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Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on river basin sediment yield

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Abstract

Precipitation intensities and the frequency of extreme events are projected to increase under climate change. These rainfall changes will lead to increases in the magnitude and frequency of flood events that will, in turn, affect patterns of erosion and deposition within river basins. These geomorphic changes to river systems may affect flood conveyance, infrastructure resilience, channel pattern, and habitat status, as well as sediment, nutrient and carbon fluxes. Previous research modelling climatic influences on geomorphic changes has been limited by how climate variability and change are represented by downscaling from Global or Regional Climate Models. Furthermore, the non-linearity of the climatic, hydrological and geomorphic systems involved generate large uncertainties at each stage of the modelling process creating an uncertainty “cascade”.

This study integrates state-of-the-art approaches from the climate change and geomorphic communities to address these issues in a probabilistic modelling study of the Swale catchment, UK. The UKCP09 weather generator is used to simulate hourly rainfall for the baseline and climate change scenarios up to 2099, and used to drive the CAESAR landscape evolution model to simulate geomorphic change. Results show that winter rainfall is projected to increase, with larger increases at the extremes. The impact of the increasing rainfall is amplified through the translation into catchment runoff and in turn sediment yield with a 100 % increase in catchment mean sediment yield predicted between the baseline and the 2070–2099 High emissions scenario. Significant increases are shown between all climate change scenarios and baseline values. Analysis of extreme events also shows the amplification effect from rainfall to sediment delivery with even greater amplification associated with higher return period events. Furthermore, for the 2070–2099 High emissions scenario, sediment discharges from 50 yr return period events are predicted to be 5 times larger than baseline values.

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1 Introduction

Anthropogenic climate changes are projected to considerably alter the hydrological cycle (Douville et al., 2002). For certain parts of the world this may lead to an increase in precipitation frequency and/or magnitude (Palmer and Ralsanen, 2002). In turn, this will lead to increases in the magnitude and frequency of flood events and the damage and hazards associated with flooding (Milly et al., 2002). Of particular concern are the 20 % of the global population that live in river basins that will experience increased flooding through increased stream flow and/or rainfall as a result of climate change (Kleinen and Petschel-Held, 2007). The impact of these floods will be widespread and may include damage to urban and rural infrastructure located on floodplains (Dutta et al., 2003; Schreider et al., 2000; Tockner and Stanford, 2002). In the UK, evidence suggests that there will be increased occurrence of extreme rainfall events and flooding in the next century (Dankers and Feyen, 2008; Ekstrom et al., 2005; Fowler and Ekström, 2009; Pall et al., 2011; Prudhomme et al., 2003) and this may cause a 100–600 % monetary increase in riverine flood damages (Feyen et al., 2012).

Whilst flooding itself is an important hazard and has been widely researched in the literature, how changes in flood magnitude and frequency will affect patterns of erosion and deposition within river basins has received little attention. However, these *geomorphic* changes will have important impacts on:

1. Channel incision and aggradation, which will alter channel capacity, flood conveyance and thus future flood risk.
2. Undermining of structures (e.g. bridges, flood defences) or siltation/deposition problems.
3. Channel pattern change, with shifts from stable meandering channels to more dynamic braided patterns.
4. Increased fine sediment concentrations in streams, which may affect water quality.

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5. Habitat changes caused by erosion and deposition, especially fine sediment which affects salmonids for example.
6. Increased movement of contaminants associated with sediments (e.g. heavy metals).
- 5 7. Fluxes of carbon associated with river sediments.

Therefore, predicting and understanding the changes in the levels of erosion and deposition in rivers that may result from climate change is essential in order to plan and manage for any adverse impacts. A variety of different approaches have tried to address the effect of historical climatic variability on channel geometry. For example, Lane et al. (2007) examined how recent changes in channel geometry, caused by changing flood frequencies and magnitudes, can affect subsequent levels of flood inundation. They found that natural changes in channel shape could have the equivalent impact on flooding as a 20 % increase in flood magnitude caused by climate change. Over longer time scales others have made more qualitative assessments of the variability in levels of erosion and deposition in river channels by interpreting sedimentological records and matching them to historical climatic events (Gomez et al., 1995; Magilligan et al., 1998), thus using information on past behaviour to infer future changes. Although these methods have proven useful and major advances have been made in dating by collating large regional databases (Macklin et al., 2010), recent work has suggested that there are limitations to using the sedimentological record as an analogue for likely future climate change impacts as: (a) climate events may not leave any evidence of geomorphic change (Jerolmack and Paola, 2010; Smith et al., 2010; Van De Wiel et al., 2007), and (b) the climate may change in ways that have not been recorded historically. Therefore, given the difficulties found in using the palaeo-sedimentological record and the uncertainties in how future climate change may manifest itself, numerical models are useful tools with which to quantitatively explore the potential geomorphic responses to a changing climate.

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Previous studies have used a range of numerical models operating at different time and space scales to explore the impacts of climate change on sediment response and channel change. These range from soil erosion models, to landscape evolution models, to channel based models. Firstly, soil erosion models typically focus on erosive hill slope processes and models such as the WEPP soil erosion model (Lafren et al., 1997) has been applied to hillslopes and fields to derive general trends in sediment response to long term climate change (O'Neal et al., 2005; Pruski and Nearing, 2002). For example, using WEPP Favis-Mortlock and Guerra (1999) modelled soil erosion over a 48-ha hillslope field in the Amazon using projected daily precipitation from 2050 and estimated that average annual sediment yield will increase by 27%. However, although hillslope scale models, like WEPP, are suitable for investigating seasonal scale responses to climate change, they are less suited for predicting responses to high intensity, short duration, rainfall events that occur at time scales much smaller (sub-hourly) than the daily time step at which the models operate (Merritt et al., 2003) and which may change disproportionately with climate change (Fowler et al., 2009). An alternative is catchment scale soil erosion models which have been applied using a high temporal resolution (sub-hourly, hourly) (Elliott et al., 2011; Nearing et al., 2005), but due to computational limits these are restricted to examining individual storms that span days. More synoptic catchment scale responses have been realized using models that sacrifice spatial heterogeneity (i.e. microtopography) for faster computation (Nunes and Nearing, 2011; Nunes et al., 2008). For example, the soil erosion model SWAT divides a catchment into sub-units with similar landscape characteristics and then routes sub-unit level runoff and sediment downstream to derive catchment scale quantities (Arnold et al., 1998). Chaplot (2007) applied SWAT on 2 catchments, 918 km² and 51 km² in area, with semi-arid and humid climates. Future changes in climate were then represented by the amplification (10–40%) of 100 yr of synthetically produced daily rainfall generated from 9 yr of observed rainfall.

