GEOMORPHOLOGICAL CHANGES AND HUMAN IMPACT IN THE ANTHROPOCENE

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Summary

During the Anthropocene, and especially during the last three hundred years, humans have caused great changes in landforms and in the rate of operation of geomorphological processes. The study of these is called Anthropogeomorphology. The increasing use of energy means that humans are now moving very large amounts of material across the Earth's surface. In addition to deliberate changes, human impacts have often had a series of unintended consequences, particularly as a result of land cover changes. These have affected rates of soil erosion by wind and water during the Holocene, and modified the operation of mass movement processes on slopes. Also very important have been various types of water management, including the construction of dams and reservoirs, and these have caused modifications in river sediment loads and flows, channel changes and alterations in coastal sediment budgets. Increasing levels of groundwater exploitation have contributed to ground subsidence and enhanced seismicity. Urbanisation has been another important driver of change. With climate change, the consequences of human activities will become still greater.

Résumé

Durant l'Anthropocène, et plus particulièrement durant les trois dernières centaines d'années, l'homme a provoqué de grands changements dans l'allure des paysages et dans la vitesse des processus géomorphologiques. Les besoins croissants en énergie l'ont conduit à déplacer des quantités de matières de plus en plus grandes à la surface de la Terre. En plus des changements intentionnels, les impacts humains ont souvent abouti à des conséquences inattendues, particulièrement en ce qui concerne les modifications du couvert terrestre. Ces dernières ont affecté les vitesses d'érosion des sols par le vent et par l'eau durant l'Holocène ainsi que le déclenchement des processus de glissements de terrain sur les pentes. Très importants également sont les divers types de gestion des eaux, incluant la construction de barrages et de réservoirs qui ont causé par exemple des modifications dans les charges et les flux des sédiments de rivière, des changements de leurs lits et des altérations dans les budgets des sédiments côtiers. Les niveaux croissants d'exploitation des eaux souterraines ont contribué à la subsidence des sols et accru leur sismicité. L'urbanisation a été aussi un autre initiateur de changements. Avec le changement climatique, les conséquences des activités humaines devraient devenir encore plus grandes.

Introduction

The purpose of this paper is to review the changes in the operation of geomorphological processes and forms brought about by human activities during the period Crutzen and colleagues have recently called the '*Anthropocene*' (e.g. Crutzen, 2002; Steffen et al. 2007; Röckstrom et al., 2009). They have employed this as a name for a new epoch in Earth's history – an epoch when human activities have 'become so profound and pervasive that they rival, or exceed the great forces of Nature in influencing the functioning of the Earth System' (Steffen, 2010). In the last three hundred years, they suggest, we have moved from the Holocene into the Anthropocene. They identify three stages in the Anthropocene. Stage 1, which lasted from c 1800-1945 they call 'The Industrial Era', Stage 2, which extends from 1945 to c 2015, they call 'The Great Acceleration', and Stage 3, which may perhaps now be starting, is a stage when people have become aware of the extent of the human impact and may thus start stewardship of the Earth System. In a sense, however, the Anthropocene started well before three centuries ago (Goudie, 2006a), and land use changes may have driven climate changes quite early in the Holocene (Ruddiman et al., 2011). Reviews of various aspects of the Anthropocene appear in a special issue of the *Philosophical Transactions of the Royal Society*, A, 339, (2011). **Table 1** shows some of the crucial drivers of anthropogenic geomorphological change, but it needs to be remembered that humans were capable of causing substantial geomorphological change well before three hundred years ago, through such mechanisms as the deliberate use of fire and because of the land cover changes that took place early in the Holocene as a result of the adoption of agriculture, pastoralism, urbanisation and mining.

TABLE 1. Some Drivers of Change
Increasing human population
Increasing consumption
Increasing geographical spread
Fire from Palaeolithic
Domestic Stock from Neolithic
Agriculture from Neolithic
Smelting and mining etc. from Bronze Age
Urbanisation from Neolithic
Transport links
Irrigation systems, dams and inter-basin water transfers

Anthropogeomorphology

Anthropogeomorphology is the study of the human role in creating landforms and modifying the operation of geomorphological processes such as weathering, erosion, and sediment transport and deposition (Goudie, 2006a). Some features are produced by direct anthropogenic processes. These tend to be relatively obvious in form and are frequently created deliberately. They include landforms produced by construction (e.g. spoil tips, embankments, sea walls), excavation (e.g., mines), hydrological interference (e.g. reservoirs and canals), and farming (e.g. terraces) (**Table 2**).

