Dear Editor,

Please find enclosed the response to the reviewers' comments and a marked-up version of the manuscript. The manuscript has been revised according to the comments of the two reviewers and the short comment by Erkan Instanbulluoglu. In addition, we took the chance to improve the text and the order of some sections for better readability. We would like to thank the Editor, the Associate Editor and the two anonymous reviewers for their constructive comments and suggestions, which helped us to improve the manuscript.

In the following, we report the text of the review in blue italic, and in black our reply.

Response to Referee 1

The manuscript describes a new suspended sediment flux model which is then used to analyze sediment dynamics and sources in a mid-size catchment. The paper is well written. Unfortunately, I have great reservations about the model novelty and the interpretation of the results. I recommend Major Revisions as I think that the manuscript can be of interest once it is more properly framed.

General comments: The authors all but ignored existing large-scale sediment flux models (see a most relevant review paper and a couple of examples below). This is a major emission that must be corrected; their model should be framed in reference to these models.

In the submitted manuscript we indeed referenced only those models that in our opinion were directly comparable to the approach we took, like tRIBS (Francipane et al., 2012) and the model of Tsuruta et al. (2018). As the reviewer suggests, we added a reference to the large-scale sediment flux models WBMsed (Cohen et al., 2013) and Pelletier (2012) in line 69 of the revised manuscript and we highlighted in particular one of the main differences between these approaches and our model, which is the lack of an explicit hydrology component. At the same time, we prefer to stay focused in the paper on physics-based modelling approaches only. Most of the models reviewed or presented in the papers suggested by the referee (De Vente et al., 2013; Cohen et al., 2013; Pelletier, 2012; Syvitski and Milliman, 2007) are statistical and steady state models which cannot be seen as reference models, because they are developed for a different purpose and cannot answer the same questions we address in our work.

The authors greatly over-sell the novelty and capabilities of the sediment model. While it is true that the hydrological framework is physically-based, the sediment model is a simple empirical equation (Eq. 2) that predicts sediment as a function of discharge, slope and a spatially variable (alpha) coefficient. Alpha is calibrated using USLE parameter combination. Sediment transport (Eq. 4) is a simple cell-to-cell and time-step balance. I see very little novelty in this model. The authors must make the argument of why this model is novel if they wish to continue claiming it.

This point and criticism has been addressed in lines 78-85 of the revised manuscript, where we highlight that the novelty consists in the combined hydrology-sediment system approach and the questions it allows to address. In particular, the novelty we perceive is based on the combination of the following elements: (a) We combine physically-based unsteady hydrological simulation of surface overland flow with a simple hillslope erosion and sediment transport component. This ensures that sediment is produced and transported along hillslopes by overland flow respecting physical processes of hillslope erosion and sediment transport as we understand them. The sediment component is simple by design (sediment production and continuity in Eq. 2 and 4 mentioned above), so that the most uncertain part of the modelling system is not over-parameterized. (b) The high spatial and temporal resolutions of the model (100 m and 1 hr) allow the inclusion of detailed topographic variations, the explicit simulation of connectivity of sediment pathways in space and time, and the modelling of fast response to heavy precipitation where it happens. (c) Continuous simulation (order of decades) by our approach, allows to track overland runoff generation and thus hillslope sediment transport, by spatially distributed simulation of the dynamics of soil moisture, snowmelt, and rainfall, not only for individual events, but over long periods of time reflecting also long-term changes of key drivers of runoff generation mechanisms (e.g. soil moisture states, rainfall seasonality, etc).

None of the physics-based models reviewed in De Vente et al. (2013) or mentioned in the introduction of the manuscript combines these three characteristics at a spatial scale comparable to our case study. This is the context in which we perceive the novelty of our work, and which allows us to explore the effects of the spatial variability in catchment erodibility and rainfall with higher confidence.

At the same time, we recognize that our model is not novel in the sense that it is the first and only such model. For example, it is similar to tRIBS (Francipane et al., 2012), DHSVM (Doten et al., 2006) and the model of Tsuruta et al. (2018). However, the first two are not applicable to large catchments and long and continuous simulations at high resolutions due to computational demand, while our setup is computationally very efficient and applicable to medium and large-scale basins, and the latter is a coarser resolution model with less physical hillslope surface runoff generation routines.

In conclusion, we do think that our approach has unique strengths that allow us to explore the hydrology-sedimentology connections leading to sediment generation pathways at high resolutions, which other approaches do not have. This is the novelty in the approach.

The evaluation of the sediment model is odd - referring to the relatively low scatter in the SSC-Q plot (Fig 3) as an argument for strong model performance. A standard model performance analysis is offered for the model's hydrological predictions (Table 1). It seems that the observed sediment is used for model calibration so we actually left with little knowledge about how well the model is doing.

Indeed the referee is correct that it is much easier to calibrate the hydrological part of the model than the sedimentological one, mainly because we do not have the data to do so. There is only one suspended sediment measurement point at the outlet of the basin where bi-weekly measurements are available for a reasonably long period. We do not consider it meaningful to tweak the simple advection-based sediment transport routine implemented in the model, to match "perfectly" the observed hourly concentrations at the outlet measured twice a week. A comparison of sediment transport at the daily scale is also not possible with the given resolution of the measurements. Rather we assumed as a qualitative measure of success the reproduction of properties of the observed sediment rating curve (SRC), i.e. the relationship between hourly discharge and suspended sediment concentration (SSC), which captures the catchment sediment dynamics. Concretely, we calibrate the sediment model parameters, i.e. the river initiation threshold RT and the α_1 erodibility parameter (Eq. 5), to reproduce (a) the observed SSC-Q cloud of point as best as we can, as well as (b) the frequency distribution of observed SSCs. We also omitted a traditional validation with a part of the dataset not used in calibration as our observed records are too short and our main focus is on the sensitivity to input data (spatial variability in surface erodibility and rainfall) not on the predictive uncertainty in SSC per se.

In the revised paper we rephrased section 2.3.3 (section 2.2.3 of the submitted manuscript) to clarify the method used (in particular, see lines 216-218) and we introduced the percentage of modelled SSCs that fall within the 5^{th} and 95^{th} percentile of the observations in SIM 1, as a quantitative indicator of the model performance (see lines 224-225).

Given the relative simplicity of the model and the way it was calibrated, the interpretation of the model results extends much beyond the model's ability to represent the discussed processes. The authors need to frame their analysis within the model's capabilities to represent the relevant processes and drivers. Some examples of overreaching are 1st sentence in the Discussion, sentence starting in lines 300, 311 and 315.

We respectfully disagree with the referee about this point. The spread around the SRC in our deterministic approach is due to (a) the spatially distributed nature of the model, which allows to simulate the heterogeneous response of the basin to hydrological forcing, based on the topographic characteristics, depth and properties of the soil, (b) the spatial variability of surface erodibility and the connectivity of hillslope flow paths to the river network, and (c) the spatio-temporal distribution of rainfall leading to overland flow and erosion (lines 293-302 of the submitted manuscript). We are of the opinion that all of these processes are robustly included in our modelling approach. Of course they cannot explain all the SRC spread because in the real natural catchments there is an added element of stochasticity in sediment mobilization, transport, and sediment supply limitations, which add to the SRC variability (lines 306-312 of the submitted manuscript). However, we believe that this does not invalidate our modelling results or their ability to provide insights into process controls, like the role of spatial variability in erosion drivers.

In the revised manuscript we have clarified the limitations of the results in lines 340-343 and 447-451. We also rephrased the research questions, as suggested by Reviewer 2, to be more specific on the conclusions we can draw from the four simulated scenarios.

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Response to Referee 2

The paper presents a hydrosedimentary model that couples the TOPKAPI-ETH hydrological model to a physically based and spatially distributed erosion and sediment transport model. [. . .]

However, the questions asked are not precise enough. It is a bit ambitious to want to answer such generic questions with only 4 scenarios. The model is very little evaluated in terms of erosion before analysing the results of the different scenarios. It is therefore difficult to give credit to the results obtained. My advice would be to reformulate questions thar are compatible with the framework offered by the tested scenarios and to rework the results and discussion sections according to these new questions.

I therefore recommend major revisions for this paper.

We modified the research questions in order to be more specific on the analyses that we performed, i.e. the investigation about the location of sediment sources, their productivity and connectivity to the river network and how these information help to explain the sediment load observed at the outlet (lines 90-98). Moreover, we further supported some of the discussion statements with additional analyses of the hydrological results, as suggested by the reviewer.

General remarks:

- *The authors do not mention the DHSVM model although it would be a very relevant tool for this type of catchment. It is necessary to justify the development of a new model compared to existing models such as DHSVM.*

(1) DHSVM is indeed a relevant tool in the framework of these type of models. DHSVM features a rigorous description of the hydrological processes and the role of vegetation and simulates sediment production by hillslope erosion, road erosion and mass wasting. TOPKAPI-ETH presents a slightly more simplified description of the hydrological processes and only includes erosion by overland flow. These choices are aimed at avoiding over-parameterization of the model and at keeping it computationally efficient and thus suitable for mesoscale and large catchment applications and small grid sizes, even when further components would be added (e.g. additional sediment transport processes). We introduced the DHSVM model in the literature review (lines 71-72) and highlighted the differences and novelties of our model in lines 72-73 and 76-85.

- *The description of the erosion model did not seem clear enough to me, especially the distinction between the representation of hillslopes and river processes.*

(2) Sediment production and transport on the hillslopes is based on a transport capacity-mass balance approach, i.e. sediment flux is assumed to be always at transport capacity, and the model simulates erosion or deposition when there is a change in transport capacity. Sediment delivered to the channel network is advected by the river flow, there is no possibility for deposition or entrainment of fine sediment from the bed in the channel. The transition between sediment transport description as hillslope process to channel process corresponds to the transition from water flow routing as overland flow to channelized flow. This takes place between hillslope and channel cells and is fundamentally determined by the drainage area threshold (RT) used to identify river cells in the DEM, i.e. the river initiation threshold, which was a parameter in our model.

We clarified in section 2.1 the distinction between the description of sediment processes on the hillslopes and in the channel (lines 119-120 and 128-131).

- *The authors use data from Swiss operational services. However the temporal frequency of SSC data is too low for a catchment of this size located in a mountainous area. Flood events are most likely under-sampled. High SSC values are probably missing from the data set for this reason.*

(3) We agree with the reviewer on this point and we explicitly stated this limitation of the data in in lines 159-161 of the revised manuscript. There is nothing we can do about the temporal frequency of the data (twice a week). All sediment monitoring stations of the Federal Office of the Environment in Switzerland have such low frequency except for few automatic

stations with turbidity measurements in recent years. In lines 214-216 of the revised manuscript we clarified that in the calibration of the model we focused only on the lowest 85^{th} percentile of the SSC dataset. This choice is motivated both by the under-sampling of extreme SSCs in the data and by the expected underestimation of high SSCs by the model, given that very localized sediment sources are not simulated.

- *One could be interested in the impact of the scenarios on the hydrological response and the indirect impact this may have on sediment dynamics.*

(4) This is a good point. We added Figure 6, where the hydrological response in the 4 simulations is compared, by means of the mean annual flow Q_{mean}, the annual flood Q_{max} and the variability of flow at the basin outlet, expressed by the coefficient of variation CV, and the mean annual surface runoff on the hillslopes Q_{OFmean}. The plots in Figure 6 explain the higher sediment production in SIM 1 and 3, by the greater runoff production indicated by Q_{mean}, Q_{max} and Q_{OFmean} (line 305-307), and shows that spatial variability of precipitation is a source of flow variability, and thus favors SSC-Q scatter (lines 347-348).

- *The concepts of structural and functional connectivity, widely present in the literature, are not discussed although they are at the heart of the subject developed in the paper.*

- *Connectivity indices are not used.*

Both comments have been addressed in point (6) below.