Secondly, landscape evolution models (for recent reviews see Tucker and Hancock, 2010; Van De Wiel et al., 2011) typically simulate hillslope and channel processes

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with an emphasis on how the interaction between both leads to longer term landscape development. Tucker and Slingerland (1997) used the GOLEM model to show how over long time scales (1000s of years) there was a lag in the sediment response of a drainage basin to stepped changes in climate drivers. Tucker and Bras (2000) also used GOLEM to examine the interaction of rainfall variability on arid and humid catchments, showing how poorly vegetated catchments were less sensitive to rainfall changes. In this model, however, climate was represented as a mean value that did not include shorter term events, and daily or even monthly changes. Temme and Veldkamp (2009) used the LAPSUS model to simulate 50 000 yr of development of the Okhombe Valley, SA, demonstrating how landscape response lags climate drivers. Further work by Temme et al. (2009) explored how future changes in climate may affect landscape change predicted by the LAPSUS model by projecting GCM predictions of future temperatures to 1000 yr into the future. Importantly, this work made a direct connection between GCM projections and geomorphology. But the temporal resolution of the climate data was daily, thus ignoring smaller scale changes including extreme rainfall events. More recently, van Balen et al. (2010) simulated the impact of late Pleistocene climate changes on the Rhine-Meuse using the CHILD model. To represent climate change, they used daily resolution predictions of runoff to drive the model, though they simulated only the larger events.

There are few soil erosion/landscape evolution models that are able to use high resolution (e.g. hourly) rainfall data to generate runoff and simulate erosion and deposition at the short-time scales needed to explore the effect of extreme events. One of these models is the CAESAR model (see Van de Wiel et al., 2007) which has been used to simulate changes in sediment yield from river catchments over the Holocene (Coulthard and Macklin, 2001), during the last 500–1000 yr (Welsh et al., 2009) and for recent storm events in Australia (Hancock and Coulthard, 2011). Importantly, the CAESAR model is event based (driven by an hourly rainfall record) but in previous studies climate changes have been represented very simply by only increasing or decreasing the magnitude of the rainfall record.

Thirdly, channel based models focus solely on how erosion and deposition within channels affects sediment delivery. Channel and upstream sediment inputs are considered, but hillslopes are not explicitly modelled (and linked) as with landscape evolution models. Verhaar et al. (2010) modelled future changes in the Saint-Lawrence River, Quebec, using a one dimensional hydraulic model. Seven scenarios of future discharges under different climate change conditions were simulated and all led to increases in sediment delivery. Gomez et al. (2009) also used a one-dimensional hydraulic and sediment transport model linked to a climate-driven hydrological model to project climate change impacts on the sediment transport regime of the Waipaoa River, NZ. Their results were mixed, showing decreases in water discharges but slight increases in suspended sediment loads under climate change. Of most concern were their projections that bed aggradation could reduce channel conveyance and thus increase the likelihood of flooding (as per Lane et al., 2007).

With all previously published approaches there are considerable limitations in how climate variability and climate change are represented through downscaling from Global or Regional Climate Models (GCMs, RCMs). For a comprehensive review of downscaling methods used in hydrological modelling see Fowler et al. (2007). Often the effect of climate change on rainfall is heavily simplified by using only mean or average climate values, which may be simply increased or decreased (e.g. Tucker and Slingerland, 1997). More sophisticated approaches have included increasing the overall magnitude of rainfall (Coulthard et al., 2000), commonly called the “perturbation method” or “delta change” approach (Prudhomme et al., 2002), or repeating data from years containing larger flood events (Hancock, 2009). The simplest approaches ignore the variability in rainfall events and even the more sophisticated methods used thus far greatly simplify the role of flood frequency, magnitude and extreme events on sediment delivery and channel response. Whilst these simplifications are perfectly justified given the scope and context of many of the reported modelling studies (e.g. when modelling millennial time scales), under climate change the changing risk of large flood events may have a profound effect on river systems and their geomorphology (Mayes et al.,

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2006; Milan, 2012) and thus a more sophisticated downscaling approach that accounts for changes to both the variability and extremes of rainfall is needed.

Another issue hampering the development of models of geomorphic change under climate change is the non-linearity of the systems involved which produces large uncertainties at each stage of the modelling chain: the uncertainty “cascade” (Schneider, 1983). Here we use a modelling cascade from GCMs, feeding into RCMs, which drive weather generators (or other downscaling methods) to simulate rainfall, which is then fed into hydrological models to generate runoff, which in turn can be used to simulate river hydraulics and finally sediment transport leading to erosion and deposition. Uncertainties result from grid resolution, process parameterization, model structure and emissions scenario in GCMs (e.g. Giorgi and Francisco, 2000; Covey et al., 2003) and when using RCM data the sources of uncertainty increase, as outputs are influenced by RCM resolution, numerical scheme, physical parameterizations and the forcing lateral boundary conditions (Rummukainen et al., 2001; Deque et al., 2007; Elia et al., 2008). Downscaling methods, such as weather generators produce another layer of uncertainty (Fowler et al., 2007). Catchment hydrology also produces non-linear responses, with the timing and size of runoff being dependent on the timing and magnitude of the driving rainfall, as well as the antecedent conditions and, for example, non-linear changes in soil moisture stores and infiltration. Sediment transport, driven by the runoff is notoriously non-linear and hard to predict (Cudden and Hoey, 2003; Gomez and Church, 1989) and the integration of sediment transport across a catchment through erosion, deposition and re-working creates another non-linearity/uncertainty. For example, recent work (Coulthard et al., 2005; Coulthard and Van De Wiel, 2007; Van De Wiel and Coulthard, 2010) describes how identical size flood events can generate bedload discharges that vary over several orders of magnitude. They summarise that a large flood is required to move a large amount of sediment, but a large flood does not necessarily mean a large amount of sediment will be moved.

Ensembles of model runs are commonly used to address this issue of modelling uncertainty: using a probabilistic approach first demonstrated in publications such as

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described by Kilsby et al. (2007) and Jones et al. (2009). Observed monthly statistics for each 5 km grid box are perturbed using the CFs to derive a set of future monthly climate statistics. The weather generator is then refitted using these perturbed statistics to generate a set of future simulations.

5 The UKCP09 Climate Projections provide an ensemble of 10 000 sets of CFs. To run all 10 000 would be too computationally intensive for this study, particularly since we are interested in the effect of different time-slices and emission scenarios on the results; therefore, a significant challenge is the use of an appropriate means of sampling this dataset to preserve the range of probabilistic information. Burton et al. (2010) take
10 a 1000 member random sample of UKCP09 projections which is then sub-sampled to identify 12 weighted samples for subsequent application in a high resolution urban flood model. Christerson et al. (2012) use Latin Hypercube Sampling to obtain 20 samples for use with hydrological models to assess changes in river flows at the UK national scale within the context of water resource planning. Alternatively, UKCP09 guidance
15 recommends that a minimum of 100 random samples of the 10 000 sets of change factors are required to maintain the representativeness of the sampled dataset.

