Using 3D observations with high spatio-temporal resolution to calibrate and evaluate a process-focused cellular automaton model of soil erosion by water

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Abstract. Future global change is likely to give rise to novel combinations of the factors which enhance or inhibit soil erosion by water. Thus there is a need for erosion models, necessarily process-focused, which are able to reliably represent rates and extents of soil erosion under unprecedented circumstances. The process-focused cellular automaton erosion model RillGrow is, given initial soil surface microtopography on a plot-sized area, able to predict the emergent patterns produced by runoff and erosion. This study explores the use of Structure-from-Motion photogrammetry as a means to calibrate ~~and validate~~and evaluate this model by capturing detailed, time-lapsed data for soil surface height changes during erosion events.

Temporally high-resolution monitoring capabilities (i.e. 3D models of elevation change at 0.1 Hz frequency) permit ~~validate~~evaluation of erosion models in terms of the sequence of formation of erosional features. Here, multi-objective functions, using three different spatio-temporal averaging approaches, are assessed for their suitability in calibrating and evaluating the model's output. We used two sets of data, from field- and laboratory-based rainfall simulation experiments lasting 90 and 30 minutes, respectively. By integrating 10 different calibration metrics, the output of 2000 and 2400 RillGrow runs for the field and laboratory experiments respectively, were analysed. No single model run was able to adequately replicate all aspects of either field and laboratory experiments. The multi-objective approaches highlight different aspects of model performance, indicating that no single objective function can capture the full complexity of erosion processes. They also highlight different strengths and weaknesses of the model. Depending on the focus of the evaluation, an ensemble of objective functions may not always be necessary. These results underscore the need for more nuanced evaluation of erosion models, e.g. by incorporating spatial pattern comparison techniques to provide a deeper understanding of the model's capabilities. Such ~~evaluat~~calibrations are an essential complement to the development of erosion models which are able to forecast the impacts of future global change. For the first time we use very high spatiotemporal resolution data to calibrate a soil erosion model.

1 Introduction

Soil erosion by water is an environmental problem of global significance (e.g. Nearing et al., 2017; Quinton and Fiener, 2023). In the future, it is likely to become more pressing in locations where anthropogenically-driven climate change brings more, and/or more intense, rainfall; and/or where changes in land usage (resulting from

changes in climate, economic factors, and/or other drivers) operate to leave soil unprotected by vegetation at times of heavy rainfall (e.g. Boardman et al., 1990; Favis-Mortlock and Boardman, 1995; Li and Fang, 2016; Dunkerley, 2019, Chen et al., 2024, Zhao et al., 2024). Such future changes are likely to result in novel combinations of the factors which cause or inhibit erosion (Foucher et al., 2024).

40 To manage soil erosion by water, quantification of the rate and extent of erosion is essential. Modelling is a primary tool for such quantification. However, when aiming to model erosion under novel circumstances, it is unwise to make use of models which work in a wholly 'black box' manner, that is by extrapolating from previously encountered combinations of erosion causing/inhibiting factors. Such models (e.g. Wischmeier, 1976; Renard et al., 1991; Panagos et al., 2015) cannot represent the impacts upon erosion rates and extents due to currently unknown thresh-

45 olds in, or non-linearities of response to, the erosion causing/inhibiting factors. It is these thresholds and non-linearities which will provide the greatest surprises with regard to future erosion. Thus, there is a vital scientific need to improve, and to continue to improve, our understanding of the processes of soil erosion by water, and to incorporate this understanding in quantitative process-focused models; with (at the same time) such models ideally making use of readily-available data sources. This is a considerable challenge: but only by doing this will we be

50 able to satisfactorily manage future soil erosion by water.

While there are many process-focused models which simulate the effects of soil erosion by water (e.g. Jetten et al., 1999; Battista et al., 2019; Raza et al., 2021; Rose and Hadaddchi, 2023), the RillGrow model (Favis-Mortlock, 1998) is unusual in adopting a cellular automaton (CA: see list of acronyms below) representation of the eroding soil surface (cf. Smith, 1991; Murray and Paola, 1997; Coulthard et al., 2002; Darboux et al., 2002; Nicholas,

55 2005). CA models have been used to study emergent phenomena in a wide variety of scientific domains (e.g. Wolfram, 1982; Wu, 1998; Cappuccio et al., 2001; Wahle et al., 2001; Silva et al., 2019; Favis-Mortlock, 2004). In RillGrow – as in the majority of CA models – all process interactions are 'local', i.e. take place only between adjacent cells of the DEM grid which represents soil surface elevations (and other soil properties). There are no process representations which operate on the DEM as a whole. As a consequence of this purely local focus, the

60 model makes no distinction between rill and inter-rill erosion processes. Instead, they are considered to be part of a continuum. The model's local (i.e. confined to a single cell and the cells which surround it) representation of erosion processes creates larger emergent multi-cell patterns: microrills and rills (Favis-Mortlock et al., 2000).

In essence, RillGrow works as follows. All or part of rain which falls onto the DEM becomes runoff. This moves down the steepest D8 adjacent cell-to-cell microtopographic slope, removing soil as it flows (this is the FD-FT

65 erosional subprocess in Kinnell, 2001). Runoff continues moving downslope until it either leaves the DEM, or accumulates as a pond in a microtopographic hollow. Ponds deepen until they overtop. Runoff leaving ponded areas continues, as previously, down the steepest adjacent cell-to-cell slope. In this way microrills are incised; their location having been determined only by microtopography. Microrills 'compete', with the most 'successful' (i.e. those that have been incised in such a way that they become part of a connected network which conveys runoff

70 downslope) growing further to become rills. Eventually, a highly connected rill network is formed by the model. The model uses a timestep for each iteration which is dynamically controlled by the maximum speed of cell-to-cell runoff during the previous timestep, to ensure that cell-to-cell flow in the model obeys the Courant condition (Courant et al., 1928). With cell sizes of mm to cm, timesteps are of the order of hundredths of a second. Thus, RillGrow simulations require considerable computing power for large grid sizes: simulations are therefore (with

As with virtually all erosion models (e.g. Favis-Mortlock et al., 2001), there is a need to calibrate the empirical inputs which RillGrow requires, and then to evaluate model results against observations (Jetten et al., 1999; Batista et al., 2019). The relatively unusual modelling approach adopted by RillGrow lends itself to the exploitation of novel tools for calibration and validation (Epple et al., 2022). This is particularly so with regard to the capture of spatial patterns, such as rill networks.

In an early RillGrow study (Favis-Mortlock, 1998), a moving-head laser scanner was used to capture microtopography: first of the initial soil surface of a laboratory-based plot, and then of the eroded soil surface of the plot following simulated rainfall. The initial-surface DEMs which resulted from these scans were used as input to RillGrow, and the end-of-experiment DEMs were used to validate evaluate the model's output. This strategy – comparing the model's spatial output only with the end-of-experiment DEM – however leaves open the possibility of "the right answer for the wrong reason" since modelled rills may form in a temporal sequence which is different from reality. The sequence with which erosional channels are incised (i.e. the dynamic development of flow routing patterns) is of major importance when considering temporal changes in connectivity on areas ranging from plot-sized to field-sized (Baartman et al., 2020).

Thus, there is a need for intra-experiment DEM captures ("time slices") to improve model valid evaluation. A subsequent laboratory-based RillGrow study used data from Helming et al. (1998) and did make use of intra-experiment DEMs. However, it was necessary to pause the simulated rainfall in order to use the laser scanner to capture the intra-experiment microtopography, then to restart the simulated rainfall. These within-experiment pauses were necessary for two reasons. Firstly, because laser scanning could not be carried out with simulated rain falling on the moving scanner head (and even if it could, the scanner head would interfere with the uniformity of the simulated rain). Secondly, because laser scanning as used in this experiment was not instantaneous: the scanner required some minutes to cover the whole plot area. Pausing an experiment in this way, to capture a snapshot of rapidly changing microtopography, is potentially problematic. Diminishing flow in rills during intra-experiment stoppages will result in within-rill deposition, which may influence subsequent within-rill detachment when rainfall is restarted; also, a newly-developed soil crust (or "seal") may begin to dry out and so change its properties, particularly with regard to infiltration.

Another RillGrow study (Favis-Mortlock et al., 1998) made use of simple photogrammetry to capture initial and final DEMs of a small area, together with a single intra-experiment DEM which was obtained without pausing the experiment. Whilst this was a step forward, a single intra-experiment DEM is not enough to satisfactorily validat evaluate the temporal sequence with which erosional patterns form; also, there were problems with raindrops obscuring parts of the eroding area.

SfM photogrammetry can easily capture multiple intra-experiment DEMs because almost all processing is automatic (Eltner and Sofia, 2020), it therefore promises to be a useful tool to calibrate and validate spatially-explicit erosion models such as RillGrow. SfM photogrammetry permits intra-experiment measurement of changes of soil surface microtopography at mm to cm resolution on plot- and hillslope-sized areas, with mm to cm accuracy (e.g.

Eltner et al. 2018, Hänsel et al., 2016). So far, SfM photogrammetry in the field of erosion studies has mainly been applied to UAV imagery. However, its potential for application with terrestrially-installed camera systems to increase the frequency of geomorphic change detection to hours (e.g. Blanch et al., 2024) or even to seconds (Eltner et al., 2017) has been illustrated. Note that with time-lapse SfM photogrammetry, falling raindrops obscuring the plot or hillslope are ~~not usually~~less of an issue (unlike the approach used in Favis-Mortlock et al., 1998) due to the high frequency of data capture and thus increased likelihood to capture images during rainfall gaps.

For~~In regard of~~ model calibration and evaluation, the most commonly-used approach involves space-time averaging: a simple comparison of measured and modelled runoff and sediment yield at the end of the plot (or at the catchment outlet) and at the end of the period of observation. Sometimes this is supplemented by comparisons of measured and modelled time series, constructed from additional plot-end (or catchment outlet) measurements during the period of observation. ~~Although, t~~There have been ~~multiple~~ attempts to evaluate erosion models using spatial data, e.g. from field surveys, aerial images, and fallout-radionuclide data (Brazier et al., 2001; Fischer et al., 2018; Jetten et al., 2003; Saggau et al., 2022; Vigiak et al., 2006). However~~,~~ it has been, and still is, much less common to compare measured and modelled spatial patterns of erosion. It is even less common to do so using ~~considering~~ more than one ~~a range of~~ method for comparison ~~methods in space and time~~.

From the perspective of the historical development of erosion models (e.g. Nicks, 1998) it is unsurprising that model evaluations have concentrated on simple spatio-temporal averaging approaches. The USLE (Wischmeier, 1976) and subsequent models based upon the USLE (e.g. MUSLE: Williams, 1975; RUSLE: Renard et al., 1991; USLE-M: Kinnell and Risse, 1978) are only capable of generating results which are averaged over both time and space. Subsequent, more process-focused, erosion models such as WEPP (Nearing et al., 1989) or Erosion-2D (Schmidt, 1991) introduced a 2D spatial element: a hillslope profile. Later came models with an explicit spatial focus, such as LISEM (de Roo et al., 1996) and Erosion-3D (Schmidt et al., 1996). The evaluation of erosion models has therefore lagged ~~somewhat~~ behind the development of the models themselves.

The aims of this study were first to use several multi-objective functions to calibrate ~~and evaluate~~ a process-focused soil erosion model (RillGrow), and then to evaluate these objective functions in terms of information gained from each function. We used time-lapse SfM photogrammetry and measured sediment yield from two plot-sized rainfall simulations, one in the field and the other in the laboratory. Ten different objective functions were considered to ~~find the best~~calibrate model parameters. The best-performing model runs were chosen to be those with the lowest residuals for multiple objective functions. ~~We introduce a~~This novel approach to testing erosion models ~~by~~ consider~~ing~~s both spatio-temporal high resolution 3D models of change, and ~~as well as~~ multiple sediment yield measurements at the plot outlet ~~during rainfall simulations~~.

2 Methods

2.1 Data acquisition

The field and laboratory rainfall simulators of the Czech Technical University in Prague were used in this study (Figure 1). Rainfall simulators ~~Rainfall simulators are utilized to monitor surface runoff and erosion processes because they~~ can both control several characteristics of incident raindrops, and ~~help to~~ accelerate erosion processes

150 for a faster monitoring of soil <s>land</s> surface changes. Thus s<s>S</s>imulators have become an integral part of erosion research, including <s>and</s> erosion model calibration and evaluation (Iserloh et al., 2013, Prosdocimi et al., 2017, Bosio et al., 2023).

Figure 1: Rainfall simulator used in the field (a) and in the laboratory (b).

  During the field experiment, the rainfall simulator (Kavka, 2018) was used on a plot that had been prepared as
155 cultivated fallow. For the <s>In the</s> laboratory experiment, the rainfall simulator (Kavka, 2019) was used on a disturbed soil sample which had been prepared similarly to the field experiment. Further site and experiment properties are given in Table 1.

  Both rainfall simulation experiments used <s>a similar</s>the same approach regarding runoff and sediment sampling: <s>according to</s> a standard procedure described by <s>for conducting experiments with the CTU rainfall simulators</s>
160 <s>(</s>Stašek et al. (<s>,</s> 2023). At the bottom of <s>On the lowest side of</s> the plot <s>surface r</s>unoff is routed into <s>concentrated by</s> a metal funnel. <s>S</s> and samples are collected <s>into sampling vessel</s> with volumes of one to two litres every 2.5 - minutes after the start of runoff <s>started</s>. <s>The s</s>Samples were weighted to obtain the volume of surface runoff, <s>.</s> <s>T</s>then<s>, they</s> were filtered using KA-3M <s>by</s> paper filters<s>res KA-3M</s> (Papírny Pernštejn, Czechia) and dried at 105°C in an air drier, in order to obtain the amount of soil per sample.

