Modelling the long-term geomorphic response to check dam failures in an Alpine channel with CAESAR-Lisflood

Jorge Alberto Ramirez, Mirjam Mertin, Nadav Peleg, Pascal Horton, Chris Skinner, Markus Zimmermann, Margreth Keiler

PII: S1001-6279(22)00030-0
DOI: https://doi.org/10.1016/j.ijsrc.2022.04.005
Reference: IJSRC 429

To appear in: International Journal of Sediment Research

Received Date: 5 September 2021
Revised Date: 7 April 2022
Accepted Date: 21 April 2022


This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2022 Published by Elsevier B.V. on behalf of International Research and Training Centre on Erosion and Sedimentation/the World Association for Sedimentation and Erosion Research.
Modelling the long-term geomorphic response to check dam failures in an Alpine channel with CAESAR-Lisflood

Jorge Alberto Ramirez\textsuperscript{a,*}, Mirjam Mertin\textsuperscript{a, b}, Nadav Peleg\textsuperscript{c, d}, Pascal Horton\textsuperscript{a, b}, Chris Skinner\textsuperscript{e}, Markus Zimmermann\textsuperscript{a, b}, Margreth Keiler\textsuperscript{f, g}

\textsuperscript{a} Institute of Geography, University of Bern, Bern, Switzerland
\textsuperscript{b} Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
\textsuperscript{c} Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
\textsuperscript{d} Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland
\textsuperscript{e} Energy and Environment Institute, University of Hull, Hull, United Kingdom
\textsuperscript{f} Department of Geography, University of Innsbruck, Innsbruck, Austria
\textsuperscript{g} Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria

*corresponding author Jorge Alberto Ramirez, ramirez08063@alumni.itc.nl
**Flow and Sediment Bedrock Dynamics**

- **Erosion**:
  - Erodes in 5 yrs
  - Erodes in 15 yrs
  - Increase of sediment yield after 100 yrs

- **Bedrock Limits**:
  - Max 8 m erosion

- **Check Dams**:
  - Maintained
  - Individual failure
  - Consecutive failure

- **Downstream Check Dam Limits**:
  - Erodes erosion
  - Increase between 76% and 322%
Modelling the long-term geomorphic response to check dam failures in an Alpine channel with CAESAR-Lisflood

Abstract

Globally, between 1950 and 2011 nearly 80,000 debris flow fatalities occurred in densely populated regions in mountainous terrain. Mitigation of these hazards includes the construction of check dams, which limit coarse sediment transport and in the European Alps number in the 100,000s. Check dam functionality depends on periodic, costly maintenance, but maintenance is not always possible and check dams often fail. As such, there is a need to quantify the long-term (10–100 years) geomorphic response of rivers to check dam failures. Here, for the first time, a landscape evolution model (CAESAR-Lisflood) driven by a weather generator is used to replicate check dam failures due to the lack of maintenance, check dam age, and flood occurrence. The model is applied to the Guerbe River, Switzerland, a pre-Alpine catchment containing 73 check dams that undergo simulated failure. Also presented is a novel method to calibrate CAESAR-Lisflood’s hydrological component on this ungauged catchment. Using 100-year scenarios of check dam failure, the model indicates that check dam failures can produce 8 m of channel erosion and a 322% increase in sediment yield. The model suggests that after check dam failure, channel erosion is the remobilization of deposits accumulated behind check dams, and, after a single check dam failure channel equilibrium
occurs in five years, but after many check dam failures channel equilibrium may not occur until 15 years. Overall, these findings support the continued maintenance of check dams.

Keywords: Landscape evolution model, Check dam failure, Weather generator, Natural hazards

1. Introduction

Mountainous regions are susceptible to flood and debris flow hazards due to their steep slopes and the potential to produce and transport significant amounts of sediment. Flood events, which include intense bedload transport, often put populations on alluvial fans of mountainous watersheds at risk (Kaitna et al., 2011; Keiler & Fuchs, 2018; Piton et al., 2017). For example, between 1950 and 2011 almost 80,000 debris flow fatalities occurred globally, with a high number of fatalities in densely populated regions where development pressure leads to construction on mountainous terrain in debris flow-prone areas (Dowling & Santi, 2014). To mitigate these hazards, flood and sediment control measures, such as different types of dams, retention basins, or drainage systems, are built into and along channels (Remaître et al., 2008). One of the most widely applied control measures are consolidation check dams (herein referred to as check dams), which are small dams constructed across a channel (Liu, 1992; Solaimani et al., 2008). Check dams can reduce the occurrence of debris flows or
sediment-laden floods by: 1) stabilizing riverbeds with fixed, non-erodible locations, 2) reducing channel slopes which decreases flow velocity and bedload transport, and 3) for a period after their construction trapping and storing coarse sediment (Piton et al., 2017). Check dams also have negative effects that include the reduction of longitudinal coarse sediment transfer along channels (Marchi et al., 2019) that can cause channel incision downstream from check dam locations (Lucas-Borja et al., 2021).

Because of the short-term effectiveness of check dams in mitigating natural hazards (Fuchs et al., 2013; Mazzorana et al., 2012), check dam construction has been widespread in densely-populated mountain regions in developed countries over the last two centuries. For example, in the European Alps alone the number of check dams is on the order of the 100,000s (Comiti, 2012; Piton et al., 2017; Piton & Recking, 2017). However, check dams often represent more of a long-term problem than solution because their effectiveness reduces with age (Dell’Agnese et al., 2013; Romang et al., 2003) and they have a limited life span of 50 to 80 years (Mazzorana et al., 2008; Piton et al., 2017). Additionally, the effectiveness of check dams strongly depends on costly maintenance efforts that include repairing structural damage, removal of sediment to prevent burial, and replacement when complete collapse occurs. For example, in Switzerland replacement of a single large concrete check dam can cost between $300,000–800,000 U.S. (Jäckle, 2013) and annual maintenance of a single river can be $2 million U.S. per year (Rimböck et al., 2015). Nevertheless, without continual check dam
maintenance structural failure is more probable (Sodnik et al., 2015) and resulting failures can amplify debris flow or flood intensity when sediment stored behind check dams are remobilized (Benito et al., 1998), thus, leading to increased hazards downstream (Cucchiaro et al., 2019).