TABLE 2. Deliberately created landforms

Feature	**Cause**
Pits and ponds	Mining, marling
Broads	Peat extraction
Spoil heaps	Mining, waste disposal
Terracing, lynchets	Agriculture
Ridge and furrow	Agriculture
Cuttings and sunken lanes	Transport
Embankments	Transport, river and coast management
Dikes, polders	River and coast management
Mounds	Defence, memorials
Craters	War, *qanat* construction
City mounds (*tells*)	Human occupation
Canals	Transport, irrigation
Reservoirs	Water management, cooling basins
Subsidence depressions	Mineral and water extraction
Moats	Defence
Banks along roads	Noise abatement

By contrast, landforms produced by indirect and inadvertent anthropogenic processes (**Table 3**) are often less easy to recognize because they involve the acceleration of natural processes rather than the operation of a new process or processes. It is indirect and inadvertent modification of process and form that is the most crucial aspect of anthropogeomorphology. By modifying land cover, humans have accelerated erosion and sedimentation (Jones and Marcus, 2006; Wilkinson and McElroy, 2007). Sometimes the results will be both spectacular and obvious, as for example when major gullies rapidly develop; other results may have less dramatic visual effects on landforms (e.g. sheet erosion) but are, nevertheless, important. By other indirect means humans may create subsidence (Johnson, 1991), cause sedimentation on floodplains, estuaries, lakes and elsewhere, trigger landslides, and even influence the operation of earthquakes through the impoundment of reservoirs (Meade, 1991). In addition, rates of weathering may be modified because of the acidification of precipitation caused by accelerated nitrate and sulfate emissions or because of accelerated salinization in areas of irrigation (Goudie and Viles, 1997).

TABLE 3. ***Indirect anthropogenic processes***

Acceleration of erosion and sedimentation

agricultural activity and clearance of vegetation, engineering, especially road construction and urbanization

incidental modifications of hydrological regime

Subsidence: collapse, settling

mining (e.g., of coal and salt)

hydraulic (e.g., groundwater and hydrocarbon pumping)

thermokarst (melting of permafrost)

Slope failure: landslides, flows, accelerated creep

loading

undercutting

shaking

lubrication

Earthquake generation

loading (reservoirs)

lubrication (fault plane)

Weathering

acidification of precipitation

accelerated salinization

lateritization

In addition, there are situations where, through a failure to understand the operation of processes and the links between different processes and phenomena, humans may deliberately and directly alter landforms and processes but thereby initiate events that were not anticipated or intended. For instance, there are many records of attempts to reduce coastal erosion, often using hard engineering techniques, which, far from solving it, only exacerbated the problem. Examples include dune stabilization schemes in North Carolina (Dolan et al., 1973), the role of sea walls in causing beach scour (Bird, 1979), and downdrift coastal erosion as a result of updrift 'protection' schemes.

Land cover changes and their consequences

Land use and cover changes brought about by humans are fundamental drivers of geomorphological change. Most importantly of all, the spread of agriculture has transformed land cover at a global scale. There have been great changes in the area covered by particular biomes since pre-agricultural times. Even in the last three hundred years the areas of cropland and pasture have increased by around five to six fold (Goldewijk, 2001).

Connected with this is the intensification of grazing by domestic stock. This can damage soil structure through trampling and compaction. Heavily grazed lands tend to have considerably lower infiltration capacities than those found in ungrazed lands. Particular fears have been expressed that the replacement of Amazonian rainforest to cattle-trampled pasture could lead to great increases in the frequency and volume of stormflow. One study showed that the frequency of storm flow in such grazed areas increased twofold, while its volume increased 17-fold (Germer et al., 2010). Trimble and Mendel (1995) demonstrated why it is that cows have the ability to cause soil compaction. Given their large mass, small hoof area, and the stress that may be imposed on the ground when they are scrambling up a slope, they are probably remarkably effective in causing soil compaction.

The relationships between grazing pressures and soil infiltration capacities are complex. On the one hand, moderate stocking levels may increase infiltration capacities by breaking down surface biological or rainbeat crusts, while on the other high stocking levels may remove all vegetation cover, cause breakdown of soil aggregates, and produce severe trampling and soil compaction, thereby decreasing soil infiltration rates (du Toit et al. 2009).

Infiltration capacities, which are so important in determining the nature of stream runoff, may also be modified by off-road vehicular movements (Webb, 1982), and the replacement of grasslands by shrublands (Bhark and Small, 2003).

One particular type of erosion associated with agriculture is called 'Tillage Erosion'. Tillage is responsible for the movement of soil material, particularly on slopes, and leads to a net soil loss from convex landscape positions and a net soil gain in concave landscape positions, Erosion rates for mechanized agriculture are often on the order of 400-800 kg m^{-1} yr^{-1} and are of the same order of magnitude or larger than water erosion rates (Van Oost et al. 2006).

