Humans are the most significant global geomorphological driving force of the 21st Century

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The transformation of the Earth's land surface by mineral extraction and construction is on a scale greater than natural erosive terrestrial geological processes. Mineral extraction statistics can be used as a proxy to measure the size of the total anthropogenic global sediment flux related to mineral extraction and construction. It is demonstrated that the annual direct anthropogenic contribution to the global production of sediment in 2015 was conservatively some 316 Gt (150 km^3), a figure more than 24 times greater than the sediment supplied annually by the world's major rivers to the oceans. The major long-term acceleration in anthropogenic sediment flux started just after the Second World War and anthropogenic sediment flux overtook natural fluvial sediment flux in the mid-1950s. Humans are now the major global geological driving force and an important component of earth system processes in landscape evolution. The changing magnitude of anthropogenic sediments and landforms over time are

significant factors in the characterisation of the proposed new epoch of geological time - the Anthropocene.

World mineral production

There are dramatic increases with time, not only in the amounts of minerals extracted, but also in the amount of overburden/waste that has to be moved/processed to get to those minerals. The exceptions to this are oil and gas (but not tar sands), which have small amounts of associated solid waste. One of the most extreme examples is that of gold where very low concentrations of the element are worked. A typical gold wedding ring containing 4 grams of gold now requires the excavation of between 4 and 20 tonnes of rock and the processing of between 1 and 4 tonnes of the contained ore; the production also uses large amounts of energy, water and chemicals (Mudd, 2017). This compares with the production of a similar ring in 1925 that would have only required the extraction of 0.3 tonnes of ore through selective mining (Muller & Frimmel, 2010).

Statistics for annual world mineral production for a wide range of mineral commodities have been compiled for the interval 1900–present by geological survey organisations (British Geological Survey, 1913–2017; United States Geological Survey, 1900–2014) and they show considerable changes in annual outputs generally increasing with time. The overall increase follows both population growth and technological advancement as bigger machinery and modern extraction techniques have allowed greater volumes of lower quality resources to be exploited. A wide range of minerals are exploited and recorded, but, with the exception of construction aggregates which are considered later in this paper, by far the most significant by mass of world production (2015 figures) are coal 39%, oil 21%, iron ore 17% and natural gas 16%; bauxite is the next highest amounting to just 2% (Brown et al, 2017). Over time, the production amounts of coal have been an indicator of economic growth and stress, recording periods of economic boom, depression and war (Price et al, 2011). The trend in coal production is also a good proxy for total mineral production (**Figure 1**). The amounts of mineral and overburden/waste are a measure of global anthropogenic geosphere transformation. They record the perturbation of the earth’s surface through human consumption of mineral resources.