Given the large number of check dams in existence, their effects on disaster risk reduction and the high cost of maintenance, there is a need for information quantifying the long-term (10–100 years) geomorphic response of catchments and rivers if check dams are not maintained and may undergo failure processes. Numerical modeling is a potential method to predict fluvial geomorphic responses. Numerical models have often been used to determine the effectiveness of check dams in regulating sediment transport (Hsieh et al., 2013; Mouri et al., 2013; Norman & Niraula, 2016; Pal et al., 2018; Quiñonero-Rubio et al., 2016; Shi et al., 2019) and mitigating natural hazards (Kwan et al., 2015; Osti & Egashira, 2008; Remaître et al., 2008), but few models have also considered the structural failure of check dams. Where check dam failures are simulated, the models are developed for single hazard events of short duration (< 24 h) occurring on small river reaches (< 10 km) (Chen et al., 2019; Liu et al., 2020). Such limitations in scale are partly due to the high computational demands of the modeling approaches applied. Furthermore, these models are driven with predetermined sediment and water inputs at fixed locations within the model domain. As such, these models
are not suitable for investigating long-term geomorphic responses across entire catchments where precipitation and ensuing floods drive sediment transport.

A viable type of numerical model to replicate long-term geomorphic responses are Landscape Evolution Models (LEMs). LEMs simulate the development of landscapes by calculating surface water flow and sediment transport (Tucker & Hancock, 2010) and have been extensively applied to quantify river channel changes (Feeney et al., 2020; Poepl et al., 2019; Ramirez et al., 2020; Ziliani et al., 2020) and sediment yield from catchments (Carriere et al., 2020; Coulthard et al., 2012b; Langston et al., 2015). Herein an existing LEM (CAESAR-Lisflood; Coulthard et al., 2013) is further developed as a step toward quantifying the long-term fluvial geomorphic response when check dams fail. For the first time, this new LEM-based application is demonstrated on a Swiss pre-alpine catchment containing a reach with 73 check dams that require costly, periodic maintenance. Additionally, a novel method is provided to calibrate the LEM’s hydrological model in an ungauged catchment. The LEM is driven with 100 years of spatially distributed simulated rainfall and check dam failure scenarios are applied that stochastically consider the quantity and location of check dam collapse. The objectives of the current study are to: 1) quantify the effect of check dam failures on channel morphology and sediment yield, 2) determine the length of time for channel equilibrium after check dam failure, and 3) determine if check dam failures activate large hillslope instabilities adjacent to the channel.
2. Study area

The Guerbe catchment (46.7°N 7.5°E) is in central west Switzerland and geographically straddles the Swiss Bernese Prealps and Swiss Plateau (Fig. 1(a)). The part of the Guerbe catchment considered in the current study is upstream from the Burgistein gauging station and this area is referred to as the Guerbe Burgistein sub-catchment (GB). The Guerbe tributary is in the southwestern GB sub-catchment and is a segment of the river with many check dams (Figs. 1(b) and (c)), while the Fallbach tributary lies to the south (Fig. 1(a)). See the Supplemental Material for a summary of the check dam construction history in the Guerbe catchment.

The primary focus of the current study is the sub-catchment containing the Guerbe River channel and check dams, hereinafter referred to as Guerbe Wattenwil sub-catchment (GW) (Fig. 1(a)). The GB sub-catchment, with the contribution of the Fallbach, was used for calibrating the hydrological component of the LEM, as it contributes to the discharge at the sole gauging station that can be used as a reference (Fig. 1(a)). Table 1 lists the characteristics of the GB and GW sub-catchments, where values for GW are included in the calculations for GB. There are marked differences between the GB and GW sub-catchments with regards to area, steepness, geology, soil depth, and rainfall. In comparison to the GB sub-catchment the GW sub-catchment has approximately one-fifth the area, a similar elevation difference, and 80% steeper slope along the Guerbe River reach.
The study area has a diverse underlying geology comprised primarily of Klippendecke, Flysch, Molasses, and Quaternary deposits (Jäckle, 2013). Klippendecke consists of steep sedimentary rocks that are composed of limestone and gypsum, the latter is prone to weathering, very soft, and aquiferous. Given these properties, this zone can deliver a large amount of loose debris. Flysch forms a sequence of marine sedimentary rocks with alternating layers of clay and sand that are highly susceptible to erosion. Additionally, the flysch layer is impermeable to water, and, therefore, prone to landslides. Molasse consists of soft marl and stronger sandstone/conglomerates and is a water-permeable layer. The remaining geological unit is Quaternary deposits, which were caused by glaciation and fluvio-glacial transport that shaped the present-day landscape and delivered sediment for soil formation in the catchment.

Due to the complex geological composition of the study area, soil types are variable. Soils markedly differ in permeability, depth, and water storage capacity and these properties affect the hydrological responses of the GB and GW sub-catchments to rainfall. The soil types are subdivided into geological units based on the source materials for soil formation (Salvisberg, 2017). The Klippendecke layer contains shallow soils with a low water storage capacity. In the Flysch layer, the dominant soils are heavily saturated and have limited water permeability and a low water storage capacity. Molasses contains soils that are very deep and with high infiltration and water storage capacity. Klippendecke and Flysch are dominant
layers in the GW sub-catchment (80% spatial coverage) and contribute to overall shallower soil depths of 0.8 m (Table 1). These soil characteristics in the GW sub-catchment produce rapid hydrological responses to rainfall with high runoff potential. The presence of molasse in the GB sub-catchment (11% in area), albeit low, increases soil depth by about 60% when compared to the GW sub-catchment (Table 1). The deeper soils found in the GB sub-catchment delay the production of runoff and produce attenuated hydrological responses to rainfall.

