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# Linking erosion with environmental and societal impacts in a rapidly changing environment

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**Abstract** In global terms, unprecedented rates of population growth and development, with their incessant demands on the land resource, are increasingly exposing society to the adverse consequences of erosion. In this paper, I review previous work on the degree and rate of change of the mega drivers of erosion (climate and human activity) in a historical context and analyse the geo-social system's response from a hazard perspective. The geo-social system faces increased complexity, resulting from population growth, urbanisation, climate change, escalating oil and grain prices, as well as increased physical and political intervention within the natural environment. Costs of erosion and mitigating measures are increasing and the cost of food production is becoming unsustainable. This rapidly changing environment has enhanced the risks associated with the erosion hazard by accelerating physical processes, increasing the elements at risk, compounding social vulnerability and increasing exposure to hazard.

**Key words** erosion; population growth; climate change; food production; sustainability; hazard; risk

## INTRODUCTION

Dictionary definitions, e.g. *Encyclopaedia of Geomorphology*, p. 331 (Goudie, 2004), usually characterise erosion as the group of processes whereby Earth materials are detached, removed and transported from any part of the Earth's surface. Transport is influenced by gravity and friction and effected by agents such as running water, waves, wind, or moving ice. Rarely, in these entries, is mention made of humans as a cause or agent of erosion, while deposition, the product of erosion, is considered a separate process.

My contention is that those omissions are reductionist artefacts that limit the full understanding of the environmental and societal impacts of erosion.

From a societal perspective (one which I will treat at both the global and local level), erosion has demonstrable dimensions of a *natural hazard* (although, in many situations, its "naturalness" can be challenged). As a hazard, erosion has two major spheres of impact: first, its chronic impact on primary production (especially food production) and, second, its, often more acute, impact on life, property, infrastructure, rivers and coastal systems. These two spheres have been the domain of agricultural/soil scientists on the one hand, and Earth scientists/geotechnical/hydraulic engineers, on the other.

Here, I examine the degree and rate of change to the mega drivers of erosion (principally climate and human activity) in an historical context, and analyse the geo-social system response from a hazard perspective.

## SERIOUS EROSION: SORTING OUT THE CAUSES

One of the mega drivers of the hazard dimension of erosion is incontrovertibly population growth. Simply put, through time, there are inexorably more mouths to feed from a finite land resource and there are more people and property presenting themselves as elements at risk to acute erosion. Wright (2004), in Canada's Massey Lectures, estimated that since the year 1900, the world's population has increased four times, while economic activity has increased 40 times. As a result of these unprecedented rates of change, the geo-social system linkages necessary for survival have become more critical and more complex (Etkin 1999; Hufschmidt & Crozier, 2008).

Even before the daunting rates of current population growth were achieved, the human factor has been used to explain the degradation of the soil resource and collapse of agricultural based societies over periods of thousands of years in Europe and other parts of the world. Blaikie &

Brookfield (1987), and more recently Thornes (2008), identify a number of studies concluding that abandonment of agricultural economies was coincident with the onset of extensive episodes of widespread erosion and gullying. With reference to the present Mediterranean landscape, Blaikie & Brookfield (1987) note that: "*Little remains of the indigenous forest cover, and large montane areas, especially on limestone, are now almost bare of soil. ... it has long been accepted as established that the heavy decline in agricultural potential of the region has been due to millennia of exploitative agriculture*". It is little comfort to us, in a world of rapidly increasing consumption and rapidly changing climate, that those offering alternative views for the onset of these socially destructive erosion episodes (e.g. Vita-Finzi, 1969) resort to climate change as an explanation.