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Table 1: Rainfall, plot and soil characteristics for both field and laboratory rainfall simulation experiments

	Field experiment	Laboratory experiment
Rainfall properties		
Rainfall intensity (mm h^{-1})	~140	~120
Kinetic energy (J m^{-2} mm^{-1})	10	7.8
Nozzle type	WSQ40	WSQ40
Plot properties		
Rained-on area (m)	2 x 8	1 x 4

Slope (%)	9	40
Duration of experiment (min)	90	30
Surface	Seed bed condition (cultivated fallow/bare soil)	
Soil properties		
Soil type	Loam	
Clay/Silt/Sand %	10.5 / 56.6 / 32.9	
Organic carbon %	1.49	
Soil depth and condition	Undisturbed soil - arable soil with 35 cm deep topsoil, cultivated to the depth of 10 cm with a hand cultivator and hand roller (Stašek et al., 2023)	Disturbed soil - 15 cm "topsoil" and 5 cm of sand "bottom". After filling rolled

Nine SLR cameras (Canon EOS 450D, 600D, 1100D, 2000D and Nikon D700) were used to create the photo-grammetric data for both field and laboratory experiments (Figure 2). These captured images every ten seconds in a synchronized manner, using a remote trigger which had been constructed in-house. The cameras used different, but fixed, focal lengths to ensure a stable principal distance during the experiment. At the field site the cameras were mounted at a height of about 4 m. This captured a region of interest (RoI) of about 4 m² covering the lower part of the plot. In the laboratory the whole plot wascould be captured (about 4 m²). In addition, images were also captured with a Sony Alpha 6600 (142 and 148 images at the field site, and 77 and 79 images atin the laboratory, site before and after the experiment, respectively), by walking around the plot to measure the entire area underneath the rainfall simulator. Ground control points (GCPs) were distributed around the plot (15 and 22 for the field and laboratory experiments, respectively) and measured with mm-accuracy using a total station, in order to scale and reference the image measurements.
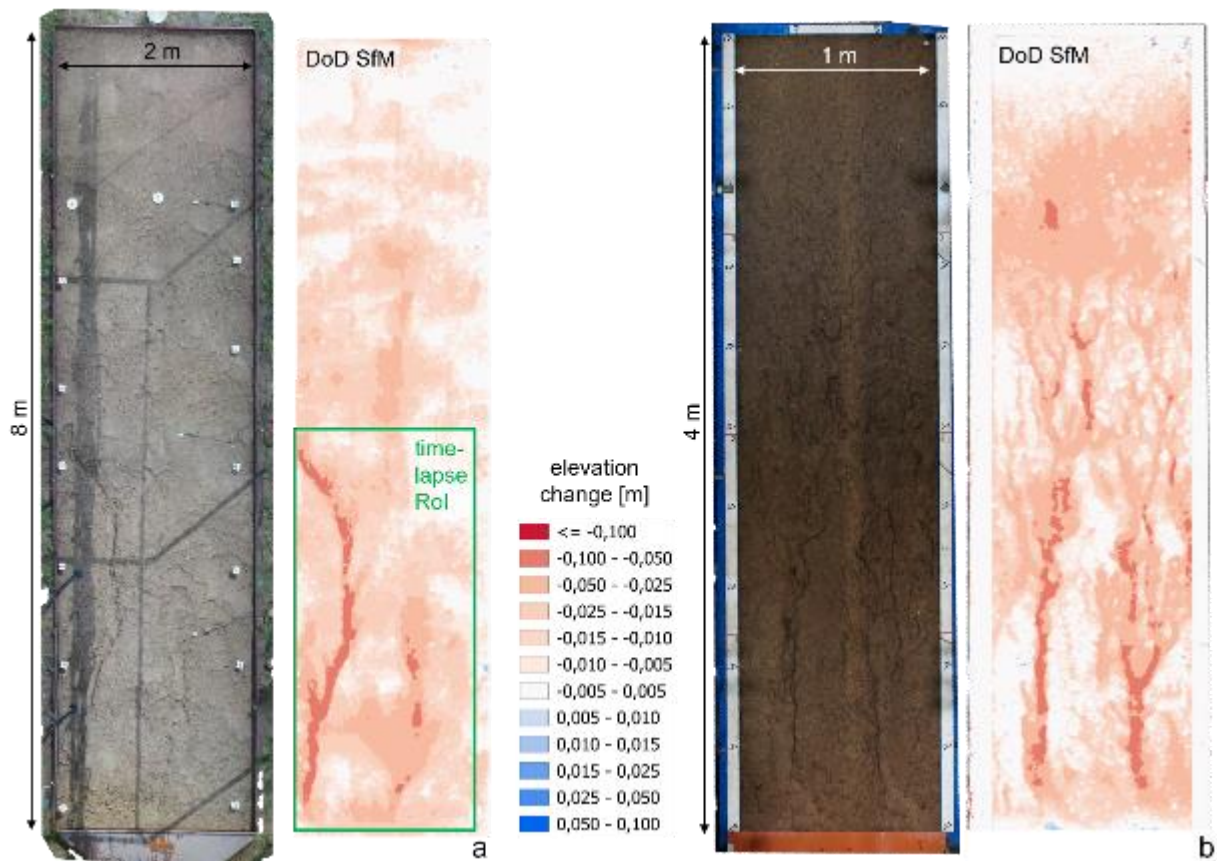
Figure 2: Ortho photo (left) and elevation change map (right) of the field (a) and laboratory (b) experiments. The cameras for time-lapse SfM are marked with red boxes. The green box (in a) shows the region of interest, for which temporal high resolution change observations were made.

2.2 Image data processing

Images ~~that were~~ captured with the Sony Alpha 6600 were used to derive 3D representations of the whole plot for both field and laboratory experiments ~~with the highest possible quality and resolution,~~ using Agisoft Metashape (v. 2.0.2) and following the standard SfM photogrammetry steps (e.g. Eltner and Sofia, 2020). Processing of the time-lapse image data ~~involved some more~~ required extra steps to get the 3D models, following ~~and was done according to~~ Grothum et al. (2024). Images were sorted ~~according to their~~ by acquisition time ~~and~~ then processed using the API of Metashape (v. 2.0.2) to automatically generate a time series of DEMs using time-lapse SfM photogrammetry (Eltner et al., 2017, Blanch et al., 2024). In total, 708 and 220 filtered (for outliers), dense 3D point clouds were calculated for the field and laboratory experiments, respectively. ~~The p~~Point clouds from the whole plot and time series were then rasterized using an interpolation approach that retains the average height value for points falling in the same raster cell. Empty cells were linearly interpolated considering the nearest non-empty cells. For both field and laboratory experiments, the image-based 3D models of the whole plots were rasterized to a resolution of 3 cm and 1.5 cm, respectively. These DEMs were then used as input to the RillGrow model. The time-lapse data were rasterized to resolutions of 1 cm and 0.5 cm for field and laboratory, respectively.

Note that the time series of DEMs covers a smaller RoI at the field site because the cameras were not able to cover
the whole erosion plot.

DoDs were also constructed by point cloud differencing considering M3C2-PM (James et al., 2017) to estimate
significant changes based on the accuracy of the image-based 3D reconstruction. ~~In this way, t~~The variance of the
tie points, resulting from the bundle adjustment, is applied to estimate the spatially distributed error, which is then
transferred to the dense point cloud using a distance-based weighted average if several points fall within a given
search radius. ~~Considering error propagation, t~~The error information is then used with the multi-scale cloud-to-
cloud approach (M3C2, Lague et al., 2013) to calculate the point cloud differences. The first point cloud of the
time-series is used as a reference point cloud to which all subsequent point clouds are differentiated, to ensure the
same orientation of the point normal used by the M3C2 tool. The final point clouds of difference are rasterized to
DoDs with the same resolution as the time-lapse DEMs (i.e. 1 cm and 0.5 cm) considering only the significant
changes and using the M3C2 distance as the Z (vertical) value. However, no interpolation was performed this
~~time~~stage due to large data gaps, especially at the beginning of the experiments, when there were only small
changes in soil surface elevation which fell within the noise level of the data.

2.3 The simulation model for soil erosion by water

~~In essence,~~ RillGrow works as follows. Rain falls onto the DEM at random locations, as individual drops. The
number of drops per timestep is calculated from user-input mean and standard deviation of rainfall intensity.
Raindrop volume is calculated from the mean and standard deviation of raindrop diameter (also user inputs, as is
raindrop fall velocity).~~All or part of rain which falls onto the DEM becomes runoff~~Infiltration (if chosen by the
user; otherwise, the soil is assumed to be saturated) is calculated using the explicit Green-Ampt Model of Salvucci
and Entekhabi (1994). Overland flow moves from grid cell to grid cell in the D8 direction of steepest slope until
it leaves the grid or can move no further i.e. is ponded. The depth of water in ponded cells increases as more
overland flow arrives. Eventually overtopping may occur. The speed of overland flow on the grid is calculated
using either a Manning-type or the Darcy-Weisbach flow velocity equation: if this is chosen then the friction factor
may be a user-input constant, based on the Reynolds' number, or calculated using the Lawrence (1997) approach.
No distinction is made between rill and inter-rill overland flow.

During flow routing, each wet cell has a sediment load which has been received from the adjacent upstream cell(s).
Transport capacity is calculated using equation 5 from Nearing et al. (1997). If the sediment load exceeds the
transport capacity, then excess sediment is deposited assuming a linear function of the difference between sediment
load and transport capacity (equation 12 in Lei et al., 1998). If the sediment load is less than the transport capacity,
then soil is eroded from the cell using a probabilistic detachment equation by Nearing (1991): this represents FD-
FT (Flow Detachment - Flow Transport) in the Kinnell (2001) classification of erosion subprocesses. No distinc-
tion is made between rill and inter-rill flow erosion.

~~. This moves down the steepest D8 adjacent cell-to-cell microtopographic slope, removing soil as it flows (this is
the FD-FT erosional subprocess in Kinnell, 2001). Runoff continues moving downslope until it either leaves the~~

~~DEM, or accumulates as a pond in a microtopographic hollow. Ponds deepen until they overtop. Runoff leaving ponded areas continues, as previously, down the steepest adjacent cell to cell slope.~~ In this way microrills are incised; their location having been determined only by microtopography. Microrills 'compete', with the most 'successful' (i.e. those that have been incised in such a way that they become part of a connected network which conveys runoff downslope) growing further to become rills. Eventually, a highly-connected rill network is formed ~~by the model~~.

In the version of RillGrow used in this study, splash redistribution was represented using the diffusion equation approach of Planchon et al. (2000), together with a water depth-splash efficiency relationship. This represents RD-ST (Raindrop Detachment - Splash Transport) in the Kinnell (2001) classification of erosion subprocesses. ~~The model uses a timestep for each iteration which is dynamically controlled by the maximum speed of cell to cell runoff during the previous timestep, to ensure that cell to cell flow in the model obeys the Courant condition (Courant et al., 1928). With cell sizes of mm to cm, timesteps are of the order of hundredths of a second. Thus, RillGrow simulations require considerable computing power for large grid sizes: simulations are therefore (with current versions of the model) confined to plot-sized areas. In addition to erosion by overland flow, r~~Recent versions of RillGrow also consider ~~deposition, soil redistribution by rainsplash (RD ST (Raindrop Detachment, Splash Transport) and RD FT (Raindrop Detachment, Flow Transport): Kinnell, 2001),~~ gravitational collapse: ~~;~~ ~~and infiltration.~~ "slumping" represents mass movement on wet cells, this occurs most frequently along rill sidewalls. If a cell's shear stress (due to overland flow) exceeds a user-input threshold, and the cell is saturated (i.e. subsurface soil water for the cell is at its maximum value) then slumping occurs. Soil is assumed to flow hydrostatically down the steepest D8 soil-surface gradient surrounding the cell until it reaches a user-input angle of rest. "Toppling" similarly represents mass movement, but the soil cell does not need to be saturated: if any cell-cell gradient exceeds a user-input threshold, then soil is assumed to move until it reaches a user-input angle of rest.

Detached and deposited sediment is considered to comprise three size fractions (clay, silt, sand). The soil grid is represented as one or more erodible layers above an unerodible basement. Each soil layer can possess different usr-input erodibilities for flow, splash, and slumping, for each of the three size fractions.

Early versions of RillGrow (Favis-Mortlock, 1998) adopted simple, mostly empirical, representations of the erosion and deposition due to overland flow. Nonetheless, the model was able to satisfactorily replicate spatial patterns of observed rill networks and amounts of runoff and soil loss on plots in the laboratory and field (Favis-Mortlock et al, 1998; 2000). Subsequent development of the model has moved towards representations which are more – but still, unavoidably, not wholly – physics-based. Thus as with all current erosion models, some calibration of user inputs is necessary (Favis-Mortlock et al., 2001). A flowchart of the RillGrow model, outlining its representation of hydrological and erosional processes, is shown in Figure 3. ~~The e~~Equations used in the model are given in Supplement 4-1.

Rain falls onto the grid at random locations, as individual drops. The number of drops per timestep is calculated from the mean and standard deviation of rainfall intensity, both of which are user inputs. Raindrop volume is calculated from the mean and standard deviation of raindrop diameter, which are use inputs. Raindrop fall velocity is also a user input.

Infiltration (if chosen by the user; otherwise, the soil is assumed to be saturated) is calculated using the explicit Green-Ampt Model of Salvucci and Entekhabi (1994). Overland flow moves from grid cell to grid cell in the D8 direction of steepest slope until it leaves the grid or can move no further. The depth of water in ponded cells increases as more overland flow arrives at the cell. Eventually overtopping may occur. The speed of overland flow on the grid is calculated using either a Manning type or the Darcy-Weisbach flow velocity equation: if this is chosen then the friction factor may be a user input constant, based on the Reynolds' number, or calculated using the Lawrence (1997) approach. No distinction is made between rill and inter-rill overland flow. In the version of RillGrow used in this study, splash redistribution was calculated using the diffusion equation approach of Planchon et al. (2000), together with a water depth-splash efficiency relationship. This represents RD-ST in the Kinnell (2001) classification of erosion subprocesses.

