

Human-driven global geomorphic change

Juan Remondo^{a,*}, Luis M. Forte^b, Antonio Cendrero^{a,b}, Piotr Cienciala^c, Achim A. Beylich^d

^a DCITIMAC, Universidad de Cantabria, 39005 Santander, Spain

^b IGS, Universidad Nacional de La Plata, Argentina

^c Dept. of Geography and GIS, University of Illinois at Urbana-Champaign, USA

^d Geomorphological Field Laboratory (GFL), Selbustrand, Norway

ARTICLE INFO

Keywords:

Great Acceleration
Geomorphic change
Human geomorphic drivers
Global denudation
Geomorphic disasters
Anthropocene

ABSTRACT

We synthesize evidence suggesting a chain of global cause-effect relationships, linking population and economic development with cumulative effects on changes in landscape dynamics, including denudation and sediment transport/deposition. Temporal trends in global patterns of geomorphic processes or process combinations such as denudation, sedimentation, or frequency of geomorphic disasters, appear to reflect growing human pressure. Erosion rates, intensified by anthropogenic factors, are currently one to two orders of magnitude greater than prior to the 20th century, and are growing further. Per capita human transfer of Earth materials has increased tenfold. A considerable increase in the frequency of disasters related to geomorphic processes has also taken place in just over half a century, outpacing changes in other natural disasters. It is especially significant that the ratio between the frequency of geomorphic (implying water/land interaction, obviously influenced by climate change) disasters and frequency of purely climate-related disasters has increased more than ten-fold since the early 20th century. The changes described in geomorphic processes (global geomorphic change) appear to respond mainly to land surface modification, which reflects a “Great Geomorphic Acceleration” after the mid-twentieth century. However, these stressors, characteristic of the “Anthropocene”, likely interact with climate change, increasing concerns about future implications for Earth surface dynamics and underscoring the need to not only reduce GHG emissions, but also improve land use practices, which modify the conditions of the terrain.

1. Introduction

Concern about the extent and consequences of human-driven environmental changes and their significance for proposing a new geologic epoch characterized by the human influence on natural systems (“Anthropocene”, Crutzen, 2002; Lewis and Maslin, 2015; Syvitski et al., 2020), goes back to the 19th and 20th centuries (Marsh, 1864; Stoppani, 1871–73; Vernadsky, 1929; Ter-Stepanian, 1988). Here we use the term “Anthropocene” in the informal sense, as a recent period during which many aspects of the Earth System have been dominated by human activities (Swindles et al., 2023). We do not opine on whether that period is best viewed as a new geological epoch/series or event (Head et al., 2022 vs. Gibbard et al., 2022) or even on its eventual formal recognition but, in terms of timeframe, we understand it as beginning in the mid-20th century, consistent with what was proposed by Zalasiewicz et al. (2015).

One of the main drivers of the observed environmental modifications is human-driven climate change (IPCC, 2021; Chapter 3), but it is not the

only one to be considered when analysing Earth surface processes or process combinations, such as denudation. Drivers such as urbanization and other activities implying land use changes also play an important role, globally (Seto et al., 2010; Brondizio et al., 2016; Lambin et al., 2021). The important human contribution to denudation was clearly illustrated by Brown (1956), who referred to “technological denudation”, and the need to pay attention to the “geomorphic dimension of global change” was suggested by Cendrero and Douglas (1996). The significance of human activities for Earth surface processes in general, has been discussed by several authors (among others, Slaymaker et al., 2009; Goudie, 2020; Syvitski et al., 2022; Cendrero et al., 2022).

An important intensification of geomorphic processes (due in most cases to the action of water on land surface) appears to be one of the characteristics of the Anthropocene (Syvitski et al., 2005; Cendrero et al., 2011; Cendrero et al., 2022; Bruschi et al., 2011, 2013; Brown et al., 2017; Goudie, 2020; Owens, 2020; Syvitski et al., 2022). Effects on geomorphic processes can of course reflect changes in the “water factor” (rainfall regime, storm frequency or intensity, etc.) or in the “land

* Corresponding author.

E-mail address: juan.remondo@unican.es (J. Remondo).

<https://doi.org/10.1016/j.geomorph.2024.109233>

Received 22 May 2023; Received in revised form 16 April 2024; Accepted 29 April 2024

Available online 30 April 2024

0169-555X/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

surface factor" (land cover, landforms, surface materials, etc.), as well as processes such as weathering, erosion, evapotranspiration, etc. In terms of direct drivers, the atmospheric water cycle is mainly affected by climate change (although land cover changes do play a role; Zhou et al., 2023), whereas the primary direct driver of land surface transformation is land-use change (climate can have an indirect impact, e.g., through vegetation, cryosphere, or surface waters).

Extraction and use of natural resources in general (UNEP, 2016; Krausmann et al., 2018) or mineral resources in particular (Cooper et al., 2018), land transformation (Kennedy et al., 2019; Lambin et al., 2021) or urban expansion (Liu et al., 2021), have greatly increased in recent times and represent a major change in human pressure on the environment. Particularly noteworthy is the case of sand, gravel, crushed stone and aggregates (the second most exploited natural resource in the world after water), the extraction of which has tripled in the last two decades to reach an estimated 40–50 billion metric tons per year (UNEP, 2022), reflecting increasing urban expansion and infrastructure development. One expression of the effects of those activities on surface processes is the "human geomorphic footprint" (Rivas et al., 2006), expressed as area directly transformed and volume of soil, sediment and rock deliberately displaced by human activities. According to the latter authors, the volume of geologic materials thus displaced globally is one order of magnitude greater than "natural" erosion (itself greatly conditioned by human land transformation). Recently presented results (Syvitski et al., 2022) indicate that anthropogenic sediment production increased by 467 % between 1950 and 2010.

The possibility that such actions in large part represent an important non-climate component of human influence on geomorphic processes, of a global character, has been previously highlighted (East and Sankey, 2020; Rivas et al., 2006; Brown et al., 2017; Russell et al., 2017; Chen et al., 2022; Cendrero et al., 2022; Syvitski et al., 2022). The indicated human-induced effects on global geomorphic systems show a sharp augmentation around the mid-20th century, coinciding with the "Great Acceleration", manifested in many other physical, chemical, and biological components of the Earth System (Steffen et al., 2015; Forte et al., 2016; Syvitski et al., 2020; Cendrero et al., 2020, 2022; Zalasiewicz et al., 2021). They also coincide with the phase transition proposed on the basis of the "Anthropocene Equation" (Gaffney and Steffen, 2017; Bertolani and Francisco, 2018).

It is now worth examining the extent to which some of the geomorphic changes we are witnessing are dependent on global climate change or on land surface transformation, both of which are human-driven, directly or indirectly. Our aim is not to discuss the unquestionable importance of climate change, but rather to highlight the extensive effects of land use/land cover changes on Earth's surface processes worldwide, which we believe may be currently underestimated. For example, it could be that rainfall events of a given magnitude or intensity, which did not cause floods, landslides, or significant erosional activity in the past, have that effect now due to a higher geomorphological sensitivity, as a consequence of land use/land cover changes (Douglas, 1967; Hooke et al., 2012; Russell et al., 2017; Johnston et al., 2021). The increasing rates of direct and indirect human-caused denudation and sediment deposition or increasing frequency of landslide and flood related disasters, at the global scale, do not show any clear relationship with changes in the mean annual precipitation regime (Remondo et al., 2005; Bonachea et al., 2010; Cendrero et al., 2020, 2022; Owens, 2020; Syvitski et al., 2022). Of course, the intensity of precipitation may be more determining (Blanco and Lal, 2010; Wischmeier and Smith, 1978; Zachar, 1982). Given the available data, we cannot rule out such a possibility. IPCC's Sixth Assessment Report (Arias et al., 2021a,b) indicates that frequency and intensity of heavy precipitation events has increased over many land areas. At the same time, the magnitude of the reported precipitation changes varies geographically and, both empirical analyses and modeling imply that in areas where warming relative to the reference period (1850–1900) did not exceed 2 °C, the magnitude of these changes have likely been on the order of

~10 %. It seems rather unlikely that such changes alone could account for an order of magnitude (or more) increases in sediment yield. For example, many studies have modeled the increases in soil erosion associated with the projected increases of rainfall erosivity (a function of precipitation intensity) or runoff. The results typically suggest that the percent increase in the modeled soil loss/sediment yield would be within the same order of magnitude as the percent increase in rainfall erosivity (Borrelli et al., 2020; Panagos et al., 2021). Similarly, the ratio of soil erosion rate increase to runoff increase was estimated to be <2 (Nearing et al., 2004). Moreover, in some climate types, precipitation mostly comes in the form of snow. For many such areas, IPCC (Arias et al., 2021a,b) indicates decreased snowpack storage. Under such circumstances, in absence of compensating inputs of rainfall (e.g., Hammond and Kampf, 2020) or glacial influence, water yield (or perhaps even peak flows) could in some cases decline accordingly (Kraaijenbrink et al., 2021). Thus, if sediment export trends were to mirror the varied hydrological trends, we would expect to see a highly heterogeneous response. Yet, many of the cited studies demonstrated that the anthropogenically elevated sediment mobilization seems to be a remarkably widespread phenomenon (of course, when the effect of sediment trapping in dams is accounted for).

Therefore, without completely ruling out the indirect effects of this and other manifestations of climate change, and aware of the fact that other drivers could play a role, it appears that land surface changes in general are at least equally important as a driver of the trends observed. More research is needed to assess whether the elevated geomorphic activity reflects lower erosional thresholds due to anthropogenic conditioning vs. other, climate-related factors such as more extreme events, for which long-term statistics are not readily available (IPCC, 2021, Chapter 11).

Recognizing the difficulties of disentangling the climate and land transformation components of geomorphic change, our aim is to bring the reader's attention to the importance of human drivers for a fuller understanding of these physical processes. To this end, building on a former contribution (Cendrero et al., 2022) and on the basis of new data, we will discuss some possible links between population growth, economic and technological development, resource extraction/consumption, land transformation and the intensification of geomorphic processes (and associated hazards/disasters), at the global level. We examine data going back to the beginning of the 20th century, when possible, in order to analyse changes in denudation or frequency of extreme geomorphic events (and potential drivers), that might have occurred in the (proposed) Holocene-Anthropocene transition (Steffen et al., 2015).