Land with a permanent vegetation cover is characterized by soil losses which are more than an order of magnitude lower than those on agricultural land (Cerdan et al., 2010). Pimentel (1976) estimated that in the USA soil erosion on agricultural land operates at an average rate of about 30 tonnes per hectare per year, which is approximately eight times quicker than topsoil is formed. He calculated that water runoff delivers around 4 billion tonnes of soil each year to the rivers of the forty-eight contiguous states, and that three-quarters of this comes from agricultural land. He estimated that another billion tonnes of soil is eroded by the wind, a process which created the Dust Bowl of the 1930s. More recently, Pimentel et al. (1995) argued that about 90 per cent of US cropland is losing soil above the sustainable rate, and that about 54 per cent of US pasture land is overgrazed and subject to high rates of erosion. However, as Trimble and Crosson (2000) and Boardman (1998) point out, determination of general rates of soil erosion is fraught with uncertainties.

Many techniques have now been developed to try and control accelerated erosion (see Morgan, 2005), including the use of no-tillage cultivation, the introduction and planting of cover crops, ploughing along rather than down the contours of the land, and the construction of banks and terraces.

Figure 1. Water and soil conservation banks at Matmata, Tunisia.

Holocene erosion and sedimentation rates

One way of obtaining rates of soil erosion during the Holocene is to estimate rates of sedimentation on continental shelves and on lake floors. The former method was employed by Milliman et al. (1987) to evaluate sediment removal down the Yellow River in China during the Holocene. They found that, because of accelerated erosion, rates of sediment accumulation on the shelf over the last 2,300 years have been ten times higher than those for the rest of the Holocene (i.e. since around 10,000 BP).

There have numerous studies of the history of erosion in the Holocene in Europe and Britain (see, for example, Dusar et al., 2011; Notebaert and Vertsraeten, 2010). In British and Irish catchments, Foulds and Macklin (2006) suggest that geomorphic instability linked with Holocene land-use changes was especially intense in the Bronze Age and the Iron Age. On the other hand, rates of sedimentation on British floodplains appear to have accelerated greatly in the last thousand or so years (Macklin et al. 2010) and this can be related to the agricultural revolution of the Middle Ages. Similarly, Heine et al. (2005), working in Bavaria, showed how agricultural intensification led to both slope colluviation and floodplain sedimentation. Also working in Germany, Dreibrodt (2010) suggested that erosion was at a maximum in the late Bronze Age and pre-Roman iron age (c 1600 BC-1000AD), high and late Medieval times (c 1000-1350 AD) and late modern times (from c 1500 until today). The combination of slope clearance for agriculture with times of intense storms would be an especially powerful stimulus to soil erosion, and catastrophic soil erosion in Central Europe was identified for the first half of the fourteen century and in the mid-18th to the early 19th century by Dotterweich (2008). Some of the sediment produced by accelerated erosion accumulates as colluvium downslope, some on floodplains, and some in lake basins.

Among the consequences of land-use change that have been identified in Holocene Britain are slope instability, which leads to gullying and deposition of debris cones and alluvial fans in upland catchments, and colluviation in the lowlands; valley floor sedimentation; increased runoff leading to incision (mainly in upland catchments); and high water tables and flooding (mainly in lowland catchments) (Foulds and Macklin, 2006). That said, one inevitable consequence of the accelerated erosion produced by human activities has been accelerated sedimentation (see, for example, Komar et al.'s 2004 study of sedimentation in Tillamook Bay, Oregon). Some of the eroded material accumulates downslope as colluvium (Verstraeten et al. 2009), some on floodplains, some in lakes and some in estuaries. This has been heightened by the deliberate addition of sediments to stream channels as a result of the need to dispose of mining and other wastes.

Comparably serious sedimentation of bays and estuaries has also been caused by human activity on the eastern coast of America. The trend in sedimentation rate (Pasternack et al. 2001) over the last three centuries demonstrates the low rate in pre-European settlement times, the high rates in the mid nineteenth century at a time of peak deforestation and of intensive agriculture, and the decline that took place in the twentieth century. Salt marshes expanded rapidly at this time as a result of rapid rates of sediment delivery (Kirwan et al., 2011).

García-Ruiz (2010) has provided a full analysis of how land use changes in Spain have affected soil erosion rates. One change that has taken place in recent decades is the abandonment of farmland because of rural depopulation and the problems of mechanization on small packets of land on steep slopes. On the one hand one would expect vegetation re-colonisation to cause erosion rates to be reduced, but on the other the lack of maintenance to field terraces on steep slopes can cause gully erosion to occur. Soil erosion is also severe in some vineyards because their soils are often left bare for much of the year, and many vineyards are on steep slopes. Olive and almond cultivation, some of which has been encouraged because of European Union subsidies, can also be a major cause of accelerated erosion on susceptible soils.