- *The process of detachment by rain is not taken into account in the model. Only the process of detachment by runoff is taken into account. This is questionable when the objective is to estimate the effect of spatial variability of precipitation.*

(5) Detachment by rain, together with the overland flow entrainment capacity, defines the amount of sediment available for transport. In our model, we do not simulate the local rainsplash detachment and overland flow entrainment separately from the mobilization processes at the grid scale, rather we assume that sediment on the hillslopes is always available to fulfill the overland transport capacity. Sediment availability is only limited by the soil depth (sediment layer thickness), however, this limitation does not play a role in our simulations. It would be necessary to include the process of rainfall detachment by rainsplash if the model distinguished between the processes of sediment detachment at the microscale, determining the sediment available for transport, and sediment mobilization.

We agree that the submitted manuscript is unclear in this regard. In the revised manuscript we replaced "sediment production" with "sediment mobilization" at several points and we rephrased lines 119-120, to clarify that we model the maximum amount of sediment that overland flow can transport, and not the amount detached by rainfall processes or overland flow entrainment.

- *Connectivity index maps could be used to study the spatial organization of erosion (Section 4.2). It is questionable whether there is any real added value in using the model presented in this study to address this issue.*

(6) The vast majority of connectivity indices provides a static description of the structural or functional sediment connectivity, based on the upslope contributing area as a proxy for discharge to estimate stream power (Heckmann et al., 2018). The sediment delivery ratio SDR simulated by our model quantifies the proportion of eroded sediments that are routed to a point on a river network or outlet of a selected subbasin, by action of overland flow and channel flow. As such, SDR is a dynamic indicator of functional connectivity, where the discharge (and thus stream power) is considered explicitly as a function of the temporal and spatial variability of the hydrological forcing and topographic characteristics, instead of being represented by the upstream area only. In fact, besides accounting for the time dependency of discharge, SDR also integrates the variability in space of the functional connectivity, by substituting the unique Q-A relationship used in traditional connectivity indices, with the explicit simulation of overland flow on the hillslopes.

We have applied this analysis at the subbasin scale, but SDR could be potentially computed for each grid cell to build a connectivity map. Mahoney (2017) propose a comparable approach that quantifies dynamic functional connectivity, based on hydrological modelling too. We added this discussion points to complement section 5.2 (lines 380-386).

- *In section 3.4, the authors examine the results at the temporal scale of the flood event. It is difficult to examine the effect of soil moisture on erosion and sediment transport without giving guarantees on the performance of the model in reproducing flows under dry and wet conditions.*

(7) We added a comparison between the hydrological model performance for the low initial soil moisture (SM_0) events and the high SM_0 ones, which are analysed in section 3.4 of the submitted manuscript. This comparison is presented in Table S2 of the revised manuscript with the performance indices, and in Figure S3 as a density plot, and it shows that the model tends to overestimate the flow in both types of events, but especially at low initial soil moistures. Based on the findings of Paschalis et al. (2014) and Shah et al. (1996), we do expect to see an effect of initial soil moisture on erosion and sediment transport, as it is suggested by Figure 10b of the revised manuscript. However, we also note that our results do not allow for a clear conclusion, given the small difference between the sediment load distributions of low and high SM_0 events and the tendency to overestimate flow in low SM_0 events. We modified the discussion of Figure 10b according to these observations (lines 433-438).

- *The summary at the beginning of Section 4.3 is interesting.*

We thank the reviewer for the appreciation. It is indeed an important part to link together the catchment-wide analysis of the sediment dynamics with the sediment signal at the outlet.

Specific remarks :

- *p2 l33: I would suggest adding "especially in small to medium catchments (up to 1000 km2) after "the strong non-uniqueness of suspended sediment concentrations (SSCs)".*

We agree with the suggestion and we added it in line 38-39.

- *p2 l37: I would suggest adding "and transfers " after "in sediment mobilization".*

We agree with the suggestion and we added it in line 43.

- *p2 l39 to 52: rewrite this part which is not clear and take into account the concepts of structural and functional connectivity.*

We rewrote this part, now introducing the concepts of structural and functional connectivity, and the indices of sediment connectivity (lines 44-58).

- *p2 l48: add reference Misset et al (2018)*
  Misset C., Recking A., Legout C., Poirel A., Cazilhac M., Esteves Michel, Bertrand M. (2019). An attempt to link suspended load hysteresis patterns and sediment sources configuration in alpine catchments. Journal of Hydrology, 576, 72-84. ISSN 0022-1694

Thanks for suggesting this reference, it is now included in line 48.

- *p2 l56: replace "transport" by "transfer" in several places in the text*

We agree with this comments and we now replaced "transport" with "transfer", where "transport" indicated the group of processes transferring sediments from the sources to the outlet. We kept the word "transport" to indicate the specific processes of sediment transport in the hillslope or channel cells.

- *p3 l65: replace "cesar-lisflood" with "caesar-lisflood".*

Thanks, we corrected this typo.

- *p3 l62 to 75: add the reference to the DHSVM model and explain the added value of the model presented in relation to this model*

See point (1).

- *p3 l77: "a physically explicit spatially distributed deterministic model": simplify the formula. What does "explicit" mean here?*

“Explicit” means that the model is based on a physical representation of most processes, but it still contains some conceptualisations or approximations of the processes. For general understanding, we replaced “explicit” with “based” in the revised manuscript.

- *p3 l83: "mean annual discharge" instead of "average discharge".*

We agree and modified it in line 146.

- *p3 l87 : " mostly driven by overland flow ". What about rainfall processes ?*

This is correct, we modified the sentence in line 150.

- *p4 l97: what is the scale for the soil map?*

The scale is given by the coordinates on the x- and y- axes (units are the same as in Figure 1a).

- *p4 l103: Is it really 2D whereas the equations presented p5 are 1D?*

The solution is 1D in the direction of the steepest descent at the grid scale for surface and subsurface flow. All inflows from the neighbourhood cells are integrated in space. For clarity, we removed the "2D" from line 110.

- *p5 l105 to 114: I do not understand how the hydrographic network is represented and discretized. The same question applies to the hillslopes. A specific part is missing for describing the discretization used in the model.*

The entire basin is discretized as a 100 m resolution grid in the horizontal dimension, and with 3 layers in the vertical direction (one upper soil layer, one lower soil layer and the groundwater layer). Some of these cells are hillslope cells, others are partially hillslope and partially river network cells, depending on the river width. The river width has been set in these cells between a minimum of 10 m and a maximum of 48 m, proportionally to the upstream area of the cell as in the downstream hydraulic geometry relations of Leopold and Maddock (the min and max widths are derived from cross section measurements provided by the Swiss Federal Office of the Environment). The river network cells are identified in the DEM by means of a flow accumulation routine in the preprocessing phase, and the initiation of the river network is set by the drainage area RT threshold (see point (2) above). In the revised manuscript, we added this description of the model discretization between lines 104 and 109.

- *p5 l107: " catchment scale ": it is not precise enough. What scale?*

The model allows high resolution simulations in catchments up to large scales (>1000 km^2). We added this information in line 116.

- *p5: put the dimensions of the variables presented in the equations. I do not understand the distinction between hillslopes and rivers in terms of erosion and transport processes. What is the link between the terms D and E?*

The erosion and transport processes on hillslopes and channels are clarified in point (2). D and E are not related to each other. D represents the erosion or deposition of sediment on the hillslopes, while E is the flux of sediments between the water column and the river bed in the river network. We added the dimensions of the variables in section 2.1.

- *p5 Eq.4: I do not understand the definition of X. It should be a width rather than a length for the calculation of the flux.*

X is the length of the river cell. Eq. (4) is the integration over the "along-flow" dimension of Eq. (3), which is a 1D equation and therefore is already integrated over the cell width.

- *p7 l166-167: is this a wash load hypothesis?*

Yes, it can be described as such. However, we estimate that sediment transported in suspension in this catchment is between clay and medium sand grain size, therefore it includes also rather coarse grain sizes.

- *p8 Fig3 : SSC values seem low for a mountainous catchment area. This is certainly related to the lack of observed values during floods.*

Indeed, the bulk of observed SSCs are not very high (less than 20 mg/l) but during floods they can be much higher. In the revised manuscript we discussed this limitation in lines 159-161 and 214-216 (see point (3)).

- *p8 l186-188: it is questionable to use the slope of the Q-SSC relation given the dispersion that exists between these two variables (even in log scale)*

We aim at reproducing the Q-SSC relation, as representative of the basin overall sediment dynamics, by matching the modelled and observed clouds of points, i.e. their relation and dispersion, by looking at the SSC frequency distribution. In the revised manuscript, we rephrased the description of the calibration procedure (see lines 216-218), to clarify that we did not match the slope of regression lines of observations and simulations, rather we looked at both the trend in the relation and the dispersion. In line 224-225, we also added the percentage of simulated SSC that fall within the observed percentiles, as discussed in the reply to Reviewer 1.

- *p10 l226-228: what forms of erosion are observed within the basin?*

Deep, permanent gullies and small shallow landslides characterize soil erosion in the northwestern part of the basin (Fontanne catchment). The southeastern region is characterized by shallower gullies and scree, the major landslides are also located in this area and have a significant role in the sediment budget of the basin (Norton et al., 2008; Van Den Berg et al., 2012). In lines 271-272 of the revised manuscript we added a reference to the discussion section 5.2, where the geomorphological differences between the two regions of the basin are described.

- *p10 l234: "Hinderer et al. (2013)" is not present in the reference list.*

Hinderer et al. (2013) is in the reference list of the submitted manuscript at lines 475-477.

- *p10 l237: "The underestimation of sediment load (...) we do not like to reproduce the largest measured sediment concentrations". This is a working hypothesis that should be placed in « Material and Method ».*

We modified the sentence to explain better that, since we underestimate highest hourly SSCs, we also underestimate annual sediment loads and therefore underestimate the yield estimates found in the literature (lines 279-281 of the revised manuscript).

- *p10 Fig5: indicate the observed data as red dots on the SSC time series.*

Thanks for the suggestion, the observed data have been added to the SSC time series in Figure 5a.

- *p11 Fig6(a): over which periods are the intensities calculated: over the rain periods only or over the whole period of simulation?*

Intensities are calculated over the entire simulation period.

- *p11 l242: I suggest modifying "where SIM 2 and 3 are compared respectively with SM1".*

We agree and we modified the sentence (line 292).

- *p13 Fig8(b): There is a black dot without a text caption*

This is T3, we fixed it.

- *p17 l369-372: I am not convinced by this hypothesis, which depends heavily on the nature of the soils and the infiltration model used.*

We modified this discussion point (lines 408-413) based on the hydrological performance of the model for the low and high initial soil moisture events and highlight that our results hint to a greater sensitivity of sediment load to precipitation spatial distribution when the initial SM_0 is low, but that at the same time they do not allow for a clear conclusion (see point (7) above).

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Modelling impacts of spatially variable erosion drivers on suspended sediment dynamics

Giulia Battista[1], Peter Molnar[1], and Paolo Burlando[1]

[1]Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

Correspondence: Giulia Battista (battista@ifu.baug.ethz.ch)

Abstract.

The estimate of suspended sediment load in rivers is ~~often highly problematic because of the strong variability in suspended sediment concentrations with discharge. Previous studies that investigated~~ difficult, because sediment production and transport process at the catchment scale are strongly variable in space and time. Among the sources of this variability ~~highlight the need to explicitly account for the main hydrological processes controlling sediment erosion and transport at the catchment scale, their spatio-temporal variability and interactions with the topography and surface characteristics of~~ are the spatially distributed nature of overland flow as an erosion driver, and of surface erodibility given by soil type and vegetation cover distribution. Temporal variability mainly results from the time sequence of rainfall intensity during storms and snowmelt leading to soil saturation and overland flow.

We present a new spatially distributed soil erosion and suspended sediment transport module integrated in the ~~basin. In this paper we propose a novel physically explicit spatially distributed hillslope erosion and sediment transport model including these erosion drivers, based on the~~ computationally efficient physically based hydrological model TOPKAPI-ETH~~. We investigate its suitability to reproduce the variability of sediment concentrations at the outlet of a pre-alpine river basin in Switzerland and quantify the impacts of key spatially variable~~ , with which we investigate the effects of the two erosion drivers - ~~rainfall~~ precipitation and surface erodibility - on ~~sediment dynamics. Our analysis shows that deterministic modelling can capture a significant part of the~~ catchment sediment fluxes in a typical pre-alpine mesoscale catchment. By conducting a series of numerical experiments, we quantify the impact of spatial variability of the two key erosion drivers on erosion-deposition patters, sediment delivery ratio, and catchment sediment yields.

