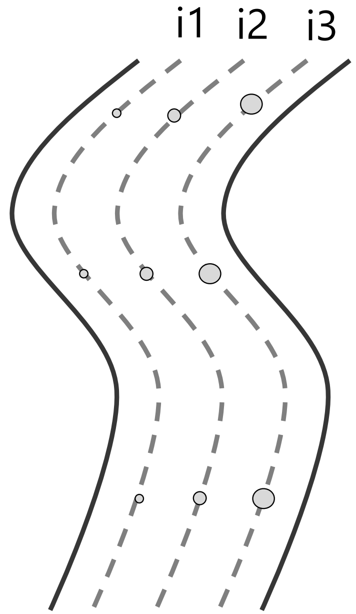
- Should represent geomorphic processes:
  - ❖ Deposition and re-entrainment of sediment within the channel or in floodplains
  - ❖ Sediment connectivity in river network
  - ❖ Impact of particle size
- Need continuous flow records for whole river network:

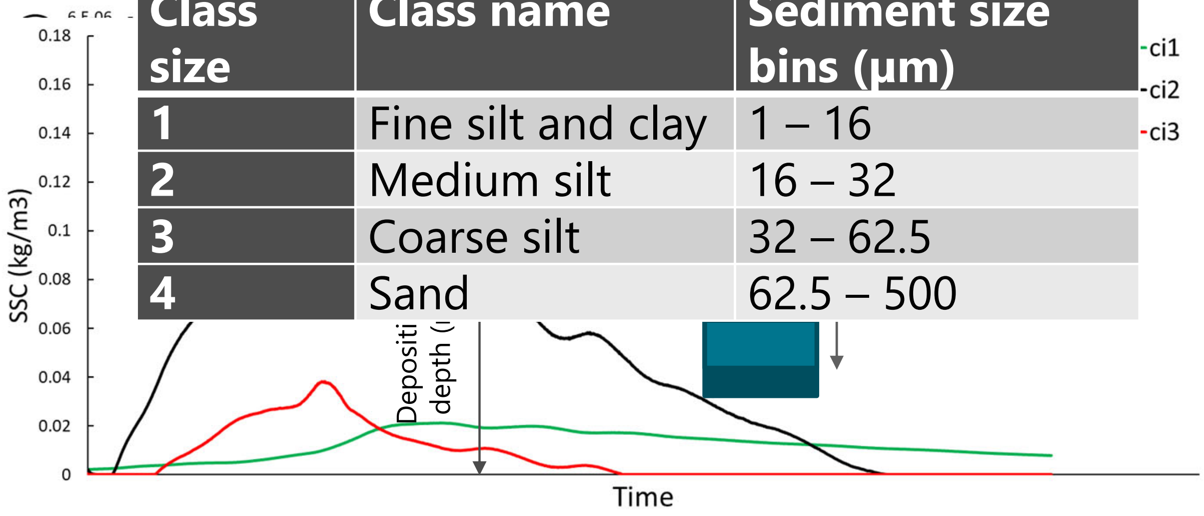
❖ Coupled with catchment hydrological models



Routing sediment for each fraction

- TEST-River components will be modelled independently for each fraction:
  - ❖ SSC routing (through river network)
  - ❖ Deposition (at each reach segment)
  - ❖ Re-entrainment (at each reach segment)
- Fractions will be **summed at each time step** to calculate total SSC, and total erosion and deposition.