An example of using long-term sedimentation rates to infer long-term rates of erosion is provided by Hughes et al.'s (1991) study of Kuk Swamp in Papua New Guinea They identified low rates of erosion until 9000 BP, when, with the onset of the first phase of forest clearance, erosion rates increased from 0.15 cm per thousand years to about 1.2 cm per thousand years. Rates remained relatively stable until the last few decades when, following European contact, the extension of anthropogenic grasslands, subsistence gardens and coffee plantations has produced a rate that is very markedly higher: 34 cm per thousand years.

Another good long-term study of the response rates of erosion to land use changes is provided by a study undertaken on the North Island of New Zealand by Page and Trustrum (1997). During the last 2,000 years of human settlement their catchment underwent a change from indigenous forest to fern/scrub following Polynesian settlement (*c.*560 BP) and then a change to pasture following European settlement (AD 1878). Sedimentation rates under European pastoral land use were between five and six times the rates that occurred under fern/scrub and between eight and seventeen times the rate under indigenous forest. In a broadly comparable study in another part of New Zealand, Sheffield et al. (1995) looked at rates of infilling of an estuary. In pre-Polynesian times rates of sedimentation were 0.1 mm per year, during Polynesian times the rate climbed to 0.3 mm per year, while since European land clearance in the 1880s the rate has shot up to 11 mm per year (see also Nichol et al., 2000). Other examples of such trends in New Zealand are provided by Glade (2003), while a` good case study of the effect of European settlement on soil erosion rates in neighbouring Australia is given by Olley and Wasson (2003).

Figure 2 shows badlands in Swaziland that have been created as a result of the removal of the woodland cover, probably by Iron Age smelters.

Figure 2. Erosion scars, dongas, developed in Swaziland as a result of vegetation clearance

Accelerated erosion by wind

Dust storms are an important manifestation of surface erosion by wind, and human activities may have had an important effect on dust storms in the world's drylands. Von Suchodoletz et al. (2010) have even speculated that humans intensified dust storm activity in the northwest Sahara as early as 7-8 ka ago. The situation becomes less speculative as we move towards the present, and Neff et al. (2008), for instance, used analyses of lake cores in the San Juan Mountains of south-western Colorado, USA, to show that dust levels increased by 500% above the late Holocene average following the increased western settlement and livestock grazing during the nineteenth and early twentieth centuries. The USA Dust Bowl of the 1930s was caused by a combination of a major drought and adverse land management, with the latter having a feedback effect on the drought itself (Cook et al., 2009**).** A dust core from the Antarctic Peninsula (McConnell et al., 2007) showed a doubling in dust deposition in the twentieth century, and this is explained by increasing temperatures, decreasing relative humidity, and widespread desertification in the source region – Patagonia and northern Argentina. Marx et al. (2011) demonstrated that in the last 200 years, there has been a 2 to 10 fold increase in dust deposition rates following settlement by European farmers. Finally, analysis of a 3200 year marine core off West Africa shows a marked increase in dust activity at the beginning of the nineteenth century, which was a time which saw the advent of commercial activity (including groundnut production) in the Sahel (Mulitza et al., 2010). Using a variety of data sources, Mahowald et al. (2010) have tried to estimate the global picture of changes in dust storm activity for the twentieth century. They suggest a doubling of desert dust took place over much of the globe.

Urbanisation

Erosion rates are affected by urbanization, one of the other great drivers of recent centuries. The highest rates of erosion are produced in the city construction phase, when there is a large amount of exposed ground and much disturbance produced by vehicle movements and excavations. In pioneer studies, Wolman and Schick (1967) and Wolman (1967) have shown that the equivalent of many decades of natural or even agricultural erosion may take place during a single year in areas cleared for construction. In Maryland they found that sediment yields during construction reached 55,000 tonnes per square kilometre per year, while in the same area rates under forest were around 80-200 tonnes per square kilometre per year and those under farm 400 tonnes per square kilometre per year. New road cuttings in Georgia were found to have sediment yields up to 20,000-50,000 tonnes per square kilometre per year. Likewise, in Devon, England, Walling and Gregory (1970) found that suspended sediment concentrations in streams draining construction areas were two to ten times (occasionally up to 100 times) higher than those in undisturbed areas. In Virginia, USA, Vice et al. (1969) noted equally high rates of erosion during construction and reported that they were ten times those from agricultural land, 200 times those from grassland and 2,000 times those from forest in the same area. Rates of sediment production may be especially high in humid tropical cities, where there is highly intense rainfall (Chin, 2006).