There have been similar debates in New Zealand as to what drives major erosion episodes. Detailed evidence has been presented for the occurrence of a major erosional episode in New Zealand, coincident with the onset of European farming practices in the 1870s (Trustrum & Page, 1992; Page *et al.*, 2000; Glade, 2003). These findings support the long-held (but arguably belated) beliefs (Cumberland, 1944, p3) that observed erosion rates were not normal and that introduced land-use practices, involving conversion of forest or scrub to pasture, as well as the introduction of vegetation browsing species, enhanced landscape susceptibility to erosion. That humans were to blame was strongly asserted by Cumberland (1944) in his book *Soil Erosion in New Zealand*, where he refers to "culturally-accelerated waste of soil" and, for example, his unequivocal classification of tunnel-gully erosion as "anthropogenic erosion". But confidence in these attributions has been tested, if not moderated, by work of Howard (1978), Cunningham (1978), Grant (1981, 1983) and Whitehouse (1993), all of whom observed that many of the erosional features formerly linked to European disruption of a delicate environment had other explanations. For example, the extensive New Zealand South Island high country screes, formerly recorded as evidence of "severe" or "extreme" erosion, were in fact realised to be relatively stable, relict features from earlier climatic regimes. Source areas in the Southern Alps were observed over a period of 85 years, to be not widening, as might be expected from browsing-induced deterioration of vegetation cover, and similarly source areas were often observed to be located well above the timberline, so could not be readily attributed to the observed forest deterioration. Further evidence for naturally driven episodic behaviour of erosion was provided by Grant (1981, 1983) who investigated a series of erosion episodes affecting the North Island of New Zealand over the last 1000 years, the largest of which commenced and ceased before any human habitation of the country, suggesting that climate variability was the primary cause.

The role of human intervention in river systems, as opposed to source areas, is much less equivocal. Davies & McSaveney (2006) have recently given us a timely reminder of the unintended erosional and depositional consequences attendant upon almost any form of channel modification (usually for flood protection purposes), currently practised in gravel-bed dominated rivers. Hydro-electric dams (and increasingly irrigation dams) also have well-understood impacts on the fluvial system. Downstream channel incision (as a result of sediment starvation), coupled with aggradation of lake-head deltas, are effects well-documented in New Zealand and elsewhere (Vorosmarty *et al.*, 2003). The identification of the key factors driving erosion systems is clearly important for management, but, irrespective of whether they are climatic or human, major changes can be expected to the erosional regime, in the light of the widely anticipated (and indeed observed) rates of change in climatic and human systems.

## POPULATION PRESSURE FOOD PRODUCTION AND EROSION

Returning to the global arena, population growth and the anticipated demand for food has long focused our attention on the productive capacity of land and impediments to sustained production associated with soil degradation and erosion. As Neurath (1994) observes, in the period between 1650 AD and 1850 AD, world population doubled from 550 million to 1200 million (an annual growth rate of 0.3–0.5%). During this epoch, Malthus (1798) wrote his famous essay, drawing attention to the exponential growth of populations, compared to the geometric growth of food production. In ensuing years, those concerns were allayed somewhat by the fact that the world continued to feed itself, largely by extension of production into still available arable land. In the 30 years between 1850 and 1890, the area of cropland tripled worldwide (Goudie, 1993).

The real population explosion, however, began between 1950 and 1975 when the world's population grew 60% from 2500 million to 4000 million (equal to an annual growth rate of 2%, twice as fast as in the preceding 25 years). It is was not surprising then to see a neo-Malthusian movement arise in the form of the *Club of Rome* and its sponsorship of the widely influential publication *Limits to Growth* (Meadows *et al*., 1972).

While population increase was placing huge demands on food production, the capacity to produce was being severely limited by soil degradation and erosion. Pimentel *et al.* (1995) concluded that during the 40 years since 1955, nearly one third of the world's arable land had been lost by erosion, and losses continue at a rate of 10 million hectares per year.

Yet again, the dire warnings of tensions between population driven demand and a finite and deteriorating soil resource were muted (or delayed) by technocratic achievements. These came most notably in the form of *Mr Brown's Green Revolution*. The success of Lester Brown's (1975) push for intensification and increased productivity seemed to support Rousseau's challenge to Malthus, by demonstrating that the inventive capacity of mankind would eventually provide a solution to all problems; or as expressed by Mao Zedong's article of faith: "with every mouth comes a pair of hands". However, the green revolution was only possible due to the increased application of petroleum-based fertilisers. This appeared sustainable at the time when one barrel of oil cost about the same as one bushel of wheat. Neurath (1994) points out that in 1972 one bushel of wheat and one barrel of oil each cost about US$1.90, by 1980, a barrel of oil cost US$30. In 2008, it has reached US$100. As a result of fertiliser costs and downstream environmental concerns, the green revolution is no longer regarded as a panacea (IAASTD, 2008).