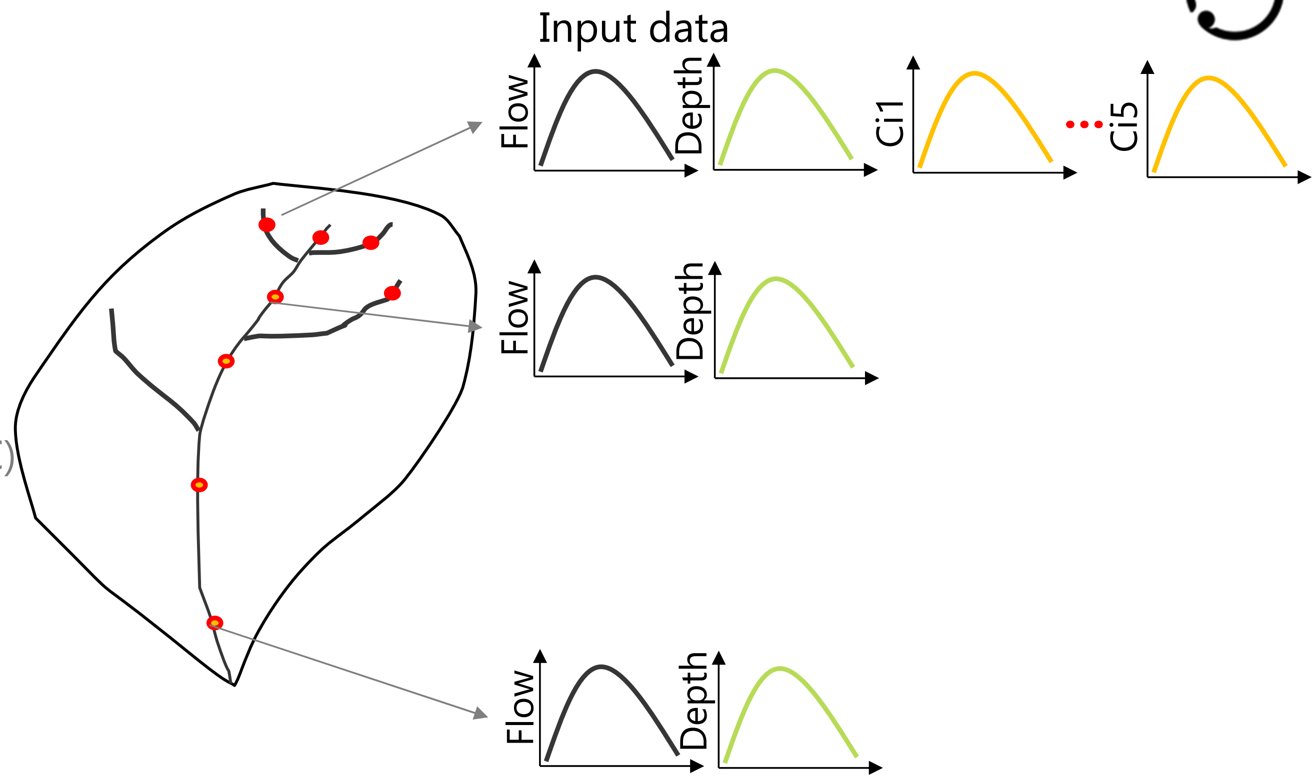




Class size	Class name	Sediment size bins (µm)
1	Fine silt and clay	1 – 16
2	Medium silt	16 – 32
3	Coarse silt	32 – 62.5
4	Sand	62.5 – 500

Model data

- Model Boundary data:
  - ❖Flow data
    - •Water depth
    - •Water discharge
  - ❖Sediment data
    - •Sediment conc (C)