Main findings are that the spatial variability ~~in suspended sediment concentrations. Spatial variability~~ of erosion drivers affects sediment yield by (i) increasing sediment production due to a spatially variable precipitation, while decreasing it due to a spatially variable surface erodibility, (ii) favoring the clustering of sediment source areas in space, and (iii) decreasing their connectivity to the river network by magnifying sediment buffers. ~~Finally, we discuss the results in the context of the geomorphology and landscape characteristics of our study area and compare our findings with other modelling and empirical studies on sources of sediment concentration variability~~The results highlight the importance of resolving spatial gradients controlling hydrology and sediment processes when modelling sediment dynamics at the mesoscale, in order to capture the key effects of sediment sources, buffers, and hillslope hydrological pathways in determining the sediment signal.

Introduction

Fine sediment ~~transported in suspension by rivers drives and influences important geomorphic and ecological processes~~produced in catchments by upland erosion and transported by rivers as suspended load is an important part of the global sediment budget (e.g. Peucker-Ehrenbrink, 2009) and an important driver of water quality and aquatic biota in rivers (e.g. Bilotta and Brazier, 2008). Human activity strongly interacts with the natural processes of suspended sediment production and transport, on the one hand by practices ~~which~~ that enhance soil erosion, like agriculture, mining and deforestation, and on the other hand with the construction of sediment retention structures ~~like dams (e.g., Syvitski et al., 2005; Montgomery, 2007; Syvitski and Kettner, 2011). The monitoring of suspended sediment concentration is essential to understand how these two opposite disturbances affect the sediment balance.~~ such as dams (e.g., Syvitski et al., 2005; Montgomery, 2007; Syvitski and Kettner, 2011; Borrelli et al., 2017). In the context of enhanced soil erosion, phenomena like the loss of soil productivity, the reduction of water quality due to higher turbidity and concentration of pollutants, and accelerated reservoir siltation are expected (e.g. Pimentel et al., 1987; Davies-Colley and Smith, 2001). The combined effect of enhanced soil erosion and sediment retention by dams modifies the river sediment equilibrium and can result in river incision in the case of sediment starvation, ~~undermining~~ contributing to undermine the stability of bridges and other infrastructures, and ~~eventually in coastal erosion, leading to increased flood risk in coastal areas (Chen and Zong, 1998; Schmidt and Wilcock, 2008)~~leading to coastal erosion (Kondolf, 1997; Chen and Zong, 1998; Schmic. The opposite case of excessive sediment load in rivers may also lead to an increase in flood risk in alluvial floodplains due to sediment deposition ~~(Walling, 2006; Rickenmann et al., 2016)~~(Yu, 2002; Walling, 2006; Rickenmann et al., 2016). The intensity of these effects is expected to grow in the future, as the magnitude and number of highly erosive extreme precipitation events are ~~expected to increase~~ foreseen to increase in some parts of the world due to climate change ~~(e.g. Nearing et al., 2004; Yang et al., 2~~ ~~.~~ and anthropic influence on land cover increases (e.g. Yang et al., 2003; Nearing et al., 2004; Peleg et al., 2019). Therefore, the monitoring and understanding of suspended sediment dynamics is essential to explain how disturbances produced by such human interventions may affect the sediment balance.

~~The most widespread method for sediment yield estimation~~ Fine sediment yield in rivers is usually estimated from intermittent measurements of sediment concentration ~~are~~ by means of sediment-discharge rating curves (see Gao (2008) for a review). However, the development and use of these curves is often highly problematic because of the strong non-uniqueness of suspended sediment concentrations (SSCs)~~. The~~ , especially in small to medium sized catchment (up to 1000 km^2). Here, the same value of discharge (Q) often leads to a wide range of SSCs, producing highly scattered SSC-Q rating curves ~~(e.g., Walling, 1977; Ferguson, 1986; Asselman, 2000; Walling and Webb, 1982; Horowitz, 2003)~~(e.g., Walling, 1977; Walling and Webb. The strong variability in SSC is attributed to the high non-linearity of the sediment production and transport processes in time and space, and the presence of threshold and feedback mechanisms in sediment mobilization ~~(e.g., Fryirs et al., 2007; Bracken et al., 2015;~~ and transfer (e.g., Asselman, 1999; Collins and Walling, 2004; Seeger et al., 2004; Fryirs et al., 2007; Bracken et al., 2015).

~~Drivers of temporal variability in sediment transport are identified in the dynamic nature of meteorological forcing and hydrological conditions, in the differential activation of the dominant sediment sources , and in natural or artificial modifications of hillslope and channel sediment connectivity (e.g. Vercruysse et al., 2017). Geomorphic internal variability may also play a~~

~~role as a driver of temporal variability of soil loss at the plot scale (Kim et al., 2016). Spatial variability in sediment transport is driven by the distribution of sediment sources within the catchment and the transport capacity of the erosive agents, catchment connectivity and efficiency of sediment transport within the stream network (e.g. Vercruysse et al., 2017).~~

~~It is not simple to identify the different sources of variability in sediment production. Some studies have investigated the relationship between hydrometeorological conditions and suspended sediment transport, where~~ Temporal and spatial variability in suspended sediment transport can originate from several sources (see Vercruysse et al. (2017) for a review). Among the sources of temporal variability, the role of hydrometeorological conditions (rainfall, antecedent wetness conditions and runoff) has been widely investigated, with a particular focus ~~has been~~ on the shape and direction of the hysteresis loops of the SSC-Q relation ~~(Dominic et al., 2015; Seeger et al., 2004; Duvert et al., 2010; Zabaleta et al., 2007; Smith et al., 2003). The effects of human landscape modifications on the SSCs have also been explored, for example by looking at the~~ (Smith et al., 2003; Seeger et al., 2004; . Other sources of variability are the exhaustion of preferential sediment sources, the activation of new ones, and changes in the connectivity of such sources to the river network. These aspects have been studied for example as consequences of land use change and flow regulation ~~(Siakeu et al., 2004; Olarieta et al., 1999; Costa et al., 2018). A few studies focused on the spatial distribution of catchment characteristics and erosion drivers at the river basin scale. Among those,~~ (Olarieta et al., 1999; Siakeu et al., 2004; . Variability of sediment transport in space depends on the distribution of sediment sources within the catchment, the catchment sediment connectivity, and the efficiency of sediment transport within the stream network. Wass and Leeks (1999) related differences in sediment loads across the basin to geomorphic and climatic gradients~~. Some studies~~ , while Fryirs and Brierley (1999) and Lang et al. (2003) reconstructed the change ~~in time~~ of sediment sources ~~on hillslopes~~ in time and their coupling with the channels~~(Fryirs and Brierley, 1999; Lang et al., 2003) and developed conceptual frameworks for sediment connectivity at multiple spatial and temporal scales (Fryirs, 2013; Bracken et al., 2015).~~ . The problem of catchment sediment connectivity has been addressed from a conceptual point of view, by introducing the ideas of structural and functional connectivity, to distinguish between the physical connection among landscape units and the connectivity generated by the system process interactions (Wainwright et al., 2011; Fryirs, 2013; Bracken et al., 2015). Based on these concepts, several indices have been introduced to assess sediment connectivity in a river basin (see Heckmann et al. (2018) for a review).

The above studies highlight the need to account for both types of variability (~~time and space~~temporal and spatial) in order to investigate basin sediment dynamics. ~~Therefore, when modelling suspended sediment transport at the catchment scale it is necessary to explicitly account for the~~ Including this variability is especially important at the medium and large catchment scale and in mountainous environments, where the gradients of climatic and physiographic variables are most relevant. Few studies have focused specifically on the impacts of spatially variable erosion drivers on suspended sediment dynamics in such environments. A systematic investigation of this research gap can be performed by means of numerical models that include the main hydrological processes, their temporal dynamics and distribution in space, as well as their interaction with the topography and morphology of the basin. ~~Moreover, there is a need for these models to be suitable for medium to large scale catchment applications, where the gradients of climatic and physiographic variables are more relevant. Such models are then expected to reproduce the spatio-temporal variability of suspended sediment concentrations and to serve as a tool to investigate its causes.~~

~~Several existing distributed soil erosion sediment transport~~ Several existing models are partially suitable for this task. ~~However, most of them are~~ The main limitations are that many are only suitable for event-applications (Answers (Beasley et al., 1980), KINEROS (Woolhiser et al., 1990), WEPP (Nearing et al., 1989)) or present ~~highly simplified , if not absent, hydrological components,~~ simplified hillslope hydrology and runoff formation solutions, as in the case of WATEM/SEDEM (Van Rompaey et al., 2001)~~or~~ , landscape evolution models, e.g. ~~Cesar-Lisflood~~ Caesar-Lisflood (Coulthard et al., 2013), SIBERIA (Hancock et al., 2000)~~.~~, or some large-scale sediment flux models, e.g. WBMsed (Cohen et al., 2013) and Pelletier (2012) . More suitable approaches are tRIBS (Francipane et al., 2012), which includes ~~a physically based long-term hydrological component , however it is only suitable for small scale applications. On the other end of the spectrum, Tsuruta et al. (2018) developed~~ physically based hydrological component suitable for long-term process simulations, and DSHVM (Doten et al., 2006) , which features a detailed hydrology-vegetation component and sediment module. However, the number of processes represented in these two models, requires a high computational power and their applications have so far been limited to small basins and/or short time scales. Finally, Tsuruta et al. (2018) present a spatially distributed model especially for large basins, which, being based on a land-surface model, ~~presents~~ features an approximated coarse-scale representation of hydrological and sediment connectivity on the hillslopes.

In this work, we ~~propose a novel spatially distributed hillslope erosion and sediment transport model, obtained by integrating a sediment production and transport component~~ present a new modelling approach especially suitable for alpine catchments with highly variable climate and complex topography, that integrates a new spatially distributed soil erosion and suspended sediment transport module within the computationally efficient~~physically explicit~~ , physically based hydrological model TOPKAPI-ETH (Fatichi et al., 2015). ~~This hydrological model contains a physically meaningful representation of hydrological processes and is at the same time suitable for large scale, high resolution and long term simulations. We present the application of the model to a medium-size~~ The model combines unsteady simulation of surface and subsurface water fluxes with a simple hillslope erosion and sediment transport component. The sediment component is simple by design, to avoid over-parameterization and to maintain computational efficiency enabling applications to medium and large catchments. The model allows continuous high spatial resolution (Δx=100 m) simulations to track overland flow and hillslope sediment transport by local changes in soil moisture dynamics produced by rainfall, snowmelt and lateral drainage over long periods of time. The model also allows high temporal resolution (Δt=1 hr) simulations that capture fast runoff response to the hydrological drivers, which, together with the topographically driven flow routing, reproduces the connectivity of water and sediment pathways in the catchment over time.

The overall aim of this research is to provide a state-of-the-art catchment hydrology-sediment modelling framework to better understand the sources of variability in suspended sediment concentrations and their effects on predictions of sediment yield. Accordingly, we conducted numerical experiments on a mesoscale pre-alpine ~~river basin and we investigate its suitability to reproduce variability in sediment transport. We focus specifically on the impact of spatially variable~~ river basin, where we turned on and off the spatial variability in two key erosion drivers - rainfall and surface ~~erodibilty~~ erodibility - to quantify their individual and combined effect on suspended sediment ~~dynamics at the catchment scale. We aim at addressing the following~~ mobilization and transfer. We address the following specific research questions: (~~RQ 1) To which extent can a physically~~

~~explicit spatially distributed deterministic model capture the variability of suspended sediment concentrations? (RQ 2) How does the spatial variability of key erosion drivers affect the spatial organization of suspended sediment transport, i.e. the location and productivity~~ RQ1) Does fully distributed physically-based hydrology-sediment modelling predict variability in SSC-Q relations that is in agreement with observations? We argue which key hydrological processes are needed in such a model and why. (RQ2) Can we identify the location of sediment sources and ~~their connectivity to the river network? (RQ 3) How does sediment yield at the outlet depend on the spatial organization of suspended sediment transport?~~ quantify their productivity and connectivity with such a modelling approach? We assess the effect of the spatial distribution of rainfall and surface erodibility on hillslope erosion-deposition patterns and sediment mobilization and we quantify the sediment source connectivity to the river network by analysing the sediment delivery ratio along the main stream and in tributaries. (RQ3) Is the effect of spatially distributed erosion drivers visible in sediment yield at the catchment outlet? We show how integration of the spatially variable inputs in space impacts sediment yield under different scenarios.