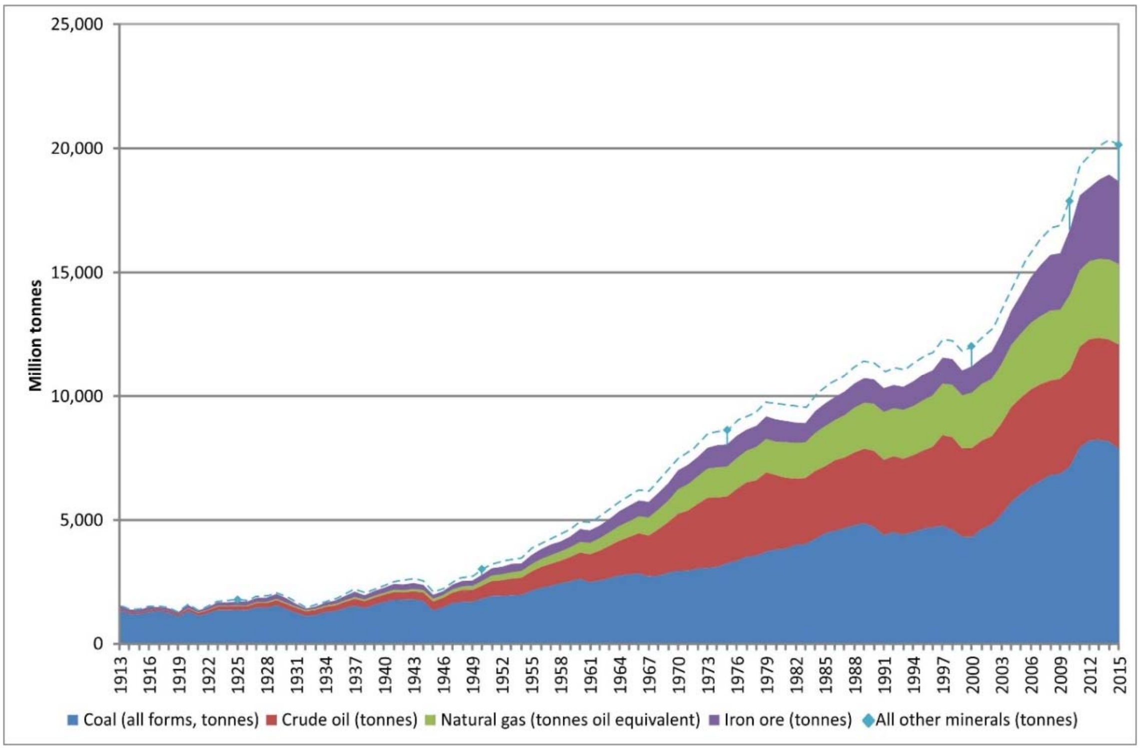


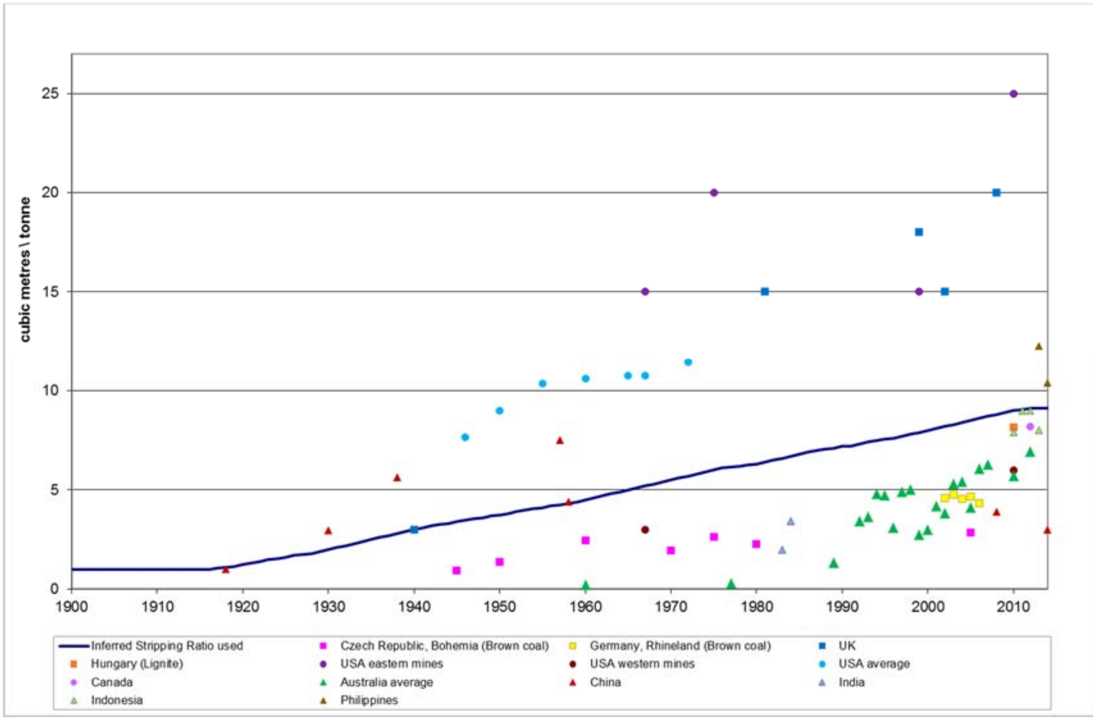
Figure 1 World production of coal, crude oil, natural gas and iron ore, with all other minerals (except for construction aggregates) interpolated between key year intervals