On each wet cell, transport capacity is calculated using equation 5 from Nearing et al. (1997). If a wet cell's sediment load is less than the transport capacity, then soil is eroded from the cell using a probabilistic detachment equation by Nearing (1991). This represents FD-FT in the Kinnell (2001) classification of erosion subprocesses. Following flow routing, each wet cell has a sediment load which has been received from the adjacent upstream cell (or cells). The model then calculates the transport capacity for the cell using equation 5 from Nearing et al. (1997). If the sediment load exceeds the transport capacity, then excess sediment is deposited assuming a linear function of the difference between sediment load and transport capacity (equation 12 in Lei et al., 1998). If the sediment load is less than the transport capacity, then soil is eroded from the cell using a probabilistic detachment equation by Nearing (1991): this represents FD-FT in the Kinnell (2001) classification of erosion subprocesses. Note that no distinction is made between rill and inter-rill flow erosion. If a wet cell's sediment load is greater than the transport capacity, then soil is deposited on the cell using equation 9 from Cheng (1997).
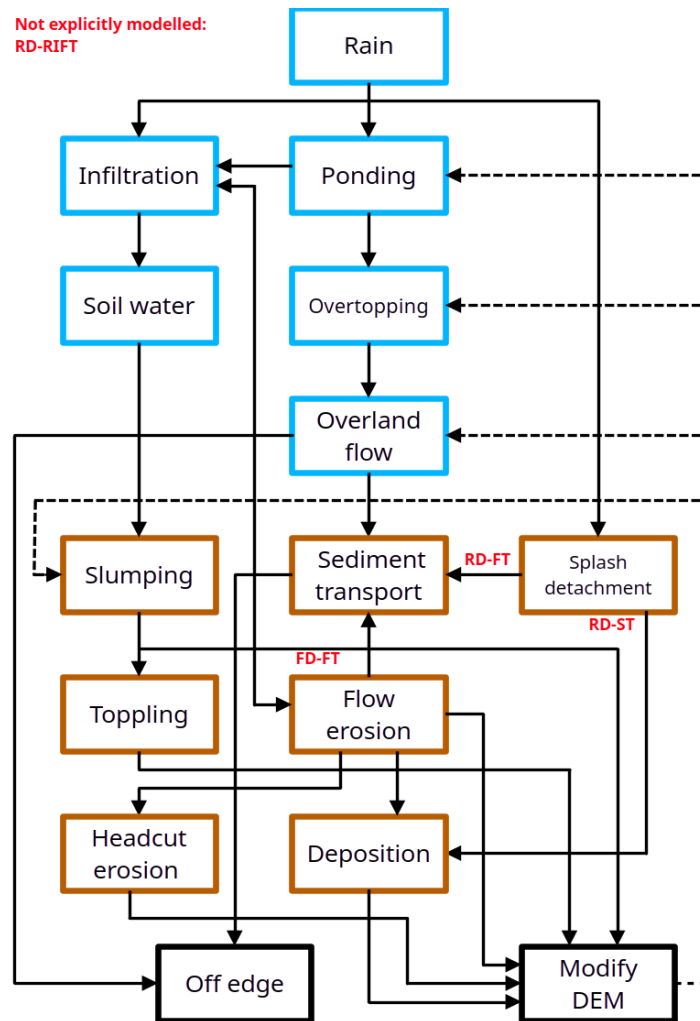
Figure 3: Flow chart of RillGrow. Blue-edged boxes indicate hydrological processes or stores, brown-edged boxes indication erosional processes, black-edged boxes are model specific. The codes (RD-ST, FD-FT etc.) describe erosional subprocesses, see Kinnell (2001). Plain black lines represent process linkages, dashed black lines represent feedback.

295   ~~In the RillGrow model "slumping" represents mass movement on wet cells: it occurs most frequently along rill sidewalls. If a cell's shear stress (due to overland flow) exceeds a user-input threshold, and the cell is saturated (i.e. subsurface soil water for the cell is at its maximum value) then slumping occurs. Soil is assumed to flow hydrostatically down the steepest D8 soil surface gradient surrounding the cell until it reaches a user-input angle of rest. "Toppling" similarly represents mass movement, but the soil cell does not need to be saturated: if any cell~~
300   ~~cell gradient exceeds a user-input threshold, then soil is assumed to move until it reaches a user-input angle of rest. A representation of headcut erosion is still under development: in the version of the model used in this study, if the cell-cell gradient at the extreme upslope end of a rill exceeds an empirical threshold, headcut erosion occurs, resulting in upstream movement of the headcut. Since headcut erosion is relatively slow, it is represented using 'stored retreat' in increments which are less than the size of a cell, until the 'stored retreat' is equal to the cell size.~~
305   ~~At this point, the cell is eroded and incremental headcut erosion begins in the next cell upstream.~~

~~Detached and deposited sediment is considered to comprise three size fractions (clay, silt, sand). The soil grid is represented as one or more erodible layers above an unerodible basement. Each soil layer can possess different erodibilities for flow, splash, and slumping, for each of the three size fractions.~~

310 The model uses a timestep for each iteration which is dynamically controlled by the maximum speed of cell-to-cell runoff during the previous timestep, to ensure that cell-to-cell flow in the model obeys the Courant et al. (1928) condition. With cell sizes of mm to cm, timesteps are of the order of hundredths of a second. Thus, RillGrow simulations require considerable computing power for large grid sizes: simulations are therefore (with current versions of the model) confined to plot-sized areas.

315 **2.4 Input parameters and model runs**

To perform the erosion modelling with a range of model input parameters, a Monte Carlo-like approach was used. This employed Latin hypercube (LHC) sampling to draw the parameters approximately randomly. The parameter space was divided into bins, with sizes defined by the chosen parameter value range and the number of drawings. This LHC approach aims to ensure a near-random distributed sampling of parameter combinations, so that the
320 whole parameter space is covered and the variability of the data is represented. LHC sampling has been used to calibrate hydrological models (e.g. Singh et al., 2023).

Seven RillGrow input parameters were considered in this way.

- 'DEM base level': vertical distance between the lowest DEM cell elevation and plot outlet level
- 'N for splash efficiency': this determines soil redistribution due to splash i.e. RD-ST (raindrop
325   detachment, splash transport) and RD-FT (raindrop detachment, flow transport) in Kinnell (2001)
- 'Maximum flow speed': a cut-off for cell-to-cell runoff speed which cannot be exceeded
- 'K for detachment': determines soil detachability by flow i.e. FD-FT (flow detachment, flow transport) in Kinnell (2001)
- 'Radius of soil shear stress': this controls the size of the 'patch' over which shear stress is distributed,
330   which controls slumping (gravitational cell-to-cell movement of saturated cells which both exceed a given cell-to-cell gradient and which exceed a shear stress threshold).
- 'Threshold shear stress for slumping'
- 'Angle of rest for slumped soil'

Whilst other input parameters could have been chosen, we focused on these following a first simple Monte Carlo
335 simulation using 3000 runs and testing twelve parameters.

Subsequently, 2000 and 2400 RillGrow simulation runs were made for the laboratory and the field site, respectively, at the high-performance computing centre of the Dresden University of Technology. As it was not practically feasible to save model output at every timestep, selected points in time were chosen, with a higher temporal resolution at the beginning of the simulation and decreasing temporal steps later on. ~~At~~For the field site, in total
340 36 temporal points (minutes 0.2, 0.5, 1, 2, 3, 5, 7, and afterwards every 3 minutes until 90 minutes) were

considered. ~~At~~For the laboratory site 19 temporal points (minutes 0.1, 0.2, 0.5, 1, 2, 3, 4, and then every 2.5 minutes until 30 minutes) were considered.

2.5 Objective functions for erosion model evaluation

Erosion model results were compared with measured sediment yield and measured DoDs considering, in total, ten

345   different objective functions and their combinations. The objective functions for different observations were tested with regard to their suitability for ~~to~~ calibrat~~e~~ing the erosion model. We distinguish between three different spatio-temporal characteristics – i.e. space-time averaged, time-averaged, and area averaged (Table 1) – and different options to calculate comparison metrics – i.e. total change, root mean squared error (RMSE), dynamic time warping (DTW) distance, and normalized Nash-Sutcliffe efficiency (NNSE). Also, observations from different sources,

350   both image-based elevation change models (EC) and sediment yield (SY) measurements, were used (Table 2). Finally, the combination of different objective functions was investigated.

Space-time-averaged data

This considers total change in measurements, for example change in the total sediment lost during the rainfall

355   simulation experiment, compared to the modelled sediment lost. Space-time averaged EC refers to the cumulative height change measured at the end of the experiments (i.e. the difference as M3C2-PM between the initial and the final time-slice DEM), compared to the modelled EC.

Time-averaged data

360   Here, we ~~To~~ compare the observed and modelled spatial pattern of erosion. ~~, we performed a time averaged evaluation of the erosion model.~~ This involved two objective functions. The first objective function estimated the pixel-wise difference: i.e. did a direct comparison of the measured 3D model and the simulated soil surface. ~~In order t~~To do this, the observed DEM must be resampled to the same resolution as the simulated raster. Calculated pixel height differences are eventually aggregated to an average value. The second objective function is a dense

365   vector representation (DVR) using a deep learning (DL) method to calculate image embeddings, i.e. an abstract image representation summarized in one vector, to compare them in the latent (i.e. abstract) feature space. This approach is used here to assess the similarity of spatial patterns. The DL approach is less sensitive to offsets in the position of rills (i.e. several pixel differences in the position of the modelled rill compared with the observed rill). The CLIP (Contrastive Language-Image Pre-training: Radford et al., 2021) model was used to transform the im-

370   ages into the feature space because it has shown to be robust across domains: this is especially relevant for our application with height images, which are usually not part of the training datasets. Afterwards, the cosine similarity score is used to derive a value of similarity between the transformed images. To perform this comparison, the DEMs were transformed to an 8-bit 3-channel image, prior to some filtering of strong height outliers to avoid artefacts by keeping only 95% of height values and the remaining 5% (i.e. the largest heights) being replaced by

375   the closest inlier value. The best performing model runs were chosen with regard to the average difference and similarity values of the final model run of each time series, i.e. we did not compare ~~each~~every simulated and observed 3D surface of a series with each other but compared only the last ones.

The aArea-averaged data

Comparison here is between are time series of spatially-averaged (i.e. whole-plot) changes. In case of the EC data, the DoDs based on the M3C2-PM approach were used to estimate the average height change per point in time, thereby always considering the first DEM of the time series as the reference model for the change calculation of the subsequent models. The simulated DEMs were also differentiated using the first model as reference to eventually receive the simulated time series of the modelled EC. To compare the time series, three different metrics were considered.

- The RMSE is an accuracy metric that calculates the square root of the quadratic mean of the differences between the modelled and measured values.

- The DTW distance is a measure that tries to find the optimal match between two sequences and whose remaining mismatch can be considered as an estimate of the time series similarity. It has the advantage that it is invariant to some non-linear behaviour. This metric has been applied to align complex time series of topographic change (Anders et al., 2021).

- The third metric is the NNSE , which is the preferred metric to assess model performance (Batista et al., 2019). It is a measure that relates the modelled error variance to the measured one. The closer the value to unity, the better the model predicts the erosion.

Thus, in total six metrics were estimated, i.e. the three summarizing time series values calculated for both EC and SY comparisons.

Combinations of objective functions

The cCombination of different objective functions wasere also evaluated. The multi-objective function approach considers eight different combinations (Table 2). For the multi-objective approach, the best models were found by keeping the models whose metrics are within the top values, e.g. for finding the best ten models the objective function values were iteratively sorted and evaluated until at least ten models remain within the top values of each list. We assume that the use of more objective functions enables us to deal better with equifinality (Beven et al., 2006) due to different processes being captured with different calibration metrics, although only two data sources were used as input, i.e. images and sediment yield measurements. For instance, the time-averaged spatial similarity compares the overall appearance of the rill network whereas the RMSE of the time series of elevation change ideally captures overall erosion within the plot.

Table 2: Summary of objective functions and their combinations used for the soil erosion model calibration.

Single objective function			Multi-objective function	
Total EC	Space-time averaged	Difference of Ttotal elevation change [m]	EC t_series	EC time series assessment with RMSE, DTW and NNSE
Total SY		Difference of Ttotal sediment yield [kg]	SY t_series	SY time series assessment with RMSE, DTW and NNSE
RMSE EC	Area-averaged	Root mean squared error elevation change [m]	EC & SY t_series	EC & SY time series assessment with RMSE, DTW and NNSE
RMSE SY		Root mean squared error sediment yield [m]	EC t_series & total change	EC t_series and considering total change

DTW EC		Dynamic time warping distance elevation change [m]	SY t_series & total change	SY t_series and considering total change
DTW SY		Dynamic time warping distance sediment yield [kg]	EC & SY t_series & total change	EC & SY t_series and considering their total change
NNSE EC		Normalized Nash-Sutcliffe efficiency elevation change [m]	EC t_series & total change & spatial pattern (no DL)	EC t_series & total change and considering per pixel EC
NNSE SY		Normalized Nash-Sutcliffe efficiency ~~elevation change~~ sediment yield [kg]	EC t_series & total change & spatial pattern	EC t_series & total change and considering per pixel EC and sim DL EC
Per pixel EC	Time-averaged	Per pixel elevation difference [m]	EC & SY t_series & total change & spatial pattern (no DL)	EC & SY t_series & total change and considering per pixel EC
Sim DL EC		Similarity of spatial pattern assessed with deep learning	EC & SY t_series & total change & spatial pattern - all	Considering all single objective functions

410 For the field experiment, results from the model runs often showed very strong artefacts. Therefore, a filter approach was applied that assumed smoother changes of the soil surface, including rill incision~~s~~, to automatically detect and correspondingly exclude these faulty simulation runs. Elevation changes between the first and last DEM, (i.e. the DoD) of each simulation run were smoothed using a Gaussian filter with a five-pixel kernel. The smoothed model was then subtracted from the original DoD to identify very strong changes. The approach is

415 adopted from Onnen et al. (2020). If the difference was below an arbitrary threshold of 5 cm, the change at that pixel is considered valid. Finally, the ratio between the number of affected and non-affected artefact pixels is calculated and if the ratio is below 0.2%, the simulations are considered not plausible.

3 Results

Results are shown separately for the field and laboratory experiments. Animations of elevation changes to the soil

420 surfaces of the field and laboratory rainfall simulation experiments may be viewed using Fig. S1 and Fig. S2 for field and laboratory, respectively. Note~~,~~ that some flickering is observable in both time-series. This ~~, which~~ is due to the unavoidable circumstance of capturing images during rainfall, although rainfall does not fall continuously, leading to a slight increase in data noise. Nevertheless, image matching and DEM calculation was still possible because most drops were detected as outliers during the SfM processing.