Within the study area, the precipitation gradient varies from 2000 mm/yr in the mountains to 1100 mm/yr at lower elevations. The southern part of the GB sub-catchment and all of the GW sub-catchment are prone to heavy summer thunderstorms with intensities near 30 mm/h (Panziera et al., 2018). Overall, the GW sub-catchment annually receives proportionally 15% more rainfall than the GB sub-catchment (Table 1). The discharge of the Guerbe River, produced by the GB sub-catchment, is measured at the Burgistein gauging station installed in 1982 (Fig. 1(a)). The mean annual flow of the GB sub-catchment is 1.33 m³/s and the maximum discharge over 22 years is 84 m³/s which was measured on July 29, 1990. The GW sub-catchment is an ungauged catchment with a nivo-pluvial flow regime (Jäckle, 2013). Maximum runoff for each year occurs during snowmelt throughout May and June, and a second runoff peak occurs in December, which is triggered by rainfall in late fall (Aschwanden & Weingartner, 1985). During the last decades, the GW sub-catchment’s flow...
regime has slightly changed towards a more pluvially driven runoff regime, with winter precipitation often falling as rain instead of snow.

3. Methods and data

Channel and hillslope morphological response to check dam failure in the Guerbe catchment was simulated using a LEM driven with a rainfall generator. The steps taken to do this research include: 1) calibration of the rainfall generator model, 2) calibration of the hydrological component of the LEM, 3) development of check dam failure scenarios, and 4) application of the LEM to simulate a 100 years of check dam failure and landscape change.

As an overview, Table S1 in the Supplemental Material summarizes the models and data used in the current study.

3.1. Rainfall modelling

A numerical rainfall generator model, based on the stochastic Space-Time Realizations of Areal Precipitation (STREAP) model that was initially developed by Paschalis et al. (2013) and further developed by Peleg et al. (2017b), was used for this purpose. The weather generator model allows simulation of a prolonged series (100 years) of gridded rainfall at high space-time resolution, based on observed gridded rainfall data of a much shorter period (a few years) while preserving the rainfall space-time properties. The model was applied in the past to simulate rainfall fields that were used as inputs into hydrological models (e.g., Paschalis et al., 2014; Peleg et al., 2017a) and into the CAESAR-Lisflood (CL) model (Peleg et al., 2020b;
Skinner et al., 2020). It reproduces the length of the storm, and intra-storm periods, the wind (direction and velocity) that advects the storm, and the intermittent rainfall fields. Rainfall for the current study was generated with 1 km grid cells and hourly resolution (Figs. 2(b) and (c)). Peleg et al. (2017a) discussed the model calibration procedure in detail and data used for calibration are discussed in the Supplemental Material.

3.2. *Landscape evolution modelling*

3.2.1. *Numerical model*

The CAESAR-Lisflood (CL) model is the integration of the CAESAR landscape evolution model and the Lisflood-FP hydrodynamic model (Coulthard et al., 2013). The CL model includes flow dynamics and sediment transport and operates at river reach or catchment scale. In reach mode, the CL model operates over a river reach and receives predetermined water and sediment inputs directly added to the river reach. In catchment mode, as used in the current study, the CL model is driven with a rainfall time series and the total drainage basin including the tributaries and adjacent slopes are modeled to estimate discharge, sediment transport and landscape change (Coulthard et al., 2013). Additional inputs for the CL model include a digital elevation model (DEM) representing the topography, and a grain size distribution. The operation of the CL model is as follows: 1) a modified version of TOPMODEL (Kirkby & Beven, 1979) generates surface runoff from rainfall, 2) the hydraulic model Lisflood-FP primarily uses the topography and water depths to route computed
discharge between raster cells in the DEM, 3) sediment transport is calculated by the choice of equation (Einstein, 1950; Wilcock & Crowe, 2003) applied to each sediment fraction, and 4) after the sediment is transported topographic change is estimated based on sediment eroded or accumulated. Landslides in the CL model are simulated when the slope between locations in the landscape exceeds a user defined slope threshold and this triggers the instantaneous downward movement of material (Coulthard et al., 2002). The output from the CL model includes a time series of discharge and total sediment load at the catchment outlet and DEMs reflecting topographic changes at a specified time interval.

Although several LEMs exist (Veldkamp et al., 2017), from a modelling standpoint, the CL model offers decisive advantages for the current study because the CL model:

1) is computationally efficient due to time saving algorithms that include a dynamic time step and parallelization of the hydraulic model. These code developments make it possible to simulate long-time scales and multiple scenarios (Coulthard et al., 2012b; Ramirez et al., 2016; Welsh et al., 2009).

2) has low data requirements and needs minimal parametrization.

3) can be driven with distributed rainfall that represent gradients (Coulthard & Skinner, 2016).

4) is open source and allowed check dam failure processes to be directly implemented in the model.
Applications of the CL model in Alpine (Peleg et al., 2020b; Welsh et al., 2009) and anthropogenically modified landscapes (Lowry et al., 2019) provide further support for using the CL model in the current study. For example, Ramirez et al. (2020) used the CL model in a Swiss Alpine river, near the Guerbe catchment, to accurately replicate observed extreme channel change and lake delta development resulting from failed engineering works. Likewise, Feeney et al. (2020) found that historic channel changes over decadal scales in U.K. rivers were adequately predicted with the CL model. At locations in Australia’s Northern Territory, the CL model has also demonstrated the capacity to generate sediment yield and erosion rates comparable to field estimates (Hancock et al., 2010; Lowry et al., 2019). For example, in an applied setting, Coulthard et al. (2012a) used the CL model to reasonably predict the volume and timing of bedload and suspended sediment on a 30 m experimental plot on a trial rehabilitated landform. These studies indicate that the CL model is well suited to model channel change and sediment yield in a heavily engineered, pre-Alpine landscape like the Guerbe catchment.

3.2.2. Topography

A Swiss ALTI3D DEM of 2 m spatial resolution was obtained and clipped to the extent of the GB sub-catchment boundary (Fig. 1(a)). The 2 m DEM was spatially resampled to 15 m to reduce the number of raster cells and computational overhead of the simulations but maintain the representation of key aspects of the topography (e.g., channel width, check dam spacing).
This DEM was used for the calibration of the CL’s hydrological model (Fig. 1(a)). A second 15 m spatial resolution DEM was produced using the GW sub-catchment boundary (Fig. 3(a)) and this DEM was used to model landscape changes.