3 The CAESAR model

The CAESAR landscape evolution model (Coulthard et al., 2000, 2002, 2005; Coulthard and Van De Wiel, 2007; Van De Wiel et al., 2007) simulates landscape development
20 by routing water over a regular grid of cells and altering elevations according to erosion and deposition from fluvial and slope processes. CAESAR can be run in two modes: a catchment mode (as used here), with no external in-fluxes other than rainfall; and a reach mode, with one or more points where sediment and water enter the system. For both modes the model requires the specification of several parameters or initial
25 conditions including elevation, grain sizes and rainfall (catchment mode) or a flow input (reach mode). In theory, CAESAR model operation is simple, where rainfall falling on

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we have chosen to use the Einstein (1950) method. A calculation of shear stress is required to drive the Einstein formulation and this is calculated from flow velocity.

Deposition of sediments differs between bed load and suspended load. For each iteration all transported bed load material is deposited in the receiving cells where it can be re-entrained in the next iteration. Deposition of suspended sediments, however, is derived from fall velocities and concentrations for each suspended sediment fraction.

Incorporating multiple grainsizes, selective erosion, transport and deposition of the different size fractions will result in spatially variable sediment size distributions. Since this variability is expressed not only horizontally, but also vertically, it requires a method of storing sub-surface sediment data. This is carried out by using a system of layers comprising an active layer representing the stream bed; multiple buried layers (strata); a base layer; and, if required, an immovable bedrock layer. The layers have a fixed thickness and their position is fixed relative to the bedrock layer. Up to 20 strata can be stored at any cell on the grid. As the active layer represents the river bed, it has a variable thickness between 25% and 150% of the stratum thickness. Erosion removes sediment and causes the active layer thickness to decrease. If the thickness becomes less than a threshold value, then the upper stratum is incorporated in the active layer to form a new, thicker active layer. Conversely, deposition adds material to the active layer, causing it to grow. If the active layer becomes greater than a set value a new stratum is created, leaving a thinner active layer.

Limited slope processes are also included, with mass movement when a critical slope threshold is exceeded, together with soil creep. These allow material from slopes to be fed into the fluvial system as well as the input from landslides (both large scale and small – e.g. bank collapse). After the fluvial erosion/deposition and slope process amounts are calculated, the elevations and grain size properties of the cells are updated simultaneously.

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4 Integration of climate and geomorphic models

In this study we model how the River Swale in Northern England responds to simulated changes in rainfall under climate change. The Swale is an upland catchment of 186 km² (Fig. 1) with 500 m of relative relief. The catchment is underlain by a mixture of coarse sandstones overlying carboniferous limestone and was glaciated during the last glacial period. The river is cobble/gravel bedded with rough grazing and pastoral agriculture the main land use. The Swale is the focus of previous studies using the CAESAR model (Coulthard et al., 2005; Coulthard and Macklin, 2001, 2003) and being an upland catchment is an important source of coarse sediment and the primary supplier of fine sediment to downstream fluvial systems (Walling et al., 1999) and thus is an appropriate choice for this illustrative study.

CAESAR was set up using a 50 m Digital Elevation Model (DEM) of the catchment, with a secondary DEM representing bedrock sections of the channel (in some of the tributaries) that restrict channel incision in these areas. The main driver for CAESAR is hourly rainfall data and therefore 30-yr sequences of simulated hourly rainfall were generated using the UKCP09 weather generator for 5 contiguous tiles that overlay the catchment. Each CAESAR model run took 12–48 h to complete, depending upon the number and size of rainfall events within each simulation. The computationally intensive nature of this study meant that only 100 30-yr CFs per scenario were analysed in this initial study. Although this does not cover the full uncertainty range of the UKCP09 future climate projections, it provides the most comprehensive study yet of the range of uncertainty in climate change impacts on future sediment delivery and channel change, and is in line with the UKCP09 guidance of using a minimum of 100 random samples of the 10 000 sets of change factors to maintain the representativeness of the sampled dataset.

We produce scenarios for 3 different 30-yr time-slices centred on the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099), for each of the Low, Medium and High emissions scenarios. For convenience these will be subsequently referred

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to as the “nine scenarios”. For each future period 100 sets of CFs were sampled from the UKCP09 projections and used to perturb the observed statistics to generate a synthetic 30-yr hourly rainfall series for each set. A set of 100 30-yr simulations was also produced for the baseline period 1961–1990 against which to assess the future projections. Note that variations in the baseline simulations represent solely the stochastic nature of the UKCP09 Weather Generator and can be thought of as an estimate of “natural climate variability” against which to compare the projected changes (which contain an element of stochastic variability as well as changes consistent with the climate projections they are based upon). For each of the nine rainfall scenarios, 100 30-yr daily simulations were then carried out with the CAESAR model, simulating daily sediment and water discharges.

A final step in setting up the simulations was to establish that the baseline rainfall data from 1961–1990 was representative for the area in terms of the river flows produced. This was achieved by comparing data from a flow gauge at Catterick Bridge to CAESAR simulated flows. As Catterick Bridge is 20 km downstream from the area simulated here this required extending the DEM to increase the catchment area accordingly. However, it was necessary to use the smaller catchment area for the geomorphic simulations as increasing the catchment area to Catterick (250 %) significantly increased CAESAR model run times. Figure 2a shows 30-yr hydrographs from CAESAR for five randomly selected baseline rainfall datasets as well as the distribution of daily total runoff totals. Observed river flow data from Catterick Bridge is plotted (Fig. 2a) along with its histogram in black (Fig. 2b). Finally, the distribution of real flow data is overlain with the results from all five baseline scenarios (Fig. 2b). The modelled and observed flow data show a good correspondence, though there is a lack of larger flood events in the observations. This can be attributed to the short length of the observed record (15 yr) compared to the 150 yr of baseline simulated data plotted in grey.

5 Results and discussion

5.1 Overall changes in sediment yield

Figure 3 shows the sediment values for the nine scenarios and the baseline as cumulative volumes. Sharp rises in the lines indicate the presence of flood events that cause a sudden increase in sediment yield. The red line in each plot indicates the average for all 100 simulations in each scenario and the shaded cyan background indicates one standard deviation. Figure 3 demonstrates a general increase in total sediment yield with higher emissions scenarios and for later time-slices, together with a slight increase in the standard deviation. However, there is considerable variability with, for example, individual runs from the Low emissions scenario for 2040–2069 having greater total sediment yields than most runs from the High emissions scenario for 2070–2099. This reflects the uncertainty in the projected climate changes for each scenario as well as the variability introduced by the stochastic nature of the simulated rainfall, and shows how important it is to use a probabilistic approach with an ensemble of runs for each scenario.

Figure 4 describes the mean and distribution of the total sediment yield for each of the 100 30-yr simulations for the nine scenarios. Like Fig. 3, this also illustrates the projected increase in sediment yield with increased emissions scenario and for later time-slices with a 100 % increase in mean sediment yield from baseline to 2070–2099 High emissions scenario. Table 1 demonstrates that sediment yields from all the climate change scenarios are significantly different from the baseline and all 2070–2099 scenarios are significantly different from all other time slices/scenarios. Figure 4 also highlights the increase in the highest sediment yields, in particular for the 2070–2099 High emissions scenario (totals greater than 5 000 000 m³).