The process of urbanization has a considerable hydrological impact, in terms both of controlling rates of erosion and the delivery of pollutants to rivers, and in terms of influencing the nature of runoff and other hydrological characteristics (Hollis, 1988; Chin, 2006).There are various reasons for this. City drainage densities may be greater than those in natural conditions (Graf, 1977) and the installation of sewers and storm drains accelerates runoff. In addition, research both in the United States and in Britain has shown that, because urbanization produces extended impermeable surfaces of bitumen, tarmac, tiles and concrete, there is a tendency for flood runoff to increase in comparison with rural sites. Sheng and Wilson (2009) provide an analysis of how urbanisation in the Los Angeles metropolitan region has increased flood hazard.

Even small rural villages can produce substantial amounts of erosion, especially in the tropics. For example, De Meyer et al. (2011) have shown that in Uganda village compounds and associated unpaved footpaths and roads generate sediment that is a significant source of pollution in neighbouring Lake Victoria.

Water management

Another great acceleration in human transformation of the environment is water management, and in particular the construction of dams and reservoirs. There are some 75,000 dams in the USA. Most are small, but the bulk of the storage of water is associated with a relatively limited number of structures. Those dams creating reservoirs of more than 1.2×10^9 cubic metres account for only 3 per cent of the total number of structures, but they account for 63 per cent of the total storage. In all the dams are capable of storing a volume of water almost equaling one year’s runoff and they store around 5,000 cubic metres of water per person. The decade of the 1960s saw the greatest spate of dam construction in American history (18,833 dams were built then). Since the 1980s, however, there have been only relatively minor increases in storage. The dam building era is over, but the environmental effects remain and the physical integrity of many rivers has been damaged (Graf, 2001).

Globally, the construction of large dams increased markedly, especially between 1945 and the early 1970s (Beaumont, 1978). There are now more than 45,000 large dams around the world and such large dams (i.e. more than 15 m high) are still being constructed at an appreciable rate, especially in Asia. Indeed, one of the most striking features of dams and reservoirs is that they have become increasingly large. Dam construction has an array of geomorphological consequences. On the one hand the trapping of sediment may cause downstream incision of channel beds (‘clear water erosion). On the other, reductions in flood activity may permit accelerated aggradation. In the Rio Grande, vertical channel accretion of 2.75-3.0 m occurred between 1991 and 2008 (Dean and Schmidt, 2011). The reduction in peak floods below dams can also permit the expansion of riparian vegetation, such as Tamarisk, which may trap sediment (Birken and Cooper, 2006; Allred and Schmidt, 1999) and so add to the amount of accretion that occurs. Rapid aggradation has also been noted in the channel of the Yellow River in China, partly because inputs of aeolian sands are no longer so effectively flushed out (Ta et al., 2008).

Inter-basin water transfers can cause great changes in the state of lakes, as illustrated by the severe desiccation that is taking place in the Aral Sea (Saiko and Zonn, 2000). Between 1960 and 1990, largely because of diversions of river flow, the Aral Sea lost more than 40 per cent of its area and about 60 per cent of its volume, and its level fell by more than 14 m. By 2002 its level had fallen another 6 m. By 2008, the area of the Aral Sea was just 15.7% of that in 1961 (Kravstova and Tarasenko, 2010). This has lowered the artesian water table over a band 80-170 km in width, has exposed 24,000 square kilometres of former lake bed to desiccation, and has created salty surfaces from which salts are deflated to be transported in dust storms, to the detriment of soil quality.

Sediment loads in rivers

Land use change, and in particular the development of agriculture, has caused a leap in the amount of erosion of the world's land surfaces. Wilkinson and McElroy (2007) calculated that 'natural' sediment fluxes to the world's rivers are about 21 Gt/yr, and that 'anthropogenic' losses may be around 75Gt/yr.

In recent decades fossil-fuelled machinery has allowed mining activity to expand to such a degree that in terms of the amount of material moved its effects are reputed to rival the natural processes of erosion. Taking overburden into account, the total amount of material moved by the mining industry globally is probably at least 28 billion tonnes – about 1.7 times the estimated amount of sediment carried each year by the world's rivers (Young, 1992). The environmental impacts of mineral extraction are diverse but extensive, and relate not only to the process of excavation and removal, but also to the processes of mineral concentration, smelting and refining.

Sediment transport by rivers has been modified by humans in two main ways. On the one hand, the construction of dams has caused much sediment to be trapped in reservoirs. On the other, sediment delivery to rivers has been increased as a result of accelerated rates of soil erosion. In the south east USA, the results of these two tendencies have been analysed by McCartney-Castle et al. (2010). Under pre-European (1680-1700) the mean annual suspended sediment load transfer rate was 6.2 Mt per year, under pre-dam (1905-1925) conditions the rate was 15.04 Mt per year, whereas now, following dam construction, the rate is 5.2 Mt per year.