Methods

~~The Kleine Emme river basin is a glacier-free pre-alpine catchment located in central Switzerland. It has an area of 477 km^2, an elevation range of 430-2300 m. a.s.l. and a mean annual precipitation of 1650 mm (Figure 1a). The average discharge at the outlet is 12.6 m^3/s. The catchment is mostly natural, with more than 50% of the catchment surface covered by forest and grassland (Figure 1c). The Kleine Emme was chosen as a study basin because the natural regime of water and sediment flow is almost unaltered. No use of water for irrigation or hydropower is known and sediment-retaining infrastructures are absent. Moreover, the absence of glaciers means that fine sediment production in the basin is mostly driven by overland flow. Finally, the diverse geomorphology of the basin has been subject of several studies and long-term estimates of denudation rates are available (e.g., Schwab et al., 2008; Dürst Stucki et al., 2012; Schlunegger and Schneider, 2005; Van Den Berg et al., 2012; Clapuyt et al., .~~

~~Measurements of precipitation, air temperature and sunshine radiation are available from automatic weather stations located inside or in the vicinity of the basin operated by MeteoSwiss. The information about the spatial distribution of precipitation inside the basin area is available from the 1x1 km daily gridded product of MeteoSwiss RhiresD (Frei and Schär, 1998; Schwarb, 2000). Streamflow is monitored at Werthenstein and at the basin outletby the Federal Office of the Environment and at Sörenberg by the Canton Luzern (Figure 1). SSCs have been manually sampled at the outlet since 1974, but with a regular frequency of two samples a week only since 2004. The information about soil type and depth for the basin is available from the soil map of Switzerland (Bodeneignungskarte, 2012) (Figure 1b). Land cover is provided by the Corine Land Cover (Figure 1c).~~

~~(a) Digital Elevation Model (DEM) of the Kleine Emme basin and location of discharge gauges (source SwissAlti3D, 2017), (b) Soil depth, derived from the Swiss soil map (Bodeneignungskarte, 2012), (c) Land cover derived from Corine Land Cover map (CLC, 2014).~~

Hydrology-sediment model description

The model we present in this work is an extension of the hydrological model TOPKAPI-ETH (Fatichi et al., 2015), which we integrated with a new hillslope erosion and channel suspended sediment flow module. The TOPKAPI-ETH hydrological model was chosen because of its spatially distributed nature and physically ~~explicit~~ based representation of the major hydrological processes~~.~~, combined with a reasonably contained computational demand. The model is based on a regular square grid discretization in space and a 3-layer vertical discretization of the subsurface. The river network is identified in the domain by means of a flow accumulation algorithm based on the topography. The transition between hillslope and channel process description, i.e. the beginning of the model river network, is set by a user-defined critical upstream area, or river initiation threshold RT, above which water flow is modelled as channel flow. Each river network cell can be fully or partially covered by the stream, depending on the actual stream width and grid cell resolution.

In TOPKAPI-ETH ~~2D~~ surface and subsurface flow is simulated by the kinematic wave approximation, with resistance to flow given by surface roughness and soil transmissivity as a function of soil properties. Water may saturate the soil locally and lead to overland flow generation by saturation excess or by infiltration excess in case of high rainfall intensities. Soil is dried by evapotransporation~~and drainage and the~~, lateral drainage and percolation to groundwater storage. The model includes snow cover accumulation and melt, which are important in the water balance of ~~Alpine basins(see Fatichi et al., 2015). Moreover, the model is particularly suitable for catchment scale,~~ alpine basins. For further details about the model see Fatichi et al. (2015) . TOPKAPI-ETH allows long-term, high resolution simulations (~~hourly time step~~ time step Δt=1hr, grid size Δx=100 m) in medium and large catchments (>1000 km^2), ~~grid resolution ~100 m) ,~~ even when integrated with a sediment ~~production and transport~~ mobilization and transfer component, since the kinematic wave approximation of the surface and subsurface flow routing are solved analytically~~and thus keep~~, thus keeping the model computationally efficient (Liu and Todini, 2002).

In the ~~newly developed~~ new sediment module of TOPKAPI-ETH, the ~~generation~~ mobilization and routing of fine sediment ~~is assumed to take place~~ on the hillslopes ~~by the erosive~~ takes place by action of overland flow~~. The eroded sediment is routed downstream via overland flow~~, which is assumed to transport sediment at its maximum capacity~~and can deposit or erode~~. As a consequence, deposition and erosion can occur on the hillslopes at a rate D [kg m^{-3} s^{-1}] depending on the hydraulic and topographic properties of the cells along the flow path:

$$D = \nabla \cdot q_s, \tag{1}$$

where q_s [kg m^{-2} s^{-1}] is the overland flow transport capacity, modelled following Prosser and Rustomji (2000) as a function of the specific overland flow discharge q [m^3 s^{-1}] and the surface slope S:

$$q_s = \alpha q^{\beta} S^{\gamma}, \tag{2}$$

where β and γ are transport exponents, and α [kg s$^{0.4}$ m$^{-4.8}$] is a calibration parameter that captures the effect of land surface and soil properties on erosion and sediment transport. The sediment flux q_s is directed to the downstream cell with the steepest gradient. Sediment inflow into a cell can be from one or more upstream cells.

Once the sediment mobilized and routed on the hillslopes reaches the channel, it is assumed to move as suspended sediment load. The suspended sediment flux in the river network is treated as an advection process and solved with the same numerical methods used for water flow. The 1D equation of suspended sediment flux in the channel, integrated over the river cross-section, is:

$$\frac{\partial AC}{\partial t} = E - \frac{\partial QC}{\partial x}, \tag{3}$$

where Q [$\mathrm{m^3\ s^{-1}}$] is the river discharge, C [$\mathrm{g\ m^{-3}}$] is the SSC, A [$\mathrm{m^2}$] is the cross-section area of flow and E ~~is the term representing the~~ [$\mathrm{g\ m^{-1}\ s^{-1}}$] represents the exchange of sediment with the bed and local sediment sources. By following the reasoning of Liu and Todini (2002), ~~eq.~~ Equation 3 can be integrated ~~over a grid cell~~ along the length of the grid cell (i.e. in the flow direction), within which the values of the variables are assumed to be constant, and then solved analytically as a first-order ordinary differential equation:

$$\frac{\partial V_i C_i}{\partial t} = E_i X + Q_{in} C_{in} - \frac{U_i}{X} C_i V_i, \tag{4}$$

where X ~~is the~~ [m] is the length of the grid cell size, V_i [$\mathrm{m^3}$] the volume of water inside a cell ($V_i = A_i X_i$), U_i [$\mathrm{m\ s^{-1}}$] the mean flow velocity, C_i and E_i are the mean values of C and E inside the grid-cell. Q_{in} and C_{in} are the discharge and sediment concentration entering the cell i from the upstream ~~grid-cell~~ grid cell $(i-1)$.

Study site

To investigate the research questions outlined above, we chose the Kleine Emme river basin, a pre-alpine catchment located in central Switzerland, because here the natural regime of water and sediment flow is almost unaltered. The basin has an area of 477 $\mathrm{km^2}$, an elevation range of 430-2300 m. a.s.l. and a mean annual precipitation of 1650 mm (Figure 1a). The mean annual discharge at the outlet is 12.6 $\mathrm{m^3/s}$. The catchment is mostly natural, with more than 50% of the catchment surface covered by forest and grassland (Figure 1c). No use of water for irrigation or hydropower is known and sediment-retaining infrastructures are absent. Moreover, the absence of glaciers means that fine sediment production in the basin is mostly driven by overland flow and rainfall processes. Finally, the diverse geomorphology of the basin has been subject of several studies and long-term estimates of denudation rates are available (e.g., Schlunegger and Schneider, 2005; Schwab et al., 2008; Dürst Stucki et al., 2012; Van Den
.

Measurements of precipitation, air temperature and sunshine duration are available from automatic weather stations located inside or in the vicinity of the basin operated by MeteoSwiss. The information about the spatial distribution of precipitation inside the basin area is available from the 1x1 km daily gridded product of MeteoSwiss RhiresD (Frei and Schär, 1998; Schwarb, 2000) . Streamflow is monitored at Werthenstein and at the basin outlet by the Federal Office of the Environment (FOEN) and at Sörenberg by the Canton Luzern (Figure 1a). FOEN also provided the cross section measurements for the main channel of the river and measurements of suspended sediment concentration. SSCs have been manually sampled at the outlet since 1974, but with a regular frequency of two samples a week only since 2004. Because of the low temporal resolution of these measurements, which is typical of many river sediment monitoring networks, we expect this dataset to miss extreme SSCs generated by flood

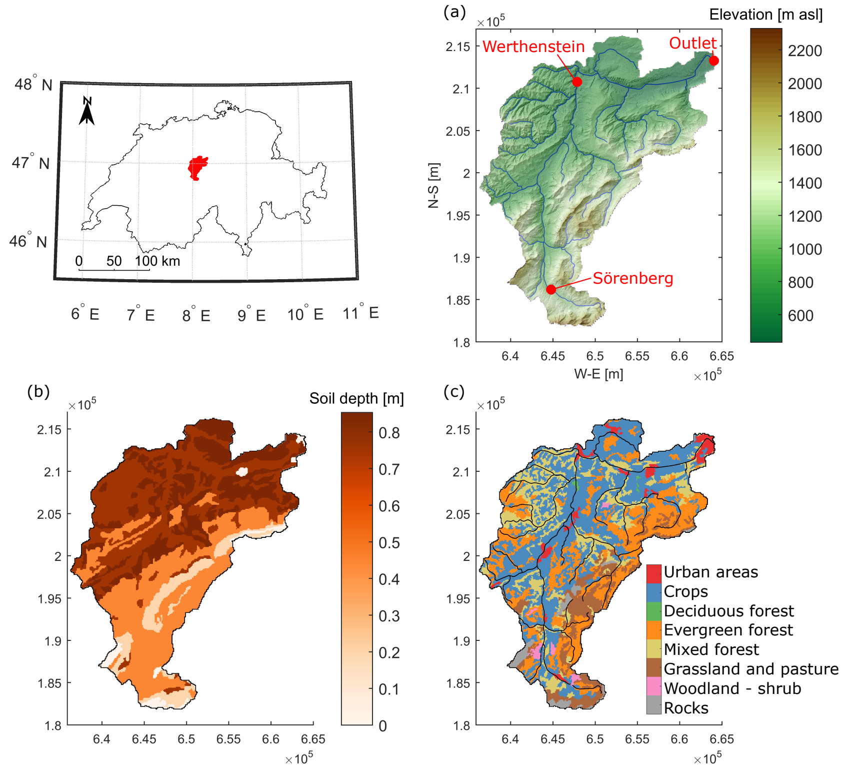

Figure 1. (a) Digital Elevation Model (DEM) of the Kleine Emme basin and location of discharge gauges (source SwissAlti3D, 2017), (b) Soil depth, derived from the Swiss soil map (Bodeneignungskarte, 2012), (c) Land cover derived from Corine Land Cover map (CLC, 2014) .

events or very localized sediment sources. Finally, the information about soil type and depth for the basin is available from the soil map of Switzerland (Bodeneignungskarte, 2012) (Figure 1b) and land cover is provided by the Corine Land Cover dataset (Figure 1c).