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5.2 Event based changes in sediment yield

The CAESAR simulations provide daily totals of sediment yields, thus it is also possible to examine how catchment sediment yield has changed on a daily event basis. Figure 5 shows histograms of daily sediment totals for all nine simulations as well as for the baseline and this shows three projected effects of climate change on sediment event distribution. Firstly, there is a general upwards displacement in the frequency of medium to large size events, with little change in the number of smaller events. Secondly, there is a notable peak in sediment delivery events of magnitude $\sim 700\,000\text{ m}^3$ in the later time slices for the High emissions scenario. Thirdly, there is a considerable increase in the magnitude and frequency of large and very large sediment yield events under the High emissions scenario which do not occur under the baseline scenario.

These three effects suggest that projected changes to rainfall magnitudes and frequencies in this part of the UK may have a profound effect on the geomorphology of the Swale catchment. Under climate change, it is projected that there will be a significant increase in the frequency of large daily sediment yields and, significantly, the appearance of several events (daily totals) that are more than twice the magnitude of the largest event found in the baseline climate simulations. In short, climate change is projected to increase the likelihood of medium and large sized sediment events and lead to the generation of very large sediment events which have not previously been recorded (in the instrumental record).

To investigate the source of these changes in daily sediment totals we plotted the frequency distribution of the daily rainfall, the resultant high flows and the consequent sediment yields for the 100 30-yr simulations for the 2070–2099 High emissions scenario (Fig. 6). This demonstrates how the catchment acts as a geomorphic multiplier of rainfall events. For rainfall (Fig. 6a), baseline rainfall distributions follow a near log-normal distribution and the 2070–2099 High emissions scenario results show a displacement of these values that increases towards the larger events. When the rainfall is processed into runoff (Fig. 6b) there is a larger increase in the higher magnitude values, especially

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for the 200–300 m³ s⁻¹ size events. When looking at how the changes in runoff influence daily sediment yield (Fig. 6c) there is an even greater increase in the largest events. In summary, increases in large rainfall events are multiplied into proportionately larger increases in the number of very large sediment yields.

5.3 The role of seasonality

Figure 7 shows the projected monthly changes to rainfall under the nine scenarios. This shows that the mean projected change from the 100 30-yr runs shows a increase in winter season rainfall (from October to March) and a decrease or no change to summer season rainfall (from April to September) when compared to the baseline climate, 1961–1990, which amplifies throughout the century. Figure 7 shows that for the first time-slice, 2010–2039, the emissions scenario is not important; however, which emissions trajectory we follow becomes increasingly important later this century in terms of the magnitude of projected changes to rainfall. However, there is little difference in terms of the emissions scenario for changes at the 5th percentile but much larger differences at the upper end of the rainfall distribution (95th percentile). It is also noticeable that although the mean daily rainfall and 5th percentile of daily rainfall get drier in the summer and wetter in winter, the 95th percentile of daily rainfall shows increases for all months under almost all emissions scenarios and time slices. Figure 7 also illustrates the large variability in individual UKCP09 weather generator simulations both for the baseline – a result of stochastic variability alone – and the nine scenarios – resulting from climate change uncertainty from the CFs and stochastic variability from the weather generator.

To further describe how these projected seasonal changes in rainfall patterns may impact upon catchment discharge and sediment delivery we have plotted the 50th to 100th percentiles of daily rainfall totals, water discharge values and sediment yields for the 12 calendar months for the 2070–2099 time-slice for all emissions scenarios.

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Table 2 how the change is in each case positive between the baseline and the future scenario for each percentile. Also apparent is the larger projected changes for the more extreme events, i.e. for the 90th and 95th percentiles and the amplification effect of this change when moving through from rainfall to discharge to sediment delivery.

This was further explored by plotting the median, 5th and 95th percentiles of each 30-yr simulation for the baseline climate and the 2070–2099 High emissions scenario on a Gumbel reduced variate plot to estimate approximate return periods for events for the baseline and how these might change for rainfall, discharge and sediment (Fig. 9). Figure 9 demonstrates that although the distributions overlap, the median annual maxima events are larger in all cases for the future case when compared to the baseline and that the changes are largest at the high return periods. Also apparent is the amplification of the signal from rainfall to discharge to sediment delivery. This is best illustrated by the changing ratio of the ~50-yr return period to the 2-yr return (details given in Table 3). The 2 to 50 yr return ratio for daily rainfall is 1.78 for baseline, increasing to 1.92 in the 2070–2099 High future scenario. For discharge the figures are 2.25 and 2.53, but for sediment the ratios are 32.89 and 84.44. Therefore the amplification effect from rain to discharge to sediment is even more exaggerated in high return period events.

Furthermore, if we look at the ratio between baseline and 2070–2099 High scenarios for rainfall the 2-yr and 50-yr rainfall events increase at approximately the same rate (1.18 and 1.28, respectively). But for sediment delivery there is a staggering five-fold increase (5.07) between baseline and 2080–2099 High scenarios at the 50-yr return period compared to a modest 1.97 ratio increase at the 2-yr return period. For the 2070–2099 scenario sediment delivery from 50 yr return period events are predicted to be 5 times larger.

5.5 Limitations

Although the approach is state-of-the-art, there are still limitations to the methods taken here. The hourly rainfall data generated by the UKCP09 weather generator is lumped

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over the whole catchment and whilst the catchment is not especially large and rainfall variability may not be great, there would be some temporal, spatial and altitudinal variability that could impact upon the study results.

Each 30 yr simulation took between 18 and 36 h (depending on the size of events) and ultimately the availability of computational time restricted the number of simulations we could carry out. Our sensitivity analysis for the baseline data indicated that 60–100 repeats were required in order for the means and standard deviations to stabilise – to account for the stochastic nature of the weather generator (see appendix Fig. 1). However, each scenario rainfall simulation from the weather generator represents not only a stochastically chosen series of events but also changes in the climate model parameters used to simulate the future climate. Therefore, if there are 100 changes in climate model parameters per scenario, ideally we would require 100 repeats for each of these 100. This would push the required computation time to ca. 100 000 days. Parallel approaches and the use of GPU methods makes this problem more tractable but at present the time/resources required is simply too great. Therefore, the results other than the baseline simulation represent a combination of randomly sampled parameter values for the future climate model *and* the stochastic component.