Even more dramatic are the data for the Colorado River in the USA. Prior to 1930 it carried around 125-150 million tonnes of suspended sediment per year to its delta at the head of the Gulf of California. Following a series of dams the Colorado now discharges neither sediment nor water to the sea (Schwarz et al., 1991). There have also been marked changes in the amount of sediment passing along the Missouri and Mississippi rivers and Meade (1996) attempted to compare the situation in the 1980s with that which existed before humans started to interfere with those rivers (*c.* AD 1700). Before 1900, the Missouri-Mississippi river system carried an estimated 400 million metric tons of sediment per year to coastal Louisiana. Between 1987 and 2006 this figure had fallen to an average of 145 million metric tons per year. About half of this decline was accounted for by sediment trapping behind dams, and the rest by such actions as bank revetments and soil erosion management (Meade and Moody, 2010). Also in the USA, the Columbia River has undergone a greater than 50% reduction in total sediment transport since the mid-nineteenth century, largely because of flow regulation (Naik and Jay, 2011).

In India, dams on the Krishna and Godavari rivers have also caused major changes in discharges and sediment loads (Rao et al., 2010). The Krishna discharged 61.9 km^3 of water between 1951 and 1959, but this had reduced to 11.8 km^3 by 2000-2008. Its suspended sediment load was 9 million tons during 1966-1969 but was as low as 0.4 million tons by 2000-2005. This change has promoted accelerated recession of its delta. In the case of the Yangtze in China, in 2003-5 sediment load in the upper river was only 17% of that in the 1950s-1960s (Xu et al. 2007). The Three Gorges Dam has had a particularly marked impact since it began to impound sediment and water in 2003 (Xu and Milliman, 2009).

On a global basis, Syvitski et al. (2005) have calculated that sediment retention behind dams has reduced the net flux of sediment reaching the world's coasts by c 1.4 billion metric tons per year, and that over 100 billion metric tons have been trapped within the last 50 years. Reservoirs behind dams now trap c 26% of the global sediment delivery to the coastal ocean (Syvitski and Milliman, 2007).

Conversely, Syvitski et al. (2005) have calculated that humans have simultaneously increased the sediment transport by global rivers through soil erosion by c 2.3 billion metric tons per year. On balance, therefore, global river sediment loads have gone up more as a result of soil erosion than they have been reduced by dam retention. However, plainly there are great differences between rivers and between areas. In central Japan, for example, sediment loads were reduced in the last decades of the twentieth century because land that had formerly been cultivated intensively had become urbanized (Siakeu et al., 2004). In the case of some major Chinese rivers draining into the western Pacific, recent declines in sediment load have been caused by a combination of factors (Chu et al. 2009): dam retention (56%), soil and water conservation (23%), water abstraction (15%) and in-channel sand mining (6%). The same is true of the Sacramento River in California. Its sediment load decreased by about one half during the period between 1957 and 2001 and this has been attributed to depletion in the amount of old hydraulic mining debris, trapping of sediment in reservoirs, riverbank protection, the construction of levees and altered land use (e.g. urbanization replacing agriculture) (Wright and Schoellhamer, 2004).

Acceleration of mass movements

There are many examples of humans accelerating mass movements by such activities as vegetation removal, loading of debris onto slopes, changing groundwater conditions, excavating the bases of slopes, and cutting away the toes of debris flows.

In south eastern France humans have accelerated landslide activity by building excavations for roads and by loading slopes with construction material (Julian and Anthony, 1996). The undercutting and removal of the trees of slopes for the construction of roads and paths has also led to landsliding in the Himalayas (Barnard et al., 2001). This is also the case in mountainous Nepal, where the number of fatal landslides shot up during the 1990s (Petley et al. 2007). This seems to be correlated with the rapid development of the road network after about 1990. Similarly, landslides that were triggered by a great earthquake in Kashmir in 2005 occurred preferentially in areas where road construction had taken place (Owen et al. 2008). Many landslides in China appear to have been triggered by surface excavation and mining activity (Huang and Chan, 2004).

In the case of northern Spain, changes in landslide occurrence in the Upper Pleistocene and Holocene can partly be attributed to periods of intense precipitation or seismic activity, but the sharp increase in landslide numbers since the early 1980s appears to be related to increasing human pressures (Remondo et al., 2005). In the case of an alpine area in Switzerland, where the area affected by landslides increased by 92% from 1959 to 2004, the causes were a combination of an increase in the occurrence of torrential rain events and an increase in cattle stocking (Meusberger and Alewell, 2008). However, on a longer time span of 3600 years, pulses of increased landslide activity in the Swiss Alps have been linked to phases of deforestation (Dapples et al. 2002).