For much of the last two decades, while some countries starved, some flourished and produced grain and butter mountains. The problem of feeding the world was seen as a geopolitical one; an issue of government and industry intervention and distribution, rather than one of productive capacity. But, by the middle of 2008, the situation appears to have changed dramatically. Ban Ki-Moon (Secretary-General of the United Nations) declared that: "the rapidly escalating crisis of food availability around the world has reached emergency"; United Nations officers were reporting food shortages and pronouncing that these could no longer be attributed to a distribution problem, but instead to production (Associated Press, 2008). In April 2008, the World Bank (2008) recorded that the wheat and corn inventories of the world amounted to only one month of supply, wheat prices had risen 181% to over US$500 per ton in the 35 months to February 2008, and other grain prices had also seen catastrophic rises. The situation was seen as resulting from increased oil prices, the lack of available arable land, poor weather, and the usurping of food production land by the biofuel industry.

Food mountains and fertiliser are no longer reliable buffers to the loss of the soil resource. In the USA today, erosion continues; causing about US$44 billion in damage each year and requiring an investment of US$6.4 billion per year to reduce erosion rates from about 17 tons $ha^{-1}$ $year^{-1}$ to a sustainable rate of about 1 ton $ha^{-1}$ $year^{-1}$ (Pimentel *et al*., 1995).

## CLIMATE CHANGE

The relationship between climatic factors and erosion processes is well understood at most scales of investigation (e.g. landsliding, Crozier, 1997; Guzetti *et al*., 2008). That level of knowledge, together with outputs of various IPCC (2007) climatic change scenarios, has allowed some reasonable hypotheses (guesses) to be advanced on the expected future impacts of erosion (e.g. for fluvial processes, Goudie, 2006). There has also been a series of attempts to model impacts for a range of erosion agents (e.g. soil erosion on crop land, Favis-Mortlock & Boardman, 1995; river discharge and flood events, Ashmore & Church, 2001; river morphology, Nanson & Tooth, 1999; landslide occurrence and reactivation, Collison *et al*., 2000; Dehn *et al*., 2000; Dixon & Brook,

2007) as well as empirically observed correlations of erosion activity and climate change (e.g. mountain permafrost melting and debris flow activity, Haeberli *et al.*, 1993). While many of the findings are inconclusive, there appears to be some consistency in the prediction of hydrological response as well as for soil erosion on cropland, more so than for other erosion processes. For example, none of the references quoted above was able to demonstrate any unequivocal increase in landslide activity in response to predicted increased rainfall and temperature. Nevertheless, in areas expected to receive increased rainfall, expert panels invariably include increased landslide activity in their list of climate impacts—I can only conclude that they have not read the literature or that they are relying on untested theory. There are, of course, uncertainties in the downscaling process. Insufficient information is available to anticipate the extent to which increased rainfall will be translated into increased intensities and duration. Similarly, there are limits to the spatial resolution for prediction and uncertainties in the nature of trends in population and economic activity. One study, notable in its attempt to include both climate change predictions and changes in social conditions as independent factors in the one landslide model, was carried out by van Beek (2002), in an area of Mediterranean climate. The three social conditions he used were peculiar to his study region, and included two cases involving change (one of continued rural exodus, and the other including reduction in population, with amalgamation of farm properties) and the other case was one of business-as-usual. The two conditions of change, when combined with predicted warming, projected a substantial reduction of landslide activity resulting ultimately from increased evapotranspiration. Clearly the impacts of social and climatic change will be manifest unevenly.

Despite regional differences, Goudie (2006), after reviewing numerous studies, concludes, that for a range of different environments, by the end of this century, increases in the rates of erosion could be of the order of 25–50%.

For New Zealand, NIWA (2007) projects an increase of 1.6–2.0°C in mean temperature by 2080 and changes of mean annual rainfall of –10% in the north and east, and +15% in the south and west. Using the Hadley General Circulation Model (GCM) predictions, this would translate to an increase of river mean flow of >15% in the west and a reduction of >15% in the east. Extreme rainfalls are likely to be heavier and more frequent with a four-fold reduction in recurrence interval. Westerly wind strength is also likely to increase. Clearly, the sorts of changes to erosion rates predicted in the international literature are also likely to be experienced in many parts of New Zealand. The direction and degree of change, however, will vary in response to location and terrain conditions.