6 Conclusions

For the first time, we are able to meaningfully simulate the potential impacts of anthropogenic climate change on catchment geomorphology and sediment yield. The results are clear and the implications concerning. Mean rainfall is projected to increase and this effect is multiplied through its translation into catchment runoff and in turn sediment yield. A 100 % increase in sediment yield is projected between the baseline and the 2070–2099 High emissions scenario. For individual events, major increases in the size of medium, large and especially very large sediment delivery events are projected. Seasonally, this is linked to increases in the size of winter rainfall, discharge

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and sediment events across all percentiles of the distribution, but also to an increase in the largest summer rainfall events and therefore flood events. Strikingly, the extreme event analysis shows that the geomorphic multiplier affects large events to an even greater extent and that sediment yields from 50 yr return period events may be five times greater.

The projected changes described above are based on the means of 100 simulations per scenario and it is important to note that not only is there an increase in the mean value with climate change – individual events show far greater projected changes than the 100% increases in sediment yield.

For those managing, or living near, upland UK rivers the implications of these results are highly significant. Increased flood sizes and sediment yields may have an important impact on the fluvial environment. Increased bedload yields can lead to channel siltation, instability and channel pattern change. This can lead to the undermining or erosion of bridges, flood defences and channel control structures. For flood defence there is a double impact. Not only is there projected to be a greater number of larger events, but the deposition of large volumes of coarse sediment will also negatively alter the capability of a river to convey flood waters, thus raising the stage for subsequent flood events. Ecologically, changes in coarse and fine grain sediment delivery will impact fisheries both in the uplands and in lowland water courses. Benefits may be both positive and negative as there may be increases in areas of medium/coarse grain size habitats as well as the deterioration of others through siltation. It is worth remembering, however, that the results show changes in probabilities and whilst some scenario simulations showed massive, potentially catastrophic, changes (far greater than the means discussed above), some showed none if any change.

Finally, there are high levels of parameter and model uncertainty at all stages of the modelling exercise, from GCM output to sediment yield, and the systems modelled are highly non-linear. Having undertaken this exercise, we find it hard to justify making any sort of future projection based on a few simulations, as identical “scenario” runs can generate very little, or catastrophic levels of change. Therefore, we urge the

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geomorphic modelling community to embrace using a probabilistic approach based on multiple repeat simulations.

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Table 1. Comparison of sediment totals using Student’s t-test, with p-values adjusted for multiple comparisons (Holm, 1979). Significant differences ($p \leq 0.05$) are bold.

		Baseline	2010–2039			2040–2069			2070–2099		
			low	med	high	low	med	high	low	med	High
	Baseline	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2010–2039	low	<0.001		1.000	1.000	1.000	1.000	1.000	0.584	0.111	<0.001
	med	<0.001	1.000		1.000	1.000	0.066	0.072	0.034	0.005	<0.001
	high	<0.001	1.000	1.000		1.000	0.041	0.046	0.019	0.003	<0.001
2040–2069	low	<0.001	1.000	1.000	1.000		0.373	0.378	0.177	0.034	<0.001
	med	<0.001	1.000	0.066	0.041	0.373		1.000	1.000	1.000	0.027
	high	<0.001	1.000	0.072	0.046	0.378	1.000		1.000	1.000	0.034
2070–2099	low	<0.001	0.584	0.034	0.019	0.177	1.000	1.000	1.000	1.000	0.064
	med	<0.001	0.111	0.005	0.003	0.034	1.000	1.000	1.000		0.777
	high	<0.001	<0.001	<0.001	<0.001	<0.001	0.027	0.034	0.064	0.777	

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Table 2. Percentiles of the annual maximum distribution for the baseline and 9 future scenarios for (a) daily rainfall (mm), (b) discharge ($\text{m}^3 \text{s}^{-1}$) and (c) total sediment yield (m^3).

(a) Annual maxima of daily rainfall (mm)	5 %	10 %	50 %	90 %	95 %
Baseline	33.8	36.3	47.8	68.6	77.6
2010–2039 Low	34.2	37.2	51.0	75.7	86.3
2010–2039 Medium	35.4	38.0	50.5	75.3	88.0
2010–2039 High	34.5	37.5	50.9	74.9	85.1
2030–2069 Low	35.0	37.9	51.7	76.5	86.3
2030–2069 Medium	35.9	38.6	52.8	79.8	91.9
2030–2069 High	36.6	39.6	54.0	81.3	92.7
2070–2099 Low	36.6	39.5	54.0	80.7	92.1
2070–2099 Medium	36.7	39.7	54.1	80.3	92.7
2070–2099 High	38.4	41.4	57.2	87.9	102.2
(b) Annual maxima of daily discharge ($\text{m}^3 \text{s}^{-1}$)	5 %	10 %	50 %	90 %	95 %
Baseline	30.6	33.9	50.8	82.4	97.6
2010–2039 Low	32.1	35.3	55.1	95.6	118.0
2010–2039 Medium	32.8	36.7	55.8	93.9	116.5
2010–2039 High	32.6	36.5	55.5	95.1	115.2
2030–2069 Low	33.0	36.6	57.2	96.7	117.1
2030–2069 Medium	33.5	37.4	58.0	104.5	129.3
2030–2069 High	34.4	38.9	60.7	106.7	127.9
2070–2099 Low	34.5	38.8	60.2	106.7	130.1
2070–2099 Medium	35.0	38.9	61.2	107.1	128.4
2070–2099 High	37.0	42.3	67.1	120.1	140.8
(c) Annual maxima of daily total sediment yield (m^3)	5 %	10 %	50 %	90 %	95 %
Baseline	411	604	2243	12 816	29 548
2010–2039 Low	534	733	2899	24 536	74 388
2010–2039 Medium	531	749	2832	22 125	62 426
2010–2039 High	561	786	2810	20 975	54 020
2030–2069 Low	580	816	3102	24 733	71 761
2030–2069 Medium	710	917	3312	33 192	104 123
2030–2069 High	689	945	3515	35 275	99 128
2070–2099 Low	647	895	3473	38 659	97 611
2070–2099 Medium	638	923	3701	32 516	91 743
2070–2099 High	729	1057	4338	50 352	125 886

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Table 3. Estimated ~50-yr and 2-yr return periods for daily rainfall (mm), discharge ($\text{m}^3 \text{s}^{-1}$) and total sediment (m^3) for the baseline and 2070–2099 High emissions scenario showing the changing ratio between the return periods.