    - •Particle size
    - •Cohesiveness
- In-river data:
  - ❖Flow data
    - •Water depth
    - •Water discharge
  - ❖River characteristics
    - •River bed slope
    - •Length of river reaches
    - •Connectivity of river reaches



Model data

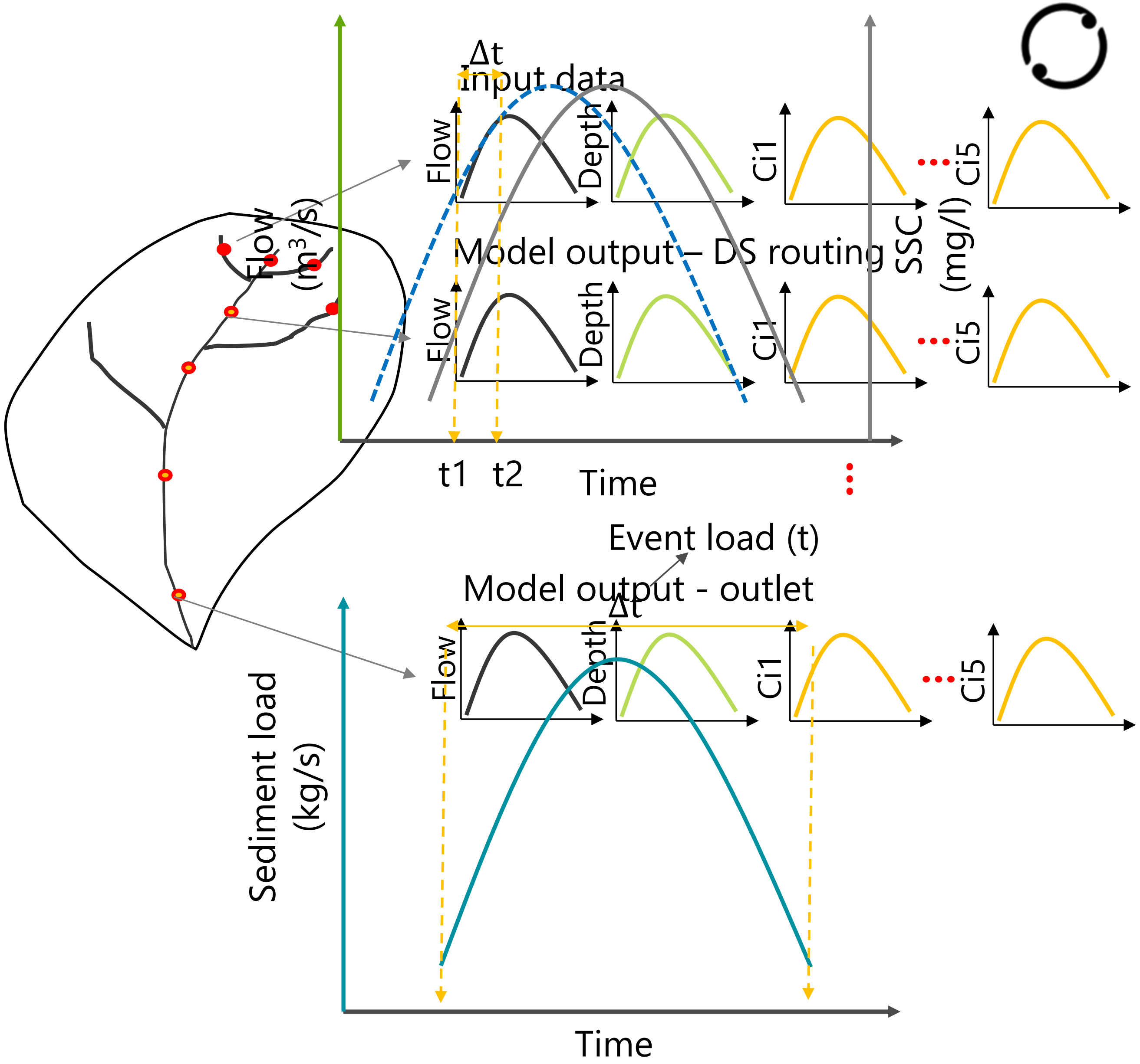
Model output:

- Sediment concentration
- Particle size
- Sediment load

$$\text{Sediment load} = \int_{t1}^{t2} SSC_t Q_t \Delta t$$

- Visual water clarity

Using a separate sub-model

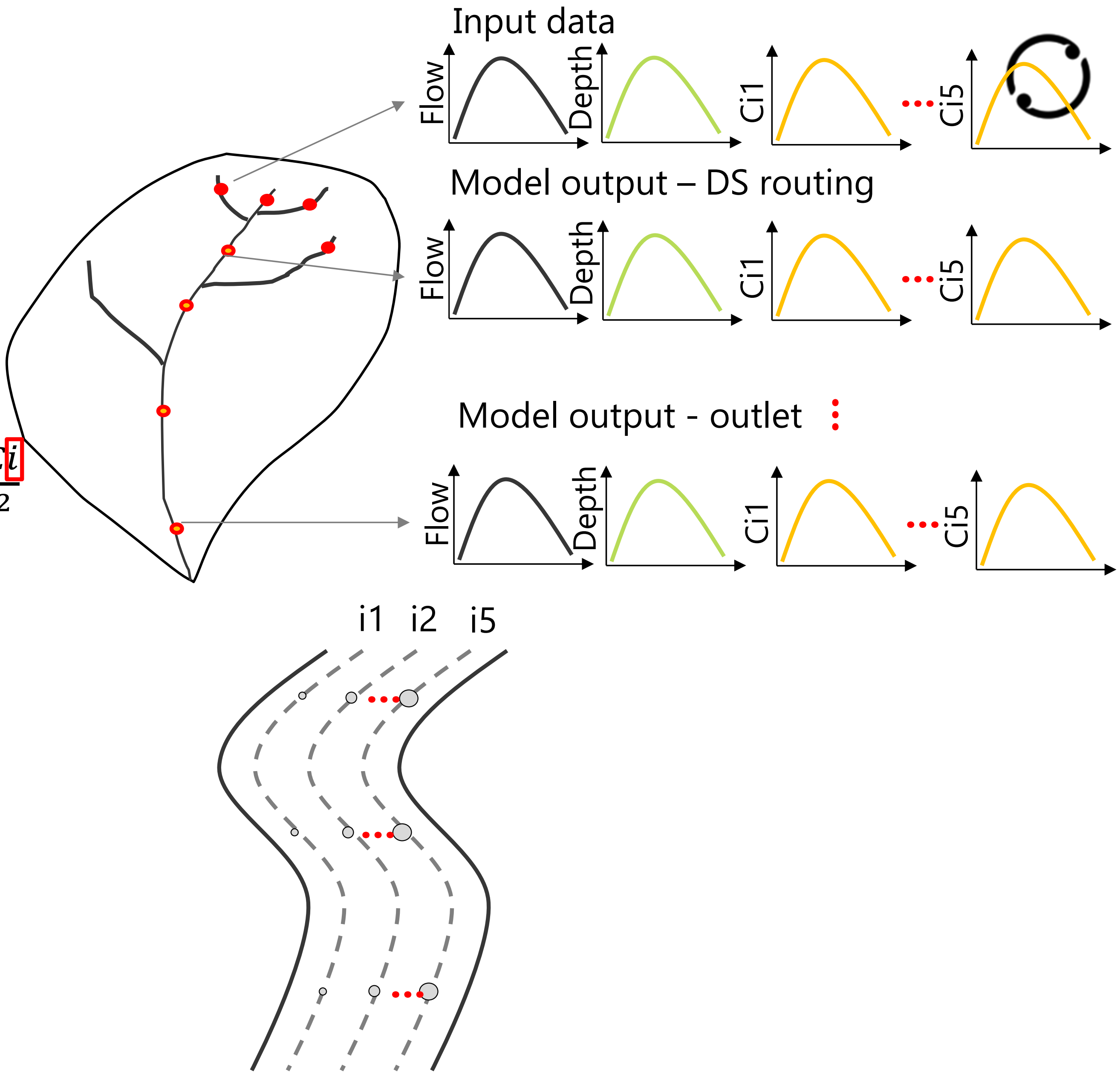


Model outline

- Mass conservation variables:

$$\frac{\partial (h c_i)}{\partial t} + \frac{\partial (q c_i)}{\partial x} = E_i - D_i + h K_d \frac{\partial^2 c_i}{\partial x^2}$$

Water depth (h); Sediment concentration (c_i); Unit flow (q); Time step (∂t); Reach Distance (∂x); Deposition Re-entrainment ($E_i - D_i$); Dispersion coefficient (K_d)



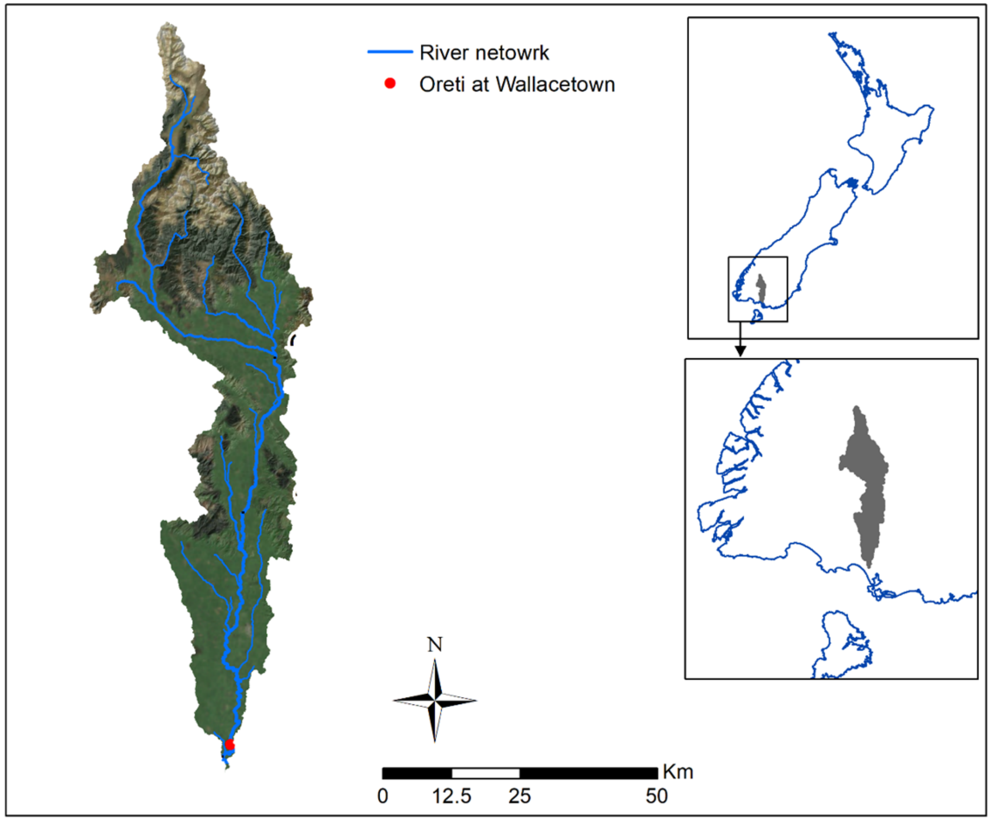
Conceptual model has been tested in stationary state

- Stationary state:

Changes through time (not space)

$$ci_{t+1} = \frac{(Ei - Di)\Delta t}{2h_{t+1}} + \frac{h_t}{h_{t+1}} ci_t$$

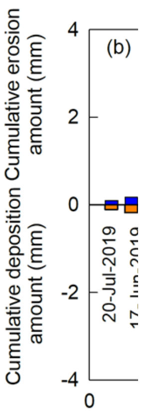
- Oreti River data (Wallacetown monitoring site)