To calculate the total anthropogenic global sediment flux the annual figures of world production for coal have been used (**Figure 1**), however, for the other minerals snapshots have been taken at key time intervals (1925, 1950, 1975, 2000, 2010 and 2015). The overburden/waste figures have been calculated for each mineral at these intervals and interpolated the intervening annual amounts. The consideration of overburden amounts relating to production was pioneered by Douglas and Lawson (2001) and further developed by Price et al (2011). In this research, the minerals treated in this way are: bauxite, arsenic, asbestos, barytes, bentonite/fullers earth, bromine, cadmium, chromium ores, diamond, diatomite, feldspar, fluorspar, graphite, gypsum, iodine, kaolin, lithium minerals, magnesite, manganese ore, mercury, mica, phosphate rock, rare earth minerals, salt, sillimanite minerals, talc, tantalum and niobium minerals, titanium minerals, zirconium minerals, beryl, borates, nephelene syenite, potash, perlite, strontium minerals, vermiculite, wollastonite, natural sodium carbonate, and mine production of antimony, bismuth, cobalt, copper, gold, lead, molybdenum, nickel, platinum group metals, silver, tin, tungsten, uranium, vanadium and zinc. Oil and gas have been excluded from these figures.

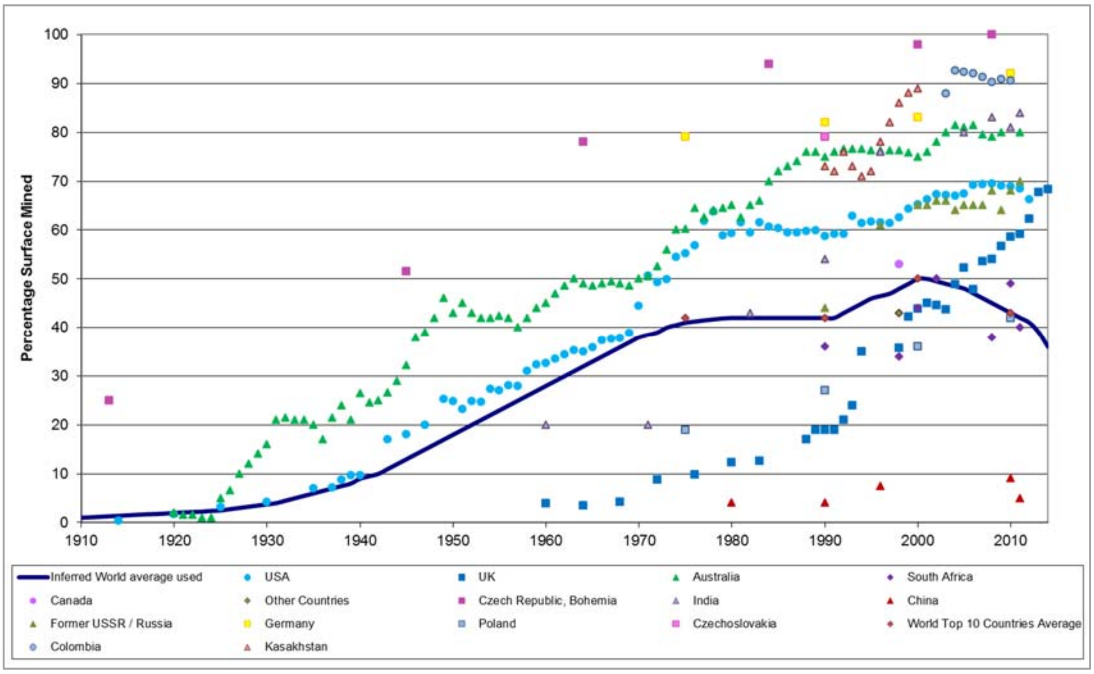
Overburden and waste calculations

To calculate the overburden/waste figures for the minerals, diverse sources have been used including mineral processing books, papers and web pages, as described in the supplementary information. Because of the wide range of minerals and the difficulty of deriving an overburden/waste figure for each year, it is considered that snapshots at the key year intervals represent the most practical approach.