	Baseline	High 2070–2099	Ratio
Rainfall (mm)			
2-yr	48.1	56.9	1.18
~50 yr	85.6	109.5	1.28
Ratio	1.78	1.92	
Discharge ($\text{m}^3 \text{s}^{-1}$)			
2-yr	50.8	66.6	1.31
~50 yr	114.4	168.5	1.47
Ratio	2.25	2.53	
Sediment (m^3)			
2-yr	2189.4	4320.2	1.97
~50 yr	72 016.8	364 779.3	5.07
Ratio	32.89	84.44	

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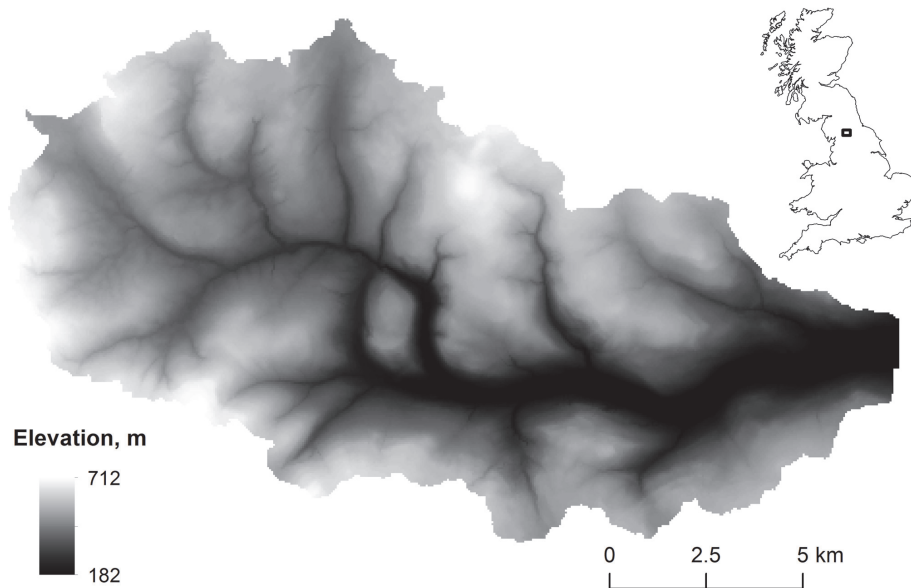


Fig. 1. The catchment of the River Swale, Yorkshire, UK.

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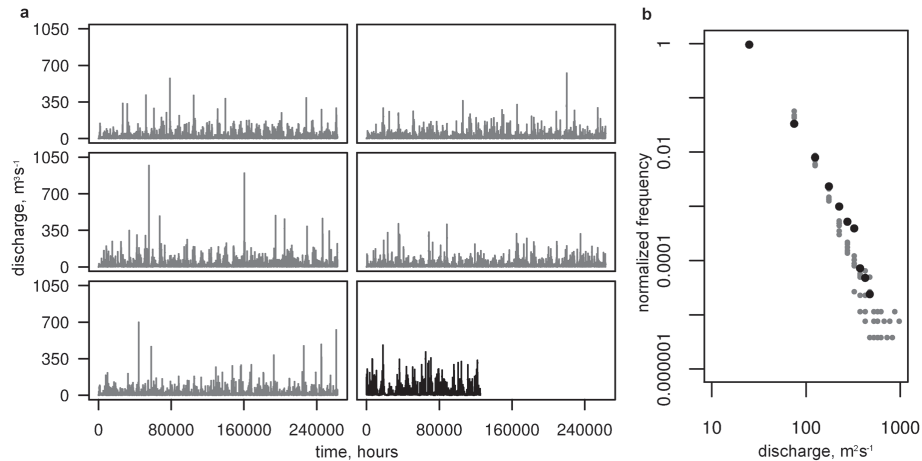


Fig. 2. Hydrographs (a) and histograms (b) from five baseline climate simulations (in gray), and observed discharge (in black).

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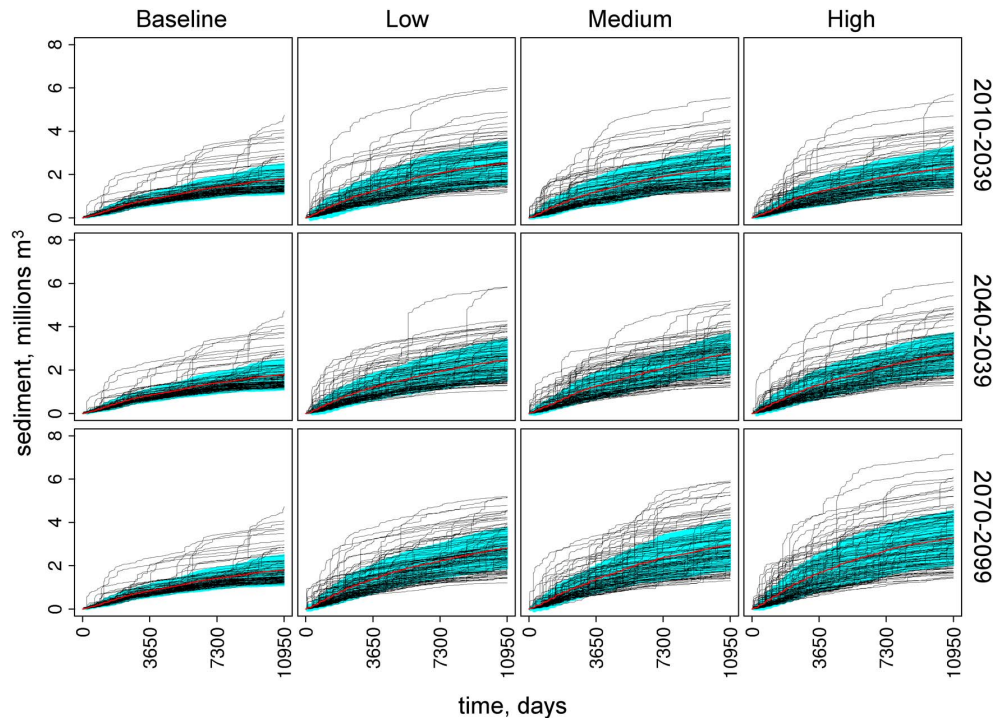


Fig. 3. Cumulative daily sediment outputs for all runs of 2010–2039, 2040–2069 and 2070–2099 (vertically) periods for the Low, Medium and High emissions scenarios (horizontally). Daily mean cumulative sediment is plotted as a red line, and daily standard deviation as cyan shading. For each time slice, the baseline climate, 1961–1990, results are plotted in the first panel for comparison.

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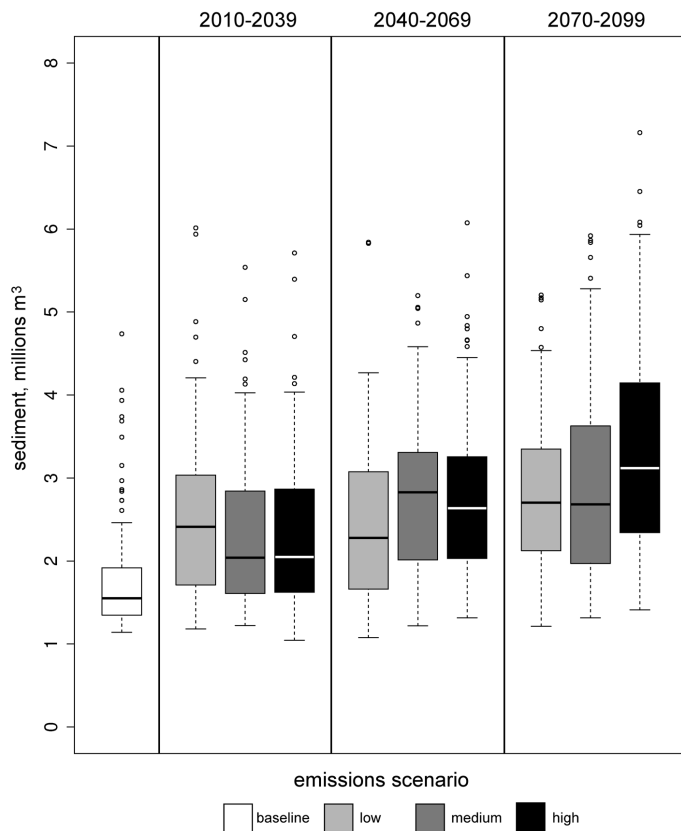