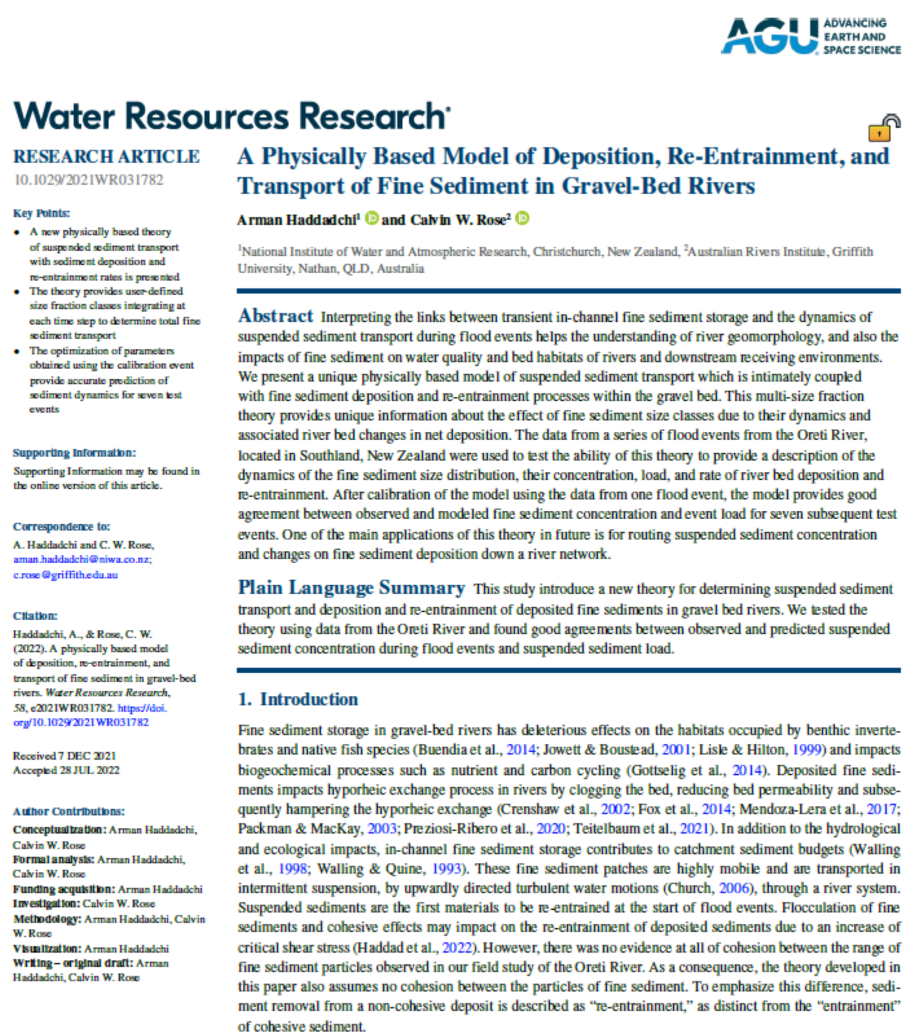


Model results - Validation

- Good agreement between modelled and observed sediment concentration and event load

- Conceptual model framework has been published in WRR





ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2021WR031782

A Physically Based Model of Deposition, Re-Entrainment, and Transport of Fine Sediment in Gravel-Bed Rivers

Arman Haddadchi[1] and Calvin W. Rose[2]

[1]National Institute of Water and Atmospheric Research, Christchurch, New Zealand, [2]Australian Rivers Institute, Griffith University, Nathan, QLD, Australia

Key Points:

- A new physically based theory of suspended sediment transport with sediment deposition and re-entrainment rates is presented
- The theory provides user-defined size fraction classes integrating at each time step to determine total fine sediment transport
- The optimization of parameters obtained using the calibration event provide accurate prediction of sediment dynamics for seven test events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Haddadchi, A., & Rose, C. W. (2022). A physically based model of deposition, re-entrainment, and transport of fine sediment in gravel-bed rivers. *Water Resources Research*, *58*, e2021WR031782. https://doi.org/10.1029/2021WR031782

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Formal analysis: Arman Haddadchi, Calvin W. Rose
Funding acquisition: Arman Haddadchi
Investigation: Calvin W. Rose
Methodology: Arman Haddadchi, Calvin W. Rose
Visualization: Arman Haddadchi
Writing – original draft: Arman Haddadchi, Calvin W. Rose

Abstract Interpreting the links between transient in-channel fine sediment storage and the dynamics of suspended sediment transport during flood events helps the understanding of river geomorphology, and also the impacts of fine sediment on water quality and bed habitats of rivers and downstream receiving environments. We present a unique physically based model of suspended sediment transport which is intimately coupled with fine sediment deposition and re-entrainment processes within the gravel bed. This multi-size fraction theory provides unique information about the effect of fine sediment size classes due to their dynamics and associated river bed changes in net deposition. The data from a series of flood events from the Oreti River, located in Southland, New Zealand were used to test the ability of this theory to provide a description of the dynamics of the fine sediment size distribution, their concentration, load, and rate of river bed deposition and re-entrainment. After calibration of the model using the data from one flood event, the model provides good agreement between observed and modeled fine sediment concentration and event load for seven subsequent test events. One of the main applications of this theory in future is for routing suspended sediment concentration and changes on fine sediment deposition down a river network.