Ashmore & Church (2001) also acknowledge that the relative roles of mega drivers of erosion, climate and human activity will depend on terrain conditions. They argue that the future effects of land-use change will dominate only in smaller basins, whereas climate change will have greater effect in large basins, as land-use changes are only likely to affect a relatively small proportion of the area. On the other hand, there appears to be compelling evidence that, on a global scale and over long time periods, human activity has caused a sharp increase in erosion from long term natural rates of 16 Gt year$^{-1}$ (surface lowering of 53 m Ma$^{-1}$) during the Pliocene to current losses of 75 Gt year$^{-1}$ (surface lowering of 600 m Ma$^{-1}$) from cropland (Wilkinson & McElroy, 2007). They argue that the accumulation of post-settlement alluvium on large flood plains (12 600 m Ma$^{-1}$) is producing the greatest geomorphic changes currently being experienced on Earth, far exceeding former inputs from Pleistocene glaciations or from current alpine erosion.

## THE COST OF EROSION

Assessments of the cost of erosion damage and control measures for the USA are given by Pimentel *et al.* (1995) in Table 1, and for New Zealand by Krause *et al.* (2001) in Table 2. The stand-out cost in both countries is the reduction in agricultural productivity, limiting further a productive response to population demands and testing the already strained technocratic solutions to increased yields. While these estimates collectively cover wind, water and mass movement erosion (in the case of New Zealand), there are few similar definitive studies for coastal erosion.

**Table 1** Annual damage and prevention costs from the effects of wind and water erosion in the USA (Pimental *et al.*, 1995).

| Damage type | | Cost (US$ millions – 1992 dollars) |
|---|---|---|
| Wind erosion | Exterior paint | 18.5 |
| | Landscaping | 2 894.0 |
| | Automobiles | 134.6 |
| | Interior, laundry | 986.0 |
| | Health | 5 371.0 |
| | Recreation | 232.2 |
| | Road maintenance | 1.2 |
| | Cost to business | 3.5 |
| | Cost to irrigation and conservation districts | 0.1 |
| | Total wind erosion costs | 9 632.5 |
| Water erosion | | |
| In-stream damage | Biological impacts | no estimate |
| | Recreational | 2 440.0 |
| | Water-storage facilities | 841.8 |
| | Navigation | 683.2 |
| | Other in-stream uses | 1 098.0 |
| | Subtotal in-stream | 5 063.0 |
| Off-stream effects | Flood damages | 939.4 |
| | Water-conveyance facilities | 244.0 |
| | Water-treatment facilities | 122.0 |
| | Other off-stream uses | 976.0 |
| | Subtotal off-stream | 2 318.0 |
| | Total water erosion costs | 7 381.0 |
| Total cost of wind and water damage | | 17 013.5 |
| Cost of erosion prevention | | 8 400.0 |
| Reduced soil productivity, wind and water | | 27 000.0 |
| Total cost of erosion | | 44 399.0 |

**Table 2** Annual cost from effects of soil erosion and sedimentation and prevention costs (Krausse *et al.*, 2001).

| Damage type | Cost (NZ$ millions – 1998 dollars) |
|---|---|
| Soil erosion effects total | 75.8 |
| Agriculture production loss | 37.0 |
| Farm infrastructure | 5.6 |
| Direct private property | 5.7 |
| Road/rail infrastructure | 26.3 |
| Utility network | 0.8 |
| Recreational facilities | 0.4 |
| Sedimentation effects total | 27.4 |
| Increased flood severity | 16.3 |
| Reduced water quality | 2.8 |
| Water storage loss | 0.2 |
| Navigation (dredging) | 7.5 |
| Water conveyance | 0.6 |
| Damage Total | 103.2 |
| Prevention costs | 23.5 |
| Total (damage and prevention) | 126.7 |

Some indication of the scale of the problem, has been produced by the European Commission (2004) EUROSION project, which estimated that about 15 000 km of coastline are actively retreating, some in spite of coastal protection. The rate of land loss is estimated at 15 km$^2$ year$^{-1}$.

While erosion losses are considered secondary to inundation losses, together, public expenditure on coastline protection increased from €2500 million in 1986, to €3200 million in 2001. In the period between 1999 and 2002, as many as 300 houses had to be abandoned and a further 3000 were affected, to the extent that their market values dropped by more than 10%. The major cause of the problem was considered to be reduction of sediment supply to coasts from both rivers and offshore sources, resulting from reduced flows and dam construction, and offshore sand mining respectively.