Model setup and calibration

Hydrology

Given the period of availability of suspended sediment measurements in the Kleine Emme, the simulation was set up for the years 2003 to 2016, where the first year is considered a warm-up period. The meteorological input data required by the hydrological component of TOPKAPI-ETH are hourly precipitation, air temperature and cloud cover. The precipitation input file was created by combining station and gridded precipitation datasets following the approach of Paschalis et al. (2014). In this approach hourly precipitation measured at the rain gauges was spatially interpolated to match the spatial distribution of the daily precipitation reported by the gridded RhiresD dataset. The hourly time series of measured air temperature were

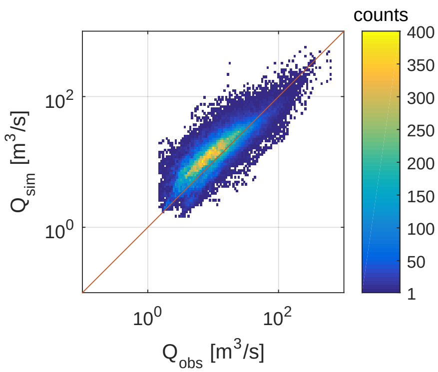

Figure 2. ~~Density~~ Performance of the hydrological model: density plot of observed vs simulated hourly discharges at the outlet of the river basin for the period 2004-2016.

extrapolated across the model domain to different elevations with a temperature lapse rate of ~~of 5.5~~ -5.5 °C/km. The cloud cover transmissivity was derived from the hourly sunshine duration measurements following the empirical relation proposed by Kasten and Czeplak (1980).

The model was run at a ~~100x100 m^2~~ Δx=100 m spatial resolution and a constant time step ~~of 1-hour~~ Δt=1 hour. To initiate the model calibration, realistic values of the hydrological parameters were assigned based on the soil characteristics and previous investigations (Paschalis et al., 2014; Pappas et al., 2015). The soil hydraulic conductivity and the residual and saturation soil water content parameters were then adjusted in order to maximize the performance of the hydrological model in terms of correlation coefficient ~~and~~ (r), Nash-Sutcliffe efficiency (~~NSE) for runoff~~ NSE) and root mean square error (RMSE) for discharge measured at three streamflow gauging stations.

The final configuration of the hydrological model performed very well in reproducing the observed discharge at the outlet and at Werthenstein (see Table 1 and Figure 2). Discharge data are available at a sub-daily resolution at Sörenberg only from the year 2005, therefore the evaluation of the performance at this station does not consider the first year of simulation. The model performance at this station is slightly worse, probably also due to the lower accuracy of the measurements, but still satisfactory.

Setup of the sediment module

The inputs needed to run the hillslope erosion and suspended sediment transport modules are the parameters α, β and γ in ~~eq. 2and parameter E in eq. 3.~~ Equation 2. The β and γ parameters are assumed spatially uniform and equal to 1.4, following Prosser and Rustomji (2000). The parameter α contains information about the soil and land surface properties that influence the rate of soil erosion. We derived the spatial distribution of α by ~~intersecting the~~ the product of the soil erodibility parameter K of the Universal Soil Loss equation (USLE), computed for Switzerland by Schmidt et al. (2018), and the land use USLE parameter C, which we derived from Yang et al. (2003) (see Figure S1). In this way we implicitly account for the influence

Table 1. Hydrological performance for the simulation period 2004-2016 at the three flow monitoring stations in terms of correlation coefficient (r), Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) for data simulated at the hourly resolution and aggregated to daily, monthly and annual values.

	Outlet			Werthenstein			Sörenberg (2005-16)		
	r	NSE	RMSE $[m^3/s]$	r	NSE	RMSE $[m^3/s]$	r	NSE	RMSE $[m^3/s]$
Hour	0.84	0.69	0.75	0.84	0.65	0.74	0.63	0.72	1.43
Day	0.91	0.80	0.53	0.90	0.78	0.52	0.80	0.56	0.83
Month	0.93	0.76	0.28	0.92	0.77	0.26	0.88	0.77	0.38
Year	0.93	-	0.18	0.92	-	0.13	0.79	-	0.10

of particle size distribution, organic matter content, soil structure, permeability, surface roughness and vegetation cover in determining the spatial distribution of surface erodibility. A comparable approach is proposed by Hancock et al. (2017).

The ratio between the product of C and K of the different classes was then kept constant in the calibration process and α was calibrated by multiplying the CK values by a spatially constant parameter α_1:

$$\alpha(x,y) = \alpha_1 C(x,y) K(x,y), \tag{5}$$

where x and y are coordinates in space. With respect to ~~the~~ channel processes, the ~~time resolution of the suspended sediment measurements at the outlet is not sufficient to quantify the exchange of suspended sediment between the water column and the river bed and the contribution of localized channel sources. For this reason, in this work the~~ water column-bed exchange and local sediment source term E in equation 3 ~~has been assumed equal to zero. The absence of fine sediment exchange with the bed is a reasonable assumption for this case study, as~~ is unknown. In the Kleine Emme significant deposits of fine sediment ~~are not present~~ in the river bed are not present and bedrock is often exposed, indicating an efficient fine sediment transport downstream (Schwab et al., 2008). ~~Neglecting localized channel sources is instead~~ Furthermore, the infrequent SSC measurements do not allow to quantify the term explicitly. This leads us to assume that E=0 for this river. However, by setting E=0 we neglect also local sediment sources along the channels, which is probably an approximation of the sediment production processes of the ~~basin.~~ specific case study. Also on the hillslopes, localized sediment sources are not explicitly modelled and are present only insofar they are represented by high C and K values. The lack of explicit inclusion of point sediment sources and their modelling is a limitation of the current ~~model~~approach, which we will address in future work.

Calibration of the sediment module

We found that the parameters that have the highest influence on matching the observed SSC at the outlet are the river initiation threshold RT, i.e. the extension of the modelled river network, ~~dependent on the river initiation threshold, RT,~~ and the α_1

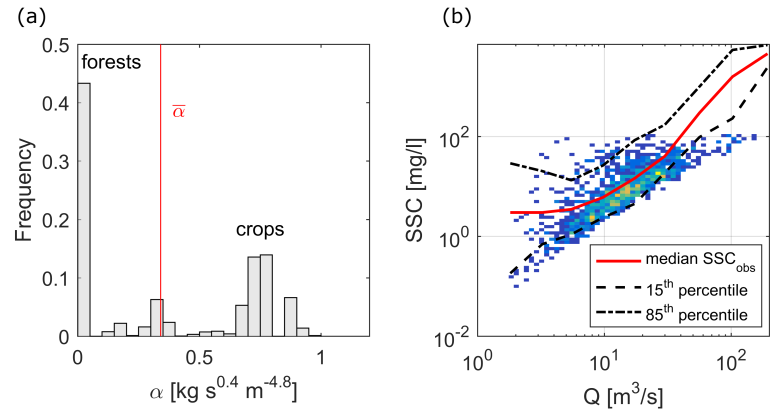

Figure 3. (a) Frequency distribution of the calibrated surface erodibility parameter α, with mean α indicated with the red line; (b) density plot of the simulated SSC at outlet compared with measurements, the lines show the median (red) and 15^{th} and 85^{th} percentile (black dashed) of the observations.

constant~~. RT defines the upstream area below which water flow is described as overland flow and above which it is described as channelized flow in TOPKAPI-ETH. This parameter~~ , defining the soil erodibility. RT has a small influence on discharge, as shown by Table S1, while it is a relevant parameter for the modelling of hillslope erosion and sediment transport. Since fine sediment ~~production~~ mobilization can only take place on the hillslopes, the extension of the channels onto the hillslopes influences the magnitude of the sediment input into first-order channels and subsequently downstream through the river network.

~~The best combination of the calibration parameters was chosen by minimizing the errors between the~~ In the calibration of the model we focused on the lowest 85^{th} percentile of the measurements, because flood events in the SSC data are likely under-sampled, due to the monitoring strategy, and the model is expected to underestimate the SSC extremes due to the simplified representation of sediment mobilization processes. The calibration was performed by matching the trend and the dispersion of the measured and modelled ~~slope of the~~ SSC-Q cloud of points~~and~~ . This was done by visual matching and by comparing the mean and variance of the observed SSCs. The final calibrated parameters ~~were~~ are α_1=0.0138 kg m$^{\cancel{2.2}}$ ~~s$^{-3.4}$~~ $^{-1.8}$ s$^{-2.6}$ and RT=0.4 km^2. The ~~resulting spatial mean of α is 0.3412 $kg\ m^{-0.8} s^{-0.4}$. The~~ histogram of α and its spatial distribution are shown in Figures 3a and 7d, respectively; the spatial mean of α is 0.3412 kg s$^{0.4}$ m$^{-4.8}$. We note that the calibrated river initiation threshold is very close to the drainage area that Schlunegger and Schneider (2005) propose as the threshold area at which channelized processes ~~become dominant on~~ start dominating over hillslope processes in the development of the landscape in this study basin (0.1-0.2 km^2).

Using this parameterization, the ~~slope of the~~ measured SSC-Q cloud of points is captured very well for moderate discharges (Figure 3b), whereas the ~~model underestimates the~~ concentrations at highest discharges ~~. If we limit the observed SSC dataset at its 85~~are underestimated, as expected. Overall, 90.4% of the simulated SSCs fall within the 5^{th} ~~percentile~~ and ~~compare it with the simulated concentrations~~ 95^{th} percentile of the observations and, if the simulated SSCs are sampled at the hours of ~~collection of the suspended sediment bottle samples, the model reproduces the~~ observations and compared to the observations limited to their 85^{th} percentile, the observed SSC mean and variance ~~of the observed concentrations~~ are reproduced with very small errors ($\overline{SSC}_{sim} = 12.40\ mg/l$, $\overline{SSC}_{obs} = 12.20\ mg/l$; $\sigma^2_{sim} = 210.47\ mg/l$,$\sigma^2_{obs} = 233.15\ mg/l$) (Figure S2). We attribute the underestimation of high sediment concentrations (above 85^{th} percentile) to ~~the simplified representation of the sediment production~~ missing localized sediment sources, i.e. mass wasting processes in the model~~and in particular to the lack of~~ , which are responsible for point sediment sources, like landslides, debris flows and bank erosion.

~~**Simulation experiments**~~

Erosion driver numerical experiments

In order to investigate the ~~causal processes explaining~~ processes leading to the scatter in the SSC-Q relation and how they affect the spatial organization of sediment transport, we performed simulation experiments ~~which~~ that quantify the role of spatial variability in two key erosion drivers - precipitation and surface erodibility. Precipitation is the main hydrological driver of hillslope erosion through the overland flow term q^{β} in ~~eq. 2. Surface~~ Equation 2, while surface erodibility is represented by the parameter α in ~~eq.~~ Equation 2.

We designed four numerical experiments by combining spatially variable and/or uniform distributions of the two erosion drivers (Figure 4). The reference experiment (SIM 1) accounts for the highest level of complexity by considering both precipitation and erodibility variable in space. This is the experiment with which the model was calibrated (see section). The second experiment (SIM 2) aims to quantify the role of the spatial variability in precipitation, by reducing it to be uniformly distributed in space. The temporal variability was preserved by setting the hourly precipitation in each cell equal to the mean hourly distributed precipitation over the catchment. The third experiment (SIM 3) is designed to investigate the role of the spatial variability in surface erodibility by reducing it to uniform surface erodibility throughout the basin, equal to the mean value of the calibrated spatial distribution of α. ~~We completed the set of simulations by performing a~~ A fourth experiment (SIM 4), where the spatial variability in both drivers was reduced to uniform~~precipitation distribution and uniform surface erodibility,~~ , was run to quantify the combined effect of the two erosion drivers.