For coal (and similarly for all the other minerals) the increases with time in ratios between overburden stripped to extracted mineral have been considered (**Figure 2a**). Currently, stripping ratios can be up to 10 times that of the mineral for brown coal and up to 25 times for hard coal (Mudd, 2010). Increasing stripping ratios reflect the greater use and size of the mechanisation (bigger excavators, excavator buckets and haulage lorries). In making these calculations for coal, the division between underground mining (with relatively small waste ratios), hard coal strip mining (with very large overburden ratios) and brown coal mining (generally with low to moderate overburden ratios) have been factored in (**Figure 2b**). Again as a practicality this has been done at the same time intervals that were used for other minerals and interpolated for the intervening years. This has given an annual multiplier for overburden/waste that has been applied to total annual coal production (including underground, surface, hard and brown coals) to provide an estimated amount of material moved of 74 Gt or 35 km^3 (assuming average density of 2.1 t/m^3) in 2015. Other mining and mineral extraction, including overburden and waste moved, provides equivalent estimates of 27 Gt or 13 km^3 in 2015 (**Figure 3**).



a)



b)

Figure 2. Factors affecting the amount of overburden and waste generated by coal extraction (see supplementary information for data sources). **Part a (top)**. Temporal changes in coal stripping (overburden) ratios for various countries and inferred global average. **Part b (bottom)**. Temporal changes in the percentage of surface mining relative to underground coal mining and inferred global average. The increase in Chinese underground coal production after 2001 causes

the downturn in inferred world average percentage, while at the same time overburden ratios for opencast (strip mining) increased.

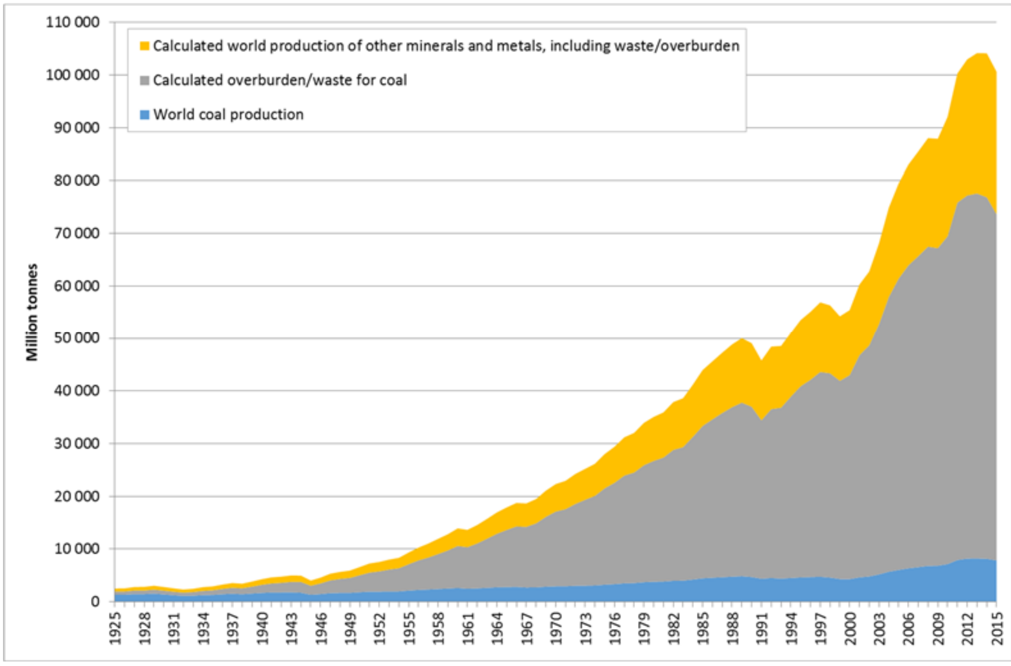


Figure 3. World production of coal, calculated overburden/waste for coal extraction and mineral production combined with its associated overburden/waste for 54 other commodities which have been inferred between points at 1925, 1950, 1975, 2000, 2010 and 2015 using coal as a proxy.

Cement, aggregates, construction work and land modification

For cement, the annual world production tonnages are known (Brown et al, 2016; Idoine et al, 2016; van Oss, 2017) (**Figure 4**). Concrete has a more or less standard ratio of cement to the amount of aggregate (sand and gravel/crushed rock); the aggregate component in concrete is an accurate multiplier over cement production (Brown et al, 2016; Idoine et al, 2016; Bennett, 2016; Willett, 2016) (see Supplementary Information Figure S1). In addition, aggregate without cement is used in construction (road base, ballast, etc). Using total aggregate production figures, compared with cement output, where these are recorded, permits a proxy to be derived for countries where accurate figures for aggregate production are not available (**Figure 4**).

