European Union Soil Thematic Strategy

Working Group on Soil Erosion

TASK GROUP 5 on

Links with Organic Matter and Contamination Working Groups and secondary soil threats

Report on

The link between soil erosion and diffuse contamination of water and air

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1. Soil erosion and the diffuse contamination of surface waters

There are a variety of different point and diffuse sources of nutrients and contaminants in river basins and many of these are shown in Figure 1. Figure 1 illustrates that certain types of land use, land management, and land activities tend to be dominated by either point (i.e. direct industrial discharges, sewage treatment works) or diffuse (agriculture, urban road network) sources of sediment and contaminants to surface waters. In consequence, it has long been known that there is a direct link between erosion of the land surface and the diffuse contamination of surface waters (Salomons and Forstner, 1984; DEFRA, 2003). Thus, it has been documented since the 1960s that there is a direct link between soil erosion on agricultural land, phosphorus delivery from land to waters, and eutrophication of rivers and lakes (Vollenweider, 1968; Omernik, 1977). The MONERIS (Modelling Nutrient Emissions in River Systems) model has estimated that 22% of the phosphorus emissions into the main river basins of Germany for the period 1993-1997 were derived from (diffuse) erosion pathways (Scherer *et al*., 2003). Similarly, it is well known that pesticides and other micro-organic contaminants have deleterious effects on water quality and aquatic habitats, and that soil erosion (and surface runoff) can be a major source in agricultural areas (Warren *et al*., 2003). Once within the aquatic environment, sediment-associated contaminants derived from the land surface by erosion processes may persist within rivers and surface water bodies (such as ponds, lakes and reservoirs) for long periods of time, and/or they may be exported towards the coastal zone (estuaries, harbours etc.) and seas and oceans. Thus, for example, the erosion of soil ultimately supplies a large proportion of the sediment (Owens and Batalla, 2003) and associated contaminants entering the North Sea (Neal and Davies, 2003; Scherer *et al*., 2003). Contaminants delivered to surface waters by erosion in particulate form may change to dissolved form once in the aquatic environment, and may be more bioavailable and/or more hazardous to aquatic ecosystems and human health than contaminants in particulate form.