Fire, whether natural or man-induced, can be a major cause of slope instability and debris flow generation by removing or reducing protective vegetation, by increasing peak stream flows, and by leading to larger soil moisture contents and soil-water pore pressures (because of reduced interception of rainfall and decreased moisture loss by transpiration) (Wondzell and King, 2003). Examples of fire-related debris flow generation are known from many sites in the USA, including Colorado (Cannon et al., 2001), New Mexico (Cannon et al., 2001a), the Rocky Mountains and the Pacific North West (Wondzell and King, 2003).

Channel changes

Humans have greatly modified the channels of many rivers. Sometimes this has been done deliberately, as when great levees are constructed or river courses are channelized and straitened. However, as with so many other instances of anthropogeomorphic change, much channel change is the inadvertent result of modification of the amounts of water and sediment that come down channels, or the modification of riparian vegetation (Goudie, 2006a). The construction of water-powered mills has also been identified as a potent cause of historical channel change in the eastern United States. Walter and Merritts (2008), using old maps and archives, showed that whereas before European settlement the streams of the region were small anabranching channels within extensive vegetated wetlands, after the construction of tens of thousands of 17^{th} – to 19^{th} century milldams, 1 to 5 m of slackwater sedimentation occurred and buried the pre-settlement wetlands with fine sediment.

In recent years, partly because some old dams have become unsafe or redundant, they have been demolished and this has had a series of impacts on channels. Most of the dams involved have been just a few metres high though one example from Australia was 15 m high (Neave et al., 2009). Among the consequences of dam removal are incision into the sedimentary fill that had accumulated in the reservoir behind the dam, migration of a knickpoint upstream, deposition of liberated sediment and the formation of bars and the like downstream. However, the precise consequences vary greatly depending on the nature and erodibility of the fill and the regime of the river. Some rivers appear to remove their fill rapidly and almost entirely, while others do not.

Earth moving

Sherlock's classic 1922 study covers a period when earth-moving equipment was still ill-developed. None the less, on the basis of his calculations, he was able to state that 'at the present time, in a densely peopled country like England, Man is many times more powerful, as an agent of denudation, than all the atmospheric denuding forces combined' (p. 333). The most notable change since Sherlock wrote has taken place in the production of aggregates for concrete. Demand for these materials in the UK grew from 20 million tonnes per annum in 1900 to 202 million tonnes in 2001, a tenfold increase. Douglas and Lawson (2001) estimated that in Britain the total deliberate shift of earth-surface materials is between 688 and 972 million tons per year, depending on whether or not the replacement of overburden in opencast mining is taken into account.

Hooke (1994) produced some data on the significance of deliberate human earthmoving actions in the United States and globally. In all he calculated that deliberate human earth moving causes 30 billion metric tons to be moved per year on a global basis. Douglas and Lawson (2001) give a rather larger figure – 57 billion tons per year. It has been estimated that the amount of sediment carried into the ocean by the world's rivers each year amounts to between 8.3 and 51.1 Gt per year (Walling, 2006). Thus the amount of material moved by humans is rather greater than that moved by the world's rivers to the oceans (Price et al., 2011). As technology changes, this ability increases still further (Haff, 2010).

Enhanced seismicity

Perhaps the most important anthropogenically induced seismicity results from the creation of large reservoirs (Takrani, 1997; Guha, 2000; Gupta, 2002; Durá-Gómez and Talwani, 2010). Reservoirs impose stresses of significant magnitude on crustal rocks at depths rarely equaled by any other human construction. With the ever-increasing number and size of reservoirs the threat rises. Cases where seismicity and faulting can be attributed to fluid extraction come, for example, from the oilfields of Texas and California and the gas fields of the Po Valley in Italy and of Uzbekistan (Cypser et al., 1998; Donnely, 2009; Suckale, 2010). Some of the seismic activity may be related to a process called 'hydrofracturing', whereby water is injected into the rock to create distinct fractures that increase permeability and thus facilitate the extraction of fluids and the production of geothermal energy (Majer et al., 2007).