425 **3.1 Results from the field experiment**

During 90 minutes of the field rainfall simulation with intensity 140 mm h^{-1}, 173.5 kg of sediment was lost from the plot. Total discharge was about 3100 l. Total net height changes measured on the entire plot (including the RoI) were 1.2 cm. At the beginning of the rainfall experiment, a rill began to form at the bottom left of the plot. Rill growth then stopped. Later, a second rill began to form in the bottom centre of the plot and then to cut back-

430 wards (i.e. upstream). Growth of this rill slowed after some time. Later, the left rill began to grow again, this time it continued to cut backwards until the end of the experiment. The formation of wide headcuts was also observed during the experiment, these appear more like terraces and are present across the slope. They retreated upslope slightly but did not evolve into rills.

Large artefacts were developed in many model simulations (Figure 4). These artefacts show very large differences in accumulation and erosion between directly neighbouring pixels, which is not a plausible erosion pattern. However, some objective functions of the time series still indicated a good fit between modelled and observed data, e.g. when considering the lowest values for DTW EC (7.8 cm) and SY (99 kg).
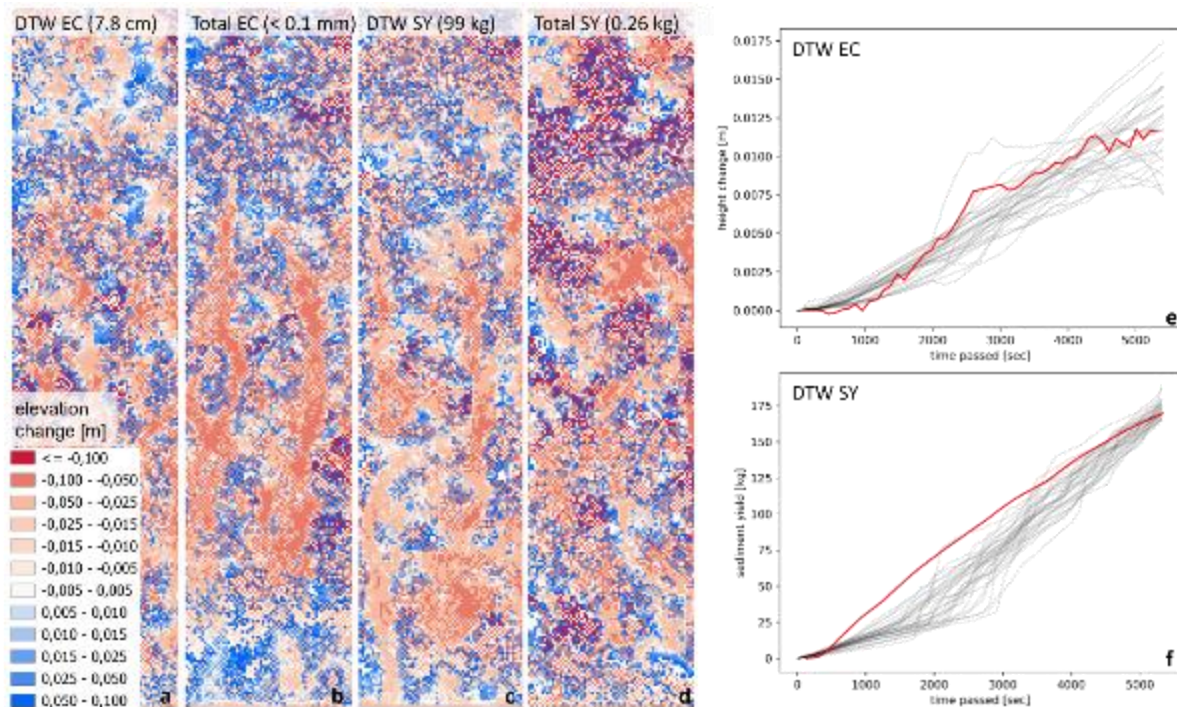
Figure 4: Although, metrics of objective functions – e.g. time series of DTW of measured (red line) and simulated (grey lines) elevation change (EC) and sediment yield (SY) at field simulation (~~at right side~~side, f) – indicate good model fit, large artefacts in the final simulated model are visible (~~left side~~a-b). For legend check Figure 2.

Also, the plotted time-series of the best 30 simulated model runs, according to the objective function DTW, seemed to indicate a good capture of the averaged EC by the erosion model. An exception was the best model runs found by the DTW SY, in which simulated splash was strongly underestimated (Figure ~~6~~4). However, total EC (0.1 mm) and SY (0.26 kg) differences show very good model run fits, again. Still, an inspection of the maps of the final DoDs shows that the best model run, when applying only the EC based metrics (Figure 4 left two plots), i.e. without considering spatial patterns, leads to noisy model runs. This might be due to high positive and negative changes in immediate proximity which are then ~~averaged out~~cancelled during the averaging of the EC. If only SY-based metrics are used, not even rill patterns are visible in the ~~best-simulated~~ best model runs (Figure 4, right two plots). The good fits in the unfiltered simulation data were therefore found for the wrong reasons, i.e. due to the very strong artefacts, and so they do not reflect finding a good fit of parameters to describe the simulated erosion process.

Using our chosen objective functions alone did not provide sufficient information to automatically assess the plausibility of model output and thus the best input parameters. Only the additional assumption of smooth DEM changes enabled the removal of these implausible models. When the filter was applied, 279 model runs remained from the original 2000. Different relationships between the objective functions became clear after filtering (scatter

plots in Figure 5 and before filtering in Fig. S3:1). In subsequent assessment of the field results, we considered only the filtered data.

460 The relationship between the different metrics of the objective functions is not linear, except for RMSE and DTW EC, which indicates that the metrics capture different aspects of soil surface change due to ~~, including~~ erosion (Figure 5). For example, the model run that has the lowest difference in EC between simulated and observed data does not have to be the same model run with the lowest SY difference. The differences between the EC and SY metrics are more complex, compared to the differences with the same data sources, i.e. camera-based or plot-465 outlet-measured. Nevertheless, in general there is a dependence visible between the different metrics. This was favourable, because we were looking to explore the behavioural parameter space constrained by different sources of data and objective functions~~looking for a model run which ideally fits all objective functions well~~. The assumption here is the more diverse the objective functions, the better the different aspects of the model are being captured. ~~Thus, we want to find the model run with parameter values that fit all constraints defined by the different objective~~ 470 ~~functions.~~ The objective functions that were chosen for the time series of EC (RMSE, DTW, NNSE for EC) and total change (EC) fit well, which is also the case for the corresponding SY metrics. The DL based similarity values reveal the most complex and least obvious relationship to the values of the other functions.

Next, we show the differences between the best model runs chosen according to the different objective functions which considered total changes (space-time averaged), time-series (area-averaged) and spatial patterns (time-av-475 eraged). Figure 6 depicts the final DoD of the best model runs, given the individual objective functions, as well as their combinations. All variants of the objective functions result in a best model run that appears realistic and that predicts at least three dominant rills: however, with different lengths, widths and depths. The predicted rills all reach quite far, compared with observations, into the belt of no erosion towards the upper end of the plot; also, only two main rills were observed. However, the observations for model evalu~~valid~~ation were only considered for 480 the RoI, within which the rills did indeed cross the whole length.
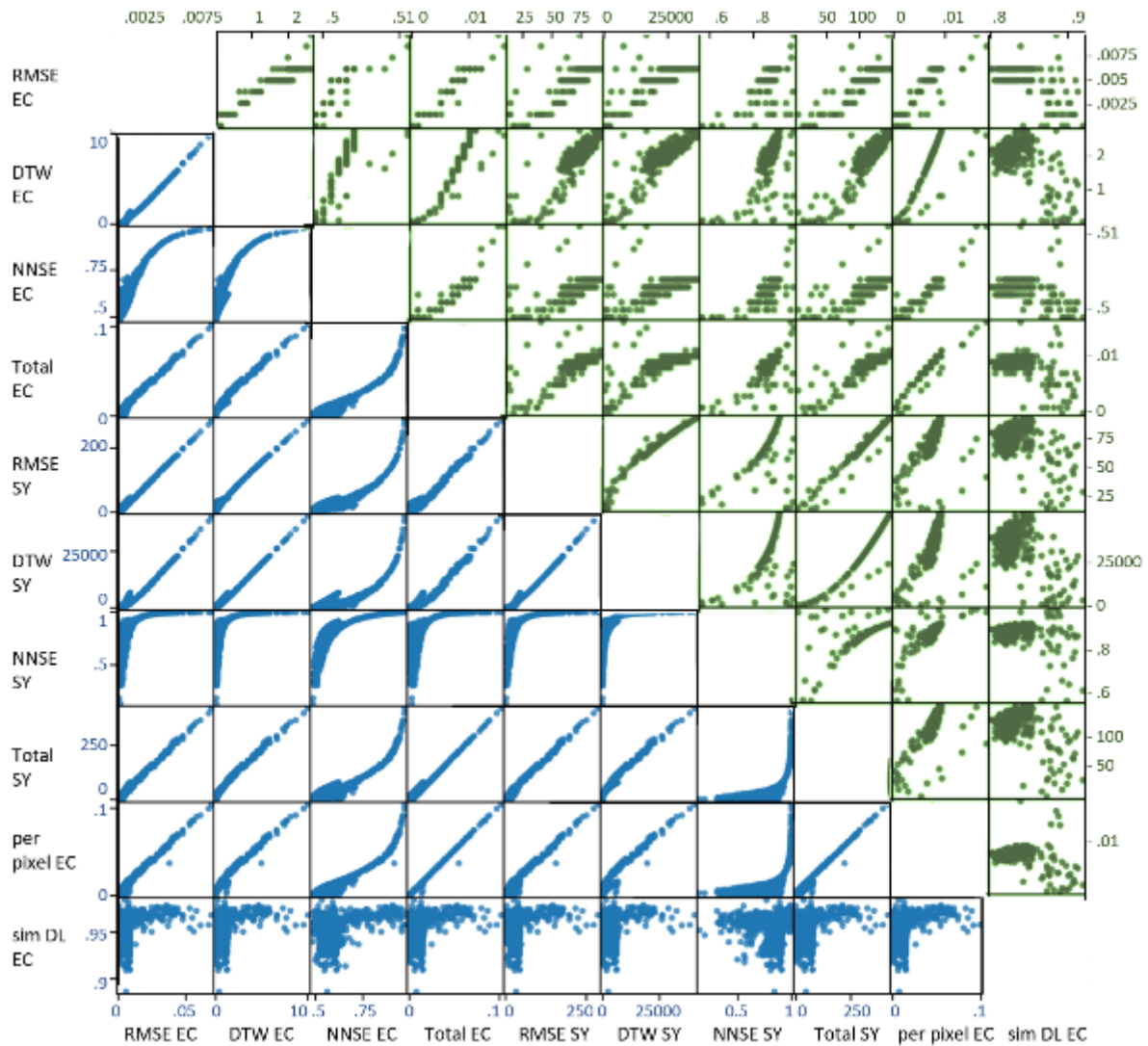
Figure 5: Scatterplots of values of objective functions at field plot (EC in [m] except for sim DL, which has no unit, and SY in [kg]). Blue scatterplots (lower triangle) correspond to the laboratory experiment and green (upper triangle) to the field experiment. The objective functions and their abbreviations are explained in table 2.

485   The best model runs differ when either single EC- or SY- based objective functions are used for evalu~~valid~~ation. If combinations are considered, there is a difference between using only EC-based metrics and SY-based metrics, or combinations of EC- and SY-based metrics. The same best model run resulted for DTW EC, total EC and sim DL EC. Thus, EC metrics that consider space-time averaged (total), area-averaged (DTW), or time-averaged (sim DL) characteristics all select the same model run. Further, in that model run no artefacts are present. This is also

490   the case for NNSE SY. The predicted SY for the best EC-metrics-based model run is however about 30 kg (~17%) off from the measured total SY but the predicted and measured total EC is almost identical. In the case of predicted total EC, the best NNSE SY-based model run is off by 1 mm total EC and by about 24 kg total SY. However, the best model run that was found based on height changes also predicts a more pronounced left rill across almost the whole plot length, which is not the case for the best model run based on the NNSE SY metric. This indicates a

495   potential better performance of EC based metrics to find the best-fitting rill pattern. The best model runs for DTW, total and sim DL EC and NNSE SY do not predict splash or interrill erosion, which does not fit the actual observation of strong splash effects (Figure 6). More splash is modelled for ~~the~~ a realisation with better DTW and SY

metrics . However, in that model run rill depth is too small. The widest rills are found for the best model run based on RMSE SY and per pixel EC.