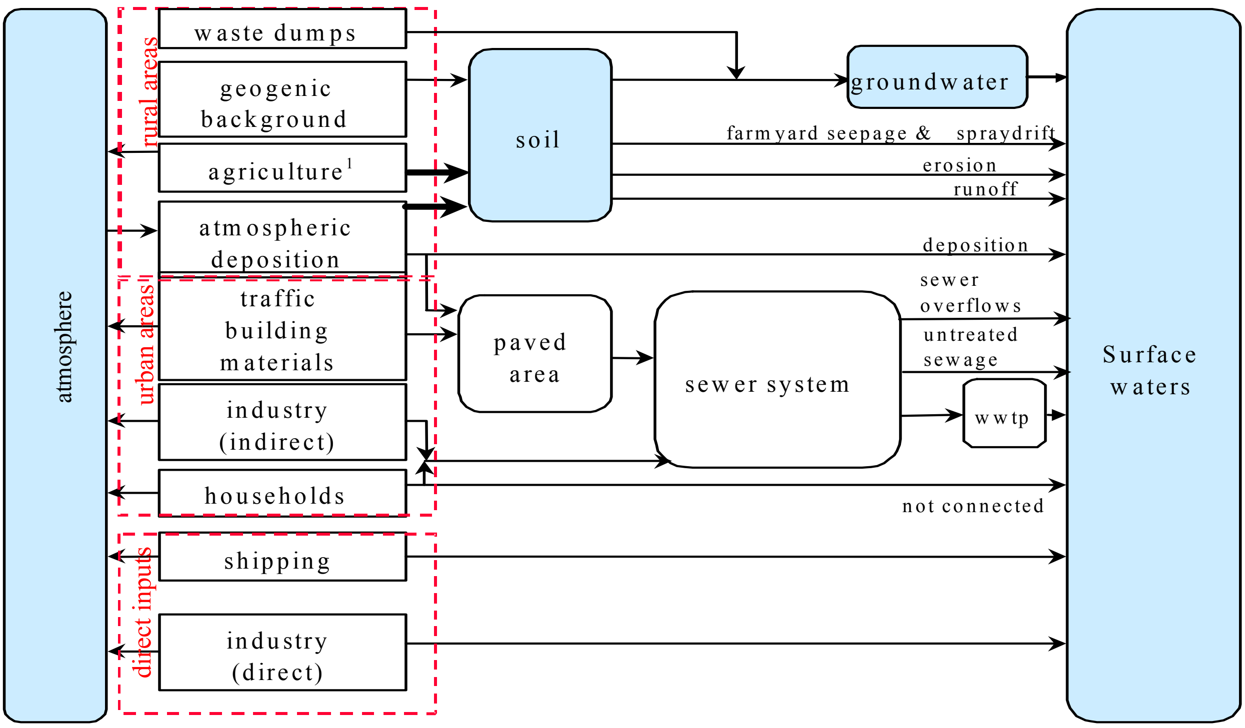

Figure 1 – *Fluxes of materials from point and diffuse sources in a river basin* (modified from Eisma, 2003).
[1]Includes application of fertilisers, sewage sludges and biowastes onto agricultural land and the resultant discharges into surface waters (e.g. through erosion processes).

There are a variety of different nutrients and contaminants that can be supplied to waters (both surface and groundwater) that derive from the erosion of soils (Table 1). Many of these nutrients and contaminants do not occur naturally within the soil (such as ^{137}Cs – which is derived from the atom-bomb tests and the Chernobyl incident) or are present in soils in elevated concentrations due to applications of wastes (e.g. sewage sludges or biowastes) or artificial inputs associated with farming and forestry practices (such as the application of phosphorus-based fertilisers). Most of the nutrients and contaminants listed in Table 1 tend to be elevated in the surface layers of the soil profile: often in the upper 0-5 cm. This reflects either atmospheric deposition (as in the case of fallout radionuclides) or artificial inputs to the soil surface, and the fact that many chemicals are sediment-associated and thus sorb tightly to soil particles (both mineral and organic) in the top layers (Owens *et al*., 1996; Haygarth *et al*., 1998). Surface erosion processes such as rain-splash detachment, overland flow and associated rill, inter-rill and gully erosion, then export the contaminated sediment to the river system. Certain land management operations such as ploughing may, however, alter the depth distribution of contaminants (Owens *et al*., 1996; Haygarth *et al*., 1998) and this will have an effect on the delivery of contaminants to waters due to soil erosion.

Contaminant	Sources
Metals (Ag, Cd, Cu, Co, Cr, Hg, Ni, Pb, Sb, Sn, Zn, As).	Geology, mining, industry, acid rock drainage, sewage treatment, urban runoff, agriculture.
Nutrients (P, N).	Agriculture, forestry, urban runoff, wastewater and sewage treatment.
Organic compounds (pesticides, herbicides, hydrocarbons).	Agriculture, industry, sewage, landfill, urban runoff.
Xenobiotica and antibiotics	Sewage treatment works, industry, agriculture.
Radionuclides (^{137}Cs, ^{129}I, ^{239}Pu, ^{230}Th, ^{99}Tc).	Nuclear power industry, military, geology, agriculture.

Table 1 - *Some of the main sources of sediment-associated contaminants to waters that can be derived from the erosion of soils and river banks (modified from Taylor, 2003).*

It is important to recognize that studies (e.g. Russell *et al*., 2001; Chapman *et al*., 2003) have shown that there are also subsurface pathways by which eroded sediments and contaminants (both sediment-associated and in dissolved form) move through the soil and are delivered to surface waters (and groundwaters), and some of these are shown in Figure 2.

In addition, the erosion of channel bank material is also a major source of sediment-associated contaminants in rivers, and should not be neglected. Work in the UK has demonstrated that typically between 10 and 40% of the suspended sediment load of rivers may be derived from channel bank sources (Owens *et al*., 2000), even in large urbanised river basins (Carter *et al*., 2003). Material eroded from channel banks is delivered directly into the river channel and thus often represents an immediate problem. The relationship between soil erosion on land and the contamination of surface waters is more complex due to sediment deposition and uncertainties associated with sediment delivery ratios.

Furthermore, some of the eroded material that is delivered to rivers in agricultural and forested catchments is relatively "uncontaminated" and *becomes* contaminated within the river by dissolved discharges from point sources (such as sewage treatment works), which subsequently sorb onto the "clean" sediment. Indeed, most river systems require a certain amount of uncontaminated sediment, nutrients and certain trace elements for sustainable geomorphological and ecological functioning.