2. Geomorphic change drivers and effects

A reflection of the set of relationships between drivers and effects proposed by Cendrero et al. (2006) could be the spatial distribution of some parameters formerly presented by Cendrero et al. (2022; fig. 10). They showed that global distributions of Gross Domestic Product (GDP) density (Gallup et al., 1999), an indicator of the intensity of human activities in a given territory, and physical effects such as the global human modification index (Kennedy et al., 2019) or subsidence due to groundwater withdrawal (Herrera-García et al., 2021) are strikingly similar. It is interesting to point out that – despite what one could expect – the spatial patterns of the indicated effects seem to show stronger similarities to the distribution of intense human activity than to climate or even relief, traditionally taken as the key (natural) predictor of sediment yield (Summerfield and Hulton, 1994; Syvitski and Milliman, 2007; Slaymaker et al., 2009).

2.1. Sediment generation and deposition

A parallelism between the evolution of sedimentation rates (a consequence of erosion rates) and GDP, during the last two centuries,

has been described in several study areas and across large regions (Bonachea et al., 2010; Bruschi et al., 2013; Cendrero et al., 2020). The results presented indicate that there has been a general increase of sedimentation rates since the end of the 19th century, in all sorts of sedimentary environments (lakes, reservoirs, fluvial channels, flood-plains, wetlands on fluvial valleys, deltas, coastal wetlands, bays and estuaries, coastal platforms) and geographical areas, consistently. This is particularly significant considering that the number of dams has increased significantly in most major river systems (Vörösmarty et al., 2003; Nilsson et al., 2005; Grill et al., 2019), causing a reduction of sediment yield in many northern hemisphere rivers since the 1980s (Dethier et al., 2022) and at a global level (Syvitski et al., 2005, 2022). In this sense, according to Syvitski et al. (2005), the sediment transported by rivers caused by anthropic erosion on a global scale increased by about 2.3 billion metric tons per year, but the flow of sediment reaching the world's coasts has been reduced by approximately 1.4 billion metric tons per year, due to retention produced by reservoirs.

As discussed in a former contribution (Cendrero et al., 2022), total GDP is an expression of human potential to carry out all sorts of activities, including those that imply land transformation and greenhouse gas emissions. Increasing GDP implies increasing resource consumption (UNEP, 2016) and activities such as construction, mining, quarrying, agriculture or forestry, which cause intense direct denudation. Excavation and accumulation of Earth materials indirectly increase denudation on unprotected surfaces thus formed and, consequently, related sediment yield (Hooke, 1999; Forte et al., 2016; Tarolli and Sofia, 2016; Russell et al., 2017; Owens, 2020). Moreover, unprotected surfaces and those occupied by different types of impervious cover (buildings, roads, greenhouses, etc.) lead to increased runoff, erosion capacity of surface waters, and flood hazard. In particular, the growth rate of artificial impervious surfaces (km^2/year) during the last three decades has been

very considerable, over 100 % in most parts of the world (except Africa and parts of Central and South America) and up to >3000 % in parts of Asia and North America (Gong et al., 2020). This, naturally, is mainly due to the expansion of urban land cover (Hooke et al., 2012). Farming and forestry also increase runoff and erosion (Walling et al., 1996; Lambin and Geist, 2015; McEachran et al., 2021). Response of geomorphic processes to those transformations has been highlighted by different authors (Syvitski et al., 2005, 2020; Bonachea et al., 2010; Tarolli and Sofia, 2016; Owens, 2020; Chen et al., 2022). A relationship between climate change and denudation, sediment fluxes or slope instability processes has also been described in several geographical areas (e.g., Gariano and Guzzetti, 2016; Beylich et al., 2017; Ho et al., 2017; Navas et al., 2018; Tsyplenkov et al., 2021).

Fig. 1 includes some indicators of the intensity of human activities (drivers) and of Earth systems responses. It shows the evolution, since 1990 of global population, GDP, energy consumption, CO_2 emissions, extraction of geological materials (technological denudation, which represents a direct modification of land surface), sedimentation rates and frequency of geomorphic disasters. Magnitudes are expressed as a standardised growth factor with respect to the initial date and are therefore comparable. All parameters increase, especially excavated materials and disasters related to geomorphic processes, but the latter show a clear change in trend (“umbrella handle”) during the present century. All data represented in Fig. 1 have a temporal bias, since their collection and accuracy have improved over time, but the graph represents the period for which data are more reliable.

The figure clearly shows that our collective capability to carry out activities affecting the environment (GDP) has grown much more than population. Some direct geomorphic effects (extraction of geological materials, as consequence of construction activities, for their use as resources, or as mining overburden and waste) have grown even more.

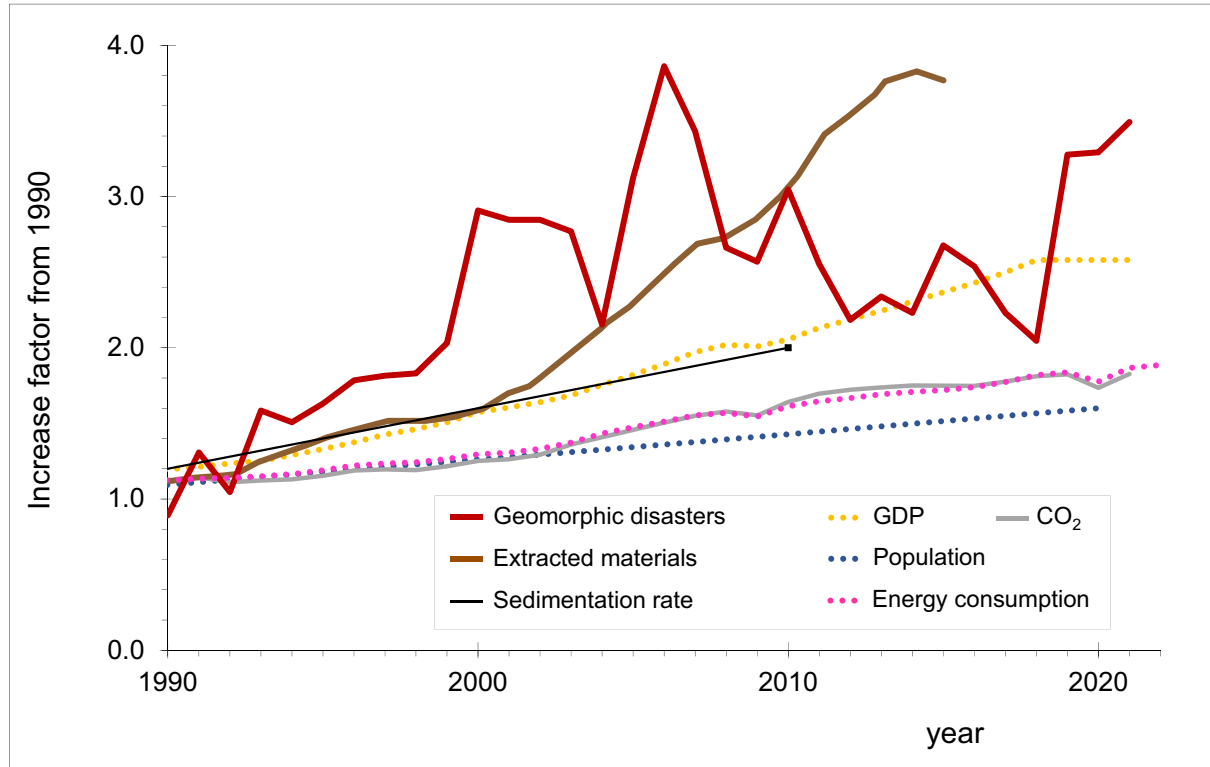


Fig. 1. Evolution of global population (World Bank, 2021a), GDP (current US\$, World Bank, 2021b), global energy consumption (Our World in Data, 2023), net CO_2 emissions (Our World in Data, 2023), amount of geological materials excavated (technological denudation) by human activities (Cooper et al., 2018), sedimentation rates (unweighted average, Cendrero et al., 2020) and geomorphological (floods and landslides) disasters frequency (EM-DAT, access 2022) in the period 1990–2022, for which global data are more reliable. All ordinate values are represented as a standardised increase factor with respect to the initial value. Note the greater growth of extracted materials and disasters frequency; the latter shows a change in trend (“umbrella handle”) in this century.

Whereas population has increased by a factor of 1.6 in just over three decades, GDP grew by 2.6 times, energy consumption by a factor of 1.9, CO₂ emissions by a factor of 1.8 and technological denudation (extraction of soil, sediment and rock) by 3.8-fold (World Bank, 2021a,b; Our World in Data, 2023; Cooper et al., 2018). The latter growth is considerably greater than the one experienced by the use of other resources (material footprint, Wiedmann et al., 2020). In other words, production of each GDP unit has required greater “technological denudation” with time, whereas it has generated less net CO₂ per GDP unit. If the period after 1900 were considered, increase factors for these parameters would be, respectively, 4.7, 23, 15, 19 and 80-fold.

Data on sedimentation rates are, given the inherent difficulties in measuring the involved processes, much less complete than for the other data sets. The results presented provide approximate (unweighted) average global values for three discrete periods, pre-1900, 1900–1950 and post 1950, and they represent a “coarse grain image” of global sedimentation since the end of the 19th century (Cendrero et al., 2020, 2022). The available sedimentation rate data are of a discrete nature, and therefore direct quantitative comparison between these and the other parameters is not possible, but they show that sedimentation (as a reflection of denudation and sediment generation) also grew more than population. Considering consistent temporal and spatial correlations between land transformation and sediment yield, as well as a robust physical basis for a causal link between them, it seems reasonable to think that the leading mechanism responsible for the observed widespread increase in the global sedimentation rates are the profound land use/land cover changes. As we underscore above, this by no means intends to discount the role of climate change. Nevertheless, as we note, the much more heterogeneous nature of recent changes in the mean precipitation regime (in some cases, decreases or lack of a detectable trend) and often relatively modest magnitude of recorded increases lead us to suggest that, thus far, climate change has likely been a secondary contributing factor. Of course, the relative importance of both factors may vary geographically and could change in the future, given the rapid acceleration in climate change (IPCC, 2021, Chapter 11). Our interpretation of the available evidence resembles the conclusions reached for biodiversity loss - in that case, land use/land cover changes are also believed to be the primary underlying mechanism (IPBES, 2019). Therefore, it is not unreasonable to think that the observed increase in global sedimentation rates (as a consequence of erosion and sediment generation) is mainly an effect of land use/land cover changes.