3.2.3. Hydrological model calibration

The calibrated parameter in the TOPMODEL hydrological model is the $m$ value that controls the change in soil moisture storage (Coulthard et al., 2002) and affects the hydrological response of the catchment in the CL model (Welsh et al., 2009). High $m$ values represent soils with reduced soil moisture storage capacity which readily produce runoff, while lower $m$ values retain larger amounts of moisture before runoff occurs (Coulthard & Van De Wiel, 2017).

Here a three-step calibration process was applied to determine $m$ values for the ungauged GW sub-catchment. In the first step, TOPMODEL parameters were calibrated with a five-year hydrological simulation using the CL model (i.e., no sediment transport) driven with simulated hourly, 1 km spatial resolution rainfall for the GB sub-catchment. Due to the spatial heterogeneity of geology and soils throughout the study area (Table 1), spatially distributed $m$ values were utilized. Assuming the soil moisture storage capacity is partly dependent on soil depth, a 125 m spatial resolution soil depth map (Bundesamt für Raumplanung, 1980; Viviroli et al., 2007) determined the spatial distribution of $m$ values (Fig. S2 (a)–(c) in Supplemental Material). In addition, to quantify the effect of spatially
distributing \( m \) values, a lumped \( m \) value simulation was done using the weighted mean of the derived \( m \) values \((m = 0.02)\), using the area of soil categories as weights. The result from this first step was five years of hourly simulated discharge at the outlet of GB using spatially distributed and lumped \( m \) values. The simulated discharge was compared to 22 years (1984–2007) of hourly observed discharge measured at the Burgistein gauging station (Fig. 1(a)).

The second step of the calibration process was a five-year hydrological simulation of the GW sub-catchment using the same rainfall inputs and calibrated parameters, lumped and spatially distributed, from the GB sub-catchment. This step was done to determine the effect of spatially distributed \( m \) values on discharge from the GW sub-catchment. In the last step, the calibrated GW sub-catchment hydrological model, with spatially distributed \( m \) values, was run for a short-term (3 h) extreme weather event and determine if the resulting simulated discharge is comparable to estimated discharge from the GW sub-catchment.

### 3.2.4 GW sub-catchment landscape and check dam failure scenarios

Grain sizes were estimated for the GW sub-catchment from field work using the line-by-number method (Fehr, 1987). Two sites were selected along the channel where check dams exist, and one site downstream from the check dam area (Fig. 1(a)). At each site, sampling was done during low flow conditions and three transects were defined. For each transect, 150 grains of sediment \( \geq 1 \) cm in diameter were measured from the surface layer. This diameter cutoff was chosen because sediment of this diameter generally comprises the armored layer in
Alpine rivers. All measurements were aggregated, with a total sample size of 1,350. To account for the presence of finer grains (< 1 cm diameter) in the total layer, the grain size distribution of the surface layer was complemented using a Fuller distribution (Fehr, 1987).

The corrected grain size distribution results were divided into nine classes with a median diameter (D50) of approximately 4 cm and a D90 (i.e., the diameter for which 90 percent of the grainsizes are smaller) of 20 cm (Fig. S1(c) in Supplemental Material).

Erosion in the CL model is limited by a non-erodible bedrock layer. A bedrock layer for the GW sub-catchment was inferred from a geological map (Swiss Geotechnical Commission, 1963) which was reclassified into either loose surface formations or rock. Where loose material existed the bedrock depth was set at 8 m below the existing topography and locations consisting of rock had a bedrock depth of 0.5 m (Bollinger, 1998). To avoid abrupt changes between bedrock and loose material, linear interpolation in space was done to derive bedrock depths in a transition zone between deep and shallow bedrock (Fig. 3(b)).

Seventy-three reinforced concrete check dams were manually identified (Fig. 3(a)) using a hillshade map derived from the 2 m spatial resolution DEM. Each check dam was digitized as a polygon, provided a unique identifier (0–72), converted to raster data with 15 m spatial resolution, and became an input for the CL model. In the CL model, check dam locations were non-erodible and represented as bedrock at the DEM surface (Fig. 3(b)). In addition, maintained check dams are assumed not to fail, while unmaintained check dams can
fail, and this failure occurs instantaneously and completely. Check dam failure in the CL model is replicated by lowering the bedrock layer at the check dam location to the inferred bedrock elevation. In doing this, sediment near the check dam location becomes available for transport.

Seven check dam failure scenarios were developed to determine the quantity and timing of check dam failures over 100 years (Table 2). A baseline scenario considers all check dams maintained and no failures occur. The other scenarios are divided into 50% or 0% check dam maintenance (Table 2). The probability of an individual check dam failure was dependent on check dam age and discharge (Fig. 4(a)) and derived from both expert knowledge and considering a general study on the physical vulnerability of check dams (Dell’Agnese et al., 2013). Uncertainty in check dam failure was considered by developing low, medium, and high scenarios of check dam failure for the 50% and 0% check dam maintenance (3 × 2 scenarios in total, see Table 2). These scenarios were produced by adjusting all failure probabilities ($P$; Fig. 4(a)) with a reduction factor (high = 0.5 $P$, medium = 0.25 $P$, and low = 0.125 $P$). Check dam age commences at zero and subsequent age is equivalent to the simulated time. Failure can potentially occur when hourly discharge exceeds a flood with a calculated return period of five years (32 m$^3$/s) and these conditions occurred 32 times in 100 years (Fig. 4(b)). Note that several flood instances occur within a 24 h period and appear as single instances in Fig. 4(b). To develop a scenario, the following steps were
done for each unmaintained check dam per flood occurrence: 1) determine check dam age, 2) ascertain the check dam failure probability, 3) produce a uniformly distributed random number between 0–1, and 4) check dam failure occurred if the random number is less than the failure probability.