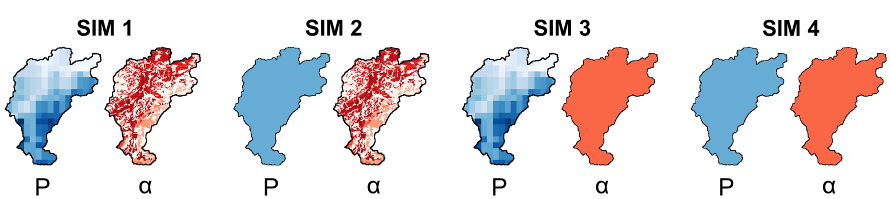

Figure 4. Summary of model runs: in SIM 1 sediment ~~production~~ mobilization and ~~transport~~ transfer are driven by a spatially distributed precipitation (P) and surface erodibility (α), in SIM 2 and SIM 3 the spatial variability in precipitation and surface erodibility have been removed, respectively, and in SIM 4 both spatial variabilities have been removed.

Results

In this chapter, in section 3.1 we evaluate the spatio-temporal variability in sediment ~~production~~ mobilization and transport and the scatter of the SSC-Q relation it produces by the fully distributed erosion drivers in SIM 1 (RQ 1). The spatial ~~organization~~ distribution of suspended sediment transport is then evaluated in subsequent sections and related to the hydrological response of the basin (RQ 2). Here we compare the activation of sediment sources and the sediment ~~production~~ mobilization in the four simulations (section) and we quantify the connectivity of sediment ~~transport~~ transfer by means of the sediment delivery ratio (section). Finally, in section , we analyze ~~how the spatial organization of suspended sediment transport affects the~~ the sediment ~~loads in the four simulations (RQ 3).~~ load at the outlet as a function of the sediment spatial properties observed in the different scenarios (RQ3).

Spatio-temporal variability in erosion and sediment transport

~~Figure 3 shows that, with the exception of the highest and lowest discharges, the~~ The modelled scatter in the SSC-Q relation ~~compares well with the variability of the measured concentrations (explaining~~ in SIM 1 explains about 30% of the measured concentration range for discharges up to the 85^{th} percentile~~)~~, while it shows a much more significant underestimation for the highest flows (Figure 3b). For a comparison between the SSC-Q scatter generated by the different scenarios of erosion drivers, the reader is referred to Figures S4 and S5. In the following we analyse the sources of this variability, by showing the time series of discharge, the sediment load and concentration for one representative year (Figure 5a) and by analysing the pattern of erosion and deposition across the basin from the entire simulation period (Figure 5b).

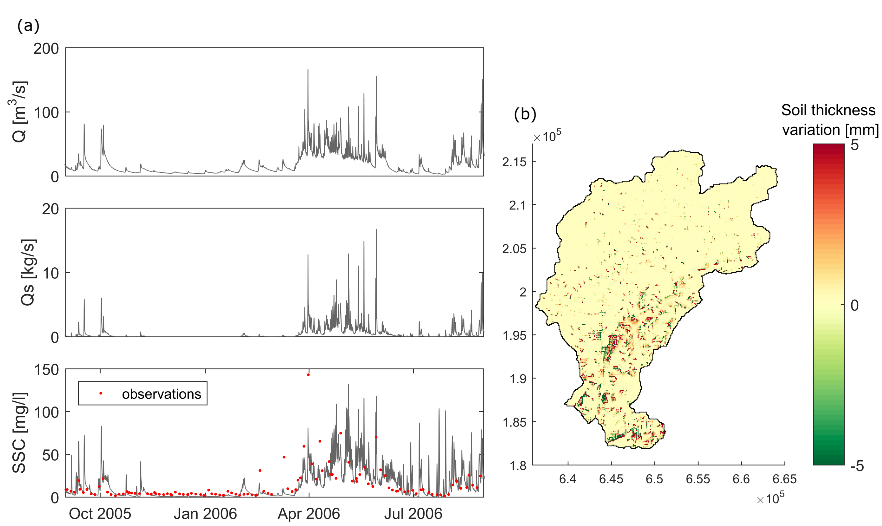

Figure 5. (a) Time series of hourly modelled discharge Q, suspended sediment load Qs and concentrations SSC for one year at the outlet~~,~~. The red dots in the SSC time plot show the observed values. (b) ~~change~~ Change in soil thickness at the end of the 13-year simulation. Positive values indicate erosion, negative values indicate deposition.

High sediment fluxes in April and May, which are evident both in observations and in the model (Figure 5), indicate the contribution of snowmelt to discharge and the erosion of the surface by widespread overland flow. Summer events (storms) provide a small contribution to the yearly sediment yield, however, they generate some of the highest sediment concentrations in the model even though the runoff remains low. As expected, high SSCs are not observed in the measurements during summer, because sediment is rarely sampled during summer floods (see section). In winter months, snow covers the majority of the catchment and maintains the sediment flux very close to zero in both observations and simulations (Figure 5a).

Most of the erosion is simulated in the south-eastern part of the basin, where slopes are steeper, soil is thinner and the highest precipitation, snow accumulation and melt occur (Figure 5b). In these regions, it is easier to saturate the soil ~~layer~~ and generate runoff over larger areas that merge and generate ~~sheets~~ connected areas of overland flow, thus producing wide erosional ~~areas~~ surfaces on steep mountain flanks. Deposition is simulated at the valley bottoms or at locations of slope reduction. In the north-western part of the basin, overland flow remains constrained to the channel headwaters due to the deeper soil and to the higher drainage density of the area. This distribution of erosion is coherent with the different geomorphological characteristics of the two areas of the basin, as further discussed in section . We observe that, because of the transport capacity approach ~~applied~~ in the hillslope transport module, areas of strong erosion ~~often come~~ are often associated with significant deposition downstream. In the following, we will refer to these areas of strong erosion as sediment source areas.

The mean annual suspended sediment load generated by SIM 1 is ~~$1.42\ 10^4\ t/y$~~ 1.42 10^4 t/y, which is ~~an underestimation of the $2.83\ 10^5\ t/y$~~ significantly lower than the 2.83 10^5 t/y computed from the measurements at Littau by Hinderer et al. (2013). Consistently, the mean annual erosion rate of ~~$0.07\ mm/y$~~ 0.07 mm/y underestimates the denudation rates derived from ~~^{10}Be~~ ^{10}Be samples in the Entlen and Fontanne ~~by Van Den Berg et al. (2012), Wittmann et al. (2007)and Norton et al. (2008)~~ sub-basins by Wittmann et al. (2007), Norton et al. (2008) and Van Den Berg et al. (2012) (between 0.38 and 0.52 mm/y), which are from active erosion areas and integrate over a much longer time span of about 10^4 years. The ~~underestimation~~ lower estimates of sediment load and erosion rates by our model compared to such data is expected~~and is attributable to fact that we do not aim to reproduce the largest measured sediment concentrations~~, given the underestimation of SSC at high flows by the model. This limitation will be further discussed in section .

Sediment sources and sediment production

~~The~~ To interpret the effect of the spatial variability ~~in~~ of precipitation and surface erodibility on ~~the~~ sediment transport, in Figure 6 we compare the hydrological response of the basin in the four simulations in terms of the mean annual discharge Q_{mean}, annual flood Q_{max}, coefficient of variation CV of the hourly discharge at the basin outlet, and mean annual overland flow runoff over the basin Q_{OFmean}. Figure 6 indicates that uniform precipitation (SIM 2 and 4) is less efficient in producing runoff (Q_{mean}, Q_{max} and Q_{OFmean}) and therefore has a lower erosive power. Spatially variable precipitation (SIM 1 and 3) produces a greater flow variability, because it allows to distinguish between convective rainfall patterns, which affect confined regions of the basin with a specific hydrological response, and stratiform rainfall patterns which affect the entire basin with lower precipitation intensities.

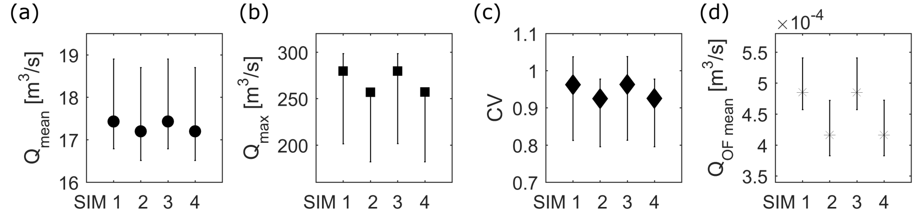

Figure 6. Comparison of the hydrological response of the basin in the four simulations: (a) mean annual discharge Q_{mean}, (b) annual flood Q_{max} and (c) the coefficient of variation CV of the hourly discharge at the basin outlet, and (d) the mean annual overland flow runoff over the basin Q_{OFmean}. The markers indicate the mean values and the lines the interval between the 25^{th} and 75^{th} percentile of the distribution from hourly data over the entire simulation period.

The sediment response of the basin in the four simulations is compared in the following by looking at the distribution of sediment source areas ~~is shown in Figure 7 , where SIM 1,~~ and their productivity. Figure 7 compares soil thickness variation in SIM 2 and 3 ~~are compared.~~ respectively to SIM 1. Figures 7b and 7c show the difference between the variable and uniform precipitation maps for erosion and deposition, respectively. Similarly, Figures 7e and 7f show the difference between the variable and uniform surface erodibility maps for erosion and deposition separately.

The results show that with uniform precipitation, erosion and deposition are reduced in the south-eastern part of the basin and increased in the north-western (Figure 7b and 7c). The overall patterns reflect the average spatial distribution of precipitation in the Kleine Emme catchment for the years 2003-2016, with the highest mean rain intensities associated with more erosion (Figure 7a). Uniform surface erodibility increases sediment erosion and deposition in the forested areas and reduces them in ~~crops~~crop areas (Figure 7e and 7f). In both cases, the overall effect of removing the spatial variability in erosion drivers is a more uniform distribution of the sediment source areas across the basin.

To quantify the erosional power of the four combinations of erosion drivers, we computed the total sediment mass detached yearly across the whole basin (referred to as sediment production) in the four simulations. The distribution of the yearly sediment production with interannual variability is reported in Figure 8. We observe that the removal of spatial variability generates two opposite effects for precipitation and surface erodibility. Sediment production increases when removing the spatial variability in surface erodibility and decreases when removing the spatial variability in precipitation, coherently with the reduced erosive power observed in Figure 6. In SIM 4 the balance between the two opposing effects determines a slight overall reduction in sediment production. The differences between the scenarios are within natural interannual variability in sediment production, but they are all statistically significant for change in median.

Connectivity of sediment ~~transport~~transfer

The connectivity of sediment ~~transport~~transfer, i.e sediment source areas linked to the river network, within the catchment for the different simulation configurations has been quantified by means of the sediment delivery ratio (SDR). The SDR is defined according to Walling (1983) as the ratio of the sediment delivered at the outlet of a selected area to the gross erosion in that