The fact that erosion has increased in recent times (mainly as an indirect effect of human activities affecting land surface), in different regions and at the global level, has been highlighted by various authors. As formerly described (Cendrero et al., 2022), in the Russian plain, since the 18th century, a two to three order of magnitude increase of erosion in cultivated areas has been reported (Sidorchuk and Golosov, 2003; Sidorchuk et al., 2006). A substantial increase in erosion rates has been documented in the Polish Carpathians since the 1950s, consequence of changing land-use policies and practices (Bucala-Hrabia, 2018; Kijowska-Strugała et al., 2018). In Iceland, denudation increased significantly because of grazing and related land cover changes during last century (Beylich, 1999; Beylich, 2011). An increase in erosion and a subsequent decrease, caused by an intensification of agricultural activity followed by abandonment, have been described in Italy (Innocenti and Pranzini, 1993; Coratza and Parenti, 2021). In major Chinese rivers, the contribution of human activities to the important augmentation of sediment fluxes observed since the middle of last century has been clearly greater than the contribution of climate change (D. Li et al., 2018; T. Li et al., 2018). At a global scale, Cohen et al. (2014) made correlations between suspended sediment from soil erosion and water discharge dynamics in large basins from 1960 to 2010. They found a considerable discrepancy between water discharge and suspended sediment fluctuations for some continents, especially Asia and Europe, which would be related to relief conditions and lithology and very likely with land use/land cover patterns. Another global analysis of soil erosion covering the period

2001–2012 (Borrelli et al., 2017) found an increase in erosion rates, attributable to land use/land cover changes, mainly from forest to cultivated land. Wuepper et al. (2020) showed that “political borders” determine, to greater extent than “natural borders”, differences in soil erosion between countries, clearly illustrating the crucial role of land use policies at the regional scale. Indirectly, this work is also suggestive of a more pronounced role of direct land transformation in comparison to climate change. The effect of the latter driver is far more likely to be modulated by natural rather than political or administrative boundaries. In any case, as numerous authors have pointed out, in “undisturbed environments” such as in cold environments, where human pressure is limited, the effects of climate change are prevalent (Beylich et al., 2016; Zhang et al., 2022).

2.2. Geomorphic disasters

The disaster data used in this work come from Emergency Events Database, created in 1988 (EM-DAT, n.d.). This database contains data on the occurrence and impacts of disasters worldwide from 1900 to the present, with individual entries for each country affected, including a description of magnitude and effects. In this work only the number of events has been considered. Comparison of magnitude or effects between disasters of very different nature implies great uncertainty. Therefore, we have restricted our analysis to event frequency, a coarse-grain analysis that, nevertheless, reveals interesting patterns.

Due to biases, EM-DAT (EM-DAT, 2023) recommends avoiding the use of what it calls historical data, prior to this century. However, considering only this short period would greatly limit any temporal analysis, and would focus on a time interval that, according to other lines of evidence, represents a change of trend (or even a reversal), from increasing to decreasing (the “umbrella handle” or “hockey stick”, using a term similar to the well-known graph that describes global temperature for the last thousand years, but in this case with the “handle” facing up). For this reason, in our analysis we slightly expanded the time window, but maintaining a quite homogeneous level of data confidence, because the same data collection criteria have been used throughout the period considered.

Some considerations about the limitations of the data used must be considered. Concerning missing events, Koç and Thieken (2018) and Lin et al. (2021) compared EM-DAT data with other databases or local data banks, highlighting some gaps. The main inaccuracies affect such data as magnitude, monetary losses, fatalities, etc., but these items are not used in this work. The quality of the data (number of events in this case) is conditioned by the criteria for data gathering and the sources of information. An event is only included in EM-DAT if one of the following criteria are fulfilled: (1) 10 or more people died in the event; (2) 100 or more people were affected by the event; (3) a state emergency was declared; and/or (4) there was a call for international assistance. The database is compiled from various sources, including UN agencies, non-governmental organizations, reinsurance companies, research institutes, and press agencies. As source reporting has improved over the years, EM-DAT data coverage has improved significantly with time, especially over the last 40 years. Limitations in the quality of disaster databases arising from data collection procedures have been discussed (Guha-Sapir and Below, 2002; Osuteye et al., 2017; Jones et al., 2021). Limitations in the availability of data on low-intensity disaster events due to the inclusion criteria specified in EM-DAT are well known and consequently, high-impact events tend to be better represented. Inhomogeneous coverage over time leads to a time bias that manifests itself in an increase in occurrence that began in the 1960s, largely due to successive improvements in data recording. Consequently, inferring information about the causes of disasters must be done with great caution. In this work we use both a short (post-1990) and a long (post-1900) data series only for comparisons between different types of disasters. The former data, covering the period with readily available remote sensing capabilities (e.g., satellite imagery from various Earth Observation programs

such as Landsat), enables analysis with higher confidence, due to reduced likelihood for temporal bias, and the latter provides information (of a fuzzier nature) on long-term evolution. The uncertainty about the “older” events affects the annual frequency of events, but especially other parameters associated with disasters such as characteristics or damage caused. However, we believe that the recording of event number since 1990 is likely to be reasonably homogenous, from the point of view of completeness. Furthermore, some types of disasters (earthquakes and volcanoes), for which instrumental records (much less affected by the indicated bias) have existed for more than a century, provide a means of comparison with other types of disasters. There are also some other biases to take into consideration. For instance, EM-DAT (EM-DAT, 2023) mentions that recording of heat waves is less complete, or that data collection is not as good in less-developed countries.

All those limitations must be kept in mind when analysing the results presented in this coarse-grain analysis. However, independent analyses on geomorphic event frequency (specifically landslides, Guzzetti and Tonelli, 2004; Damm and Klose, 2015; Lin and Wang, 2018 and Rivas et al., 2022) show broadly similar patterns to those observed in EM-DAT database, a clear general increase since the middle of the 20th century and a change in trend in the last two to three decades.

Less uncertainty is found in some regional databases, such as the Historical Analysis of Natural Hazards in Europe (HANZE) (Paprotny et al., 2018a), which includes >1564 floods that have caused damage in 37 European countries since 1870. Records on floods have been captured from many sources: news reports, government data, public data banks (including EM-DAT), and scientific literature. From this database, Paprotny et al. (2018b) show that there has been an increase in the number of events and flooded area per year during the period 1870–2016 (almost 150 years), but when correcting the number of under-recorded events they find that the increase is clearly smaller. Since the late 1980's they find an increase in frequency of events followed by a reduction after about 2000 (Paprotny et al., 2018a; fig. 5), similar to our findings. Even with corrections to include gaps, the area affected by floods per year shows continuous significant growth. These authors make it clear that due to the small number of events recorded, the correction applied has considerable uncertainty.

At a more detailed scale, the Spanish Mediterranean Coastal Flood database (Gil-Guirado et al., 2019) contains 3008 events that have caused damage in all municipalities on the Spanish Mediterranean coast, from 1960 to 2015, inventoried from a systematic review of the main newspapers of the region. The authors detect a significant growth trend in frequency (2.3 % annually with respect to the average) and in the affected area since the 1980s. This coincides with the data from the flood database on insured assets of the National Insurance Consortium of Spain (Consorcio de Compensación de Seguros, 2019). In the case of other “hydrogeomorphic” disasters, such as landslides, the biases of the data banks, especially the regional and global ones, can be much greater since they generally cause less damage.

It seems clear, therefore, that all data banks suffer from some type of bias to a greater or lesser degree. Although there is not an absolute proof, everything points to an increase in the frequency of events during the twentieth century and a possible change in recent decades.

Of particular interest is the increase in the frequency of disasters related to geomorphic processes (Fig. 1), by a factor of approximately 3.5 since 1990, even including the “umbrella handle”. The factor would be much greater if the comparison were made since the early 20th century. Of course, an augmentation of the number of any kind of registered disasters with time should be expected. However, in the case of “natural” disasters greater recorded frequency does not necessarily mean a greater occurrence of dangerous natural events. As previously discussed, factors contributing to the increase in the number of reported disasters also include better data gathering and greater exposure, derived from growing population and urban expansion. These factors affect all “natural” disasters and are a plausible explanation of their increasing frequency in all regions (Cendrero et al., 2020). Greater

exposure and improved data gathering explain the reported augmentation of disasters caused by volcanoes and earthquakes, during the last 20th century. Increasing urbanization in floodplains is also clearly behind the growing frequency of flood disasters (Tellman et al., 2021). Of course, in the case of “hydrogeomorphic” disasters (those related with water/land surface interaction, such as floods and landslides), climate change could be playing a role. However, the very important increase registered (Fig. 2), greater than the one observed for other types of natural disasters, is probably not attributable to those factors, especially if we consider that, so far, during the 21st century, the trend has been reversed (“umbrella handle”), while both climate change and occupation of floodplains keep growing. This recent trend is likely due to better mitigation and land-use practices, which probably also explain the reduction in the number of fatalities (Paprotny et al., 2018a). Moreover, the correlation between geomorphic disasters frequency and GDP is very high (with global coefficients >0.8; Cendrero et al., 2020). These authors showed, in their Fig. 3, that geomorphic disasters frequency experienced a clear and strong increase in all regions of the world, irrespective of the sense of rainfall changes (increase, stability, decrease).