The result of the foregoing procedure is a time series of the number of check dam failures. Given that check dam failure is stochastic, the procedure was repeated 100 times per scenario (Figs. 4(c) and (d)) and the mean of all replicates was recorded. Once the number of check dam failures has been determined for the 100-year period, the locations of failures were determined by producing a random list of the check dam unique identifiers (0–72). The first identifier in the random list corresponds to the first check dam that fails in time, and subsequent check dam failures are determined by sequentially iterating over this list. For all scenarios, the random sequence of failure is the same, but for scenarios with 50% check dam maintenance every second check dam was removed from the list. Three inputs are provided to the CL model to replicate check dam failures and include the: 1) map of check dam locations with unique identifiers determining where failure occurs, 2) random list of check dam failure that corresponds to the unique identifiers, and 3) time series of the number of check dam failures.

In the simulations for the GW sub-catchment, the remaining hydrological, hydraulic, and geomorphic parameters for the CL model (Table S2 in Supplemental Material) were
determined using suggested values from the CL model documentation (Coulthard et al., 2013). Geomorphic initial conditions for all scenarios were established by simulating sediment transport in the CL model with 100% check maintenance for 5000 days and commencing all simulations with the saved DEM and grainsize proportions. Afterward, each check dam failure scenario and the resulting landscape changes for the GW sub-catchment were simulated for 100 years. All results from the CL model were at the catchment scale and replicated erosion and deposition throughout the entire GW sub-catchment including the channel containing check dams. The output from each scenario was hourly sediment yield at the GW sub-catchment outlet and a DEM of the simulated topography every year. Although results were at the catchment scale, the focus of the analysis for landscape changes was performed on the reach containing check dams where major landscape changes occurred. In addition, changes in sediment yield were derived from the entire GW sub-catchment, which includes the reach containing check dams (Fig. 1(a)).

4. Results and discussion

Rainfall and hydrological modelling results are reported in the Supplemental Material, herein the focus is on geomorphic outputs from the CL model.

4.1. Channel morphology

Figure 5 shows the DEMs of difference for the check dam area after 100 years of simulation from each scenario. In the high failure scenario (Fig. 5(d)), a subtle spatial pattern begins to
appear along the channel with major upstream erosion (z1), followed by a small depositional
zone (z2), minor erosion for a 500 m portion of the channel (z3), and the remaining
downstream part of the channel has alternating locations of deep erosion and minor deposition
(z4). Interestingly, not all check dam failures result in deep erosion (> 5 m), specifically in
Figure 5(d) (z3) where erosion is limited to shallower depths (< 0.5 m). In comparison to the
50% maintenance scenarios, the 0% maintenance scenarios include more check dam failures,
and, consequently, more bed destabilization caused mostly by erosion (Figs. 5(e)–(g)). In
these scenarios, a clearer spatial pattern of erosion and deposition emerges along the channel
and is most pronounced in the high scenario with only one check dam remaining (Fig. 5(g)).
Here, the major differences from the 50% high scenario (Fig. 5(d)) are that z4 becomes a zone
of complete erosion, and an additional depositional zone (z5) suggests that sediment begins
accumulating downstream (Fig. 5(g)). Like in previous scenarios, it appears that erosion in z3
is clearly impeded. For all simulations, there is significant channel erosion but no indication
that this process has activated large hillslope instabilities adjacent to the channel.

Figure 6 shows the distribution of channel elevation changes in the check dam area,
whereas Table 2 lists the corresponding summary statistics. The baseline scenario is a stable
bed in relative equilibrium with normally distributed channel changes and a mean channel
elevation change near 0 m (Fig. 6(a)). Likewise, channel changes from the 50% maintenance
scenarios mostly reflect a normal distribution, but the increasing number of check dam
failures and resulting erosion extend the left tails of the distributions and decrease the mean
elevation change up to −1 m (Table 2). In contrast, the distribution of channel elevation
changes from the 0% maintenance scenarios become increasingly more bimodal in shape with
scenarios containing more check dam failures (Fig. 6(b)). Peaks in these distributions
represent erosion at check dam locations, and a peak is centered between 0 and −0.5 m with a
second peak at −8 m.

Figure 7 shows downstream profiles of channel elevation changes in the check dam
area. These plots confirm that check dam failures correspond with locations undergoing
erosion and bed destabilization, but additionally explain the discrepancy in the magnitude of
erosion between zones along the channel. The key to this explanation is the spatial variability
of the bedrock underlying the check dam area. Locations where bedrock is deep (e.g., 0–150
m and 1200–2300 m downstream) limits erosion to 8 m, while shallower bedrock (e.g., 300–
1000 m downstream) limits erosion to 0.5 m (Fig. 7). The profiles also suggest that individual
check dam failures (Fig. 7(c), black arrow) rarely produces deep erosion but consecutive
check dam failures in space (yet not necessarily in time) increase the probability of deep
erosion (Fig. 7(c), gray arrow).

Upon closer inspection of modeled check dam failures (Fig. 8) it becomes apparent
that erosion occurring at check dam failures is mostly sediment stored behind the check dam.
Moreover, Fig. 8 explains the differences in erosion occurring at individual and consecutive
check dam failures (Fig. 7(c)). For an individual check dam failure, the instantaneous removal of the check dam structure causes a sharp change in channel slope and erosion propagates upstream until reaching the next check dam (Figs. 8(a) and (b)). In the ensuing period, the sediment stored behind the check dam is gradually eroded to an elevation that is equivalent to the next downstream check dam (Fig. 8(b)). Consecutive check dam failures (Figs. 8(c)–(f)) differ in that erosion of sediment stored behind the second failed check dam is controlled by the underlying bedrock (Fig. 8(f)). These examples (Fig. 8) also suggest a duration for release of stored sediment. During the initial two years after failure much of the sediment stored behind check dams (55%–90%) is eroded with a small amount of the released sediment (5%–27%) depositing near the site of the failure (<120 m downstream) and the majority of sediment (72%–95%) transported further downstream. During the subsequent three years (i.e., years 3–5) the remaining sediment stored behind the check dam (10%–45%) is entirely transported downstream.