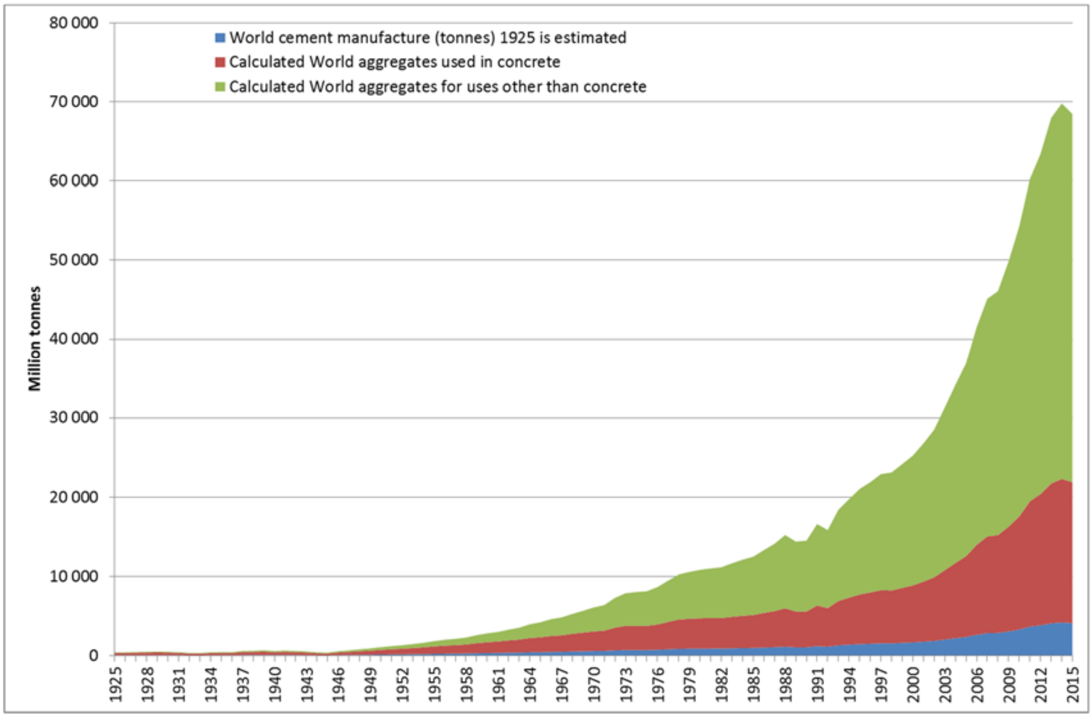


Figure 4. World cement manufacture and estimated World aggregates production, split between aggregates used in concrete and used elsewhere (note there will be a similar or greater amount of excavation related to construction).

The majority of construction works (e.g. buildings, roads, railways, tunnels, dams. docks, etc) also require earthworks. These range from minor stripping of soil to major tunnelling, cutting and embankment construction. It is concluded that, as a minimum, the amount of excavation related to these activities will be at least an equivalent quantity to the cement and aggregate consumed and the actual figure is probably much greater. Figures have been included in the final calculations that are double the amount of global aggregates and cement produced. There are many other sources of excavation and fill that have not been quantified including unsurfaced gravel roads and mountain road cuttings. These along with all the other artisan excavations (and not recorded as part of mineral production or concrete construction) have yet to be quantified. These calculations also do not include the extraction of other materials used in construction, such as brick clay, building/dimension stone or glass sand, because global data were not readily available. These calculations also do not include biological materials such as wood or rubber.