In the case of disasters related to climate/meteorological and geomorphic processes, climate change, and the related greater occurrence of extreme weather events, are an additional factor. This is probably why the frequency of “climate/meteorological” and “hydrogeomorphic” disasters increased more than the other disasters. It is important to note that the ratio between the frequency of geomorphic disasters and the frequency of purely meteorological disasters (not involving land surface behaviour), at global level, has roughly multiplied by 2 in the last four decades (and has increased by a factor of >10

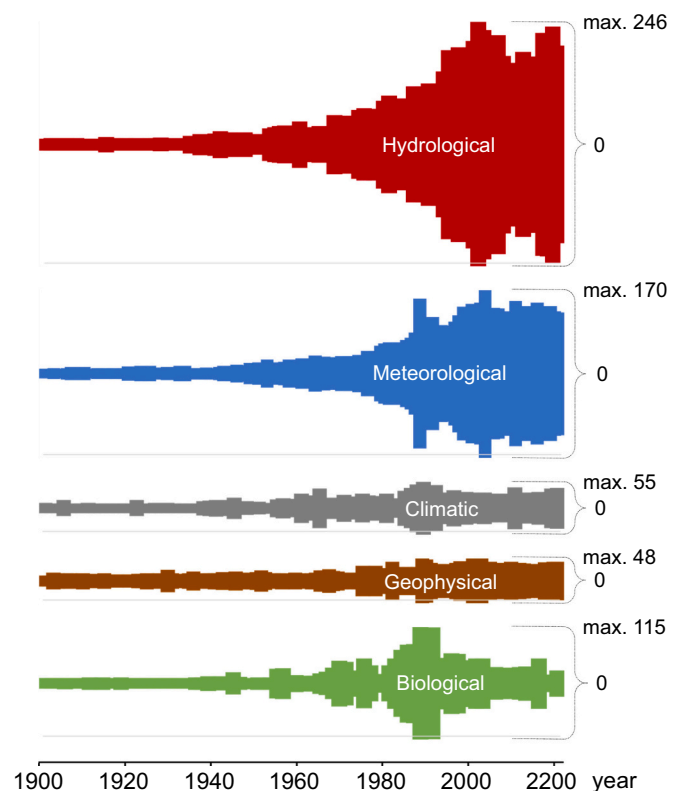


Fig. 2. Frequency of natural disasters in the world by type from 1900 to 2022. Graph prepared from the EM-DAT database (EM-DAT, access May 2023), following the criteria used by UN (2016). Hydrological: floods, landslides, waves; Meteorological: extreme temperature, fog, storms; Climatological: droughts, glacial lake outbursts, wildfires; Geophysical: earthquakes, dry mass movements, volcanic activity; Biological: epidemics, insect infestations, animal accidents.

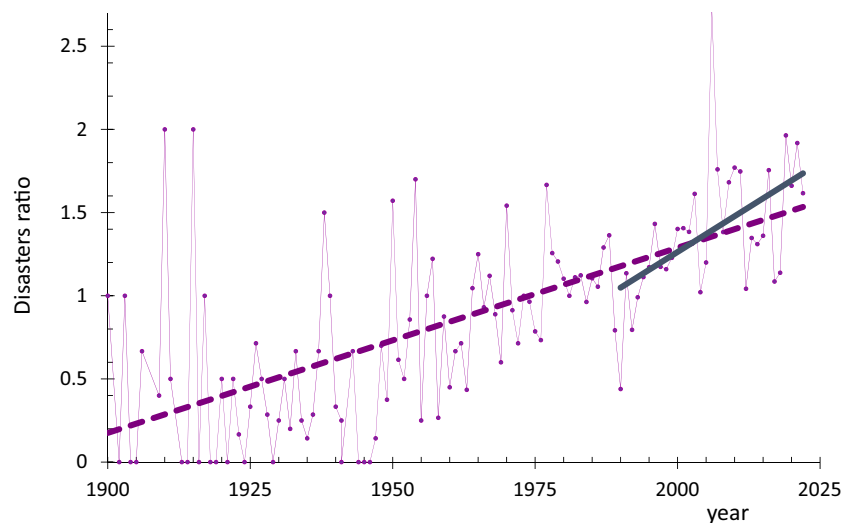


Fig. 3. Ratio of world disasters related to hydrogeomorphical disasters (floods and landslides) and disasters related to purely climate events (not associated with land surface dynamics). Annual data from EM-DAT (EM-DAT, accessed May 2023). Please note that the ratio increased by a factor of >10 since the beginning of the 20th century, and has almost doubled in the period 1990–2022 (note the greater slope in the graph).

in the period 1900–2022; Fig. 3). There is no reason we can think of for human exposure/vulnerability and data gathering procedures to differ between both groups of disasters to the extent that would explain this growing gap. Therefore, the most plausible explanation for the observed increase is that it is caused by agriculture, forestry, mining, construction, urban expansion and infrastructure development, which affect the former but not the latter disasters. Land use/Land cover changes affect the behaviour of geomorphic processes (infiltration/runoff) and the sensitivity of the surface layer (erodibility and instability of soil and regolith in general), thus increasing denudation rates as well as the frequency of hazardous events. Of course, apart from the general effect of land surface transformation on denudation, an increase in the number of intense flood and landslide events also contributes to greater sediment generation and sediment yield. Moreover, the fact that since the beginning of the 21st century a reduction in the frequency of disasters has been observed can hardly be attributed to a reversing trend in climate change. A more plausible explanation is an improvement of preventive mitigation measures, largely because of better, we insist, land-use practices.

There may be a bias towards the detriment of “climate/meteorological” disasters as we go back in time, but not in recent decades when concern about climate change is very general. However, the growth of the ratio between “hydrogeomorphic” and “climate/meteorological” disasters is greater in recent decades (despite the change in trend observed) than in the period 1900–2022.

Other geomorphic responses to land surface transformation (erosion and sedimentation rates, terrain instability and landslides, runoff and related flood hazards), have been widely documented (e.g., Amaranthus et al., 1985; Clark, 1987; Glade, 2003; Beylich et al., 2005; Imaizumi et al., 2008; Guthrie, 2015; Besset et al., 2019; Golosov and Walling, 2019; Broeckx et al., 2020; Cienfiala et al., 2020). The existence of an “Anthropocene” signal in river delta evolution was discussed by Ibáñez et al. (2019). It seems possible, or even likely, that these types of responses represent a global trend (Chen et al., 2022; Syvitski et al., 2022).

Thus, although climate change (particularly rainfall regime) affects both sediment generation/transport/deposition and frequency of geomorphic disasters, the evidence presented here indicates that, at least thus far, this factor has been less important than land surface transformation. In particular, at present, the majority global denudation appears to be caused by direct human excavation (technological), and indirectly induced by land surface alteration (Cooper et al., 2018; Syvitski et al., 2022; Cendrero et al., 2022). In this context, it is especially

suitable to consider the communiqué issued on 23rd, May 2023 during the European Climate Conference, which gathered in Warsaw 90 climate scientists from 45 countries across Europe and Central Asia, to assess climate change and the progress towards reaching climate neutrality. We quote the communiqué (our highlighting, in bold): “3. The **principal ecological manifestations are aggravated by climate change, but are primarily driven by deficient land, soil and water management**. These include: loss of biodiversity, loss of ecosystem functions and services, soil degradation and desertification, and deterioration of freshwater resources”.

2.3. Geomorphic change acceleration and drivers

The evidence presented above strongly indicates the existence of a chain of cause/effects relationships between GDP and geomorphic processes (Cendrero et al., 2006), wherein population growth and economic and technological development drive profound changes in geomorphic processes in general, including denudation and sediment dynamics. Humans appear to be now, at a global level and by far, the major geomorphic agent (Ter-Stepanian, 1988; Hooke, 2000; Steffen et al., 2004; Wilkinson, 2005; Rivas et al., 2006; Cooper et al., 2018; Owens, 2020; Syvitski et al., 2022; Cendrero et al., 2022). Denudation rates (direct and indirect) and rates of other processes have increased by one order of magnitude, or more, in less than one century (Cendrero et al., 2022). This landscape response is unique, geologically unprecedented, and distinct from those controlled by purely geological processes. As a result, the present model of geomorphic evolution shows important quantitative and qualitative differences (Rivas et al., 2006) with respect to pre-Anthropocene times. The effects of humans on geomorphic processes mediated by climate change (changes in infiltration/runoff, aridification, vegetation dynamics, etc.) are indisputable and difficult to isolate, but the sheer magnitude of Earth materials directly and indirectly displaced as consequence of human activities, suggests that this cumulative process has probably been the dominant factor. Importantly, these direct and indirect human impacts on geomorphic dynamics might be synergistic, significantly increasing the consequences of human-driven contemporary environmental change.

We emphasize that our premise is not to argue that presently geomorphic change is driven by land transformation instead of climatic factors. We rather wish to highlight that both drivers are important, with the former apparently dominating over the latter (at least thus far) and having, as the latter, a global character. It is equally essential to

acknowledge geographical heterogeneity, with respect to both the diversity of local and regional societies (Bierman et al., 2016) and biophysical environments. In “undisturbed” regions and environments, the evolution of contemporary geomorphic processes is essentially determined by climate change and geological factors, not direct human impacts (Beylich, 2016; Li et al., 2020, 2021), but they do not appear to determine the global scale of its effects.

The changes described suggest that there is a “Great Geomorphic Acceleration” (Bruschi et al., 2013; Forte et al., 2016), a part of the more general phenomenon of the Great Acceleration (Steffen et al., 2011). This acceleration is especially marked after World War II, coinciding with the moment suggested by different authors for the Holocene-Anthropocene boundary (Cendrero et al., 2011, Bruschi et al., 2011; Steffen et al., 2015; Zalasiewicz et al., 2015, 2021; Cendrero et al., 2020; Syvitski et al., 2020), which might represent a phase transition of the Earth System (Bertolani and Francisco, 2018).