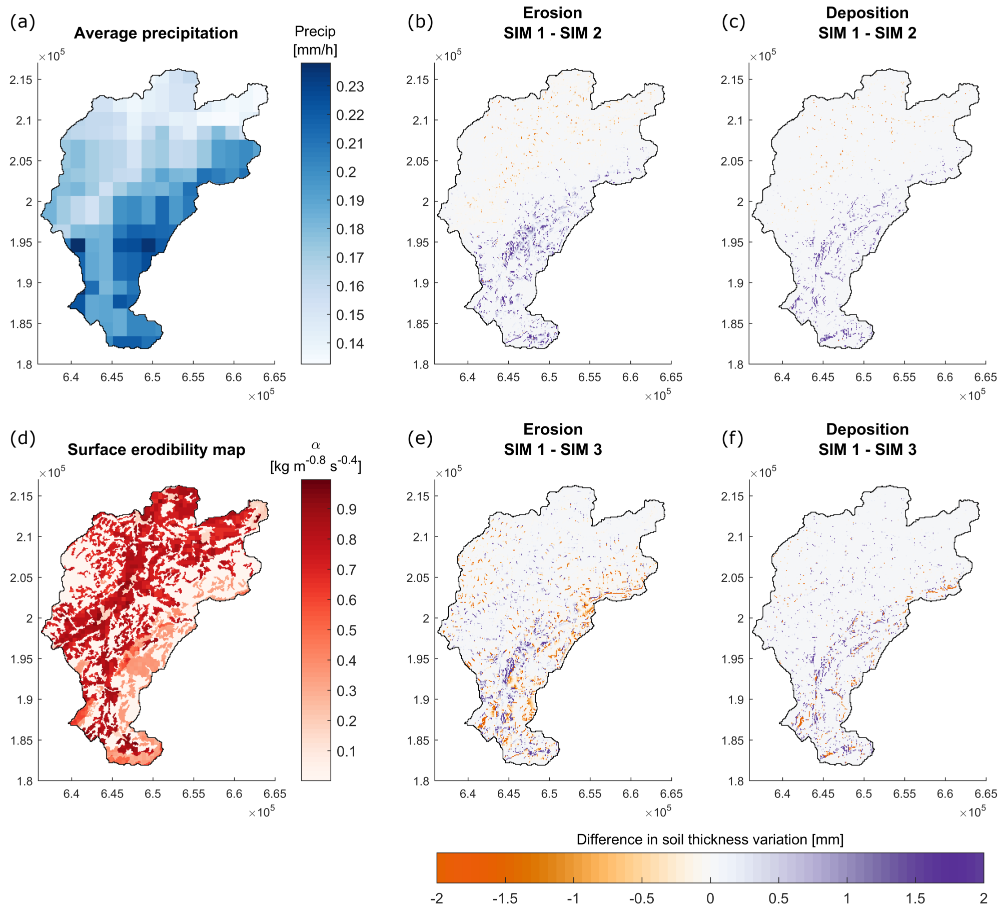

Figure 7. (a) Average spatial distribution of precipitation intensity for the period ~~2003-2016~~2004-2016, (b, c) difference between erosion/deposition generated by distributed and uniform rainfall in 13 years, (d) spatial distribution of calibrated surface erodibility α, (e, f) difference between erosion/deposition generated by distributed and uniform surface erodibility in 13 years. A positive value indicates that ~~distributed~~ uniform precipitation or surface erodibility determines ~~more~~ less erosion/~~less~~ more deposition than ~~uniform~~ variable precipitation or surface erodibility.

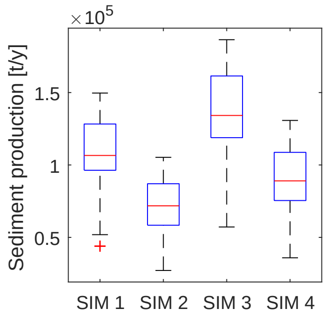

Figure 8. Sediment production in the basin as total sediment detached ~~over a year~~annually for the four simulations. Boxplots (median, interquartile range and outliers) show the internal variability in the period 2004-2016.

area. The mean annual SDRs, which were computed at the outlet point of the main tributaries and at several cross-sections along the main channel, are reported in Figure 9 as a function of the drainage area.

Sediment connectivity along the main channel shows an increasing trend as a function of the upstream area for ~~both SIM 1 and SIM 3~~ all simulations (Figure 9~~b~~c). This trend is explained by the higher SDR of the tributaries compared to that of the main channel (Figure 9b) and by the absence of significant sediment sinks in the main channel. For the subbasins with outlets along the main channel, removing the spatial variability in surface erodibility (SIM 3) has the overall effect to increase sediment connectivity. In some tributaries, however, the opposite effect is observed (T5 and T6). Finally, Figure 9c ~~compares the sediment connectivity in the four simulations in the main channel SDR. It~~ shows that removing the spatial variability in precipitation (SIM 2 and 4) also increases the SDR, therefore sediment connectivity (compared to SIM 1 and 3, respectively).

Sediment loads and initial soil moisture

The distribution of annual sediment yields at the outlet generated by the four simulation experiments ~~shows~~ showed that distributed precipitation simulations (SIM 1 and 3) ~~generate~~ generated higher sediment loads than their uniform precipitation equivalents (SIM 2 and 4) (Figure 10a). Distributed erodibility (SIM 1 and 2) ~~produces~~ produced smaller sediment loads than uniform erodibility (SIM 3 and 4).

To further investigate the differences among the sediment yield distributions, in Figure 10b we show the influence of spatial variability in rainfall and surface erodibility on event-based sediment yields for high and low initial soil moisture (SM_0) conditions. After separating the outlet hydrograph into single events, we computed the total sediment yields for each event and compared the distributions of the events with high and low initial soil moisture. Low SM_0 events are defined as those with SM_0 smaller than the 20^{th} percentile of the SM_0 distribution; high SM_0 events have a SM_0 greater than the 80^{th} percentile. The hydrological model performance for these events is good and comparable to the entire simulation performance, however it indicates a tendency to overestimation especially for low SM_0 events (see Table S2 and Figure S3).

~~Although the~~ The distributions of event sediment yields largely overlap, ~~we observe that , as expected, the distribution of event yields~~ however it is possible to observe that it is more affected by the precipitation spatial variability when ~~the~~ SM_0

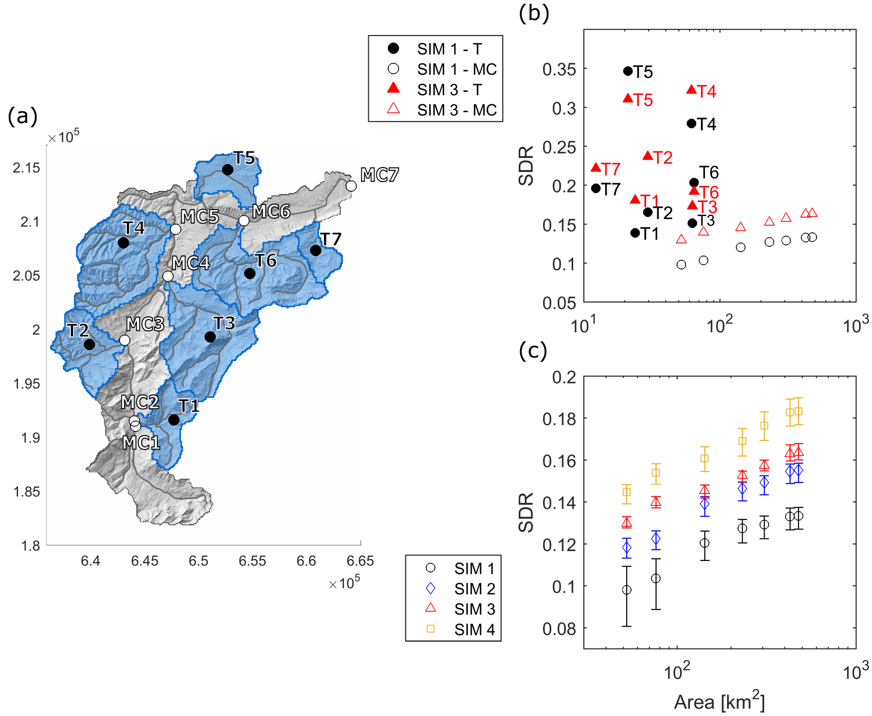

Figure 9. (a) Locations where the sediment delivery ratio has been computed: ~~in~~ at the outlet of the main tributaries (T) and along the main channel (MC)~~in the Kleine Emme basin~~, (b) mean annual SDR vs drainage area for tributaries and points along the main channel for distributed rainfall simulations, (c) comparison of mean annual SDRs ~~for~~ at the main channel points for the four simulations. The error bars show the interquartile range of the annual SDR variability.

is low. The differences between the median, 25^{th} and 75^{th} percentile of the SIM 1 and 2 are bigger for low SM_0 than for high SM_0. On the contrary, removing variability in surface erodibility seems to equally affect low and high initial SM_0 events (Figure 10b).

Discussion

Sources of concentration variability

The modelling approach presented here ~~reproduces a significant~~ can reproduce part of the observed SSC-Q ~~relation scatter, thus~~ scatter, implying that it contains ~~important~~ some of the relevant sources of sediment concentration variability in ~~time and space~~ the hydrological and sediment production processes at the catchment scale ~~. These sources are identifiable in~~ (Figure 3b). However, it also highlights that to fully capture the scatter, other sources should be included.

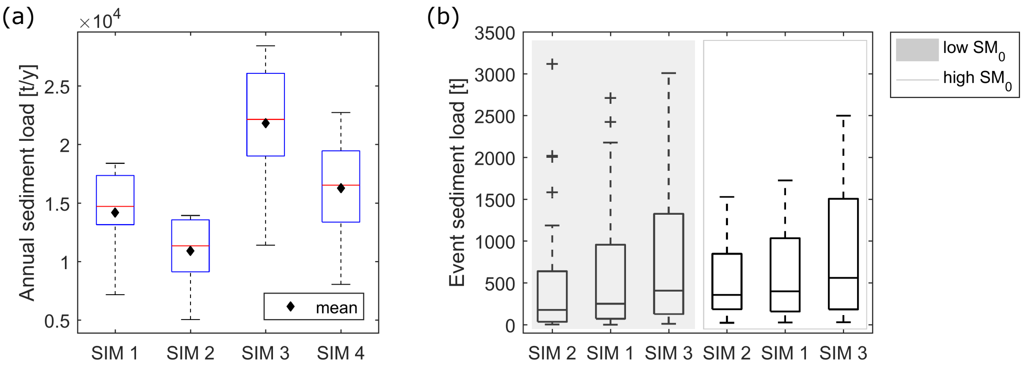

Figure 10. (a) Boxplots of annual sediment load and their mean values at the outlet of the catchment in the four simulation experiments, (b) boxplots of event sediment loads divided into low and high initial soil moisture conditions. The boxplots compare the effect of the spatial variability in precipitation and surface erodibility on events with different initial soil moisture.

The sources of variability accounted for by our deterministic modelling of the hydrology and sediment transfer are the time-varying meteorological inputs and ~~in~~ the spatially distributed nature of the model~~and are present even in deterministic modelling of the hydrology and sediment transport.~~

. The precipitation input combines both temporal and spatial components of variability. The temporal component is visible in Figure 5a, showing that the same sediment concentration can correspond to a large range of discharge values, depending on the type of event and ~~initial conditions that produce~~ the initial soil wetness conditions that precede it. Spatial variability in precipitation contributes to the SSC-Q scatter, by increasing the flow variability itself (Figure 6c) and by allowing the same discharge at the outlet to be generated by many combinations of overland flow situations over the hillslopes. Each of these combinations activates different sediment sources that have a characteristic hydrological and sediment signal and connectivity to the river network. In particular, we identify localized high-intensity summer storms as a main source of scatter, while snowmelt and winter storms produce a more homogeneous response throughout the basin. The spatially variable surface erodibility can additionally contribute to the uniqueness of the sediment signals of the activated source areas, when its spatial distribution is such to enhance the topographic heterogeneity within the basin.

Other sources of variability in sediment transport are implicit in the spatially distributed nature of the model, which allows to account for the heterogeneity of topography, soil depth and soil properties at very high resolution. These heterogeneities are responsible for the residual scatter of SIM 4, where the variability of both erosion drivers have been removed.

~~Because~~ It is worth noting that, because the sediment storage on hillslope cells is not exhausted during our simulation experiments, sediment availability does not influence sediment production in our study. Therefore, sediment availability in ~~our~~ the simulation experiments does not drive changes in the dominant sediment sources and does not add spatial variability to the sediment response.

The main limitation of our approach in reproducing SSC variability is, however, the lack of processes representing very localized sediment sources, which are usually characterized by a threshold behavior and therefore diversify the local sediment response. In this respect, Schwab et al. (2008) showed that in the Kleine Emme basin short time scale threshold processes are responsible for the export of regolith produced by soil creep in landslides. The absence of these processes in our model ~~could justify not only the~~ is likely the main reason for the smaller-than-observed modelled SSC-Q scatter, but also for the underestimation of the highest SSCs, ~~of~~ the soil erosion rate and annual sediment load, ~~observed~~ presented in section . Finally, we acknowledge that also inherent stochasticity in the sediment ~~production and transport might explain~~ mobilization and transfer are responsible for part of the observed SSC-Q rating curve scatter ~~(Malmon et al., 2003; Fuller et al., 2003).~~ (e.g. Fuller et al., 2003; Malmon et al., 2003). This inherent stochasticity cannot be reproduced by our modelling approach with deterministic simulation, but it can be included with stochastic simulation experiments and a probabilistic framework (e.g. Bennett et al., 2014). We are working on overcoming these ~~model limitations in the future~~ limitations in future research.