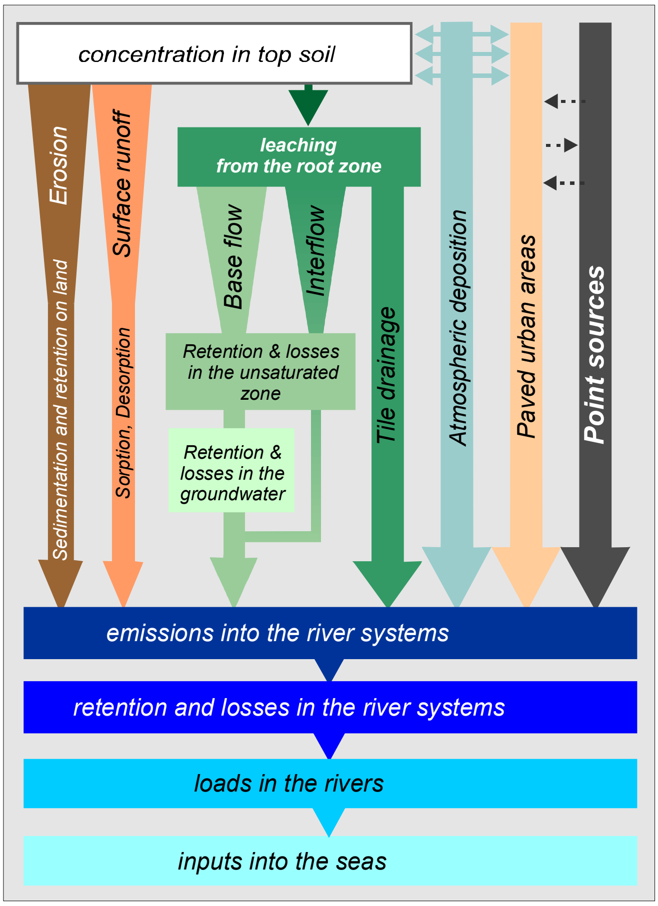

Figure 2 – *Pathways of sediment and contaminants to rivers based on the MONERIS model (Eisma, 2003).*

Once the sediment-associated contaminants enter the river there are many opportunities for deposition and storage, such as on the channel bed, on floodplains (see Table 2) and in lakes and reservoirs. Thus, Kronvang *et al.* (2003) document the presence of 19 pesticides (old and modern) and nine heavy metals in the channel bed-sediments of 30 lowland streams in Denmark. Further downstream, these contaminants may be deposited in harbours, estuaries and oceans (Power, 2002; Scherer *et al*., 2003). Important here is not only the fact that the contaminated sediment may have implications for water quality and habitat/ecological quality (Adami *et al*., 1997; Power, 2002; DEFRA, 2003) within the river corridor and further downstream, but also that such deposition on floodplains during overbank flooding results in the *creation* of contaminated soils: contaminated soils that were derived from the erosion of the land upstream and subsequently transported (perhaps with a subsequent increase in contaminant content from point sources) and deposited on the floodplain surface. In time, channel bank erosion may reintroduce this material into the river channel.

Material	Mean annual load (t year^{-1})		Mean annual floodplain deposition flux (t year^{-1})		Mean annual conveyance loss to floodplain storage (%)	
	River Swale	River Aire	River Swale	River Aire	River Swale	River Aire
Suspended sediment	45158	18462	16894	8604	27	32
Cr	1.17	2.51	0.33	0.25	22	9
Cu	3.66	2.76	0.86	0.38	19	12
Pb	29.40	3.66	24.49	1.30	45	26
Zn	32.51	9.99	17.50	2.43	35	20
Total-P	62.54	120.21	9.83	11.48	14	9

Table 2 – *Estimates of the deposition and conveyance losses of sediment and associated contaminants on the floodplains bordering the main channels of the River Swale (1346 km^2) and River Aire (1002 km^2), Yorkshire, UK (from Walling and Owens, 2003).*

An important consideration in the link between soil erosion and the contamination of waters is the well-documented relation between particle properties and size, and contaminant concentration, and the fact that sediment erosion and transport processes are particle size dependent. It is known that, for many contaminants, concentrations increase with a decrease in particle size or increase in specific surface area (Horowitz, 1991) (see Figure 3). Clay minerals have negative residual charges and this results in their ability to adsorb cations. Thus, most contaminants are concentrated in the <63 µm, and particularly the <2 µm, fraction. Equally, fine sediment particles are generally more easily transported than sand-sized material. In consequence, during the soil erosion-sediment transport process, fine (and consequently more contaminated) material is transported preferentially compared to contaminant-poor coarser material.