In light of this profound anthropogenic effect, we should consider to what extent an understanding of geomorphic processes based merely on “natural” factors (Rhoads, 2006) is possible. Such a physical-based approach has been dominant in the geosciences since the mid-20th century (Strahler, 1952). In our view, it is clear that – except in relatively remote and/or unaffected areas – attempts to understand the contemporary dynamics of geomorphic systems without explicitly considering the direct and indirect impacts of human drivers are bound to lead to inaccurate results. Research integrating biophysical and social processes (Ashmore, 2015; Sivapalan et al., 2012, 2014) seems particularly fitting and a fertile ground for new insights into Earth surface dynamics, and/or human-biophysical systems in general (Kotchen and Young, 2007; Brondizio et al., 2016; Viles, 2020). The implications of the Anthropocene geomorphic acceleration also extend to other fields, such as sustainability, suggesting that global efforts to reduce humanity’s environmental footprint must consider land surface dynamics in addition to other criteria such as climate system or biodiversity (e.g., IPBES, 2019; IPCC, 2022).

3. Concluding remarks and open questions

On the basis of the new data and results presented here, as well as those in former contributions, a few tentative conclusions can be drawn:

- Denudation and sedimentation rates have increased by about one order of magnitude since the end of the 19th century;
- The majority of denudation (understood here as transfer of geologic materials on land surface) is presently attributable to direct, technological denudation;
- The frequency of disasters related to water/land surface interaction has increased about three-fold since 1990 (much more than other manifestations of human activity, such as population, energy consumption, CO₂ emissions, etc.);
- This “Great Geomorphic Acceleration” is a dimension of the broader phenomenon of “The Great Acceleration”;
- It appears that in the Anthropocene, the traditional model of geomorphic evolution should be updated to consider the leading role of human-driven land transformation;
- Human capability to affect natural systems in general and geomorphic ones in particular, can be expressed in terms of GDP density, which is increasing more rapidly than population. In particular, the magnitude of technological denudation appears to be coupled to GDP and is increasing much more rapidly than such capability;
- This relationship offers compelling evidence for an accelerated response of geomorphic systems to socio-economic drivers. This response could represent a synergistic effect of land transformation and climate change, with the former probably as a more determining factor so far;
- If this social-geomorphic coupling were confirmed, policies and regulations for the reduction of erosion and soil loss, or disasters

linked to geomorphic processes, should focus not only on the obviously necessary climate change mitigation, but also (perhaps even more so) on direct land use/land cover change mitigation. The latter offer the possibility to act at national or even local level (bottom-up approach). The data presented suggest that, whereas we are reducing greenhouse gases emissions caused by GDP unit produced, we are also increasing our pressure and impact on geomorphic processes. However, it seems that the trend of increasing “hydrogeomorphic” disasters frequency may be slowing. This is likely as consequence of the international and national disaster mitigation efforts started in the 1990s, including better land use practices.

We believe that these conclusions represent a reasonable interpretation of existing evidence, worthy of further and different analyses to confirm or discard them. More geomorphic data, with global coverage, are necessary to advance our ability to make a more definite assessment and fully grasp the complexity of social-geomorphic linkages. Given the very important present (and probably future) role of humans as geomorphic agents, an intensification of research efforts on this topic would be desirable. It would help to improve policies for the mitigation of the effects described.

CRedit authorship contribution statement

Juan Remondo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luis M. Forte:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Antonio Cendrero:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Piotr Cienciala:** Writing – review & editing, Writing – original draft. **Achim A. Beylich:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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.

Data availability

The authors do not have permission to share data.

Acknowledgements

This work was supported, at different stages, by projects: FEDER, AEI, CGL2017-82703-R (Ministerio de Ciencia e Innovación, Spain) and PICT2011-1685; MTM2014-56235-C2-2215 (Ministerio de Ciencia, Tecnología e Innovación, Argentina).

References

- Amaranthus, M.P., Rice, R.M., Barr, N.R., Ziemer, R.R., 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. *J. For.* 83, 229–233.
- Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R.P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J.G., Cassou, C., Cherchi, A., Collins, W., Collins, W.D., Connors, S.L., Corti, S., Cruz, F., Dentener, F.J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F.J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestad, J.S., Fyfe, J.C., Gillett, N.P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J. M., Hamdi, R., Hawkins, E., Hewitt, H.T., Hope, P., Islam, A.S., Jones, C., Kaufman, D.S., Kopp, R.E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T.K., Meinshausen, M., Min, S.-K., Monteiro, P.M.S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A.C., Ruiz, L., Sallée, J.-B., Samset, B.H., Sathyendranath, S., Seneviratne, S.I., Sörensson, A.A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehle, S., Zhang, X., Zickfeld, K., 2021a.