Plain Language Summary This study introduce a new theory for determining suspended sediment transport and deposition and re-entrainment of deposited fine sediments in gravel bed rivers. We tested the theory using data from the Oreti River and found good agreements between observed and predicted suspended sediment concentration during flood events and suspended sediment load.

1. Introduction

Fine sediment storage in gravel-bed rivers has deleterious effects on the habitats occupied by benthic invertebrates and native fish species (Buendia et al., 2014; Jowett & Boustead, 2001; Lisle & Hilton, 1999) and impacts biogeochemical processes such as nutrient and carbon cycling (Gottselig et al., 2014). Deposited fine sediments impacts hyporheic exchange process in rivers by clogging the bed, reducing bed permeability and subsequently hampering the hyporheic exchange (Crenshaw et al., 2002; Fox et al., 2014; Mendoza-Lera et al., 2017; Packman & MacKay, 2003; Preziosi-Ribero et al., 2020; Teitelbaum et al., 2021). In addition to the hydrological and ecological impacts, in-channel fine sediment storage contributes to catchment sediment budgets (Walling et al., 1998; Walling & Quine, 1993). These fine sediment patches are highly mobile and are transported in intermittent suspension, by upwardly directed turbulent water motions (Church, 2006), through a river system. Suspended sediments are the first materials to be re-entrained at the start of flood events. Flocculation of fine sediments and cohesive effects may impact on the re-entrainment of deposited sediments due to an increase of critical shear stress (Haddad et al., 2022). However, there was no evidence at all of cohesion between the range of fine sediment particles observed in our field study of the Oreti River. As a consequence, the theory developed in this paper also assumes no cohesion between the particles of fine sediment. To emphasize this difference, sediment removal from a non-cohesive deposit is described as "re-entrainment," as distinct from the "entrainment" of cohesive sediment.

Routing suspended sediment down a river network

- Routing sediment particles in:
  - ❖ Space (down a river network)
  - ❖ Time (through flood event)

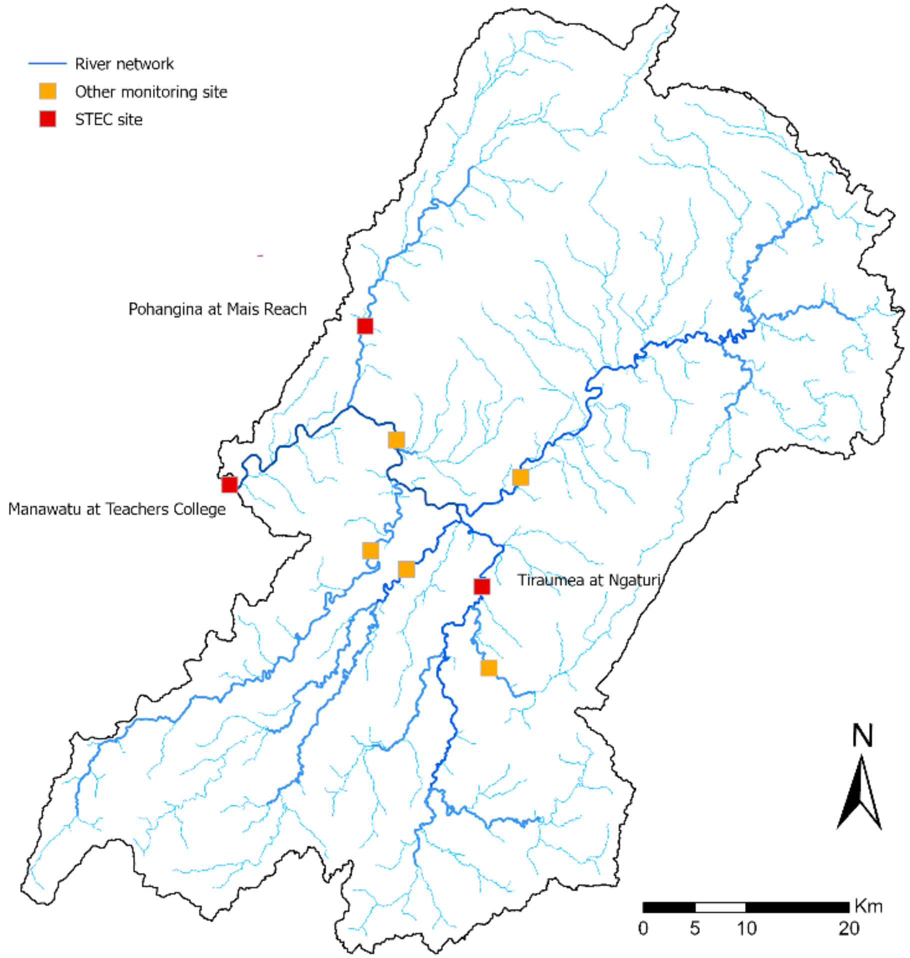
$$\frac{\partial(hci)}{\partial t} = \frac{h_{t+1}ci_{t+1} - h_t ci_t}{\Delta t}$$