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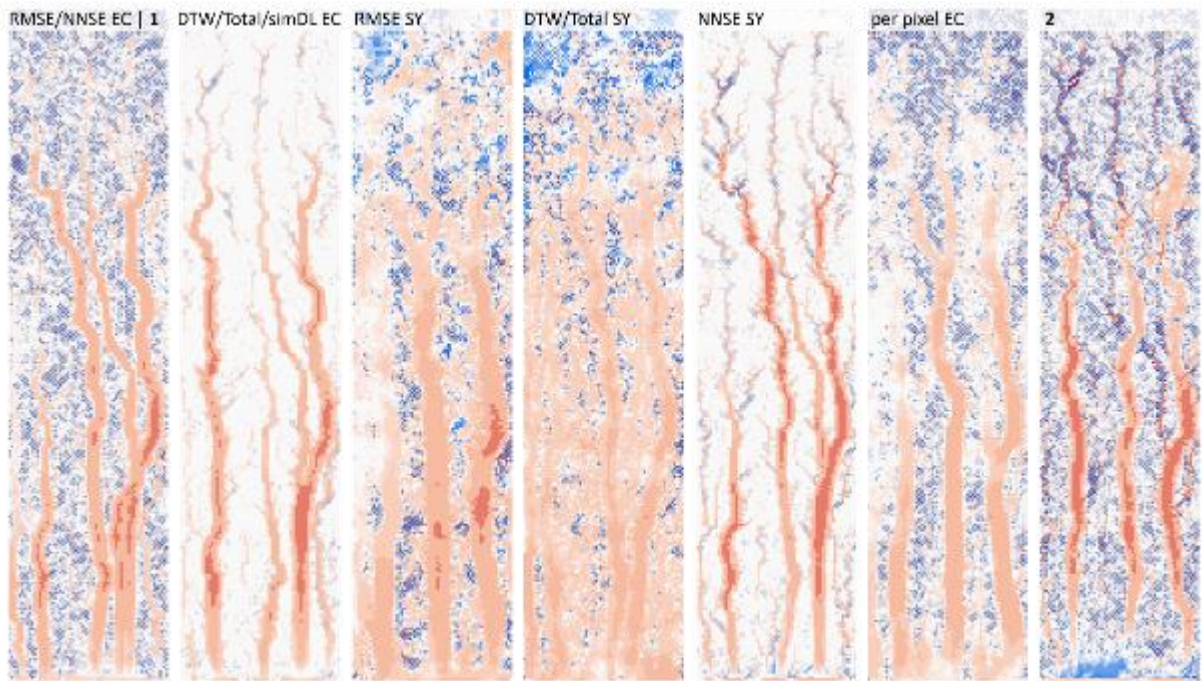
Figure 6: Simulated height change for single and combination (1: EC t_series, EC t_series & total, EC t_series & total & sp_pattern (no DL), EC t_series & total & sp_pattern; 2: SY t_series, SY t_series & total, EC & SY t_series, EC & SY t_series & total, EC & SY t_series & total & sp_pattern (no DL), all) of objective functions. For legend check Figure 2. The objective functions and their abbreviations are explained in table 2.

505 When considering the combination of objective functions, only two best model runs eventually remained. For all objective functions that consider only EC as parameter (and the various combinations; i.e. EC t_series, EC t_series & total, EC t_series & total & sp_pattern (no DL), EC t_series & total & sp_pattern) only one model run remained. The second model run was indicated for all other objective function combinations that consider EC as well as SY (i.e. SY t_series, SY t_series & total, EC & SY t_series, EC & SY t_series & total, EC & SY t_series & total &

510 sp_pattern (no DL), all). Nonetheless it is obvious that these two model runs still contain artefacts, also they do not seem to model splash adequately: this might however be masked by the artefacts. Both model runs predict three main rills, which are deeper for the second model run, i.e. when EC and SY are considered for model evalu-ation. Time series from the erosion model runs (i.e. the area averaged metrics) reveal a good fit by the best

30 model runs at the beginning of the simulation, when changes to the soil surface are still small (Figure 7).

515 After about 30 minutes the model runs begin to deviate strongly from the observations, independently of the considered objective function (RMSE, DTW or NNSE) for EC. We noted that the erosion model runs were not able to capture the observed change of erosion rates: after a slow increase of erosion, after about 15 minutes the erosion rate increased steeply then decelerated to a lower rate after about 40 minutes, which then remained nearly constant until the end of the experiment. However, the simulation runs depict more continuous erosion rates. Differences

520 between modelled and simulated time series of SY are not as strong. A better fit in regard of erosion rate and its change during the experiment is visible. Still, the erosion model runs tend to either overestimate or underestimate erosion throughout the experiment. Very few model runs fitted observations very closely. When considering NNSE no model run fitted, and all the best model runs indicated underestimation.
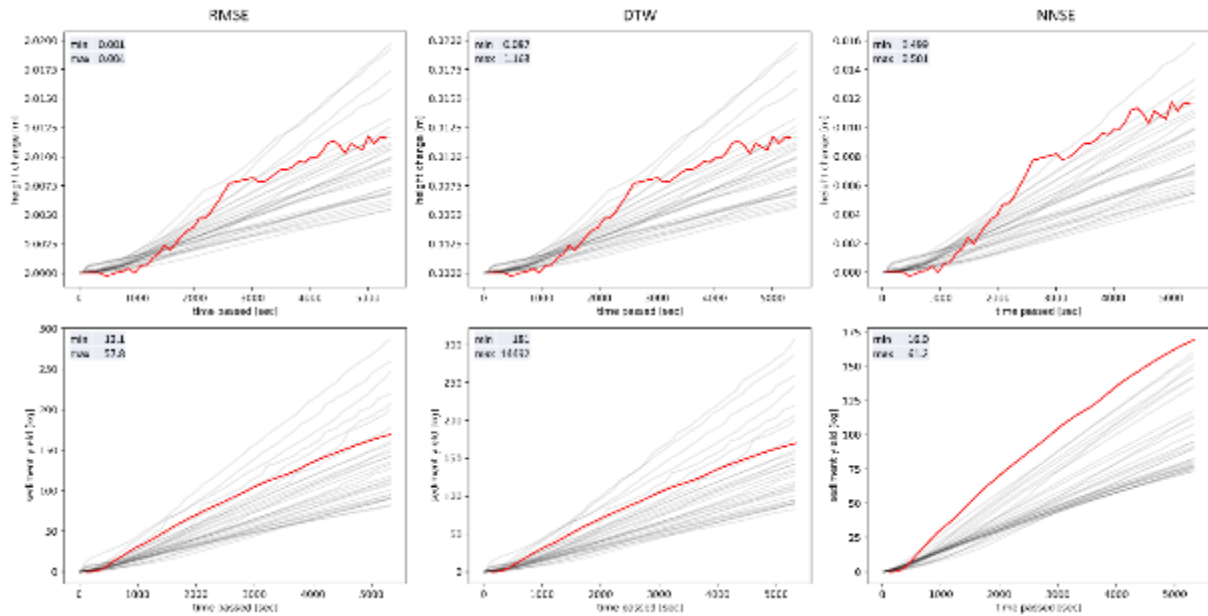
Figure 7: Time series of elevation change measured with time lapse SfM and of sediment yield measured of plot outlet of best 30 models according to objective functions RMSE, DTW and NNSE at the field plot. Note that the scale of the y-axes differ. The objective functions and their abbreviations are explained in table 2.

Considering the observations alone, i.e. EC and SY, the temporal behaviour indicates a difference in both measures. The EC depicts stronger changes of erosion rate during the rainfall simulation compared to the SY rate, which is more stable. This difference might be due to the LoD of the photogrammetry-based data. Thus, only when changes exceed some threshold they are considered, potentially underestimating splash processes in the early rainfall phase.

The time-series of the change of the spatial patterns (per pixel EC and sim DL EC) also indicate, at the beginning, a small difference between simulations and observations, since the changes of the soil surface early on in the experiment are still low. Later on, after about 15 minutes, the patterns become less similar. Figure 8 shows the similarity of spatial pattern for the top 30 model runs according to the averaged per pixel EC and sim DL EC metrics. The DL-based approach further reveals that the stronger the changes, the closer the similarity values again become: however this is not the case for the per pixel EC metric. This may indicate that it becomes easier to assess the similarity with DL, the stronger the spatial patterns become, due to increasing dominance of erosion rills; whereas during the intermediate phase, elevations of soil surfaces might be ambiguous due to greater noise.
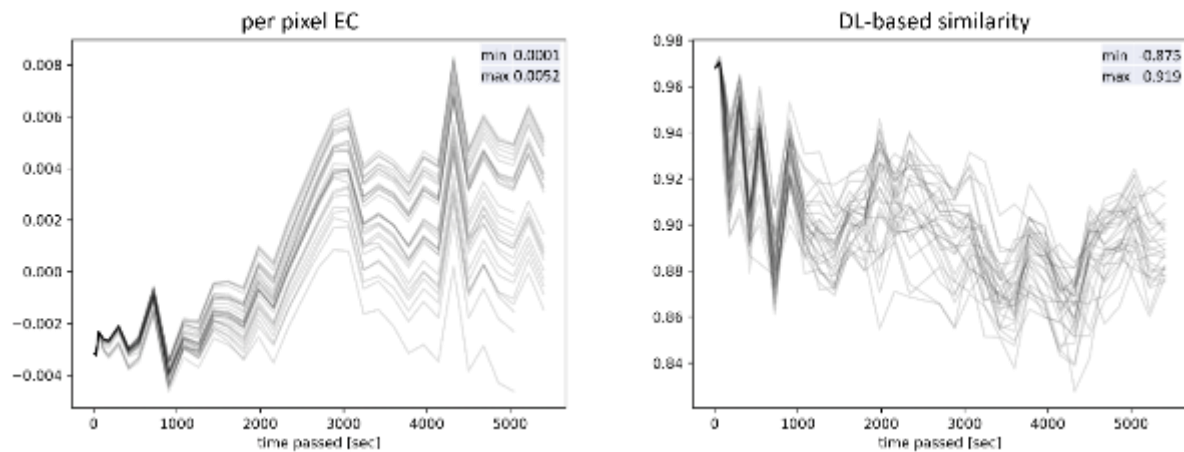
Figure 8: Time series of spatial pattern metrics for best 30 models according to per pixel EC and DL based EC similarity metric for the field experiment. The objective functions and their abbreviations are explained in table 2.

We assessed the best ten model runs considering the different objective function options to evaluate the spread of the model input parameters. Figure 9 shows the parameters within the total parameter range for the best ten model runs according to the multi-objective function approach using all objective functions. It is clear that the parameters do not cluster tightly: equifinality is apparent here, with different combinations of model input parameters giving similarly ~~validation metrics~~good model fits according to the difference between observation and prediction described by the different calibration metrics. The spread of parameter values through the whole parameter space remains, mostly for the single objective functions as well as their combinations. However, a closer look at the best ten results for all objective functions solely indicates decreased ranges ~~are indicated for~~of the parameters determining soil detachability by flow and the threshold for shear stress for slumping~~,~~. because ~~i~~In their combination with the other parameters they are no longer covering the whole of parameter space, but only partial areas, e.g. in the case of "maximum flow velocity" there is an inverse correlation with "soil detachability by flow". In general, very low flow detachment parameters were not considered, which highlights the preference of model runs with a stronger influence of flow detachment with transport by flow. Filtering of the artefacts from model runs is also visible in the parameter space because the larger splash efficiency values are mostly removed (i.e. in the upper range only very few parameter values remained), indicating that raindrop detachment with transport by raindrop splash is not adequately described by the erosion model since the simulated influence of splash is not confirmed by the observations (i.e. DoDs).

Figure 9: Parameter values of best 10 models considering all objective functions – lower triangle corresponds to the laboratory experiment and upper triangle to the field experiment.

However, a closer look at the best ten results for all objective functions indicates decreased ranges of the parameters determining soil detachability by flow and the threshold for shear stress for slumping, because in their combination with the other parameters they are no longer covering the whole of parameter space, but only partial areas, e.g. in the case of "maximum flow velocity" there is an inverse correlation with "soil detachability by flow". In general, very low flow detachment parameters were not considered, which highlights the preference of model runs with a stronger influence of flow detachment with transport by flow. Filtering of the artefacts from model runs is also visible in the parameter space because the larger splash efficiency values are mostly removed (i.e. in the upper range only very few parameter values remained), indicating that raindrop detachment with transport by raindrop splash is not adequately described by the erosion model since the simulated influence of splash is not confirmed by the observations (i.e. DoDs).

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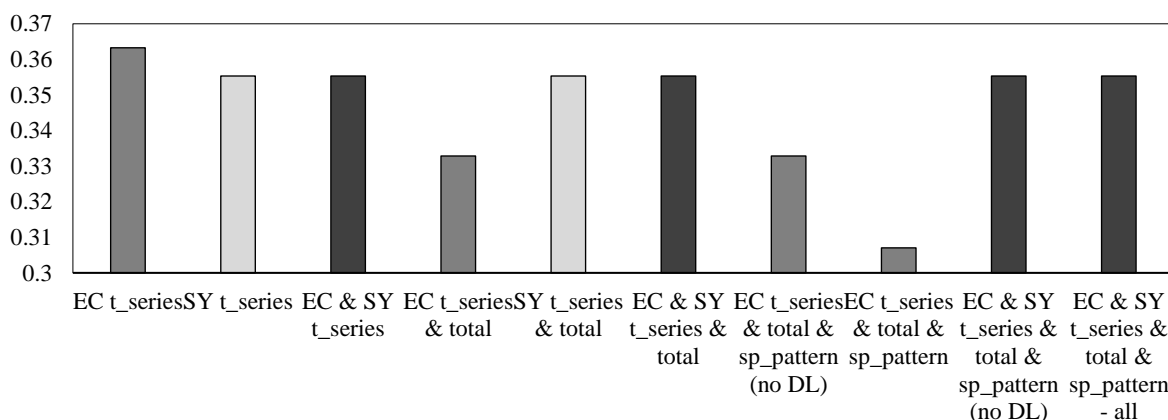
Assessing the relationship between the model parameters and the metrics of the objective functions (Fig. S3:2-8) shows that the choice of lower values for the 'angle of rest for slumped soil' input parameter leads to better model performance, whereas larger values have no influence on the performance, i.e. no large changes in regard to the metrics can be seen, either because they remain high for the time series metrics, or because they remain at a nearly constant value for the area and space-area averaged metrics. With regard to the parameter choices for 'DEM base level', 'radius of shear stress', and 'splash efficiency', no influence on model performance is visible when looking at the different metrics. Further, it appears that the larger the choice for the values of the model input parameters for 'flow detachment' and 'maximum flow velocity', a slightly better performance of the model runs is given when considering the SY-based metrics. However, this relationship is not as clear for the EC-based metrics. Higher 'shear stress slumping threshold' values lead to better erosion model performances, when considering EC metrics, but the performance worsens if SY metrics are considered.

None of the model runs ~~did a good job of~~ predict~~ed~~ing the observed rill pattern from the field experiment. ~~well, i.e. n~~Neither the number of rills (two) nor their locations were adequately modelled. However, some of the model runs did predict the rill at the left plot side and the rill in the middle of the plot. Nevertheless, no model run indicated that the rill at left would become more dominant later during the rainfall simulation and that the rill in the middle would be dominant in the beginning of experiment and then would stop growing.