Figures 9(b) and (c) summarizes the interannual change in channel elevation for high check dam failure probability scenarios with 50% and 0% maintenance. For both scenarios, the resulting median channel change is between −0.5 and 0.2 m and is low for a river undergoing major channel changes. Low net channel change can be explained by the near mirroring of magnitude and frequency of annual channel erosion and deposition. This pattern is reflected in the channel change interquartile range, minimum, and maximum (Figs. 9(b) and
Here the CL model results indicate that nearly equal amounts of sediment in the channel are continually being eroded, transported, and deposited. The magnitude of erosion and deposition is mostly controlled by the magnitude of flood events (Fig. 9(a)) and the coincidental number of check dam failures. During years with check dam failures, erosion outliers mostly represent the transport of sediment stored behind check dams, while deposition outliers are sediment deposited downstream but located near the check dam failure (e.g., year 37, Figs. 9(b) and (c)). Years that follow check dam failures mostly contain diminishing amounts of erosion outliers and few or no deposition outliers (e.g., years 38–39, Fig. 9(b) and (c)). This pattern can be explained spatially. The continual erosion of sediment stored behind the check dam is confined to a small portion of the channel and this localized, but high amount of erosion, generates outliers until it is controlled by a downstream check dam or bedrock (as seen in Fig. 8). Deposition resulting from this erosion does not compose of an outlier because the deposition is spatially distributed across a larger area in the channel and this produces lower amounts of deposition.

For both scenarios (0% and 50% maintenance), years 25–50 is the time of many check dam failures, followed by an extended period of no check dam failures (years 50–65). These contrasting periods provide an opportunity to estimate the duration of time until channel stabilization after check dam failures. In the 50% maintenance scenario, by year 50, 27 check dams have failed and 46 remain (Fig. 9(b)). During the time of no check dam failure (years
50–65), the channel immediately stabilizes and does not exhibit major erosion or deposition even though there are occurrences of moderate flows (20–30 m$^3$/s). This channel response suggests that the sediment released from failed check dams has mostly been eroded and transported out of the model domain. Upon closer inspection of individual check dam failure events (e.g., Fig. 9(b), years 31 and 37), it is apparent that after a check dam failure channel change diminishes in 4–5 years. In the 0% maintenance scenario, by year 50, 54 check dams have failed and 19 remain (Fig. 9(c)). In this scenario, a major difference in channel change occurs between years 50–65, with high amounts of channel erosion (erosion outliers between −1 and −5 m) (Fig. 9(c)) and the channel does not stabilize in the 15 years when no check dam failures occur. This failure to stabilize is mostly due to the remobilization of sediment that was released from the check dam failures in the preceding period.

4.2. Sediment yield

Table 2 provides sediment yield summary statistics for each scenario, which is the yield produced by the catchment including the channel containing check dams. The baseline scenario closely represents the sediment yield of the area upstream from the channel with check dams because no check dams have failed and released sediment that contributes to sediment yield. As such, the baseline sediment yield is approximately the amount of sediment entering the check dam channel area for all failure scenarios. Importantly, the model suggests that failure of half and nearly all check dams result in 76% and 322% increases in total
sediment yield, respectively (Table 2). Figure 10 provides a 100-year time series for each scenario including the number of check dams remaining, hourly discharge (Figs. 10(a) and (b)) and hourly cumulative sediment yield sum (Figs. 10(c) and (d). Baseline hourly sediment yields differ markedly from all check dam failure scenarios (Figs. 10(c) and (d)). Comparison between the baseline scenario and 50% check dam maintenance with low, medium, and high failure probabilities indicates an increase in average cumulative sediment yield over time of 25%, 37%, and 52%, respectively (Fig. 10(c)). Not maintaining check dams drastically increases the amount of sediment transported from the catchment. Comparison between baseline and 0% maintenance scenarios with low, medium, and high failure probabilities increases average cumulative sediment yield over time by 52%, 67%, and 81%, respectively (Fig. 10(d)).

Results provided in Fig. 10 can be used to determine the geomorphic response of the GW sub-catchment to natural forcings (e.g., heavy rainfall) and the coincidental check dam failures. The baseline scenario sediment yield for 100 years is relatively constant with a low-sloping trajectory and does not respond to periods containing 50-year (60 m³/s) and 100-year (85 m³/s) floods (Fig. 10(c), black arrows). This indicates that the existing catchment and protected channel is capable of buffering heavy rainfall and floods that transport large amounts of sediment. For all check dam failure scenarios, the overall slopes of the cumulative sediment yields are steeper, indicating greater rates of erosion and more importantly sediment
yield responds positively (i.e., “steps” in the cumulative time-series) to storms that produce floods that cause check dam failures (Figs. 10(c) and (d)). Examples of large sediment yield responses are evident between years 30–40 and 80–90 (Figs. 10(c) and (d), black arrows). As such, all check dam failure scenarios are adjusting to check dam failures that make sediment available for transport. A notable exception is the sediment yield response, from years 80–100, for the 0% check dam scenario with high failure probability (Fig. 10(d)). Although this period has several large floods and many check dam failures, the sediment yield response of the catchment progressively diminishes over time with a decrease in slope. A possible explanation for this response is the unavailability of sediment for transport in the channel containing check dams and the presence of exposed bedrock limiting more erosion.

4.3. Model behavior

The modeled baseline scenario results suggest that check dams are effective in reducing channel erosion and sediment yield, but at the cost of maintaining all the check dams. This finding confirms similar conclusions derived from the field (Castillo et al., 2007), laboratory (Piton & Recking, 2017), and numerical modelling (Li et al., 2017; Quiñonero-Rubio et al., 2016; Shi et al., 2019; Zema et al., 2014) studies. In the current study, sediment eroded consists mostly of deposits stored behind and upstream from failed check dams, and this result is also observed in flume experiments and numerical models removing transverse structures from rivers. For example, Tseng et al. (2012) developed a physical model of check dams in a
river and noted that after failure large amounts of sediment stored behind check dams are quickly transported downstream and erosion rapidly propagates upstream. Using a numerical model, Poepppl et al. (2019) found that dam removal created a knickpoint that retreated until reaching an upstream dam and eroded channel sediment consisted of deposits previously stored behind dams. Likewise, Howard et al. (2017) found that modeled weir removal produces localized erosion, near the location of the structure, that propagates upstream until channel adjustment produces pre-weir gradients. The current model output agrees with these experimental observations and model predictions and indicates that the CL model may adequately replicate the geomorphic response to check dam failures.