- Technical summary. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. <https://doi.org/10.1017/9781009157896.002>.
- Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R.P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J.G., Cassou, C., Cherchi, A., Collins, W., Collins, W.D., Connors, S.L., Corti, S., Cruz, F., Dentener, F.J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F.J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestad, J.S., Gnanadesikan, J., Gillett, N.P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J. M., Hamdi, R., Hawkins, E., Hewitt, H.T., Hope, P., Islam, A.S., Jones, C., Kaufman, D.S., Kopp, R.E., Kosaka, Y., Kossin, J., Kravovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T.K., Meinshausen, M., Min, S.-K., Monteiro, P.M.S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A.C., Ruiz, L., Sallée, J.-B., Samset, B.H., Sathyendranath, S., Seneviratne, S.I., Sörensson, A.A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehele, S., Zhang, X., Zickfeld, K., 2021b. The physical science basis. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Technical Summary*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. <https://doi.org/10.1017/9781009157896.002>.
- Ashmore, P., 2015. Towards a sociogeomorphology of rivers. *Geomorphology* 251, 149–156. <https://doi.org/10.1016/j.geomorph.2015.02.020>.
- Bertolani, O., Franciso, F., 2018. A physical framework for the earth system, Anthropocene equation and the great acceleration. *Glob. Planet. Chang.* 169, 66–69. <https://doi.org/10.1016/j.gloplacha.2018.07.006>.
- Besset, M., Anthony, E.J., Bouchette, F., 2019. Multi-decadal variations in delta shorelines and their relationship to river sediment supply: an assessment and review. *Earth Sci. Rev.* 193, 199–219. <https://doi.org/10.1016/j.earscirev.2019.04.018>.
- Beylich, A.A., 1999. *Hangdenudation und fluvial Prozesse in einem subarktisch-ozeanisch geprägten, permafrostfreien Periglazialgebiet mit pleistozäner Vergletscherung. Prozessgeomorphologische Untersuchungen im Bergland der Austfjörðir (Austdalur, Ost-Island). Berichte aus der Geowissenschaft. Aachen, Shaker.*
- Beylich, A.A., 2011. Mass transfers, sediment budgets and relief development in cold environments: results of long-term geomorphological drainage basin studies in Iceland, Swedish Lapland and Finnish Lapland. *Z. Geomorphol.* 55, 145–174. <https://doi.org/10.1127/0372-8854/2011/0055-0046>.
- Beylich, A.A., 2016. Environmental drivers, spatial variability, and rates of chemical and mechanical denudation in selected glaciated and nonglaciated cold climate catchment geosystems: from coordinated field data generation to integration and modelling. In: Beylich, A.A., Dixon, J.C., Zwoliński, Z. (Eds.), *Source-to-sink Fluxes in Undisturbed Cold Environments*. Cambridge University Press, Cambridge, pp. 385–397.
- Beylich, A.A., Lindblad, K., Molau, U., 2005. Direct human impacts on mechanical denudation in an arctic-oceanic periglacial environment in northern Swedish Lapland (Abisko mountain area). *Z. Geomorphol. Suppl.* 138, 81–100.
- Beylich, A.A., Dixon, J.C., Zwoliński, Z. (Eds.), 2016. *Source-to-sink Fluxes in Undisturbed Cold Environments*. Cambridge University Press, Cambridge, p. 408.
- Beylich, A.A., Laute, K., Storms, J.E.A., 2017. Contemporary suspended sediment dynamics within two partly glaciated mountain drainage basins in western Norway (Erdalen and Bødalen, inner Nordfjord). *Geomorphology* 287, 126–143. <https://doi.org/10.1016/j.geomorph.2015.12.013>.
- Bierman, F., Bai, X., Bondre, N., Broadgate, W., Arthur, Chen-Tung, Chen, C.-T.A., Dube, O.P., Erisman, J.W., Glaser, M., van der Hel, S., Lemos, M.C., Seitzinger, S., Seto, K.C., 2016. Down to Earth: contextualizing the Anthropocene. *Glob. Environ. Chang.* 39, 341–350. <https://doi.org/10.1016/j.gloenvcha.2015.11.004>.
- Blanco, H., Lal, R., 2010. *Principles of Soil Conservation and Management, first edition*. Springer, Heidelberg.
- Bonachea, J., Bruschi, V.M., Hurtado, M., Forte, L.M., da Silva, M., Etcheverry, R., Cavallotto, J.L., Dantas, M.F., Pejon, O.J., Zuquette, L.V., Bezerra, M.A., Remondo, J., Rivas, V., Gómez-Arozamena, J., Fernández, G., Cendrero, A., 2010. Natural and human forcing in recent geomorphic change; case studies in the Rio de la Plata basin. *Sci. Total Environ.* 408, 2674–2695. <https://doi.org/10.1016/j.scitotenv.2010.03.004>.
- Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schutt, B., Ferro, V., Bagarello, V., Van Oost, K., Montanarella, L., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nat. Commun.* 8, 2013. <https://doi.org/10.1038/s41467-017-02142-7>.
- Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L., Ballabio, C., 2020. Land use and climate change impacts on global soil erosion by water (2015–2070). *Proc. Natl. Acad. Sci.* 117 (36), 21994–22001.
- Broeckx, J., Rossi, M., Lijnen, K., Campforts, B., Poesen, J., Vanmaerck, M., 2020. Landslide mobilization rates: a global analysis and model. *Earth Sci. Rev.* 201, 102972. <https://doi.org/10.1016/j.earscirev.2019.102972>.
- Brondizio, E.S., O'Brien, K., Bai, X., Biermann, F., Steffen, W., Berkhout, F., Cudennec, C., Lemos, M.C., Wolfe, A., Palma-Oliveira, J., Chen, C.-T.A., 2016. Re-conceptualizing the Anthropocene: a call for collaboration. *Glob. Environ. Chang.* 39, 341–350. <https://doi.org/10.1016/j.gloenvcha.2016.02.006>.
- Brown, A.G., Tooth, S., Bullard, J.E., Thomas, D.S.G., Chiverrell, R.C., Plater, A.J., Murtun, J., Thorndycraft, V.R., Tarolli, P., Wainwright, J., Downs, P., Aalto, R., 2017. The geomorphology of the Anthropocene: emergence, status and implications. *Earth Surf. Process. Landf.* 42 (1), 71–90. <https://doi.org/10.1002/esp.3943>.
- Brown, H., 1956. Technological denudation. In: Thomas, W.L. (Ed.), *Man's Role in Changing the Face of the Earth*. Univ. of Chicago Press, Chicago, pp. 1023–1032.
- Bruschi, V., Bonachea, J., Remondo, J., Gómez Arozamena, J., Rivas, V., Méndez, G., Naredo, J., Cendrero, A., 2013. Analysis of geomorphic systems' response to natural and human drivers in northern Spain: implications for global geomorphic change. *Geomorphology* 196, 267–279. <https://doi.org/10.1016/j.geomorph.2012.03.017>.
- Bruschi, V.M., Bonachea, J., Remondo, J., Forte, L.M., Hurtado, M., Cendrero, A., 2011. ¿Hemos entrado ya en una nueva época de la historia de la Tierra? *Rev. R. Acad. Cienc. Exact. Fis. Nat.* 105 (1), 1–12.
- Bucala-Hrabia, A., 2018. Land use changes and their catchment-scale impact in the Polish Western Carpathians during the transition from centrally planned to free-market economics. *Geogr. Pol.* 91, 171–196. <https://doi.org/10.7163/GPol.0116>.
- Cendrero, A., Douglas, I., 1996. Earth surface processes, materials use and urban development; project aims and methodological approach. In: *Abstracts With Programs, GSA Annual Meeting, Denver, A-79*.
- Cendrero, A., Remondo, J., Bonachea, J., Rivas, V., Soto, J., 2006. Sensitivity of landscape evolution and geomorphic processes to direct and indirect human influence. *Geogr. Fis. Geodin. Quat.* 29, 125–137.
- Cendrero, A., Bruschi, V.M., Bonachea, J., Remondo, J., Rivas, V., Méndez, G., Naredo, J. M., Dantas-Ferreira, M., Pejon, O.J., Zuquette, L.V., Hurtado, M.A., Forte, L.M., Cavallotto, J.L., 2011. Evidences of major changes in Earth's surface processes. Should the Anthropocene be considered a new period in geologic history? *AG/AIG Regional Conference on Geomorphology 2011, Volume 37*. Addis Ababa, Ethiopia.
- Cendrero, A., Forte, L.M., Remondo, J., Cuesta-Albertos, J., 2020. Anthropocene geomorphic change. Climate or human activities? *Earth's Future* 8, e2019EF001305. <https://doi.org/10.1029/2019EF001305>.
- Cendrero, A., Remondo, J., Beylich, A., Cienciala, P., Forte, L., Golosov, V., Gusarov, A., Kijowska-Strugala, M., Laute, K., Li, D., Navas, A., Soldati, M., Vergari, F., Zwoliński, Z., Dixon, J., Knight, J., Nadal-Romero, E., Placzkowska, E., 2022. Denudation and geomorphic change in the Anthropocene; a global overview. *Earth Sci. Rev.* 233, 104186. <https://doi.org/10.1016/j.earscirev.2022.104186>.
- Chen, S.A., Michaelides, K., Singer, M.B., Richards, D.A., 2022. Exploring exogenous controls on short- versus long-term erosion rates globally. Global analysis of short-versus long-term drainage basin erosion rates. *Earth Surf. Dyn. EGU Discuss.* 10, 1055–1078. <https://doi.org/10.5194/esurf/10-1055-2022>.
- Cienciala, P., Bernardo, M.M., Nelson, A.D., Haas, A.D., 2020. Sediment yield from a forested mountain basin in inland Pacific Northwest: rates, partitioning, and sources. *Geomorphology* 374, 107478. <https://doi.org/10.1016/j.geomorph.2020.107478>.
- Clark, C., 1987. Deforestation and floods. *Environ. Conserv.* 14 (1), 67–69.
- Cohen, S., Kettner, Albert J., A.J., Syvitski, J.P.M., 2014. Global suspended sediment and water discharge dynamics between 1960 and 2010: Continental trends and intra-basin sensitivity. *Glob. Planet. Chang.* 115, 44–58.
- Consejo de Compensación de Seguros, 2019. *Estadística de Riesgos Extraordinarios, Serie 1971–2018*. Ministerio de Economía y Empresa, Madrid.
- Cooper, A.H., Brown, T.J., Price, S.J., Ford, J.R., Waters, C.N., 2018. Humans are the most significant global geomorphological driving force of the 21st century. *Anthr. Rev.* 5 (3), 222–229. <https://doi.org/10.1177/2053019618800234>.
- Coratza, P., Parenti, C., 2021. Controlling factors of badland morphological changes in the Emilia Apennines (Northern Italy). *Water* 13, 539. <https://doi.org/10.3390/w13040539>.
- Crutzen, P.J., 2002. Geology of mankind: the Anthropocene. *Nature* 415, 23. <https://doi.org/10.1038/415023a>.
- Damm, B., Klose, M., 2015. The landslide database for Germany: closing the gap at national level. *Geomorphology* 249, 82–93. <https://doi.org/10.1016/j.geomorph.2015.03.021>.
- Dethier, E.N., Renshaw, C.E., Magilligan, F.J., 2022. Rapid changes to global river suspended sediment flux by humans. *Science* 376, 1447–1452. <https://doi.org/10.1126/science.abn7980>.
- Douglas, I., 1967. Man, vegetation and the sediment yield of rivers. *Nature* 215, 925–928. <https://doi.org/10.1038/215925a0>.
- East, A.E., Sankey, J.B., 2020. Geomorphic and sedimentary effects of modern climate change: current and anticipated future conditions in the western United States. *Rev. Geophys.* 58, 4. <https://doi.org/10.1029/2019RG000692>.
- EM-DAT, The international disasters database, <https://www.emdat.be> (last access December 2023).
- Forte, L.M., Hurtado, M.A., Dangvas, N.V., Couyoupetrou, L., Giménez, J.E., da Silva, M., Bruschi, V.M., Cendrero, A., 2016. Anthropogenic geomorphic change as a potential generator of renewable geologic resources in the humid Pampa, Argentina. *Catena* 142, 177–189. <https://doi.org/10.1016/j.catena.2016.02.006>.
- Gaffney, O., Steffen, W., 2017. The Anthropocene equation. *Anthr. Rev.* 4 (1), 53–61. <https://doi.org/10.1177/2053019616688022>.
- Gallup, J.L., Sachs, J.D., Mellinger, A., 1999. Geography and economic development. *Int. Reg. Sci. Rev.* 22 (2), 179–232. <https://doi.org/10.1177/016001799761012334>.
- Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. *Earth Sci. Rev.* 162, 227–252. <https://doi.org/10.1016/j.earscirev.2016.08.011>.
- Gibbard, P., Walker, M., Bauer, A., Edgeworth, M., Edwards, L., Ellis, E., Finney, S., Gill, J.L., Maslin, M., Merritts, D., Ruddiman, W., 2022. The Anthropocene as an