However, the situation just described is complicated by the fact that there is an increasing body of evidence for freshwater systems that demonstrates that most sediment it transported as composite particles (a mix of mineral particles, organic material, air and water, bound together) and not as primary individual grains (Droppo, 2001). This has important implications for sediment-associated contaminant transport and deposition within rivers.

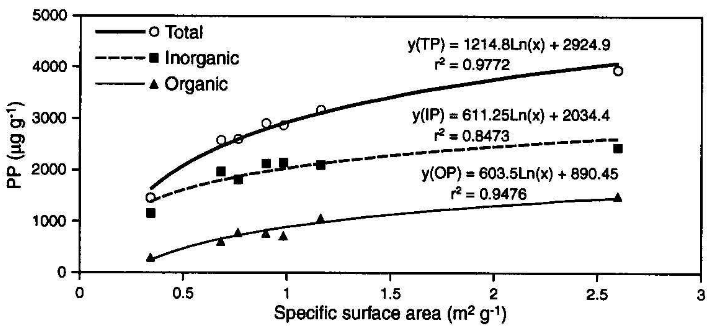

Figure 3 – *Relation between particulate phosphorus content and specific surface area based on a fractionated suspended sediment sample (from Owens and Walling, 2002).*

Both soil erosion and the delivery of sediments and contaminants from land to waters are highly variable in both time and space. This spatial and temporal variability makes it difficult to predict and model with certainty the precise link between soil erosion and the contamination of surface waters. It also makes the development of appropriate management strategies more complex. However, the literature on the general causes and processes of soil erosion and sediment delivery within Europe is reasonably substantive (e.g. Boardman *et al*., 1990; Rickson, 1994), and we know conceptually most of the main sources of those pollutants associated with diffuse contamination of waters due to erosion processes. Thus, broad recommendations could be made to reduce soil erosion and the associated diffuse contamination of surface waters in European river basins.

2. Soil erosion and links to air quality and contamination

Several studies carried out in different European countries during the last few years have clearly demonstrated the significance of wind erosion as a predominant land degradation process (U.K.: Davies, 1993; Belgium: Poesen *et al*., 1996; Netherlands: Eppink and Spaan, 1989; Germany:

Schäfer and Neemann, 1990, Schäfer *et al*., 1994; Denmark: Hansen, 1983; Poland: Podsiadlowski and Walkowiak, 1999; Sweden: Jönsson, 1992; Hungary: Kertesz *et al*., 1990). For a useful review see Gross (2002). As with soil erosion by water, wind erosion is particle size selective so that finer soil particles are preferentially eroded and transported greater distances, often tens or hundreds of kilometres (Harrison *et al*., 1996), than coarser material. Also, as described earlier, finer sediments tend to have higher concentrations of contaminants compared to parent soil due to their affinity for contaminant sorption. For example, the amount of pesticides can be up to ten times higher in the fine particle fraction than in the topsoil as a whole (Fritz, 1993).

Apart from on-site effects, emitted soil dust also causes significant off-site damages from deposition in adjacent ecosystems and is suspected to have impacts on human health. The chemical substances contained in the fine particle fraction contaminate surface waters and groundwaters and cause eutrophication in these ecosystems. This process is becoming increasingly important in Northern Europe, which is characterised by (1) the use of large amounts of fertilisers, manure and pesticides and (2) the increasing contamination of arable soils by the atmospheric deposition of various pollutants (heavy metals, dioxins, radionuclides, organic pollutants, xenobiotica, etc). The spread of pollutants via fine particle erosion of contaminated arable land has not yet been fully quantified, but must be considered important. Schulz (1992) proposed a value of 100 ng TEQ kg^{-1} for dioxin-contaminated arable land due to wind-induced emission of fine soil particles.

The impact of soil-derived aerosols on human health has not yet been thoroughly studied. However, recent research by Norton and Gunter (1999), Prospero (1999), Pope *et al*. (1999) and Rutherford *et al*. (1999) showed a clear link between atmospheric soil dust and the occurrence of respiratory problems (e.g. asthma). In the northern part of The Netherlands, an increase in health problems during and shortly after dust storms has been reported by Knottnerus (1985) and Nijf (1987). Fine soil particle emission may also play an important role in the spread of plant and animal diseases (Bout 1987, Pimentel *et al*., 1995).