Stochastic rainfall generator models can simulate gridded rainfall inputs for the CL model, as demonstrated here and in past studies (e.g., Skinner et al., ? and Peleg et al., 2021). Recently, Peleg et al. (2020a) demonstrated the advantages of using such models to simulate gridded rainfall at locations that are sparsely gauged using remote sensing devices and rainfall composite products, with satisfactory performance of reproducing local rainfall properties as well as the natural variability. The combination of rainfall generator models with LEMs, as demonstrated here, can be adapted to other CL model applications, for example, to simulate landscape evolution in ungauged catchments.

4.4 Model uncertainty, future development, and application
Reducing uncertainty in the CL model requires further development to improve the replication of check dam failure in mountainous landscapes. First, bedload transport equations in LEMs are notoriously uncertain (Skinner et al., 2018) and in steep mountain rivers most equations overpredict bedload transport during low to moderate floods (Yager et al., 2012). For this reason, various bedload transport equations for steep channels (Rickenmann, 1997; Smart & Jäggi, 1983) need to be implemented and tested in the CL model. Second, in mountainous landscapes, debris flows transport large amounts of sediment (10,000–100,000 m$^3$) in a short period of time (< 24 h; Dowling & Santi, 2014) which impact check dam failures, channel changes, and sediment yield (Salvisberg, 2017). To date, no LEMs consider debris flow processes when simulating long-term landscape evolution and efforts should be made to couple existing open source debris flow models (Mergili et al., 2017) with the CL model. Third, the process of check dam failure in the CL model should be improved by using local factors to trigger failure. For example, modeled check dam failure can be dependent on channel changes that affect local channel gradients and bed shear stress at check dam locations. When bed shear stress surpasses a threshold check dam failure occurs, but calibration and validation of this new method requires the collection of local channel conditions (e.g., channel gradient, water velocity) that precede check dam failure. Lastly, the current study applies a scenario-based approach for check dam failure that provides limited means to quantify uncertainty stemming from model boundary conditions.
With the development of faster LEMs and computers, future studies should thoroughly investigate LEM uncertainty through multiple realizations. Specifically, more work is needed driving the CL model with many realizations (hundreds) of weather, climate projections, and check dam failure scenarios. The resulting channel changes and sediment yields can be summarized to quantify the most probable outcome from check dam failure and the uncertainty in this outcome.

The methods applied in the current study further demonstrate the value of LEMs as a tool to understand the morphodynamic impacts of natural hazard management interventions at timescales relevant to decision-makers and other stakeholders (Zimmermann & Keiler, 2015). Changes in rainfall patterns due to climate change and anthropogenic impacts will result in changes in morphodynamics (Coulthard et al., 2012b; Keiler et al., 2010; Peleg et al., 2020b) and have impacts on future flood and debris flow risk that remain uncertain. For example, in the current study the worst-case check dam failure scenario in the Guerbe catchment has major implications for flood risk in communities downstream from the model domain where the channel slope decreases substantially to 3.7°, and the majority of the sediment yield is expected to deposit (Fig. 1(a)). Under this assumption and provided the present-day geometry of the downstream channel, maximum downstream channel aggradation from the worst-case scenario could be 2–3 m. Importantly, this aggradation could produce a shallower and/or narrower downstream channel that would severely reduce channel conveyance capacity and
increase the frequency and intensity of floods and debris flows. This demonstrates how LEMs have the potential to improve the current understanding of natural hazards and knowledge derived from LEMs can provide additional input into mountain hazard management decisions that must also consider socio-economic factors (Hossain et al., 2020) that include restricted financial resources, social justice, and sustainability (Fuchs et al., 2017; Klein et al., 2019; Thaler et al., 2018).

5. Conclusions

The current study shows that the CL model can integrate weather, hydrogeomorphic, and anthropogenic processes to simulate long-term landscape changes. Specifically, in the case of the Guerbe catchment, it was found that the CL model can replicate hydrologic conditions in this ungauged catchment using spatially distributed rainfall and soil depth data. Applying a stochastic approach to check dam failure, it was found that check dam failures can remobilize sediment previously deposited behind check dams and may produce severe channel erosion up to 8 m in depth. In addition, with a single check dam failure channel equilibrium can occur in five years, but with many check dam failures channel equilibrium may not occur until 15 years. No evidence was found that channel erosion after check failure triggers large hillslope instabilities and failure of nearly all check dams can lead to a 322% increase in sediment yield over 100 years. These findings provide support for continued check dam maintenance and
imply that long-term check dam failures may produce large downstream channel changes that increase flood and debris flow hazard.

References


Coulthard, T. J., Neal, J. C., Bates, P. D., Ramirez, J., de Almeida, G. A., & Hancock, G. R. (2013). Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR...