Dredging and land reclamation has a profound effect on coastal areas but the availability of statistical data on the amounts involved is limited. Using average dredging costs for numerous projects (see supplementary information) the likely volume extracted has been determined (**Figure 5**). This equates to more than 5.5 km^3 of material a year in 2015 (c. 10 Gt at a density of 1.8 t/m^3); of this a substantial proportion is emplaced to produce land and the remainder is mainly dumped at sea. These data have also been extrapolated back to 1925. The steep rise from the 1990s evident on **Figure 5** is likely to result from the significant increase in the size of cargo ships, which has required increased dredging from ports to enable them to be accommodated, combined with a notable increase in the number and size of land reclamation projects globally.

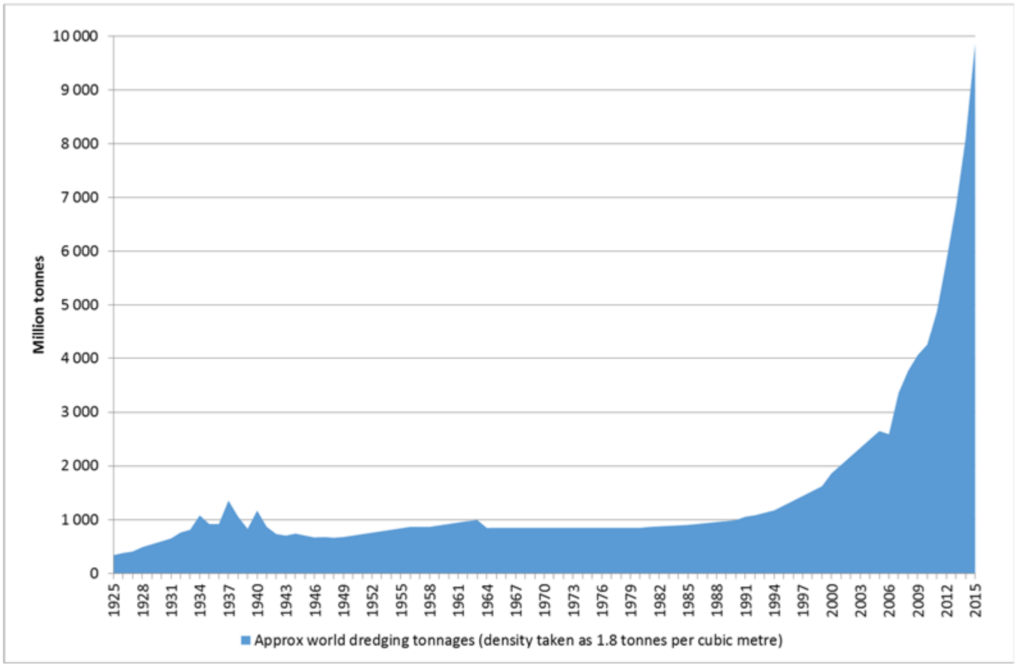


Figure 5 Calculated (2000–2012) and postulated (pre-2000) world dredging volumes.

Figures for the tonnages of artificially modified ground must be seen as a minimum, subject to future increase as more information about civil engineering projects, dredging and/or land reclamation is collated. To avoid double accounting for materials, human waste disposal (landfill) and recycling are not included. In addition, the indirect consequences of human actions on the environment due to farming, deforestation, deep sea trawling (Puig et al, 2012) and similar activities have not been considered.

Temporal trends

The production and related waste/overburden for all mineral extraction along with cement, aggregates, civil engineering excavations and dredging is conservatively estimated at 316 Gt or 150 km^3 in 2015, compared with 259 Gt or 123 km^3 in 2010 (**Figure 6**). This is a figure that is increasing due to technological advances and population increase. Annual anthropogenic sediment flux from coal, metals, minerals, cement and aggregates production for 2000 is estimated as about 81 Gt (without the figures for civil engineering and dredging), a figure more than twice what Hooke (2000) calculated for that time interval; since then the flux has more than doubled. If the estimates for civil engineering and dredging are included, the figure for 2000 is even larger at 133 Gt.