3.2 Results from the laboratory experiment

605 During the 30 min rainfall simulation in the laboratory a total 80.8 kg of sediment was lost from the plot, and the corresponding discharge was about 395 l. The total net height change measured on the plot was 1.6 cm. Thus, although the rainfall simulation intensity was the same as the field experiment, a larger negative height change (about 25%) was seen, as well as greater sediment yield (considering that on the laboratory plot, nearly half the SY had already been lost after only one third of the total experiment duration of the field plot). Discharge amounted

610 only to about 8% of the field runoff. These differences are mainly due to the significantly higher slope gradient for the laboratory experiment. The animation (Fig. S1) of elevation changes during the field experiment shows the formation of a rill network which is markedly different from the network developed during the field experiments. At first, a dominant rill formed~~s~~ at the lower right plot side. A second main rill then ~~develops~~ developed on the lower third of the plot, at the left side. After about 15 minutes, the left rill ~~merges~~ merged with a third rill that

615 began to grow at the bottom of the plot after about ten minutes, cutting upslope until it meets the other rill. At the end of the experiment an intricate dendritic rill pattern ~~is~~ was observable, especially in the upper third of the plot which ~~is~~ was also dominated by sheet erosion, draining into the two main rills. The rill network formed in the first 15 to 20 minutes and then changed little, mainly just deepening.

Again in contrast to the field experiment, in the laboratory rainfall simulation no strong artefacts were observed in

620 the erosion model output. Therefore no filtering was necessary and all 2400 model runs could be used for the evaluation using the different single objective functions (Figure 1~~1~~0). Although the best model runs of the various calibration functions predict the observed filigree rill pattern and/or a few single strong rills, none of them ~~model~~ad~~f~~equately represent the strong sheet erosion. In the best model runs based on the area-averaged parameters (RMSE, DTW, NNSE) four dominant rills are predicted that are wide and deep, and situated across the whole plot

625 region. Considering total SY for calibration~~,~~ yields three obvious rills, with t~~. T~~he right-hand rill fit~~tings~~ the observ~~ed~~ ~~ation~~ data well as it is also bifurcated. However, none of the SY-based best model runs capture the overall fine rill pattern. The best model runs for the space-time- and area-averaged EC-based metrics also predict wide rills covering the lower plot region, which is closer to the camera-based observations. The observed total SY is underestimated by 12 kg (DTW, RMSE, total EC) to 16 kg (NNSE EC), whereas the residual of predicted total

630 SY for the best SY-based model runs range between 1 kg (DTW SY) and 3 kg (NNSE, RMSE SY). The best model run for the objective function considering per pixel EC is the only one that predicts two dominant rills. However, these rills are still too wide and short compared with observations. The best model run for the second metric focusing on spatial pattern, i.e. sim DL EC, predicts the formation of many small rills. Thus, it is closest to the observed dendritic rill pattern, but the rills are too shallow and this model run completely misses the observed

635 sheet erosion.

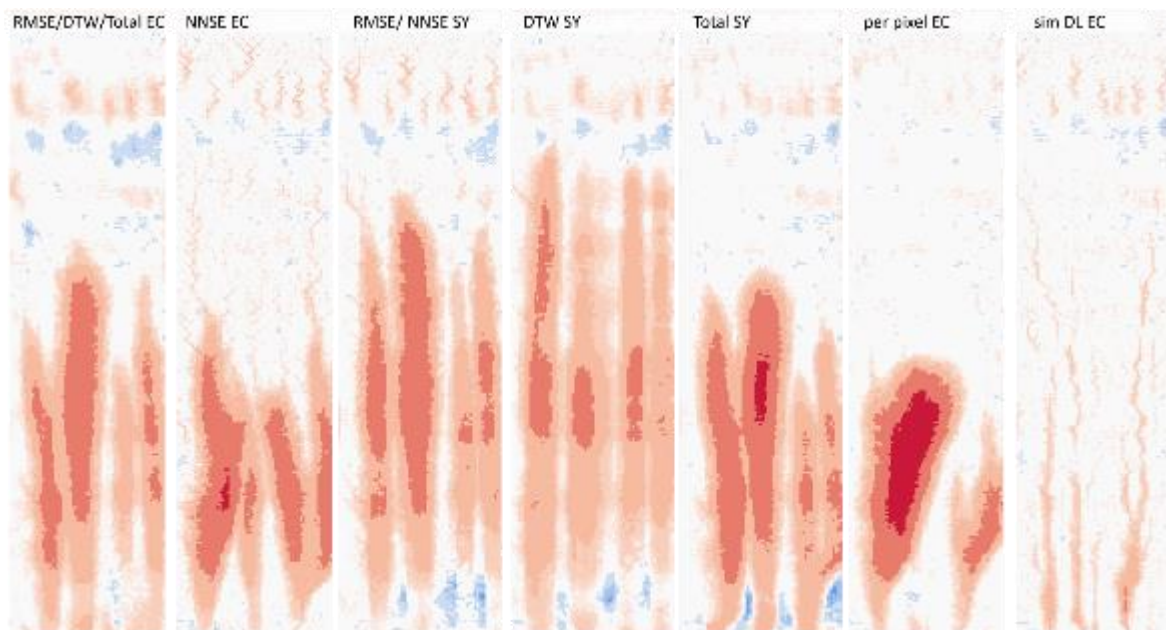



Figure 140: Simulated height change of the best model in regard of the single objective functions. For legend check Figure 2. The objective functions and their abbreviations are explained in table 2.

When combining the objective functions, it is not possible to find a single best model run that fits the observations

640 well (Figure 1211). In case of EC and SY time series based parameters, model runs predict patterns with rills that are too wide and too long, and which cover the whole plot. The combination of objective functions considering only EC-based metrics, including the spatial pattern, indicate model runs with rill erosion dominating in the lower to the middle part of the plot: however these are still too long, and there is a belt of no erosion at the upper plot region. If SY-based metrics are combined with EC-based ones, then predicted rills are shorter, but still do not

645 resemble the observations as the rills remain too wide. Overall, in the camera-based observations in the upper plot region strong sheet erosion is visible, which is not predicted by the erosion model.

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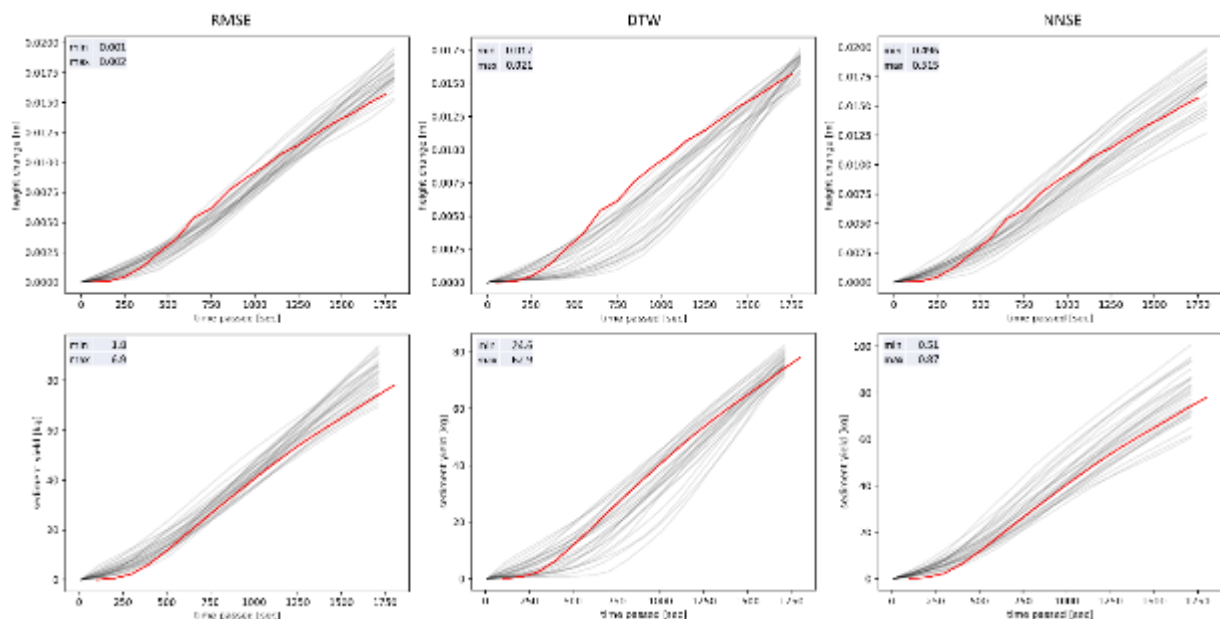
Relationships between the different calibration metrics are more obvious for the laboratory experiment (Figure 5). Correlations between all objective function values, except for NNSE and the DL based spatial pattern comparison, are clearly linear. The relationship between the values of the NNSE SY and EC and the remaining metrics is obvious and non-linear. The DL based similarity metric alone reveals an unclear relationship to the values of the

655   other functions.

When assessing the temporal behaviour of the best 30 model runs according to the area-averaged metrics, the EC-based approaches reveal model runs that fit well or tend to underestimate soil erosion in the middle period of the experiment (Figure 1312). The best model runs according to the RMSE and NNSE EC do a better job of predicting height change over time, while the DTW EC based models give a best fit at the beginning and end of the experiment

660   (as it is expected due to the way in which the DTW is calculated). The NNSE EC based simulations show the largest variance between the best 30 model runs at the end of the experiment. In contrast to the field experiment, the rate of change for the observed EC and SY is similar in the laboratory rainfall simulation, which may result from more intense change at the beginning of the experiment, leading to crossing of the LoD threshold early on. The best model runs according to the SY-based calibration values also fit the observations well. The RMSE and

665   NNSE SY-based best model runs overestimate erosion, especially at the beginning, but also slightly throughout the rainfall experiment. The NNSE-based best model runs scatter strongly towards the end of the experiment. The best model runs according to the DTW SY metric reveal a stronger variation in regard of the temporal behaviour of the sediment yield with a few model runs strongly underestimating erosion.

670   **Figure 1312: Time series of elevation change measured with time lapse SfM and of sediment yield measured of plot outlet of best 30 models according to objective functions RMSE, DTW and NNSE at the laboratory plot. Note that the scale of the y-axes differ. The objective functions and their abbreviations are explained in table 2.**

In both field and laboratory experiments, the spatial pattern metrics indicate a high agreement between model results and reality at the beginning of the experiment. Later in the experiments these begin to diverge, when

675   considering the per pixel EC (Figure 1413). However, the best model runs according to the DL-based metric

already show an increase in the deviation between observation and model very early in the experiment; towards the end the differences decrease again. This is not surprising because the best 30 model runs were chosen using the difference of last model runs in the time series. In general, model runs of the laboratory experiment were more similar to each other than was the case for model runs of the field experiment.

680

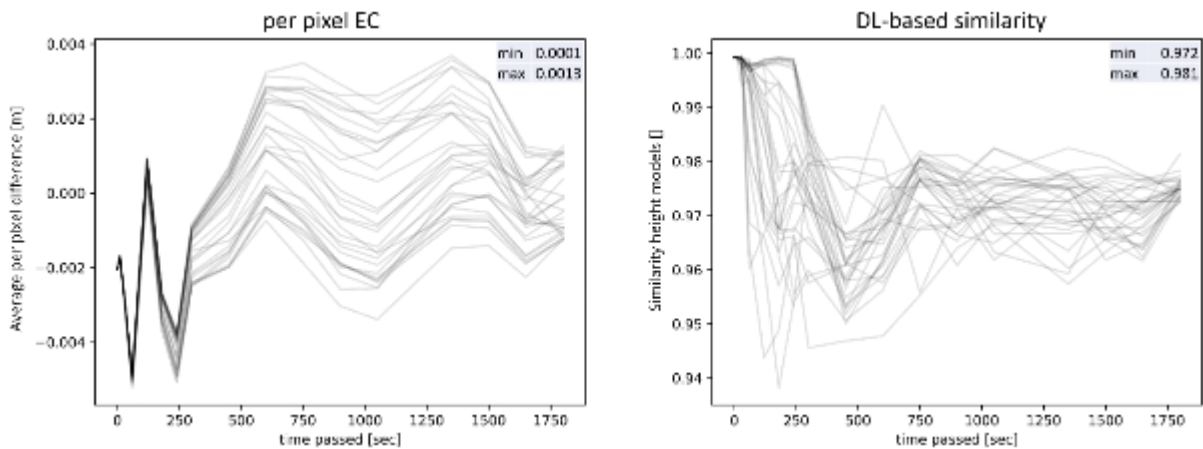
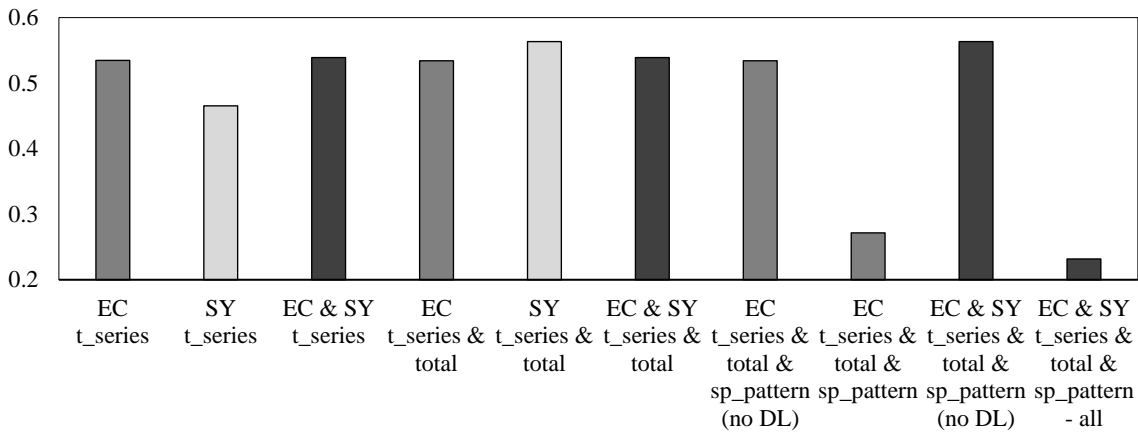



Figure ~~14~~13: Time series of spatial pattern metrics for best 30 models according to per pixel EC and DL based EC similarity metric for the laboratory experiment. The objective functions and their abbreviations are explained in table 2.