## GEO-SOCIAL SYSTEM RESPONSE: EVOLVING HAZARD AND RISK

A hazard-risk analysis of erosion must confront four dynamics: (a) the behaviour of the physical process in terms of frequency and magnitude, change in character, and acceleration; (b) changes in the degree of exposure of elements to risk; (c) increase in the quantity and quality of elements at risk; and (d) changes in the vulnerability status of those elements. Using this approach (Crozier & Glade, 2005; Hufschmidt *et al.*, 2005; Hufschmidt & Crozier, 2008), the consequences of population and climate pressures and other factors can be represented by 11 major response categories, reflecting both acute damage and/or long-term chronic degradation of resources.

**(a) Increased hazard** In areas of existing use, erosion accelerates or changes character (rates exceed the tolerable), or is induced (first-time failure); the effectiveness of existing adaptive or mitigating measures is reduced or exceeded.

(i) *driven by change in climate*: increased rainfall intensity, increased frequency of extreme events (fluvial and mass movement erosion), increased aridity (wind erosion), sea level rise and increased storminess (coastal erosion);

(ii) *driven by unsustainable land-use practices*: degrading soil and increasing susceptibility to erosion agents - caused by population pressure, economic pressures, or greed; leading to diminishing returns;

(iii) *driven by physical intervention*: increased erosion from physical intervention results from insertion of structures such as dams, coastal works, or aggregate mining. Much of the coastal erosion in Europe has been attributed to interruption of the normal sediment supply to the coast;

(iv) *driven by political intervention*: an example of political intervention enhancing erosion was the Land Development Encouragement Scheme introduced in New Zealand by the Muldoon Government, in 1978. The scheme involved incentives to clear native vegetation on existing farms and to replace it with pasture, a process that often resulted in unsustainable levels of erosion.

**(b) Increased exposure of elements at risk**

(i) *political intervention*: forcing populations into areas where they are unable to cope with the erosion hazard. For example, partitioning of India in 1949 resulted in population migration into flood prone areas of Bangladesh where the new arrivals were unfamiliar with the environment and ill-equipped to handle endemic flood events. Similarly, Krushev's Virgin Lands scheme, involving forced migration to Siberia in a failed effort to produce food;

(ii) *ignorance*: locating in a new area ignorant of the consequences;

(iii) *no other options*: all the "good" land has already been occupied, no choice of land for settlement (*ecological marginalisation*);

(iv) *voluntary choice*: this involves an awareness of the consequences but an acceptance of the risk or alternatively harbouring a false perception of the risk.

**(c) Increase in the elements of risk**: more people and more assets, mean regular events can become disasters, not because of change in the magnitude of the event but due to the greater density of population and assets.

**(d) Increased vulnerability**:

(i) *through use of unsustainable mitigation measures*: in areas of existing use, where adaptive measures required to counter erosion-related losses to production or to meet increased production levels are no longer sustainable, affordable, environmentally acceptable, or available;

examples of this are the cost of fertiliser, the unacceptable environmental consequences of biocides, genetic modification, and irrigation practices, as well as reduction in water availability. With the reduced effectiveness of these mitigating measures, communities become more vulnerable to losses from erosion.

(ii) *through urbanisation*: urbanisation is an increasing global phenomenon, only possible by translocation of resources from widespread source areas to the concentrated urban nodes. The dependency on those conduits (life-lines) introduces a degree of fragility to the system. When erosion processes, such as landslides, disrupt those life lines, the consequences are a function of the population densities they serve.

## CONCLUSION

As population continues to increase and urbanise, with attendant dual pressures of land degradation and demand for resources, erosion continues to increase in its intensity and consequences. The criticality of the situation has been addressed through time by policy and technology; but resulting mitigating measures have produced only temporary, illusory, and unsustainable solutions. The wild card of accelerated climate change provides less comfort than concern. The totality of the situation cannot be ignored in the global context because the outcome is expressed in human suffering.

There are, however, still opportunities for the scientific community to reduce the risk. Impacts are, and will continue to be, geographically uneven. The tasks therefore, are not novel but remain imperative. We need to define the carrying capacity of landscape units, quantify rates of erosion, and identify tolerable rates of erosion. We need to identify the geosystem response to the drivers of erosion, but more importantly we need to be able to identify geo-indicators that tell us when tipping points of sustainability are being approached. And when science or the community get it wrong or are overwhelmed, there needs to be an effective mechanism for global response. If mankind is unwilling to accept the concept of limits to growth through confrontation with erosion, it will be unable to avoid the consequences of continued growth.

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