3. Application of biowastes and sewage sludges to land and the effects on soil, water and air quality

This Report has primarily focused on the link between soil erosion and the contamination of waters (and air). It is also important to recognise that there is an important link between the application of contaminated wastes (such as biowastes and sewage sludge) to soils and the effect that this may have on soil erosion. In turn, the application of contaminated wastes may increase the risk of diffuse contamination of waters (and air), by altering the susceptibility of the soil to erosion and by increasing the level of contaminants in the soil. Under certain circumstances, the application of organic matter can reduce soil erosion by, for example, increasing soil binding and aggregation. However, contaminated wastes may increase erosion by altering soil hydrology and the stability of the soil. Particularly important is the need to consider the timing of waste application in relation to soil type and to the management of the land. Thus, for example, if a soil needs to be ploughed to incorporate certain wastes, then this must be done so as not to increase the risk of erosion.

Indeed, there is much concern over the likely consequences of the application of wastes to land (LABO, 2004). Some recommendations are listed in Appendix A.

4. Information and needs

There is probably a reasonable amount of evidence in Europe to suggest a strong link between soil (and channel bank) erosion and the subsequent delivery of contaminated material to surface waters (and probably groundwaters). Similarly we have plenty of evidence relating to the existence of contaminated sediment (transported and deposited) in European rivers. We also have evidence from tracing and fingerprinting studies to show that much of this sediment is derived from the erosion of the land surface. We are, however, lacking detailed information in Europe on:

- Accurate fluxes of sediment and associated-contaminants *between* the land and rivers
- Estimates of the contribution of soil erosion to river sediment and contaminant loads
- The role of aggregation and flocculation on sediment and contaminant transport
- Accurate estimates of basin-scale storage of sediment and contaminants in rivers systems
- Role, design and location of topographic and buffering features for controlling delivery
- Detailed information on the contamination of the atmosphere from surface erosion processes; and
- The link between the application of wastes to land and the effect of this on soil biology, hydrology and erosion potential.

5. Conclusion

Clearly, soil erosion, by water and wind processes, has implications for the quality of soils and their ability to perform important soil functions, in particular the ability to sustain agricultural and forestry production. As such, soil erosion represents a key component of the EU Soil Thematic Strategy and national policies and initiatives (DEFRA, 2004). In addition, soil erosion and the delivery of contaminants to water and air influence the quality of surface waters, groundwaters and air, and, in turn, freshwater ecosystems and human health. In this respect, soil erosion on land and the erosion of river banks have important implications for the ability of Members Countries to implement and comply with the EU Water Framework Directive (2000/60/EC).

6. Sources of information and acknowledgements

Some of the ideas presented in this Report stem from the EU-funded European Sediment Research Network (SedNet), and in particular SedNet Work Package 2 - *Sediment management at the river basin scale* - and thanks are due to Ramon Batalla, Marc Eisma, Heinz Glindemann and Kevin Taylor for inputs. Further information on SedNet and WP2 can be found at www.sednet.org. Thanks are also extended to Arnold Arnoldussen, Holger Böken, Olaf Düwel, Rob Jarman and W. Schäfer and members of the soil erosion working group for helpful advice and information.

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Appendix A

The members of the Working Group on Soil Erosion recommend the following.

To safeguard soils in good conditions on a long term and sustainable basis and to effectively protect neighbouring water bodies and other ecosystems, exogenic organic matter (EOM) should only be applied for the improvement of the soil's resilience against erosion in accordance with the following principles:

(a) The application of EOM must not introduce new pollutants or other hazardous substances into the soil nor must the application of EOM lead to a long-term accumulation of pollutants or other hazardous substances in the soil.

(b) When EOM is applied, a parallel monitoring programme for pollutants and hazardous substances must be established. There may be exceptions for the use of on-farm applications of EOM (e.g. animal manures), which stay in a closed circle within the farm system. For some substances (e.g. xenobiotics, antibiotics) a 'start-of-pipe' solution will be required, since hazards to soil-borne organisms may occur while the active substances are not detectable/traceable in the soil. In some areas in Europe, the phosphorus levels in soils may also limit the applicability of EOM to avoid over-fertilisation and the diffuse contamination of surface waters.

(c) Since wind and water erosion processes may lead to the transfer of the pollutants of applied EOM, certain sources of EOM (especially sewage sludges and biowaste composts) should not be applied to soils at risk of erosion (wind or water), or in areas in the immediate vicinity of sensitive environments, so as to minimise the risk of the contamination of surface waters, groundwaters and air.