Fig. 4. Box plot showing the distribution of total sediment over 100 30-yr runs using different UKCP09 WG CFs for the 2010–2039, 2040–2069 and 2070–2099 time-slices for the Low, Medium and High emissions scenarios. The baseline climate (1961–1990) is shown in the left hand panel; the variability in these simulations comes from stochastic variability alone.

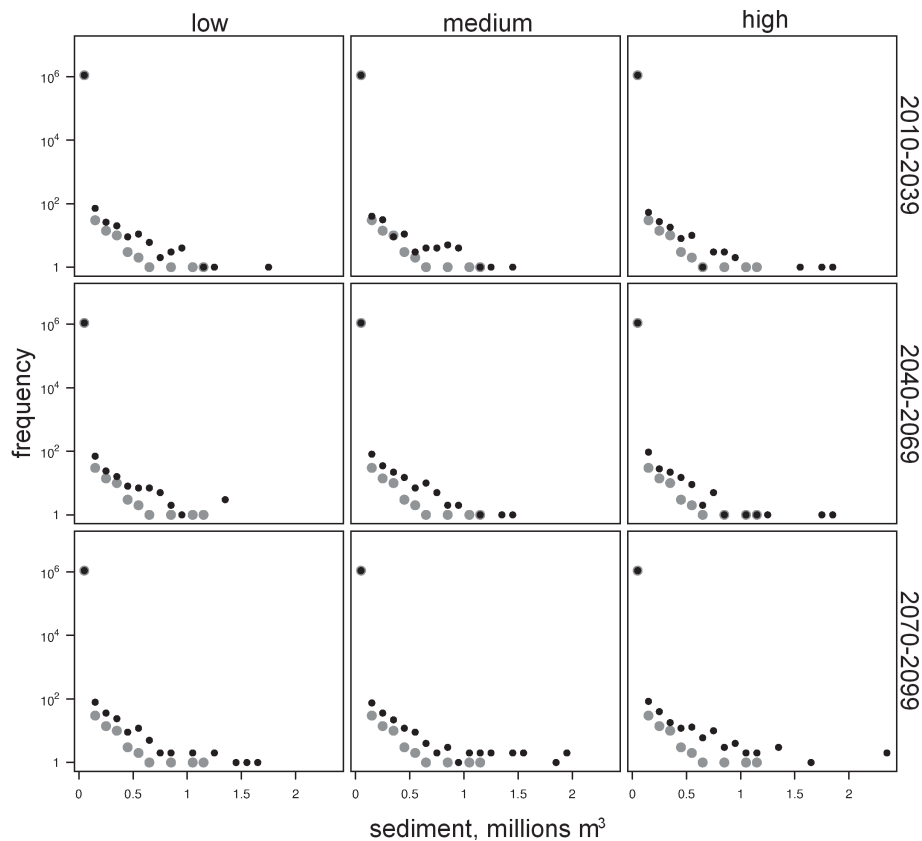


Fig. 5. Frequency plots of daily sediment totals from all nine climate change scenarios (in black), shown against results for the baseline climate, 1961–1990 (in gray).

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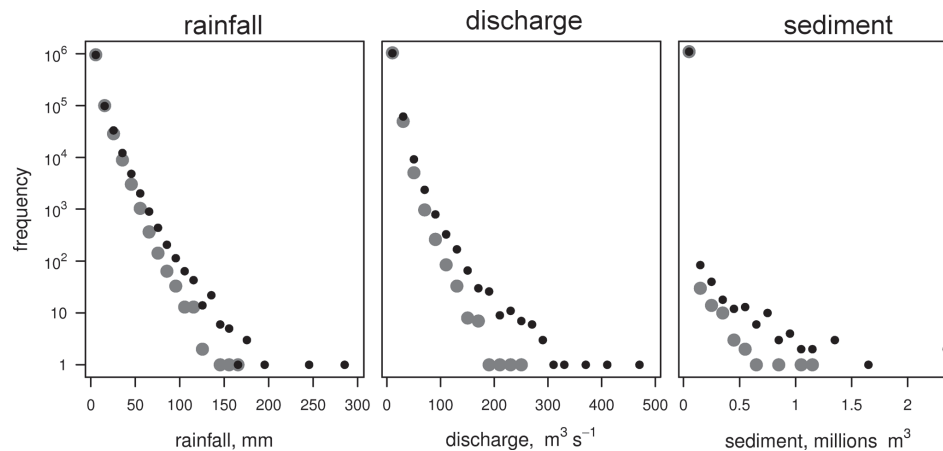
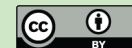


Fig. 6. Frequency plots of daily rainfall totals, daily discharge values and daily sediment totals for the High emissions scenario for the 2070–2099 time-slice (in black) and for the baseline climate, 1961–1990 (in gray).

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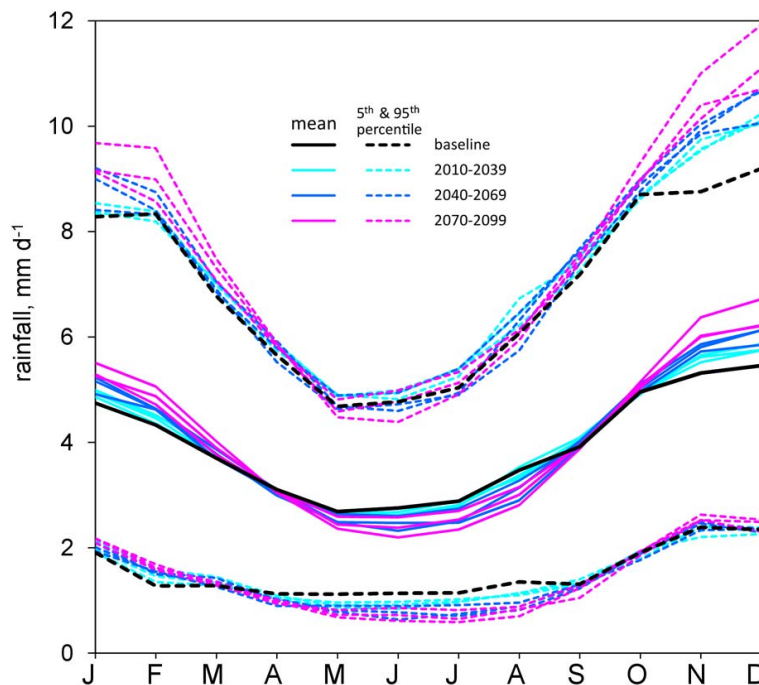


Fig. 7. Mean daily precipitation and 5th and 95th percentiles from the 100 30-yr simulations for the Low, Medium, and High emissions scenarios and three time periods 2010–2029 (in cyan), 2040–2069 (in dark blue), 2070–2099 (in pink), and baseline (in black).