Compared to the field experiment, the combination of objective functions enables a more obvious narrowing down

685 of the range of parameter values with regard to the 'threshold of shear stress for slumping' and the 'angle of rest for slumped soil' input parameters, both in favour of lower values (Figure 9). For the input parameter 'distance to the DEM base level', lower values are chosen for the best ten model runs. The remaining parameters are spread across the entire range.

~~The best 30 model runs had a lower range of parameters when all EC based metrics and when all objective~~

690 ~~functions were considered (Figure 15). The remaining combinations of objective functions reveal higher but similar ranges and no difference can be seen if EC and/SY is considered.~~

~~**Figure 15: Range of parameters of best 30 models for different combinations objective functions at the laboratory experiment. Note that the y-axis values start at 0.2.**~~

695 For the laboratory experiment, relationships between the erosion model input parameters and the metrics of the objective functions indicate similar characteristics to the field experiment, except for the SY and considering the 'threshold of shear stress for slumping' parameter (Fig. S3: 9-15). Overall, no model run did a good job of

predicting the response of the soil in the laboratory rainfall simulation experiment to the multiple and interacting processes of soil erosion. Rills were too long and wide and no finely-detailed rill pattern was predicted.

4 Discussion

This evaluation of a single soil erosion model used three approaches to spatio-temporal averaging (Table 1). While other erosion model evaluations (e.g. Favis-Mortlock et al., 1996; Jetten et al., 1999) have considered multiple erosion models, few if any previous erosion model evaluations have considered all three spatio-temporal averaging approaches. ~~The most commonly used approach involves space-time averaging: a simple comparison of measured and modelled runoff and sediment yield at the end of the plot (or at the catchment outlet) and at the end of the period of observation. Sometimes this is supplemented by comparisons of measured and modelled time series, constructed from additional plot-end (or catchment outlet) measurements during the period of observation. It has been, and still is, much less common to compare measured and modelled spatial patterns of erosion.~~
~~From the perspective of the historical development of erosion models (e.g. Nicks, 1998) it is unsurprising that model evaluations have concentrated on simple spatio-temporal averaging approaches. The USLE (Wischmeier, 1976) and subsequent models based upon the USLE (e.g. MUSLE: Williams, 1975; RUSLE: Renard et al., 1991; USLE M: Kinnell and Risse, 1978) are only capable of generating results which are averaged over both time and space. Subsequent, more process-focused, erosion models such as WEPP (Nearing et al., 1989) or Erosion-2D (Schmidt, 1991) introduced a 2D spatial element: a hillslope profile. Later came models with an explicit spatial focus, such as LISEM (de Roo et al., 1996) and Erosion 3D (Schmidt et al., 1996). The evaluation of erosion models has therefore lagged somewhat behind the development of the models themselves.~~

An important finding from this study is that is that each averaging approach, as exemplified by each group of objective functions, illuminates different aspects of erosion model performance, as discussed below. No single objective function is capable of identifying all strengths and weaknesses of the model tested. Thus, as we appreciate more strongly the interacting temporal and spatial complexities of soil erosion – whether at the process-dominated plot scale, as in this study, or the connectivity-controlled catchment scale (Favis-Mortlock et al., 2022) – and incorporate representations of this complexity in future erosion models, it is clear that we will need approaches to model evaluation of the kind described in this study.

A particular challenge, when comparing measured and modelled patterns of rill erosion, results from the problem of small spatial offsets in rill location. A modelled rill network might, as judged by eye, be very similar to an observed rill network. But a simple pixel-by-pixel comparison of measured and modelled DEMs could still give poor results since rills may well be spatially offset between the two DEMs, perhaps by very small distances. Additionally, measured and modelled rill depths may differ. There is much less of a problem when considering interrill changes, since these are dispersed across the whole of the eroding area and thus averaged values can be used. AI-based similarity objective functions (Radford et al., 2021), as used in this study, could provide a potential solution to this issue. Such objective functions can give a clear measure of the fit between model and observation even if the rills are not at identical locations.

We found the best field experiment model runs using either EC-based single objective functions, i.e. DTW, total and sim DL, which suggests that in some cases an ensemble of objective functions might not be needed. However,

735   it also became clear that there is a sensitivity towards the choice of the single objectives, because for the metrics RMSE, NNSE and per pixel EC, another best model run was found. Finding the best model runs using only EC-based measures suggests that the erosion model calibration might be possible without using sediment yield observations in certain scenarios. This has important implications for the usage of our approach to calibrate models also at larger scales, i.e. when time series of catchment data via UAV or aerial measurements may not be available.

740   The calibration metric DTW is not the most suitable for the SY-based measurements, for the field experiment. However, if it is EC-based, the best model run was found to outperform the fit of the RMSE and NNSE EC-based metrics. This may be due to the averaging of the SY changes with no spatial consideration, whereas the averaged EC-values are still based on spatial measurements. The best temporal behaviour of soil surface change (EC) or SY were captured before the artefact filtering, i.e. the DTW, RMSE and NNSE values and corresponding plotted time

745   series indicated a very good model fit. It is clear that splash redistribution is indeed an important process in our two experiments. But the erosion model was not able to represent this process adequately. Further work is needed to avoid creating the artefacts that make the model outcome implausible.

When using time-lapse SfM-photogrammetry to measure soil erosion it must be considered that erosion-masking processes, such as soil compaction and settling, can lead to faulty erosion measurements (Kaiser et al., 2018, Epple

750   et al., subm.). In these two experiments, such processes are assumed to be negligible due to the application of very strong rainfall events on relatively compacted soils (soil bulk density of 1.23 tm-3). Similar considerations apply when using laser scanners, e.g. Wang and Lai (2018).

From the perspective of future work: this study has clearly indicated weaknesses in some process representations within RillGrow, particularly splash redistribution. Work is ongoing to improve this. In addition, the computational

755   needs of the model meant that the multiple model runs required by the current study used a great deal of computing power and time. A parallel-processing version of RillGrow is being developed.

In addition to considering changes in DEM elevation, it might also be useful in future studies to consider measurements of ponding and runoff forming at the soil surface (Zamboni et al., 2024) or spatially distributed velocity quantities (Wolff et al., 2024). These can be used to provide further calibration/evaluation opportunities

760   focusing on the hydrological, rather the sedimentological, processes.

Another approach for future work could focus on the assessment of weighting the different objective functions. This is of interest because this study reveals that some objective functions are more important than others, such as when considering spatial patterns versus time series of averaged change metrics (e.g. DTW EC versus sim DL EC and their combinations, i.e. EC t_series & total & sp_pattern at the field experiment). We tested a weighted error

765   after standardizing the objective function values. However, such a uniform approach did not produce good results for the field experiment, i.e. the best model runs contained only very small rills. Thus the optimum weighting of the different functions is not known. Another ~~aspect for~~potential improvement is the consideration of the parameter distribution. The best ten or thirty model runs revealed that the output is not one set of parameters, but actually a set of parameter distributions. However, these distributions are not independent, i.e. if one parameter is chosen, it

770   means that a specific other needs to be drawn. Therefore, in the future, conditional drawings should be considered (i.e. Bayes principle).

5 Conclusions

This study advances the calibration and evaluation of soil erosion models by considering various objective functions that consider spatio-temporal aspects differently. Several thousand runs of the erosion model RillGrow were performed with parameters drawn approximately randomly, by use of a Latin Hyper Cube approach. Outputs from these model runs were compared to sediment yield measured during field- and laboratory-based rainfall simulation experiments, and model outputs were compared to SfM photogrammetry-derived observations, i.e. representations of soil surface change with spatial resolutions of few cm and temporal resolutions of 10 seconds. Ten calibration metrices were used to find the best-performing model runs.

Results highlight the need for more sophisticated evaluation techniques that go beyond traditional space-time averaging methods. Different spatio-temporal averaging approaches illuminate different aspects of model performance, indicating that no single objective function could fully capture the complexities of erosion processes. The study also identified challenges in model ~~valid~~evaluation, such as the issue of spatial offsets in rill locations, and suggests AI-based similarity functions as a potential solution. Additionally, the study clearly identified limitations in the process representations ~~with~~in the version of RillGrow used in the study, particularly regarding splash erosion. Such a finding is very useful ~~with regard to~~for prioritising ongoing refinement of the erosion model.

The exploration of alternative calibration metrics and the potential for parallel-processing to address computational demands illustrates the evolving landscape of erosion mode~~l~~lling. Our findings suggest that future research should focus on refining objective functions that also consider novel observations of the soil erosion processes, as such observations are likely under future global change. Future research should also consider parameter distributions to improve calibration ~~and validation~~ outcomes.

Overall, ~~these results~~this study strongly emphasize~~s~~ the need for more nuanced evaluation of erosion models, including the incorporation of spatial pattern comparison techniques. This is necessary to provide deeper understanding of any erosion model's capabilities. Only with such improved model evaluations will we be able to adequately develop and evaluate a future generation of soil erosion models, which will be vital tools in forecasting and managing the erosional impacts of future global change

List of acronyms

CA	Cellular Automaton
CLIP	Contrastive Language-Image Pre-training
DEM	Digital Elevation Model
DL	Deep Learning
DoD	DEM of Differences
DTW	Dynamic Time Warping
DVR	Dense Vector Representation
EC	Elevation Change

FD-FT	Flow Detachment, Flow Transport" (Kinnell, 2001)
GCP	Ground Control Point
LHC	Latin HyperCube
LoD	Level of Detection
NNSE	Normalized Nash-Sutcliffe Efficiency
PM	Precision Map
RD-FT	Raindrop Detachment, Flow Transport (Kinnell, 2001)
RD-ST	Raindrop Detachment, Splash Transport (Kinnell, 2001)
RMSE	Root Mean Square Error
RoI	Region of Interest
SfM	Structure from Motion
SLR	Single Lens Reflex
SY	Sediment Yield
UAV	Unmanned Aerial Vehicle

Data & Code availability: The raw data and source code for model evaluation are available here: https://doi.org/10.25532/OPARA-602. The source code of RillGrow can be accessed here: https://github.com/davefavismortlock/RillGrow.

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References

Baartman, J. E. M., Nunes, J. P., Masselink, R., Darboux, F., Bielders, C., Degré, A., Cantreul, V., Cerdan, O., Grangeon, T., Fiener, P., Wilken, F., Schindewolf, M., and Wainwright, J.: What do models tell us about water and sediment connectivity?, Geomorphology, 367, 107300, https://doi.org/10/gg5phb, 2020.

Batista, P. V. G., Davies, J., Silva, M. L. N., and Quinton, J. N.: On the evaluation of soil erosion models: Are we doing enough?, Earth Sci Rev, 197, https://doi.org/10.1016/j.earscirev.2019.102898, 2019.

Beven, K.: A manifesto for the equifinality thesis. Journal of Hydrology 320, 18-36, https://doi.org/10.1016/j.jhydrol.2005.07.007, 2006.

Blanch, X., Guinau, M., Eltner, A., and Abellan, A.: A cost-effective image-based system for 3D geomorphic monitoring: An application to rockfalls, Geomorphology, 449, https://doi.org/10.1016/j.geomorph.2024.109065, 2024.

Boardman, J., Evans, R., Favis-Mortlock, D. T., and Harris, T. M.: Climate change and soil erosion on agricultural land in England and Wales, Land Degradation and Rehabilitation, 2, 95–106, 1990.

Bosio, R., Cagninei, A., and Poggi, D.: Large Laboratory Simulator of Natural Rainfall: From Drizzle to Storms, Water (Switzerland, 15, https://doi.org/10.3390/w15122205), 2023.

Brazier, R. E., Beven, K. J., Anthony, S. G. and Rowan, J. S.: Implications of model uncertainty for the mapping of hillslope-scale soil erosion predictions, Earth Surf. Process. Landforms, 26, 1333–1352, 2001.

Cappuccio, R., Cattaneo, G., Erbacci, G., and Jocher, U.: A parallel implementation of a cellular automata based model for coffee percolation, Parallel Comput, 27, 685–717, 2001.

Chen, Y., Wei, T., Li, J., Xin, Y., and Ding, M.: Future changes in global rainfall erosivity: Insights from the precipitation changes, J Hydrol (Amst), 638, 131435, https://doi.org/10.1016/j.jhydrol.2024.131435, 2024.

Cheng, N.-S.: Simplified Settling Velocity Formula for Sediment Particle, Journal of Hydraulic Engineering, 123, 149–152, https://doi.org/10/fkvvcg, 1997.

Coulthard, T. J., Macklin, M. G., and Kirkby, M. J.: A cellular model of Holocene upland river basin and alluvial fan evolution, Earth Surf Process Landf, 27, 269–288, https://doi.org/10.1002/esp.318, 2002.

Courant, R., Friedrichs, K., and Lewy, H.: Über die partiellen Differenzengleichungen der mathematischen Physik", Math Ann, 100, 32–74, 1928.

Darboux, F., Gascuel-Odoux, C., and Davy, P.: Effects of surface water storage by soil roughness on overland-flow generation, Earth Surf Process Landf, 27, 223–233, https://doi.org/10/dncj4g, 2002.

de Roo, A.P.J., Wesseling, C.G., and Ritsema, C.J.: LISEM: A Single-Event Physically Based Hydrological and Soil Erosion Model for Drainage Basins. I: Theory, Input and Output. Hydrological Processes 10, 1107–1 117, 1996

Dunkerley, D. L.: Rainfall intensity bursts and the erosion of soils: an analysis highlighting the need for high temporal resolution rainfall data for research under current and future climates, Earth Surf. Dynam, 7, 345–360, https://doi.org/10.5194/esurf-7-345-2019, 2019.

Eltner, A. and Sofia, G.: Structure from motion photogrammetric technique, in: Developments in Earth Surface Processes, vol. 23, 1–24, https://doi.org/10.1016/B978-0-444-64177-9.00001-1, 2020.

Eltner, A., Kaiser, A., Abellan, A., and Schindewolf, M.: Time lapse structure from motion photogrammetry for continuous geomorphic monitoring, Earth Surf Process Landf, 42, 2240–2253, https://doi.org/10.1002/esp.4178, 2017.

Eltner, A., Maas, H.-G., and Faust, D.: Soil micro-topography change detection at hillslopes in fragile Mediterranean landscapes, Geoderma, 313, 217–232, https://doi.org/10.1016/j.geoderma.2017.10.034, 2018.