- event, not an epoch. *J. Quat. Sci.* 37 (3), 395–399. <https://doi.org/10.1002/jqs.3416>.
- Gil-Guirado, S., Pérez-Morales, A., López-Martínez, F., 2019. SMC-Flood database: a high-resolution press database on flood cases for the Spanish Mediterranean coast (1960–2015). *Nat. Hazards Earth Syst. Sci.* 19, 1955–1971. <https://doi.org/10.5194/nhess-19-1955-2019>.
- Glade, T., 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. *Catena* 51 (3–4), 297–314. [https://doi.org/10.1016/S0341-8162\(02\)00170-4](https://doi.org/10.1016/S0341-8162(02)00170-4).
- Golosov, V., Walling, D., 2019. Erosion and Sediment Problems: Global Hotspots. UNESCO, Paris. UNESCO Digital Library. <https://unesdoc.unesco.org/ark>.
- Gong, P., Li, X., Wang, J., Bai, Y., Chen, B., Hu, T., Liu, X., Xu, B., Yang, J., Zhang, W., Zhou, Y., 2020. Annual maps of global artificial impervious area (GAIA) between 1985 and 2018. *Remote Sens. Environ.* 236, 111510 <https://doi.org/10.1016/j.rse.2019.111510>.
- Goudie, A.S., 2020. The human impact in geomorphology – 50 years of change. *Geomorphology* 366, 106601. <https://doi.org/10.1016/j.geomorph.2018.12.002>.
- Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Macedo, H.E., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M.E., Meng, J., Mulligan, M., Nilsson, C., Olden, J.D., Opperman, J.J., Petry, P., Liermann, C.R., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-flowing rivers. *Nature* 569, 215–221. <https://doi.org/10.1038/s41586-019-1111-9>.
- Guha-Sapir, D., Below, R., 2002. Quality and Accuracy of Disaster Data: A Comparative Analyse of 3 Global Data Sets. CRED Working Paper, p. 18.
- Guthrie, R.H., 2015. The catastrophic nature of humans. *Nat. Geosci.* 8 (6), 421–422. <https://doi.org/10.1038/ngeo2455>.
- Guzzetti, F., Tonelli, G., 2004. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. *Nat. Hazards Earth Syst. Sci.* 4, 213–232. <https://doi.org/10.5194/nhess-4-213-2004>.
- Hammond, J.C., Kampf, S.K., 2020. Subannual streamflow responses to rainfall and snowmelt inputs in snow-dominated watersheds of the western United States. *Water Resour. Res.* 56 (4), e2019WR026132.
- Head, M.J., Zalasiewicz, J.A., Waters, C.N., Turner, S.D., Williams, M., Barnosky, A.D., Steffen, W., Waprich, M., Haff, P.K., Syvitski, J., Leinfelder, R., 2022. The proposed Anthropocene Epoch/Period is underpinned by an extensive array of mid-20th century stratigraphic event signals. *J. Quat. Sci.* 37 (7), 1181–1187.
- Herrera-García, G.P., Ezquerro, R., Tomás, M., Béjar-Pizarro, J., López-Vinientes, M., Rossi, R.M., et al., 2021. Mapping the global threat of land subsidence. Nineteen percent of the global population may face a high probability of subsidence. *Science* 371 (6524), 34–36. <https://doi.org/10.1126/science.abb8549>.
- Ho, K., Lacasse, S., Picarelli, L. (Eds.), 2017. *Slope Safety Preparedness for Impact of Climate Change*. Taylor & Francis, London, 571pp.
- Hooke, R.L., 1999. Spatial distribution of human geomorphic activity in the United States: comparison with rivers. *Earth Surf. Process. Landf.* 24, 687–692. [https://doi.org/10.1002/\(SICI\)1096-9837\(199908\)24:8<687::AID-ESP991>3.0.CO;2-#](https://doi.org/10.1002/(SICI)1096-9837(199908)24:8<687::AID-ESP991>3.0.CO;2-#).
- Hooke, R.L., 2000. On the history of humans as geomorphic agents. *Geology* 28 (9), 843–846. [https://doi.org/10.1130/0091-7613\(2000\)28<843:OTHOHA>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<843:OTHOHA>2.0.CO;2).
- Hooke, R.L., Martín-Duque, J.F., Pedraza, J., 2012. Land transformation by humans: a review. *GSA Today* 22 (12), 4–10. <https://doi.org/10.1130/GSAT151A.1>.
- Ibáñez, C., Alcaraz, C., Caiola, N., Prado, P., Trobajo, R., Benito, X., Day, J.W., Reyes, E., Syvitski, J.P.M., 2019. Basin-scale land use impacts on world deltas: human vs natural forcings. *Glob. Planet. Chang.* 173, 24–32. <https://doi.org/10.1016/j.gloplacha.2018.12.003>.
- Imaizumi, F., Sidle, R.C., Kamei, R., 2008. Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. *Earth Surf. Process. Landf. J. Br. Geomorphol. Res. Group* 33, 827–840. <https://doi.org/10.1002/esp.1574>.
- Innocenti, L., Pranzini, E., 1993. Geomorphological evolution and sedimentology of the Ombrone river delta, Italy. *J. Coast. Res.* 9, 481–493. <https://www.jstor.org/stable/i394712>.
- IPBES, 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. In: Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (Eds.), Full Report, IPBES Secretariat, Bonn, Germany, p. 1148.
- IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <https://doi.org/10.1017/9781009157896>, 2391 pp.
- IPCC, 2022. *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, USA.
- Johnston, E.C., Davenport, F.V., Wang, L., Caers, J.K., Muthukrishnan, S., Burke, M., Duffenbaugh, N.S., 2021. Quantifying the effect of precipitation on landslide hazard in urbanized and non-urbanized areas. *Geophys. Res. Lett.* 48, 16. <https://doi.org/10.1029/2021GL094038>.
- Jones, R.L., Guha-Sapir, D., Tubeuf, S., 2021. Human and economic impacts of natural disasters: can we trust the global data? *Sci. Data* 9, 572. <https://doi.org/10.1038/s41597-022-01667-x>.
- Kennedy, C.M., Oakleaf, J.R., Theobald, D.M., Baruch-Mordo, S., Kiesecker, J., 2019. Managing the middle: a shift in conservation priorities based on the global human modification gradient. *Glob. Change Biol.* 25, 811–826. <https://doi.org/10.1111/gcb.14549>.
- Kijowska-Strugała, M., Bucala-Hrabia, A., Demczuk, P., 2018. Long-term impact of land use changes on soil erosion in an agricultural catchment (in the Western Polish Carpathians). *Land Degrad. Dev.* 29 (6), 1871–1884. <https://doi.org/10.1002/ldr.2936>.
- Koç, G., Thieken, A.H., 2018. The relevance of flood hazards and impacts in Turkey: what can be learned from different disaster loss databases? *Nat. Hazards* 91, 375–408. <https://doi.org/10.1007/s11069-017-3134-6>.
- Kotchen, M.J., Young, O.R., 2007. Meeting the challenges of the Anthropocene: towards a science of coupled human-biophysical systems. *Glob. Environ. Chang.* 17, 149–151. <https://doi.org/10.1016/j.gloenvcha.2007.01.001>.
- Kraaijenbrink, P.D., Stigter, E.E., Yao, T., Immerzeel, W.W., 2021. Climate change decisive for Asia's snow meltwater supply. *Nat. Clim. Chang.* 11 (7), 591–597.
- Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, D., 2018. From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015. *Glob. Environ. Chang.* 52, 131–140. <https://doi.org/10.1016/j.gloenvcha.2018.07.003>.
- Lambin, E.F., Geist, H.J. (Eds.), 2015. *Land-use and Land-cover Change: Local Processes and Global Impacts*. Springer-Verlag, Berlin.
- Lambin, E.F., Turner, B.I., Nyakundi, F., 2021. Commentary: policy challenges for global land use. *Glob. Environ. Chang.* 71, 102411 <https://doi.org/10.1016/j.gloenvcha.2021.102411>.
- Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. *Nature* 519, 171–180. <https://doi.org/10.1038/nature14258>.
- Li, D., Lu, X.X., Yang, X., Chen, L., Lin, L., 2018a. Sediment load responses to climate variation and cascade reservoirs in the Yangtze River: a case study of the Jinsha River. *Geomorphology* 322, 41–52. <https://doi.org/10.1016/j.geomorph.2018.08.038>.
- Li, D., Li, Z., Zhou, Y., Lu, X., 2020. Substantial increases in the water and sediment fluxes in the headwater region of the Tibetan Plateau in response to global warming. *Geophys. Res. Lett.* 47 (11), e2020GL087745 <https://doi.org/10.1029/2020GL087745>.
- Li, D., Overeem, I., Kettner, A.J., Zhou, Y., Lu, X., 2021. Air temperature regulates erodible landscape, water, and sediment fluxes in the permafrost-dominated catchment on the Tibetan Plateau. *Water Resour. Res.* 57, 2, e2020WR028193 <https://doi.org/10.1029/2020WR028193>.
- Li, T., Wang, S., Liu, Y., Fu, B., Zhao, W., 2018b. Driving forces and their contribution to the recent decrease in sediment flux to ocean of major rivers in China. *Sci. Total Environ.* 634, 534–541. <https://doi.org/10.1016/j.scitotenv.2018.04.007>.
- Lin, Q., Wang, Y., 2018. Spatial and temporal analysis of a fatal landslide inventory in China from 1950 to 2016. *Landslides* 15, 2357–2372. <https://doi.org/10.1007/s10346-018-1037-6>.
- Lin, Y.C., Khan, F., Jenkins, S.F., Lallemand, D., 2021. Filling the disaster data gap: lessons from cataloging Singapore's past disasters. *Int. J. Disaster Risk Sci.* 12, 188–204. <https://doi.org/10.1007/s13753-021-00331-z>.
- Liu, X., Huang, Y., Xu, X., Li, X., Li, X., Ciais, P., Lin, P., Gong, K., Ziegler, A.D., Chen, A., Gong, P., Chen, J., Hu, G., Chen, Y., Wang, S., Wu, Q., Huang, K., Estes, L., Zeng, Z., 2021. High-spatiotemporal resolution mapping of global urban change from 1985 to 2015. *Nat. Sustain.* 3, 564–570. <https://doi.org/10.1038/s41893-020-0521-x>.
- Marsh, G.P., 1864. *The Earth as Modified by Human Action (a New Edition of Man and Nature, 1877)*. Scribner, Armstrong & Co., New York.
- McEachran, Z.P., Karwan, D.L., Slesak, R.A., 2021. Direct and indirect effects of forest harvesting on sediment yield in forested watersheds of the United States. *JAWRA J. Am. Water Resour. Assoc.* 57, 1–31. <https://doi.org/10.1111/1752-1688.12895>.
- Navas, A., Serrano, E., López-Martínez, J., Gaspar, L., Lizaga, I., 2018. Interpreting environmental changes from radionuclides and soil characteristics in different landform contexts of Elephant Island (Maritime Antarctica). *Land Degrad. Dev.* 29, 3141–3158. <https://doi.org/10.1002/ldr.2987>.
- Nearing, M.A., Pruski, F.F., O'neal, M.R., 2004. Expected climate change impacts on soil erosion rates: a review. *J. Soil Water Conserv.* 59 (1), 43–50.
- Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308, 405–408. <https://doi.org/10.1126/science.1107887>.
- Osuteye, E., Johnson, C., Brown, D., 2017. The data gap: an analysis of data availability on disaster losses in sub-Saharan African cities. *Int. J. Disaster Risk Reduct.* 26, 24–33. <https://doi.org/10.1016/j.ijdr.2017.09.026>.
- Our World in Data. Available in: <https://github.com/owid/co2-data> (last access May 2023).
- Owens, P.N., 2020. Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. *J. Soils Sediments* 20, 4115–4143. <https://doi.org/10.1007/s11368-020-02815-9>.
- Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M., Poesen, J., Borrelli, P., 2021. Projections of soil loss by water erosion in Europe by 2050. *Environ. Sci. Policy* 124, 380–392.
- Paprotny, D., Sebastian, A., Morales-Nápoles, O., Jonkman, S.N., 2018a. HANZE: a pan-European database of exposure to natural hazards and damaging historical floods since 1870. *Earth Syst. Sci. Data* 10, 565–581. <https://doi.org/10.5194/essd-10-565-2018>.
- Paprotny, D., Sebastian, A., Morales-Nápoles, O., Jonkman, S.N., 2018b. Trends in flood losses in Europe over the past 150 years. *Nat. Commun.* 9, 1985. <https://doi.org/10.1038/s41467-018-04253-1>.
- Remondo, J., González-Díez, A., Soto, J., Díaz de Terán, J.R., Cendrero, A., 2005. Human impact on geomorphic processes and hazards in mountain areas. *Geomorphology* 66, 69–84. <https://doi.org/10.1016/j.geomorph.2004.09.009>.