The trend of increasing excavation has continued from the earliest records. However, a significant acceleration in the trend occurred in 1945 (**Figure 6**), coinciding with the proposal by Zalasiewicz et al (2015) for the start of the Anthropocene Epoch and flux of anthropogenic materials may be considered an ancillary marker. A further acceleration since 2000 coincides with a significant increase in the consumption of minerals in China, which has caused it to become the world's biggest consumer of most of the minerals considered. This trend also correlates well with the concept of the 'Great Acceleration' and the graphs produced by Steffen and others (Steffen et al, 2004; Steffen et al, 2015). The total material moved, as calculated in this research amounts to approximately 150 Gt for the period 1925–1949 in contrast to approximately 670 Gt for the period 1950–1974 and 2,200 Gt for 1975–1999. Between 2000 and 2015 the total material moved is calculated as approximately 3,700 Gt in 16 years (rather than the 25 year blocks for the other figures), which illustrates the further acceleration seen in **Figure 6**.

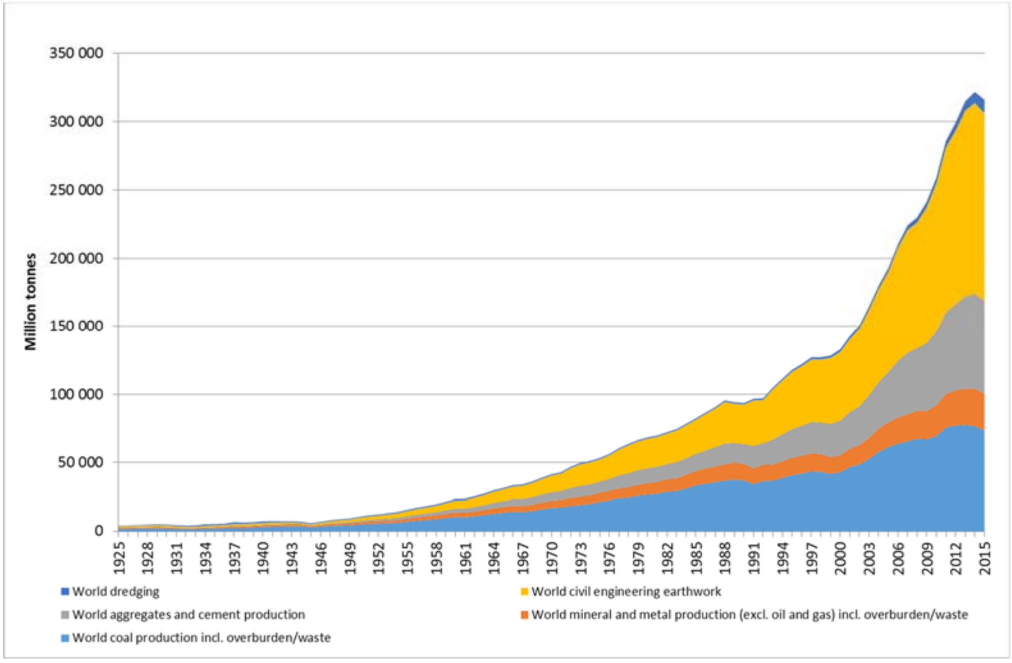


Figure 6. Graph of total world tonnages for coal, metals and minerals, including overburden and waste, with world total tonnages for cement and aggregates, civil engineering and dredging.

It is calculated (Syvitski, 2011) that pre-human river sedimentation to the sea was 15.1 Gt a year reducing to 12.8 Gt as a result of human activities. It is estimated that anthropogenically moved materials exceeded the natural sediment flux in rivers by ~1955. Other major anthropogenic sediment fluxes are seen in the seas (Puig et al, 2012) which are also disturbed by dredging and dumping.

In alignment with the socio-economic trends used to recognise a 1950 onset for the 'Great Acceleration' (Steffen et al., 2004, 2015), the human mass-transfer of geological materials across the planet is shown to rise rapidly from 1950. This supports the premise that an upturn in anthropogenic sediments could be used as one of the factors to support the recognition of the Anthropocene as a geological epoch. Humans are clearly the biggest sediment mover on the planet leaving an anthropogenic signature above ground, below ground and in the new sediments of the rivers, lakes and seas. The prophecies made by Sherlock as long ago as 1922 about "Man as a geological agent" are much greater than he could have imagined (Sherlock, 1922).

Keywords

Anthropocene, sediment, mineral extraction, construction, global, geological, landscape evolution, statistics

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Declaration of interests

The authors declare that there are no conflicting interests with regard to this research.

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