Spatial organization of suspended sediment transport

The explicit combination of hydrological processes and topographic and land use effects in the model ~~allows to investigate how~~ can help to investigate the spatial organization of sediment transport, and in particular, how this is affected by the spatial variability in erosion drivers~~affects the spatial organization of sediment transport.~~ . Spatial variability enhances the heterogeneity of erosion and deposition across the catchment, thus favoring the clustering of sediment source areas (Figure 7). Sediment production is increased by the ~~spatial aggregation of~~ spatially variable precipitation (SIM 1 and SIM 3), due to increased erosive power (Figure 8). The effect of a spatially variabile surface erodibility depends on the distribution of overland flow relative to that of surface erodibility and, in this case, the lower sediment productions of SIM 1 and 2 (Figure 8) indicate that the two distributions combine more intense overland flow with lower erodibility areas, thus reducing the overall sediment production.

In Figure 9 we use the modelled SDR as a measure of sediment transfer connectivity, as it quantifies the proportion of mobilized sediment that is routed to the outlet of a selected subbasin by action of overland and channel flow. As such, the modelled SDR can be seen as a dynamic indicator of functional connectivity, where the discharge is represented explicitly in time and space as a function of the hydrological forcings and topographic characteristics, as opposed to the widely used approximation as a function of the upstream area. In this way, our approach integrates the variability of functional connectivity both in time and space. A comparable approach to dynamically quantify the functional connectivity has been proposed by Mahoney et al. (2018), which is also based on hydrological modelling.

As shown by the sediment delivery ratio, the connectivity of sediment sources is reduced by the spatial variability of precipitation and this effect can be explained by the geomorphic connectivity of the catchment. The concentration of the distributed precipitation, the shallower soils and steeper slopes in the southeastern region of the basin, i.e. tributaries T1, T3, T6 and the upper stretch of the main channel (see Figure 9a), favor overland flow generation, and thus hydrological connectivity. However, the lower topographic connectivity of these subbasins overall determines a reduction in the sediment ~~transport~~ transfer connectivity. Such lower connectivity is indicated by the low SDRs of these subbasins in SIM 3, which does not account for the land use effect, and suggests the presence of geomorphic sediment buffers (Fryirs, 2013). The different topographic connectivity of the southeastern and northwestern regions reflects the different geomorphology of ~~the~~ these two parts of the basin. In fact, the southeastern region of the basin is characterized by a predominantly Last Glacial Maximum landscape with wide valleys and major instabilities, which are in most cases not directly connected to the river network ~~(Van Den Berg et al., 2012; Schwab et al., 2008; Clapuyt et al., 2019)~~(Schwab et al., 2008; Van Den Berg et al., 2012; Clapuyt et al., 2019 . On the other hand, the northwestern part of the basin, i.e. tributaries T4 and T5, shows a rejuvenating landscape where recent fluvial dissection created narrow and deeply incised valleys with a strong coupling between hillslopes and channels ~~(Norton et al., 2008; Schlunegger and Schneider, 2005)~~(Schlunegger and Schneider, 2005; Norton et al., 2008).

The reduction of sediment ~~transport~~ transfer connectivity by spatially distributed surface erodibility can be attributed to the ~~hypothesis applied~~ assumption in the sediment module that sediment discharge is always in equilibrium with the overland flow transport capacity. Based on this assumption, a spatially variable α allows, on the one hand to modulate the sediment ~~production~~ mobilization in space and, on the other hand, to define preferential areas of sediment deposition and therefore ~~to define~~ sediment connectivity. By associating a lower transport capacity to forests, their role as sediment buffers blocking sediments will emerge. Vice versa, high α values in ~~grasslands~~ crop areas will mean the absence of obstacles to sediment flux. Therefore, the smaller sediment ~~transport~~ transfer connectivity of SIM 1 and 2 compared to SIM 3 and 4 reflects the location of sediment buffers (i.e. forests) with respect to the channel network. In fact, in most of the basin, forested areas surround channel headwaters, thus disconnecting the sediment sources on the hillslopes and mountain flanks ~~to enter~~ from the river network ~~(see also, Clinnick, 1985; Schoonover et al., 2006; Parkyn et al., 2005; Mekonnen et al., 2015)~~ (see e.g. Clinnick, 1985; Parkyn et al., 2005; Schoonover et al., 2006; Mekonnen et al., 2015).

Sediment load and connectivity

The analyses presented in the previous sections ~~allow to understand~~ focus on the driving processes of sediment ~~production and transport~~ mobilization and transfer across the basin and the reasons for the reduction in SDR with variable erosion drivers. In this section we analyse how their balance determines the sediment load at the outlet.

In the distributed surface erodibility simulations (SIM 1 and 2) a reduced sediment yield (Y) is observed at the basin outlet and it is determined by a reduction in both sediment production (P) and sediment ~~transport connectivity (~~transfer connectivity (expressed by the SDR) with respect to uniform erodibility simulations (SIM 3 and 4):

$$\downarrow Y = SDR\downarrow \cdot P\downarrow . \tag{6}$$

In the distributed precipitation simulations (SIM 1 and 3) instead, an increased sediment yield at the basin outlet is observed compared to uniform precipitation simulations, ~~this~~ which results from a combination of a smaller SDR and a much greater sediment production across the basin. The increase in sediment yield indicates that the greater sediment production dominates over the decreased sediment connectivity:

$$\uparrow Y = SDR\downarrow \cdot P \Uparrow . \tag{7}$$

This result means that the localized sediment source areas are triggered by the very high erosive power of localised precipitation captured by distributed simulations. Their signal reaches the outlet despite the system is globally less efficient in evacuating the eroded sediments. These hotspots of erosion are generated where precipitation falls with a high intensity, soil saturation is reached soon during storms, eventually favoured by shallow soils, and therefore hydrological and sediment flux connectivity are locally high.

In a hydrological modeling experiment conducted with TOPKAPI-ETH on the same catchment, Paschalis et al. (2014) demonstrated the dependence of the discharge peak on the clustering of high soil moisture areas. Our results show that the high soil moisture areas may also define the sediment signal. This finding also suggests that a large proportion of the sediment yield can be supplied by just few localized sediment sources (e.g. Pelletier, 2012). The role of soil moisture in producing high sediment concentrations has also been highlighted by Dominic et al. (2015) and Brasington and Richards (2000), who attribute the peaks of SSCs to the connection of remote sediment sources during the wetting up of the catchment.

~~The~~ Given the relevance of soil moisture spatial distribution ~~also explains why~~ for runoff generation, we also expect event sediment yields ~~are~~ to be more affected by the precipitation spatial variability, i.e. precipitation intensity, at low initial soil moisture than at high initial soil moisture~~(see Figure 10)~~, as it is suggested by Figure 10b. This is ~~due to the crucial role of precipitation intensity at low initial soil moisture in determining soil saturation and creating hydrological connectivity~~further supported by findings of Paschalis et al. (2014) and Shah et al. (1996) which indicate that higher initial basin saturation reduces the dependency of runoff on precipitation spatial distribution. However, we also highlight that in our study the relatively small difference between the sediment load distributions of low and high SM_0 events and the tendency to overestimate flow in low SM_0 events, do not allow for a clear conclusion.

Conclusions

We presented a ~~novel~~ new spatially distributed soil erosion and suspended sediment transport ~~model based on~~ module integrated into the computationally efficient physically ~~explicit~~ based hydrological model TOPKAPI-ETH. ~~We showed that, by explicitly modelling hydrological processes, topographic and land cover effects on sediment transport in space and time, the model reproduces the creation of hotspots of sediment production, their catchment-wide connectivity, and thus the variability of sediment dynamics at the catchment scale.~~

~~Even if with a significant underestimation, when applied to a pre-alpine river basin~~The model allows for continuous long-term, high temporal and spatial resolution simulations of erosion and sediment transport by overland flow on hillslope and in channels in medium to large basin. With the aim of exploring the impacts of two key spatially variable erosion drivers on suspended sediment dynamics, ~~such a deterministic model reproduces a considerable~~ we conducted a series of numerical experiments on a mesoscale river basin. We compared the effects of spatially variable rainfall and surface erodibility with combinations of uniform and variable spatial distributions of these drivers.

Our results show that, first, the proposed model can reproduce part of the scatter of the observed SSC-Q relation, ~~thus indicating that it contains some of the main temporal and spatial sources of concentration variability. The difference between observed and simulated SSC variability can be attributed to the contribution of localized threshold~~ which is generated by spatially and temporally variable meteorological inputs and spatial heterogeneities of the physical properties of the basin, leading to a multitude of possible flow and sediment pathways. At the same time, our results suggest that other processes are also relevant to capture the scatter, such as localized sediment sources and ~~to~~ the inherent randomness ~~present in~~ of sediment production and ~~transport at the catchment scale.~~ transfer, which are not included in our model.

~~In this paper we used the model to investigate the role of spatial variability of erosion drivers on the spatial organization of suspended sediment transport. We consider precipitation and surface erodibility and observe that accounting for their spatial variability favors the simulation of clusters of~~

Second, we found that spatial variability in both drivers favors the clustering of sediment source areas and ~~reproduces the effect of sediment buffer in reducing the connectivity of sediment sources~~ reduces their overall connectivity to the river network~~.~~ ~~Sediment buffers in the case study basin are represented by topographically driven discontinuities in the south-eastern part of the basin and forests located around the river network across the whole basin. Accounting for the spatial variability of surface erodibility also~~ , by capturing the buffering effect of forests and low slope areas. At the same time, spatially variable surface erodibility reduces sediment production, ~~which together with the reduced sediment transport connectivity determines a~~ while a spatially variable precipitation increases sediment production by high rates of erosion in areas of high rainfall and overland flow intensity.

Third, we found that the combination of the effects of spatial variability on sediment production and connectivity determines an overall lower sediment yield ~~at the outlet. The spatial distribution of precipitation has the effect to increase sediment production , which despite the reduced connectivity generates an increase in sediment yield , thus highlighting the key role of clusters of~~ for surface erodibility, due to reduced sediment production and to buffering effects, and a greater sediment yield for precipitation, due to locally very high soil erosion. This last result is due to areas of high soil moisture ~~areas in defining the sediment signal.~~ in the catchment that are easy to saturate, which produce high local sediment inputs and catchment loads in spatially variable simulations.

~~Our results highlight the~~

Although our findings were obtained with reference to the specific climatic and geomorphologic feature of the Kleine Emme catchment, we think they indicate the general importance of resolving the spatial ~~variations controlling the sediment production and transport processes to improve the predictive ability of model-based sediment dynamics assessments. A spatially distributed computationally efficient model like TOPKAPI-ETH integrated with a sediment module is be~~ variability in sediment mobilization and transfer processes when modelling sediment dynamics at the basin scale. The model we presented is particularly suitable for applications at medium and large scales, where gradients in climatic and physiographic characteristics ~~control sediment production~~ represent a key control of sediment mobilization and transfer. Moreover, ~~the type of analyses that we performed offer ways to investigate effects of future changes in rainfall intensity and patterns as well as scenarios of land use~~this model offers a valuable tool for investigating future scenarios of precipitation and land cover, which are expected to take place due to climate change or ~~anthropic interventions. Future works should look into the relation of localized sediment sources and mass wasting processes with spatial variability in precipitation and should focus on the effect of temporal changes of surface erodibility on concentration variability.~~ human land use management.

Data availability. DEM, soil and land use maps, discharge and suspended sediment concentrations data and simulation results are available at https://doi.org/10.3929/ethz-b-000358874. Meteorological input data can be requested at https://gate.meteoswiss.ch/idaweb/login.do.

Author contributions. GB developed the model, carried out the simulations and the analyses of the results. PM and PB contributed to the conceptualization of the model and to the discussion of the results. GB prepared the manuscript with contributions and edits from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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