Epple, L., Kaiser, A., Schindewolf, M., Bienert, A., Lenz, J., and Eltner, A.: A Review on the Possibilities and Challenges of Today's Soil and Soil Surface Assessment Techniques in the Context of Process-Based Soil Erosion Models, Remote Sens (Basel), 14, https://doi.org/10.3390/rs14102468, 2022.

Favis-Mortlock, D., Boardman, J., and MacMillan, V.: The Limits of Erosion Modeling, in: Landscape Erosion and Evolution Modeling, edited by: Harmon, R. S. and Doe, W. W., Springer US, Boston, MA, 477–516, https://doi.org/10.1007/978-1-4615-0575-4_16, 2001.

Favis-Mortlock, D., Boardman, J., Foster, I., and Shepheard, M.: Comparison of observed and DEM-driven field-to-river routing of flow from eroding fields in an arable lowland catchment, Catena (Amst), 208, 105737, https://doi.org/10.1016/j.catena.2021.105737, 2022.

Favis-Mortlock, D. T.: A self-organising dynamic systems approach to the simulation of rill initiation and development on hillslopes, Comput Geosci, 24, 353–372, 1998.

Favis-Mortlock, D. T.: Self-organization and cellular automata models, in: Environmental modelling: finding simplicity in complexity, edited by: Wainwright, J. and Mulligan, M., Wiley, Chichester, UK, 2004.

Favis-Mortlock, D. T. and Boardman, J.: Nonlinear responses of soil erosion to climate change: a modelling study on the UK South Downs, Catena (Amst), 25, 365–387, 1995.

870   Favis-Mortlock, D. T., Quinton, J. N., and Dickinson, W. T.: The GCTE validation of soil erosion models for global change studies, J Soil Water Conserv, 51, 397–403, 1996.

Favis-Mortlock, D. T., Guerra, A. J. T., and Boardman, J.: A self-organising dynamic systems approach to hillslope rill initiation and growth: model development and validation, IAHS Press Publication, Wallingford, UK, 1998.

875   Favis-Mortlock, D. T., Boardman, J., Parsons, A. J., and Lascelles, B.: Emergence and erosion: a model for rill initiation and development, Hydrol Process, 14, 2173–2205, 2000.

Fischer, F. K., Kistler, M., Brandhuber, R., Maier, H., Treisch, M. and Auerswald, K.: Validation of official erosion modelling based on high-resolution radar rain data by aerial photo erosion classification, Earth Surf. Process. Landforms, 43(1), 187–194, doi:10.1002/esp.4216, 2018.

880   Foucher, A., Evrard, O., Rabiet, L., Cerdan, O., Landemaine, V., Bizeul, R., Chalaux-Clergue, T., Marescaux, J., Debortoli, N., Ambroise, V., and Desprats, J.-F.: Uncontrolled deforestation and population growth threaten a tropical island's water and land resources in only 10 years, Sci. Adv, 10, 5941, https://doi.org/10.1126/sciadv.adn5941, 2024.

Grothum, O., Epple, L., Bienert, A., Eltner, A.: Beobachtung und Rekonstruktion von Bodenerosionsprozessen
885   mit permanenten Kamerastationen. Publikationen der DGPF e.V., Band 32, 106-115, 2024.

Hänsel, P., Schindewolf, M., Eltner, A., Kaiser, A., and Schmidt, J.: Feasibility of High-Resolution Soil Erosion Measurements by Means of Rainfall Simulations and SfM Photogrammetry, Hydrology, 3, 2016.

Helming, K., Römkens, M. J. M., and Prasad, S.: Surface roughness related processes of runoff and soil loss: a flume study, Soil Science Society of America Journal, 62, 243–250, 1998.

890   Iserloh, T., Ries, J. B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M. T., Fernández-Gálvez, J., Fister, W., Geißler, C., Gómez, J. A., Gómez-Macpherson, H., Kuhn, N. J., Lázaro, R., León, F. J., Martínez-Mena, M., Martínez-Murillo, J. F., Marzen, M., Mingorance, M. D., Ortigosa, L., Peters, P., Regüés, D., Ruiz-Sinoga, J. D., Scholten, T., Seeger, M., Solé-Benet, A., Wengel, R., and Wirtz, S.: European small portable rainfall simulators: A comparison of rainfall characteristics, Catena (Amst), 110, 100–112,
895   https://doi.org/10.1016/j.catena.2013.05.013, 2013.

Jetten, V., Roo, A., and Favis-Mortlock, D.: Evaluation of field-scale and catchment-scale soil erosion models, Catena (Amst), 37, 521–541, https://doi.org/10.1016/S0341-8162(99)00037-5, 1999.

Jetten, V., Govers, G. and Hessel, R.: Erosion models: Quality of spatial predictions, Hydrol. Process., 17(5), 887–900, doi:10.1002/hyp.1168, 2003.

900   Kaiser, A., Erhardt, A., and Eltner, A.: Addressing uncertainties in interpreting soil surface changes by multitemporal high-resolution topography data across scales, Land Degrad Dev, 29, 2264–2277, https://doi.org/10.1002/ldr.2967, 2018.

Kavka P., Strouhal L., Jáchymová B., et al.: DOUBLE SIZE FULLJET FIELD RAINFALL SIMULATOR FOR COMPLEX INTERRILL AND RILL EROSION STUDIES, Stavební Obzor - Civil Engineering Journal, 27,
905   183–194, https://doi.org/10.14311/CEJ.2018.02.0015, 2018.

Kavka P., M. Neumann, T. Laburda, and D. Zumr: Developing of the Laboratory Rainfall Simulator for Testing the Technical Soil Surface Protection Measures and Droplets Impact, in: 17th European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2019 - Proceedings 2019-Septe, https://doi.org/10.32075/17ECSMGE-2019-0392., 2019.

910   Kinnell, P. I. A.: Comments on "vertical hydraulic gradient and run-on water and sediment effects on erosion processes and sediment regimes, Soil Science Society of America Journal, 65, 953–956, 2001.

Kinnell, P. I. A. and Risse, L. M.: USLE-M: Empirical Modeling Rainfall Erosion through Runoff and Sediment Concentration, Soil Science Society of America Journal, 62, 1667, https://doi.org/10.2136/sssaj1998.03615995006200060026x, 1998.

915   Lawrence, D. S. L.: Macroscale surface roughness and frictional resistance in overland flow, Earth Surf Process Landf, 22, 365–382, https://doi.org/10/bjjnxv, 1997.

Li, Z. and Fang, H.: Impacts of climate change on water erosion: A review, Earth Sci Rev, 163, 94–117, https://doi.org/10.1016/j.earscirev.2016.10.004, 2016.

Murray, A. B. and Paola, C.: Properties of a cellular braided-stream model, Earth Surf Process Landf, 22, 1001–
920   1025, 1997.

Nearing, M. A.: A probabilistic model of soil detachment by shallow turbulent flow, Transactions of the American Society of Agricultural Engineers, 34, 81–85, 1991.

Nearing, M. A., Foster, G. R., Lane, L. J., and Finkner, S. C.: A process-based soil erosion model for USDA-Water Erosion Prediction Project technology, Transactions of the American Society of Agricultural Engineers,
925   32, 1587–1593, 1989.

Nearing, M. A., Norton, L. D., Bulgakov, D. A., Larionov, G. A., West, L. T., and Dontsova, K. M.: Hydraulics and erosion in eroding rills, Water Resour Res, 33, 865–876, https://doi.org/10.1029/97WR00013, 1997.

Nearing, M. A., Xie, Y., Liu, B., and Ye, Y.: Natural and anthropogenic rates of soil erosion, International Soil and Water Conservation Research, 5, 77–84, https://doi.org/10.1016/j.iswcr.2017.04.001, 2017.

930 Nicholas, A. P.: Cellular modelling in fluvial geomorphology, Earth Surf Process Landf, 30, 645–649, https://doi.org/10.1002/esp.1231, 2005.

Nicks, A. D.: The use of USLE components in models, in: Modelling Soil Erosion by Water, edited by: In, B. J. and Favis-Mortlock, D. T., Springer-Verlag NATO-ASI Series I-55, Berlin, 1998.

Onnen, N., Eltner, A., Heckrath, G., Van Oost, K.: Monitoring soil surface roughness under growing winter wheat with low altitude UAV sensing. Earth Surface Processes and Landforms, 45(14), 3747-3759, https://doi.org/10.1002/esp.4998, 2020.

935

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., and Alewell, C.: The new assessment of soil loss by water erosion in Europe, Environ Sci Policy, 54, 438–447, https://doi.org/10.1016/j.envsci.2015.08.012, 2015.

940 Planchon, O., Esteves, M., Silvera, N., and Lapetite, J. M.: Raindrop erosion of tillage induced microrelief: possible use of the diffusion equation, Soil Tillage Res, 15–16, 1–14, 2000.

Prosdocimi, M., Burguet, M., Prima, S., Sofia, G., Terol, E., Rodrigo Comino, J., Cerdà, A., and Tarolli, P.: Rainfall simulation and Structure-from-Motion photogrammetry for the analysis of soil water erosion in Mediterranean vineyards, Sci. Total Environ, 574, 204–215, https://doi.org/10.1016/j.scitotenv.2016.09.036,

945 2017.

Quinton, J. N. and Fiener, P.: Soil erosion on arable land: An unresolved global environmental threat, Progress in Physical Geography: Earth and Environment, 48, 136–161, https://doi.org/10.1177/03091333231216595, 2024.

Radford, A., Kim, J. W., Hallacy, C., Ramesh, A., Goh, G., Agarwal, S., Sastry, G., Askell, A., Mishkin, P.,

950 Clark, J., Krueger, G., and Sutskever, I.: Learning Transferable Visual Models From Natural Language Supervision, 2021.

Raza, A., Ahrends, H., Habib-Ur-Rahman, M., and Gaiser, T.: Modeling Approaches to Assess Soil Erosion by Water at the Field Scale with Special Emphasis on Heterogeneity of Soils and Crops, Land (Basel), 10, 422, https://doi.org/10.3390/land10040422, 2021.

955 Renard, K. G., Foster, G. R., Weesies, G. A., and Porter, J. P.: RUSLE - Revised Universal Soil Loss Equation, J Soil Water Conserv, 46, 30–33, 1991.

Rose, C. W. and Haddadchi, A.: Review of soil erosion modelling involving water with field applications, Soil Res, 61, 735–754, https://doi.org/10.1071/SR23080, 2023.

Saggau, P., Kuhwald, M., Hamer, W. B. and Duttmann, R.: Are compacted tramlines underestimated features in soil erosion modeling? A catchment-scale analysis using a process-based soil erosion model, L. Degrad. Dev.,

960 33(3), 452–469, doi:10.1002/ldr.4161, 2022.

Salvucci, G. D. and Entekhabi, D.: Explicit Expressions for Green-Ampt (Delta Function Diffusivity) Infiltration and Cumulative Storage, Water Resour Res, 30, 2661–2663, https://doi.org/10.1029/94WR01494, 1994.

Schmidt, J.: A mathematical model to simulate rainfall erosion, Catena Suppl, 19, 101–109, 1991.

965 Schmidt, J., von Werner, M., Michael, A.: EROSION 2D/3D: ein Computermodell zur Simulation der Bodenerosion durch Wasser. Sächsische Landesanstalt für Landwirtschaft, Dresden, Germany, 1996.

Silva, A. R., Silva, A. R., and Gouvêa, M. M.: A novel model to simulate cloud dynamics with cellular automaton, Environmental Modelling & Software, 122, 104537, https://doi.org/10.1016/j.envsoft.2019.104537, 2019.

970 Smith, R.: The application of cellular automata to the erosion of landforms, Earth Surf Process Landf, 16, 273–281, 1991.

Stašek, J., Krása, J., Mistr, M., Dostál, T., Devátý, J., Středa, T., and Mikulka, J.: Using a Rainfall Simulator to Define the Effect of Soil Conservation Techniques on Soil Loss and Water Retention, Land (Basel), 12, 431, https://doi.org/10.3390/land12020431, 2023.

975 Vigiak, O., Sterk, G., Romanowicz, R. J. and Beven, K. J.: A semi-empirical model to assess uncertainty of spatial patterns of erosion, Catena, 66(3), 198–210, doi:10.1016/j.catena.2006.01.004, 2006.

Wahle, J., Neubert, L., Esser, J., and Shreckenberg, M.: A cellular automaton traffic flow model for online simulation of traffic, Parallel Comput, 27, 719–735, 2001.

Wang, Y.-C. and Lai, C.-C.: Evaluating the Erosion Process from a Single-Stripe Laser-Scanned Topography: A

980 Laboratory Case Study, Water (Basel), 10, 956, https://doi.org/10.3390/w10070956, 2018.

Williams, J. R.: Sediment yield prediction with universal equation using runoff energy factor, US Department of Agriculture, Agricultural Research Service Publication ARS-S-40, 1975.

Wischmeier, W. H.: Use and misuse of the Universal Soil Loss Equation, J Soil Water Conserv, 31, 5–9, 1976.

985 Wolff, F., Lotsari, E., Spieler, D., Elias, M., and Eltner, A.: Enhancement of two-dimensional hydrodynamic modelling based on UAV- flow velocity data, in: Earth Surf Processes Landf esp.5853, https://doi.org/10.1002/esp.5853, 2024.

Wolfram, S.: Cellular Automata as Simple Self-Organising Systems, 1982.

Wu, F.: SimLand: a prototype to simulate land conversion through the integrated GIS and CA with AHP-derived transition rules, International Journal of Geographical Information Science, 12, 63–82, 1998.

990 Zamboni, P., Blümlein, M., Lenz, J., Goncaves, W., Marcato Jr., J., Wöhling, T., Eltner, A.: Measuring Water Ponding Time, Location and Connectivity on Soil Surfaces Using Time-Lapse Images and Deep Learning. Preprint available at: http://dx.doi.org/10.2139/ssrn.4852219, 2024.

Zhao, Y., Zhu, D., Wu, Z., and Cao, Z.: Extreme rainfall erosivity: Research advances and future perspectives, Science of The Total Environment, 917, 170425, https://doi.org/10.1016/j.scitotenv.2024.170425, 2024.