- Rhoads, B.L., 2006. The dynamic basis of geomorphology reenvisioned. *Ann. Assoc. Am. Geogr.* 96 (1), 14–30. <https://doi.org/10.1111/j.1467-8306.2006.00496.x>.
- Rivas, V., Cendrero, A., Hurtado, M., Cabral, M., Giménez, J., Forte, L., del Río, L., Cantú, M., Becker, A., 2006. Geomorphic consequences of urban development and mining activities; an analysis of study areas in Spain and Argentina. *Geomorphology* 73 (3–4), 185–206. <https://doi.org/10.1016/j.geomorph.2005.08.006>.
- Rivas, V., Remondo, J., Bonachea, J., Sánchez-Espeso, J., 2022. Rainfall and weather conditions inducing intense landslide activity in northern Spain (Deba, Guipúzcoa). *Phys. Geogr.* 43 (4), 419–439. <https://doi.org/10.1080/02723646.2020.1866790>.
- Russell, K.L., Vietz, G.J., Fletcher, T.D., 2017. Global sediment yields from urban and urbanizing watersheds. *Earth Sci. Rev.* 168, 73–80. <https://doi.org/10.1016/j.earscirev.2017.04.001>.
- Seto, K.C., Sánchez-Rodríguez, R., Fragkias, M., 2010. The new geography of contemporary urbanization and the environment. *Annu. Rev. Environ. Resour.* 35, 167–194. <https://doi.org/10.1146/annurev-environ-100809-125336>.
- Sidorchuk, A., Litvin, L., Golosov, V., Chernysh, A., 2006. European Russia and Byelorussia. In: Boardman, J., Poesen, J. (Eds.), *Soil Erosion in Europe*. Wiley, pp. 73–93.
- Sidorchuk, A.Y., Golosov, V.N., 2003. Erosion and sedimentation on the Russian Plain, II: the history of erosion and sedimentation during the period of intensive agriculture. *Hydrol. Process.* 17, 3347–3358. <https://doi.org/10.1002/hyp.1391>.
- Sivapalan, M., Savenije, H.H.G., Blöschl, G., 2012. Socio-hydrology: a new science of people and water. *Hydrol. Process.* 26, 1270–1276. <https://doi.org/10.1002/hyp.8426>.
- Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C.A., Wescoat, J. L., Rodríguez-Iturbe, I., 2014. Socio-hydrology: use-inspired water sustainability science for the Anthropocene. *Earth's Future* 2, 225–230. <https://doi.org/10.1002/2013EF000164>.
- Slaymaker, O., Spencer, T., Embleton-Hamann, C. (Eds.), 2009. *Geomorphology and Global Environmental Change*. Cambridge U. Press, Cambridge.
- Steffen, W., Sanderson, R.A., Tyson, P.D., Jäger, J., Matson, P.A., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H.-J., Turner, B.L., Wasson, R.J., 2004. *Global Change and the Earth System: A Planet Under Pressure*. Springer-Verlag, Berlin, Heidelberg, N. York.
- Steffen, W., Grinevald, J., Crutzen, P., McNeill, J., 2011. The Anthropocene: conceptual and historical perspectives. *Phil. Trans. R. Soc. A* 369, 842–867. <https://doi.org/10.1098/rsta.2010.0327>.
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the Anthropocene: the Great Acceleration. *Anthr. Rev.* 2 (1), 81–98. <https://doi.org/10.1177/2053019614564785>.
- Stoppini, A., 1871–73. *Corso di Geologia*. Bernardoni e Brigola Editori. Milano.
- Strahler, A.N., 1952. Dynamic basis of geomorphology. *Geol. Soc. Am. Bull.* 63, 923–938.
- Summerfield, M.A., Hulton, N.J., 1994. Natural controls of fluvial denudation rates in major world drainage basins. *J. Geophys. Res. Solid Earth* 99 (B7), 13871–13883.
- Swindles, G.T., Roland, T.P., Ruffell, A., 2023. The ‘Anthropocene’ is most useful as an informal concept. *J. Quat. Sci.* 38 (4), 453–454. <https://doi.org/10.1002/jqs.3492>.
- Syvitski, J., Vörösmarty, C.J., Kettner, A., Green, P., 2005. Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308 (5720), 376–380. <https://doi.org/10.1126/science.1109454>.
- Syvitski, J., Waters, C.N., Day, J., Milliman, J.D., Summerhayes, C., Steffen, Zalasiewicz, J., Cearreta, A., Gáluszka, K., Hajdas, I., Head, M.J., Leinfelder, R., McNeill, J.R., Poirier, C., Rose, N.L., Shotik, W., Waprich, M., Williams, M., 2020. Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. *Commun. Earth Environ.* 1, 32. <https://doi.org/10.1038/s43247-020-00029-y>.
- Syvitski, J., Restrepo, J., Saito, Y., Overeem, I., Vorosmarty, C.J., Houjie Wang, H., Olago, D., 2022. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* 3, 179–196. <https://doi.org/10.1038/s43017-021-00253-w>.
- Syvitski, J.P., Milliman, J.D., 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J. Geol.* 115 (1), 1–19.
- Tarolli, P., Sofia, G., 2016. Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology* 255, 140–161. <https://doi.org/10.1016/j.geomorph.2015.12.007>.
- Tellman, B., Sullivan, J.A., Kuhn, C., Kettner, A.J., Doyle, C.S., Brakenridge, G.R., Erickson, T.A., Slayback, D.A., 2021. Satellite imaging reveals increased proportion of population exposed to floods. *Nature* 596, 80–86. <https://doi.org/10.1038/s41586-021-03695-w>.
- Ter-Stepanian, G., 1988. Beginning of the technogene. *Bull. Int. Assoc. Eng. Geol.* 38, 133–142.
- Tsyplenkov, Anatoly, Vanmaercke, Matthias, Collins, Adrian L., Kharchenko, Sergey, Golosov, Valentin, 2021. Elucidating suspended sediment dynamics in a glacierized catchment after an exceptional erosion event: the Djankuat catchment, Caucasus Mountains, Russia. *Catena* 203, 105285. <https://doi.org/10.1016/j.catena.2021.105285>.
- UNEP, 2016. In: Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H.P., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T. (Eds.), *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel*. United Nations Environment Programme, Paris, p. 198.
- UNEP, 2022. *Sand and Sustainability: 10 Strategic Recommendations to Avert a Crisis*. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland.
- Vernadsky, V.I., 1929. *La Biosphère*. 2^e édition revue et augmentée, Paris, Librairie Félix Alcan, Réed. Avec une préface de Jean-Paul Deléage: Paris, Seuil, coll. «Points/Science», 2002.
- Viles, H., 2020. Biogeomorphology: past present and future. *Geomorphology* 366, 106809. <https://doi.org/10.1016/j.geomorph.2019.06.022>.
- Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharmad, K., Green, P., Syvitski, J.P.M., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Glob. Planet. Chang.* 39 (1–2), 169–190. [https://doi.org/10.1016/S0921-8181\(03\)00023-7](https://doi.org/10.1016/S0921-8181(03)00023-7).
- Walling, D.O., Swanson, F.J., Marks, B., Cissel, J.H., Kertis, J., 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, USA. *For. Ecol. Manag.* 85, 291–309.
- Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. *Nat. Commun.* 11, 3107. <https://doi.org/10.1038/s41467-020-16941-y>.
- Wilkinson, B.H., 2005. Humans as geologic agents: a deep time perspective. *Geology* 33 (3), 161–164. <https://doi.org/10.1130/G21108.1>.
- Wischmeier, W.H., Smith, D.D., 1978. *Predicting Rainfall Erosion Losses. Agricultural Handbook*, 58. United States Department of Agriculture, Washington, p. 537.
- World Bank, 2021. World Development Indicators, Popular Indicators, Population. <https://data.worldbank.org/indicator/SP.POP.TOTL.2018>, pp. 61–109.
- World Bank, 2021b. World Development Indicators, Popular Indicators, GDP. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>.
- Wuepper, D., Borrelli, P., Finger, R., 2020. Countries and the global rate of soil erosion. *Nat. Sustain.* 3, 51–55. <https://doi.org/10.1038/s41893-019-0438-4>.
- Zachar, D., 1982. *Soil Erosion. Developments on Soil Science*, 10. Elsevier, Amsterdam, p. 547.
- Zalasiewicz, J., Waters, C.N., Williams, M., Barnosky, A.D., Cearreta, A., Crutzen, P., Ellis, E., Ellis, M.A., Fairchild, I.J., Grinevald, J., Leinfelder, R., McNeill, J., Poirier, C., Richter, D., Steffen, W., Vidas, D., Waprich, M., Wolfe, A.P., Zhisheng, A., 2015. When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quat. Int.* 383, 196–203. <https://doi.org/10.1016/j.quaint.2014.11.045>.
- Zalasiewicz, J., Waters, C.N., Ellis, E.C., Head, M.J., Vidas, D., Steffen, W., Thomas, J.A., Horn, E., Summerhayes, C.P., Leinfelder, R., McNeill, J.R., Gáluszka, A., Williams, M., Barnosky, A.D., Richter, B., Gibbard, P.L., Syvitski, J., Jeandel, C., Cearreta, A., Cundy, A.B., Fairchild, I.J., Rose, N.L., Ivar do Sul, J.A., Shotyk, W., Turner, S., Waprich, Zinke, M.J., 2021. The Anthropocene: comparing its meaning in geology (chronostratigraphy) with conceptual approaches arising in other disciplines. *Earth's Future* 9, 3. <https://doi.org/10.1029/2020EF001896>.
- Zhang, T., Li, D., East, A.E., Walling, D.E., Lane, S., Overeem, I., Beylich, A.A., Koppes, M., Lu, X., 2022. Warming-driven erosion and sediment transport in cold regions. *Nat. Rev. Earth Environ.* 3, 832–851.
- Zhou, S., Yu, B., Lintner, B.R., Findell, K.L., Zhang, Y., 2023. Projected increase in global runoff dominated by land surface changes. *Nat. Clim. Chang.* 13, 442–449. <https://doi.org/10.1038/s41558-023-01659-8>.