$$\frac{\partial(qci)}{\partial x} = \frac{q_{t+1}ci_{t+1} - q_t ci_t}{\Delta x}$$

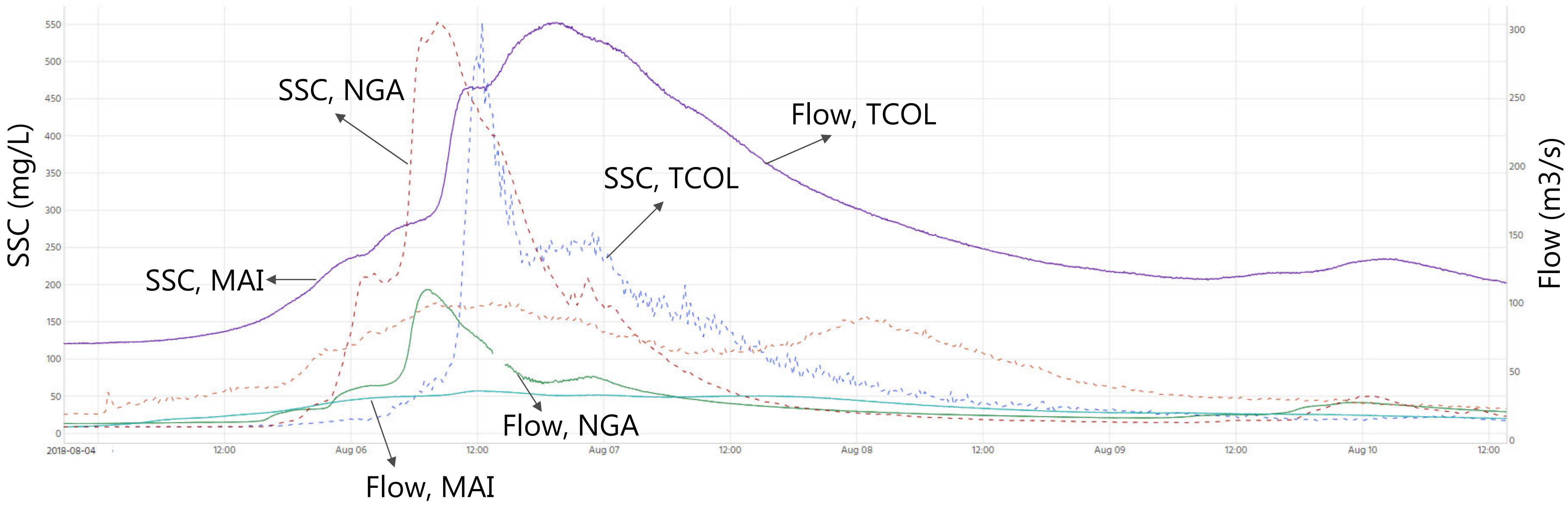
$$hK_d \frac{\partial^2 ci}{\partial x^2} = \frac{hk_d}{2}\left[\frac{\left(ci_{x+1,t+1} - 2ci_{x,t+1} + ci_{x-1,t+1}\right) + \left(ci_{x+1,t} - 2ci_{x,t} + ci_{x-1,t}\right)}{\Delta x^2}\right]$$

Routing model calibration

- Manawatū River catchment
- Three monitoring sites with intense sampling regime:
  - ❖ Tiraumea at Ngaturi,
  - ❖ Pohangina at Mais Reach
  - ❖ Manawatū river at Teachers College.