Ground Subsidence

Humans can cause ground subsidence in a variety of ways: disruption of permafrost, the draining of organic soils, groundwater abstraction, mining of minerals, and exploitation of water and hydrocarbon resources. Some of the most dangerous and dramatic examples of subsidence are collapses that have occurred in limestone areas because of the dewatering of limestone caused by mining activities. In areas where thick halite (salt) deposits have accumulated as a result of their precipitation in saline lake basins, solution may cause sink holes to develop. An example of this is provided by the Dead Sea basin, where the recent decline in level caused by water abstraction has promoted their formation. More than a thousand potentially dangerous sinkholes have developed along its shorelines since the early 1980s as a result of the flow of under-saturated groundwater dissolving the evaporites. Similar problems have been encountered on the Jordanian side of the Dead Sea, with karstic collapse creating major problems for the chemical plants on the Lisan Peninsula (Closson et al., 2007).

Studies in the Ruhr district of Germany indicate values that can be as high as 5.16 m, though the mean value is 1.6 m (Harnischmacher et al., 2010). Subsidence associated with coal mining may disrupt surface drainage (Sidle et al. 2000) and the resultant depressions then become permanently flooded. In the Ruhr, a lake, Lake Lanstrop, formed between 1963 and 1967 in response to up to 9 m of subsidence (Bell et al., 2000).

It is important to remember, however, that the causes of observed subsidence are often complex and involve both natural and anthropogenic factors. In the case of coastal Louisiana, for example, the natural factors include tectonics (faulting and halokinesis), Holocene sediment compaction, the isostatic effects of sediment loading, and glacio-isostatic adjustments. The anthropogenic factors include fluid removal and surface water drainage and management (Yuill et al., 2009). That said, the very rapid rates of subsidence in the Mississippi Delta Plain at the present time, which are much higher than those in the previous 5000 years, indicate the importance of subsidence caused by hydrocarbon extraction (Morton et al., 2005). However, as the example of Venice shows (Carbognin et al., 2010) it is possible to slow or to reverse rates of subsidence by controls on fluid extraction.

Coastal change

Humans have a propensity to occupy lands in close proximity to the sea, and as a consequence they have had a multitude of impacts on coastal landforms and processes, not least because of the effects of changes in their sediment budgets and in their rates of subsidence.

In Texas, where over the last century four times as much coastal land has been lost as has been gained, one of the main reasons for this change is believed to be the reduction in the suspended loads of some of the rivers discharging into the Gulf of Mexico. The four rivers listed carried, in 1961-70, on average only about one-fifth of what they carried in 1931-40. Comparably marked falls in sediment loadings occurred elsewhere in the eastern United States. Likewise, in France the once mighty Rhône only carries about 5 per cent of the load it did in the nineteenth century; and in Asia, the Indus discharges less than 20 per cent of the load it did before construction of large barrages over the last half century (Milliman, 1990). On a global basis, large dams may retain 25-30 per cent of the global flux of river sediment (Vörösmarty et al., 2003).

A good case study of the potential effects of dams on coastal sediment budgets is provided by California by Willis and Griggs (2003). Given that rivers provide the great bulk of beach material (75 to 90 per cent) in the state, the reduction in sediment discharge by dammed rivers can have highly adverse effects. Almost a quarter of the beaches in California are down coast from rivers that have had sediment supplies diminished by one-third or more. Most of those threatened beaches are in southern California where much of the state's tourism and recreation activities are concentrated.

Figure 3. Coast erosion at Malibu, California, USA

Delta erosion is a pervasive and developing problem, not least in south and southeast Asia. This is partly because they sink under their own weight of sediment, suffer from compaction of organic sediments, may be subsiding because of the removal of fluids, and are subjected to on-going sea level rise. They also suffer from a reduced amount of sediment nourishment following dam construction upstream and from a reduction in the number of distributary channels as a consequence of a need to support navigation in a limited number of larger channels (Syvitski and Saito, 2007; Svyitski et al. 2009). Indeed, such actions have already been implicated in the changes that have taken place in the morphology of the Nile Delta and its lagoons over the last half century (El Banna and Frihy, 2009).

In addition, as Higgitt and Lee (2001) have pointed out, coastal protection works reduce sediment inputs to the coastline by reducing rates of cliff recession, while groynes, harbour breakwaters and other shoreline structures disrupt longshore sediment transport. Cross-shore sediment transport may also be modified, as, for example, by attempts to control coastal dune movement. In addition, salt marshes have been modified in many ways, not least by the introduction of invasive plants (including *Spartina*).

Conclusions

Although humans have achieved geomorphological change since prehistoric times, it is clear that during the last few centuries of the Anthropocene there has been a great acceleration in anthropogenically caused geomorphological change so that humans are now a major factor in terms of the creation of landforms and the modification of the rates of geomorphological processes. In coming decades it is likely that with global climate change the influence of humans will become still greater and that some sensitive geomorphological hotspots will undergo rapid change. A big question, however, is whether anthropogenic climate change or anthropogenic land use and land cover changes will be the dominant driver of future landform evolution.

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