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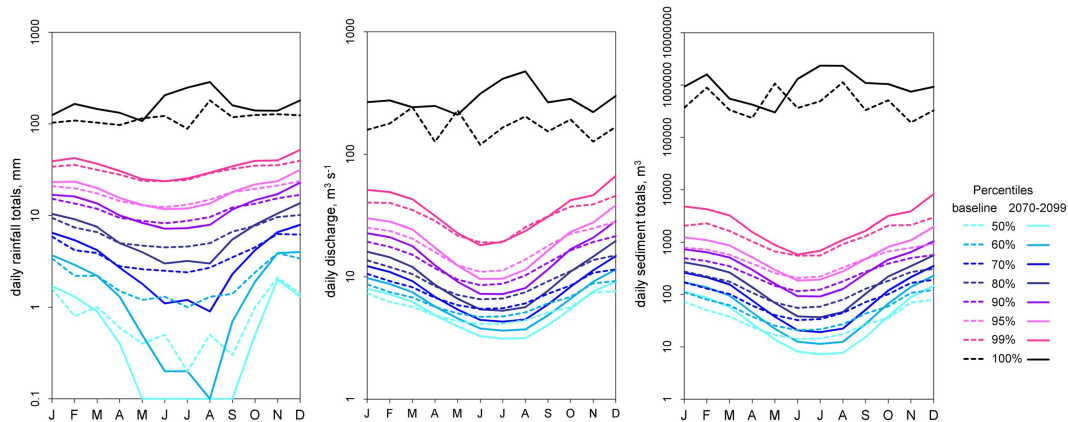


Fig. 8. Percentiles of daily rainfall, discharge and sediment totals per month for the baseline climate (1961–1990) and the High emissions scenario (2070–2099).

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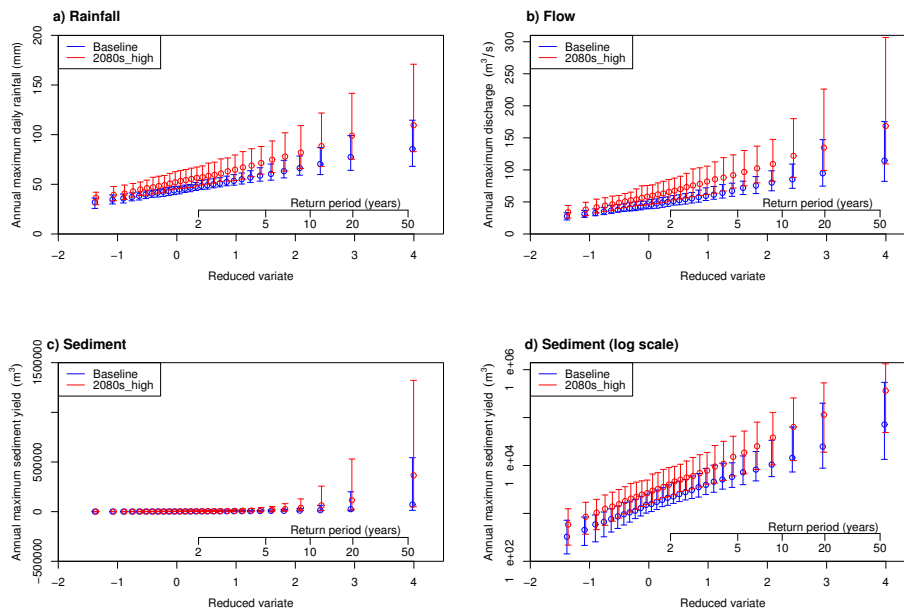


Fig. 9. Gumbel reduced variate plot of **(a)** annual maximum daily rainfall (mm), **(b)** annual maximum discharge ($\text{m}^3 \text{s}^{-1}$), **(c)** annual maximum sediment yield (m^3), **(d)** annual maximum sediment yield (m^3) on a log scale. For each of the 30-yr runs, for the baseline (blue) and High emissions 2070–2099 scenario (red), the median annual maximum event is plotted as a circle with the error bars showing the 5th and 95th percentiles from the 100 simulations. Return periods are shown on the y-axis.

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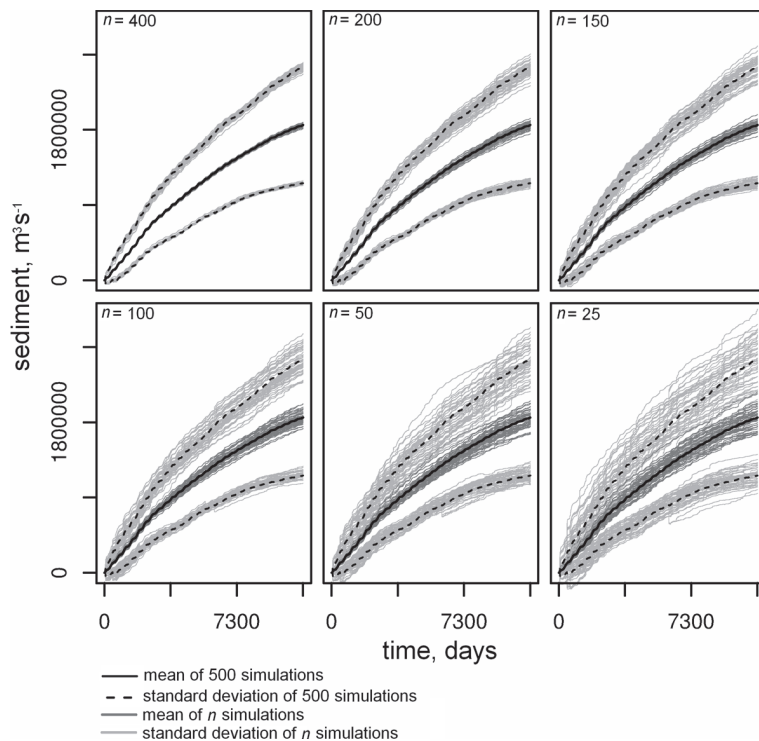


Fig. A1. Cumulative daily sediment mean (solid black) and standard deviation (dashed) from 500 baseline simulations overlaid on cumulative daily sediment mean (dark gray) and standard deviation (light gray) from n randomly selected baseline simulations. 50 replicates are shown in each plot.

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