Boundary condition data – Manwatu Flow, SSC



Summary

- **High frequency sediment data** are necessary for designing efficient sediment management measures and reduce fine sediment supply to downstream aquatic ecosystems
- Impact of fine sediment on rivers can be quantified with the three attributes:
    - ❖ Suspended sediment concentration (direct estimate)
    - ❖ Fine sediment deposition (direct estimate)
    - ❖ Visual water clarity (indirect using fine sediment concentration and size gradings with aseparate sub-model)

- **This model** provide estimates for all three attributes of concern

Conclusions & Outlook

- We developed and implemented a soil erosion and sediment transport model that predicts sediment concentration in rivers.
- We are finalizing the calibration
- Model performance will be evaluated over the next month..... paper
- Temporal soil erosion and sediment transport model will be run with soil conservation scenarios to test the assumption that reduction in mean sediment loads result in the same relative reductions in sediment concentration at low flow

Need for event-scale sediment models

- Models are needed to predict fine sediment and its relevant attributes at:
  - ❖Different locations within the catchment,
  - ❖Sufficiently high frequency to define dynamics during flood events.
- Common methods do not adequately represent variations in sediment dynamics throughout the catchment:

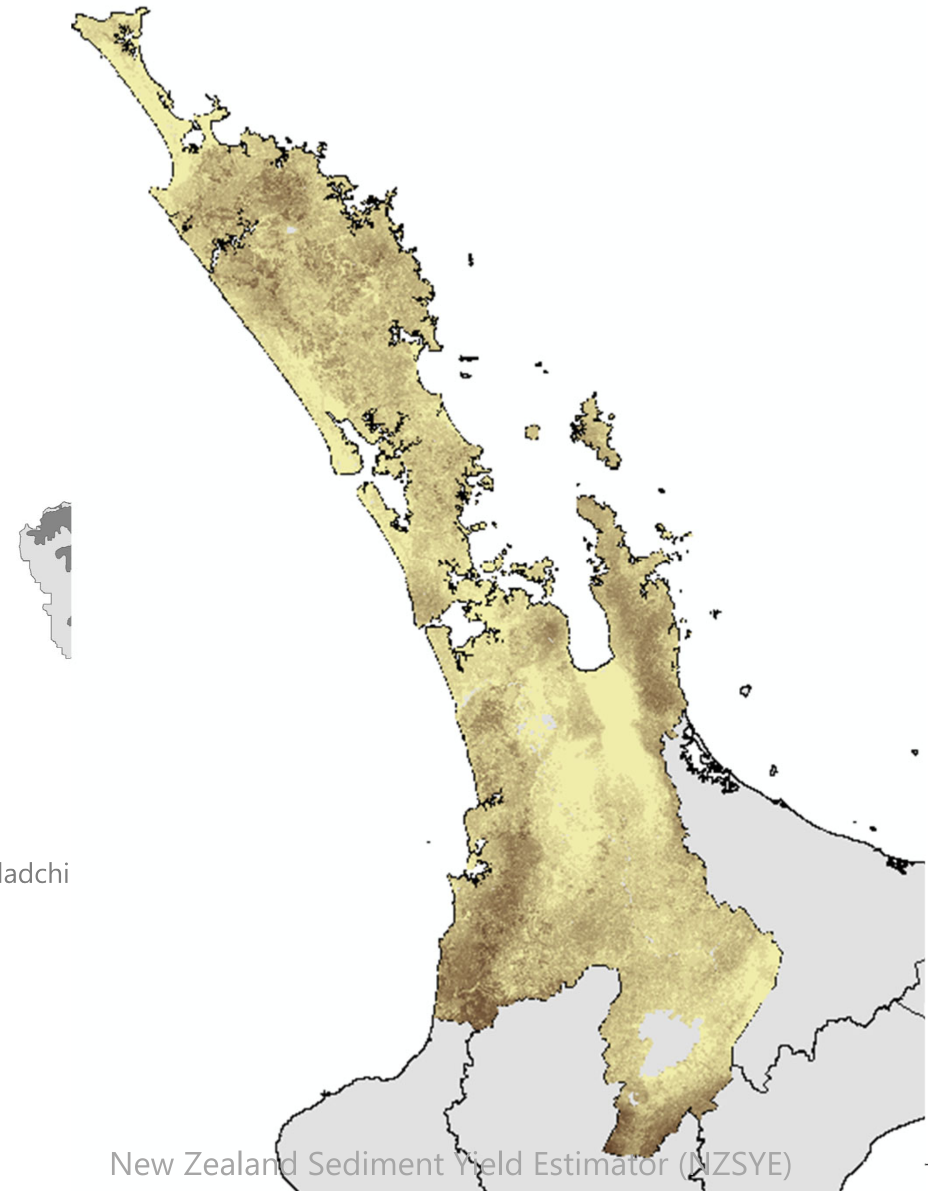
❖Sediment tracing: hardly capture the temporal resolution of sediment sources

❖Sediment monitoring: not information about the spatial variation of sediment generation

❖Empirical erosion models: Static information

❖Mass-conservation based models: lack geomorphic processes

Haddadchi



New Zealand Sediment Yield Estimator (NZSYE)