Table 1. Characteristics of the study area. Values for GW are included in the calculations for GB. (Klipp. = Klippendecke, Q. depo. = Quaternary deposits, Mor. = Moraine, Mol. = Molasse, Min = Minimum, Max = Maximum)

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Elevation (m)</th>
<th>Channel slope (deg)</th>
<th>Underlying geology (%)</th>
<th>Mean soil depth (m)</th>
<th>Annual rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guerbe Burgistein (GB)</td>
<td>51</td>
<td>567</td>
<td>2,173</td>
<td>26</td>
<td>26</td>
<td>1.3</td>
</tr>
<tr>
<td>Guerbe Wattenwil (GW)</td>
<td>12</td>
<td>790</td>
<td>2,173</td>
<td>25</td>
<td>–</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2. Summary of 100 years of landscape change in the Guerbe Wattenwil river channel (black area in Fig. 5 inset) and catchment (Fig. 3 a). Scenarios correspond to the check dam failure probability and percentage of check dams maintained for each simulation. Check dam remain indicates the number of check dams remaining at the end of the simulation. Negative channel elevation change values are erosion and positive values are deposition. (Min = Minimum, Max = Maximum, Stdev= Standard deviation)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cd maintain (%)</th>
<th>Cd remain</th>
<th>Channel Elevation change (m)</th>
<th>Sediment yield (m³)</th>
<th>Annual mean</th>
<th>10 day max</th>
<th>Total</th>
<th>Total change from baseline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>100</td>
<td>73</td>
<td>−3</td>
<td>0.01</td>
<td>0.45</td>
<td>3.46</td>
<td>1,222</td>
<td>2,110</td>
</tr>
<tr>
<td>Low</td>
<td>50</td>
<td>50</td>
<td>−8</td>
<td>−0.65</td>
<td>1.97</td>
<td>2.70</td>
<td>2,148</td>
<td>5,026</td>
</tr>
<tr>
<td>Medium</td>
<td>50</td>
<td>41</td>
<td>−8</td>
<td>−0.82</td>
<td>2.21</td>
<td>3.90</td>
<td>2,392</td>
<td>6,075</td>
</tr>
<tr>
<td>High</td>
<td>50</td>
<td>36</td>
<td>−8</td>
<td>−1.06</td>
<td>2.45</td>
<td>4.02</td>
<td>2,725</td>
<td>6,059</td>
</tr>
<tr>
<td>Low</td>
<td>0</td>
<td>27</td>
<td>−8</td>
<td>−1.62</td>
<td>3.13</td>
<td>5.60</td>
<td>3,597</td>
<td>11,026</td>
</tr>
<tr>
<td>Medium</td>
<td>0</td>
<td>10</td>
<td>−8</td>
<td>−2.37</td>
<td>3.63</td>
<td>6.72</td>
<td>4,619</td>
<td>13,666</td>
</tr>
<tr>
<td>High</td>
<td>0</td>
<td>1</td>
<td>−8</td>
<td>−2.76</td>
<td>4.04</td>
<td>11.05</td>
<td>5,152</td>
<td>8,666</td>
</tr>
</tbody>
</table>

Figure captions:

Fig. 1. (a) DEM of the Guerbe catchment upstream from the Burgistein gauging station (GB: Guerbe Burgistein) and sub-catchment containing check dams (GW: Guerbe Wattenwil). (b) Higher check dams (3–4 m height) in the upstream GW, and (c) smaller check dams (1–2 m height) in the lower GW.

Fig. 2. A comparison between the (a) observed annual rainfall which covers 52 years of data (1961–2012), and (b) a single realization of simulated annual rainfall for a period of 30 years.
(c) Simulated hourly rainfall for a grid cell (indicated with asterisk) in the Guerbe Wattenwil sub-catchment.

Fig. 3. (a) DEM and (b) estimated bedrock map of the Guerbe Wattenwil sub-catchment containing check dams.

Fig. 4. (a) Check dam failure rules implemented in the model that consider the combination of check dam age and river discharge. Failure probabilities below the dashed line are not considered for the Guerbe catchment because check dam failure in the model does not occur below 32 m³/s. (b) Hourly simulated discharge from the sub-catchment containing check dams and highlighted flood events with a recurrence interval greater than five years. Hourly check dam failure scenarios with (c) 0% and (d) 50% check dam maintenance. Scenarios are the mean of each scenario’s replicates.

Fig. 5. DEM of difference (year 100–year 1) for a (a) baseline scenario with 100% check dam maintenance, and low, medium and high check dam failure scenarios with (b, c, and d) 50% and (e, f, and g) 0% check dam maintenance, respectively. Reach depicted is the black area in the inset.

Fig. 6. Density plots of 100 years of channel change at 621 locations in the Guerbe river (black area in inset) from check dam failure scenarios with (a) 50% and (b) 0% check dam maintenance. Baseline scenario with 100% check dam maintenance appears in both plots as a reference. Negative values are erosion and positive values deposition. The legend provides the number of check dams remaining after the scenario.

Fig. 7. Channel change longitudinal profiles (year 100–year 1) of the Guerbe River (from location A to B along the black line in inset map) with (a) 100%, (b–d) 50%, and (e–g) 0% check dam maintenance. Plots labeled with check dam failure scenario, negative values are erosion and positive values deposition. Locations of check dams may differ slightly between plots because of lateral shifting of the thalweg per scenario.

Fig. 8. Longitudinal profiles from (a, b) individual and (c–f) consecutive check dam failures identified in Fig. 7(c). Time commences one year before check dam failure and concludes upon profile stabilization. For comparison purposes distances and elevations are translated to the same origin.

Fig. 9. (a) Hourly discharge. Annual channel changes in the Guerbe river (black area in inset) from check dam failure scenarios with high failure probability with (b) 50% and (c) 0% check dam maintenance. Negative values are erosion and positive values deposition. Minimum and
maximum channel changes were determined as $\text{min} = Q1 - 1.5\text{IQR}$, $\text{max} = Q3 + 1.5\text{IQR}$, where $Q1$ = the lower quartile value, $Q3$ = the upper quartile value, and $\text{IQR}$ = the interquartile range.

Fig. 10. Check dam failure scenarios with (a) 50% and (b) 0% check dam maintenance and hourly discharge (gray line). Floods producing check dam failures highlighted (light blue lines). Hourly cumulative sediment yield for baseline, low, medium, and high check dam failure scenarios with (c) 50% and (d) 0% maintenance. Arrows indicate flood events producing many check dam failures.
• Check dam failure produces 8 m of channel erosion and 322% increase in sediment yield
• In steep mountain channels, bedrock can limit post check dam failure channel erosion
• Spatially distributed rainfall and soil depth improve CAESAR-Lisflood’s replication of river discharge
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: