SedNet
European Sediment Research Network

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Contaminated Sediments in European River Basins

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Executive summary

Sediments originate in river basins mainly through land and channel erosion processes and are transported in river systems in the direction of the coast, with the oceans being the final sink. Thus land use, climate, hydrology, geology and topography determine sediment supply and transport in rivers. In the river system, temporary deposition can take place. Important in this respect are floodplains, reservoirs and lakes. In many regulated rivers, sediments are trapped behind dams and reduce the sediment supply downstream. Important impacted areas downstream include wetlands, deltas and harbours. Hence, sediments, like water, are a highly dynamic part of river systems: it is not tied to a particular area and is transported through countries in the same river basin.

Besides quantity, quality of sediment affects downstream areas. In particular, the presence of contaminants, such as heavy metals, nutrients pesticides and other organic micro-pollutants, threatens the good ecological status of waterways, wetlands and estuarine systems, which is the focal point of the European Water Framework Directive. In addition, the removal of contaminated sediments from waterways and harbours, to ensure their navigability, imposes high costs for the regulatory and responsible authorities at the local level.

The European Sediment Research Network - SedNet[1] - is commissioned by EC DG-Research in order to (main objective) set up a thematic network, initially aimed at the assessment of fate and impact of contaminants in sediment and dredged material and aimed at sustainable solutions for their management and treatment. Hence, between 2002 and 2005 scientific, policy and regulatory aspects of contaminated sediments and dredged material were addressed in 17 workshops and 3 conferences organised by SedNet. Europe's leading scientists and major sediment managers contributed to these SedNet activities. The results are summarised in this booklet, in the annexes on the enclosed CD-ROM and at the SedNet website (www.SedNet.org). The comprehensive results will be published in 2005 by Elsevier as a series of four books.

This booklet gives a short, state-of-the-art overview of the main scientific, policy and regulatory issues on contaminated sediments, based on the results of the SedNet network activities. In particular, this booklet describes the main sources, transport processes and impacts of contaminated sediment and describes the main methods used to evaluate (including chemical analysis, bioassays and impact assessment) and manage (such as treatment, disposal and beneficial uses) contaminated sediment in river basins. The booklet also presents the main policies and regulations that relate to contaminated sediment (including the EU Water Framework Directive) and describes recent developments in sediment management, such as the move towards the basin-scale approach, the use of risk-based management and the need for stakeholder participation in the decision-making process.

As a result of the activities of SedNet, and especially the workshops and conferences, SedNet has developed the following main recommendations:

- *Towards European policy development*: Further develop and eventually integrate sustainable sediment management into the European Water Framework Directive and related policy and legislation

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[1] Project acronym: SedNet; European Commission (EC) contract No. EVK1-CT-2001-20002; EC 5th RTD Framework Programme; key-action: 1.4.1 "Abatement of water pollution from contaminated land, landfills and sediments".

- *Towards sediment management*: Find management solutions that carefully balance social, economic and environmental values and are set within the context of the whole river system
- *Towards research*: Improve our understanding of the relation between sediment contamination (hazard) and its actual impact to the functioning of ecosystems (ecological status) and develop strategies to assess and manage the risks involved

More specific recommendations are given in Chapter 6.

Extended summary

Sediment

Sediment is an essential, integral and dynamic part of our river basins. In natural and agricultural basins, sediment is derived from the weathering and erosion of minerals, organic material and soils in upstream areas and from the erosion of river banks and other in-stream sources. As surface-water flow rates decline in lowland areas, transported sediment settles along the river bed and banks by sedimentation. This also occurs on floodplains during flooding, and in reservoirs and lakes. Often the natural sedimentation areas are severely restricted, e.g. because of embankments and the loss of flooding areas as a result of these embankments. At the end of most rivers, the majority of the remaining sediment is deposited within the estuary and in the coastal zone. Natural river hydrodynamics maintain a dynamic equilibrium, regulating small variations in water-flow and sedimentation by re-suspension and resettlement. In estuaries, sediment transport occurs both downstream and upstream, mixing fluvial and marine sediment as a result of tidal currents.

Its value

Sediment forms a variety of habitats. Many aquatic species live in the sediment. Microbial processes cause regeneration of nutrients and important functioning of nutrient cycles for the whole water body. Sediment dynamics and gradients (wet-dry and fresh-salt) form favourable conditions for a large biodiversity, from the origin of the river to the coastal zone. A healthy river needs sediment as a source of life. Sediment is also a resource for human needs. For millennia, mankind has utilised sediment in river systems as fertile farmland and as a source of construction material.

Contamination

Sediment acts as a potential sink for many hazardous chemicals. Since the industrial revolution, human-made chemicals have been emitted to surface waters. Due to their properties, many of these chemicals stick to sediment. Hence in areas with a long record of sedimentation, sediment cores reflect the history of the pollution in a given river basin. Where water quality is improving, the legacy of the past may still be present in sediments hidden at the bottom of rivers, behind dams, in lakes, estuaries, seas and on the floodplains of many European river basins. These sediments may become a secondary source of pollution when they are eroded (e.g. due to flooding and channel bank erosion) and transported further downstream.

Along the course of the river to the sea, transportation, dilution and redistribution of sediment-associated contaminants occurs. Many relatively small inputs, all complying with emission regulations, accumulate to reach higher levels by the time sediment reaches the river delta. In the estuary, uncontaminated marine sediments are mixed with contaminated fluvial sediments. This natural ‘dilution’ decreases contamination level in a gradient towards the sea over short distances, but does not alter the actual transported quantity of contaminants.

Despite regular sediment quality assessment by member states, a reliable estimation of the overall amount of contaminated sediment in Europe is hard to give. The main reason for this is the absence of uniformity in sampling methods, analytical techniques and applied sediment quality standards or guideline values. This causes a lack of inter-comparability. Typically, countries along the same river basin use different methods.

Adverse effects of contamination

Contaminants can be degraded or fixed to sediment components, thus decreasing their bioavailability. At a certain level, contaminants in sediment *will* start to impact the ecological or chemical water quality status and complicate sediment management. In the end, effects may occur such as the decreased abundance of sediment dwelling (benthic) species or a decreased reproduction or health of animals consuming contaminated benthic species. Contaminated sediments remain potential sources of adverse affects on water resources through the release of contaminants to surface waters and groundwater. Furthermore, contamination adversely effects sediment management, as handling of contaminated material, e.g. in the case of dredging, is several times more expensive than handling clean material.

Clean sediment can also have environmental and socio-economic impacts. For instance, turbidity and excessive sedimentation have a physical effect on benthic life, too much sediment in navigation channels requires costly dredging, and sedimentation behind dams decreases the economic lifetime of that dam. Furthermore, dams decrease the supply of sediment needed to support downstream wetlands, estuaries and other ecosystems. SedNet focussed on contamination issues, rather than on such sediment quantity issues.

For the assessment of contaminated sediment, there is not one ‘best’ method available. Each specific management question requires a tailor-made solution. Chemical analysis can be used to determine concentrations of selected hazardous chemicals and then it can be checked if the concentrations exceed pre-defined standards or guideline values. The toxic effects of sediment on organisms can be tested by using bioassays. Through a field inventory the long-term impact on sediment biota can be investigated. These assessment methods (chemical, bioassay, field) are complementary by giving a unique answer that cannot be given by any of the individual methods by themselves. But each method also has its own unique drawbacks and uncertainties.

Dredged-material management

Many water and port managers face the continuous effort of dredging in order to maintain the required water depth. Europe-wide, the volume of dredged material is very roughly estimated at 200 million cubic metres per year. There are three types of dredging: capital, maintenance and remediation dredging. Capital dredging is for example for land reclamation, deepening fairways, etc. Maintenance dredging is mainly to keep waterways at a defined depth to ensure safe navigation, and remediation dredging is to solve environmental problems of contaminated sediments. Contamination mainly leads to problems in maintenance dredging because given standards or regulations do not allow the free disposal in the aquatic system. In general with capital dredging old, uncontaminated sediments are being dredged. There is a lot of information on the different options of dredged-material management available.

Legislation and guidance

Dredging is mainly done in the coastal or marine environment. Therefore, international guidance has existed for many years to minimise the ecological effects of dredging and open water disposal. European legislation for handling dredged material is complex, because dredged material is at the borderline of water, soil and waste policies. European legislation affects the management of dredged sediments in upland areas, like the waste legislation, especially the EU Landfill Directive, and possibly the Habitats Directive, amongst others. These EU legislations do not (as yet) deal adequately with sediment.

The EU Water Framework Directive (WFD), in force since the year 2000, does not specifically address sediment management. But it can be a tool to tackle the sources of sediment contamination. It offers an opportunity to further improve our knowledge about the relation between sediment quality and water quality and to harmonise quality assessment and sediment management on a river-basin scale.

Sediment management challenges

Sediment and dredged-material management challenges and problems relate to quality and quantity issues. Quality issues relate to contamination, legislation, perception, risk-assessment, source control and destinations of dredged material. Quantity issues mainly relate to erosion, sedimentation, flooding, the effects of damming and the resulting morphological changes downstream. Often quantity and quality aspects are interrelated: the overall umbrella is the river basin.

Quality issues

The management of contaminated sediments in Europe has been mainly the direct concern of authorities dealing with navigable waterways. Contamination can inflict severely the management of dredged sediments. The costs for the removal of excess sediment increases when it is too contaminated for unrestricted relocation. Port managers are concerned that they have to bear the extra costs for managing contamination which is derived from contributions along the river basin. The ‘polluter pays’ principle is far from being applied. The problem is left for the problem owner and there is no link to those that have caused it.

Besides complicating dredging activities per se, contaminated sediment may pose ecological risks or risks to water quality. The relation between sediment quality and risks is complex and site specific, requiring assessment methods based on bioavailable contaminant fractions and bioassays rather than results based on the traditional total contaminant concentrations. However, if sediment quality impairs the chemical or ecological status, remediation measures may be needed. So far, only in a few Member States has contaminated sediment been managed due to its impact on the ecological quality of water bodies.

An integrated approach for sediment management is presently lacking. The WFD aims at source reduction which in the long term may lead to ‘clean’ sediment quality. Next to the emissions of point and diffuse sources, a source of increasing importance in this respect is historic contamination, i.e. our legacy of the past. The diffuse sources in which such contamination is present in many European basins are becoming increasingly important. Even more now, since the risk of extreme river floods, that may wash the hidden pollution into the water system once again, seems to have been underestimated in the past.

Quantity issues

Quantity aspects were not a predominant part of SedNet activities. However, they were addressed in several of the workshops since they influence the flux of (contaminated) sediments in river basins. A selection of the issues which were discussed and which have to be taken into account in basin-wide management are:

- the use of sediments in river basins for construction materials with the result of reduced sediment supply downstream, river bed incision and the associated impacts on infrastructure (e.g. bridges etc.)
- changing land use and effects of increased erosion on agricultural soils in particular
- the effects of damming, reducing sediment supply downstream and resulting in morphological changes to floodplains and deltas

- damming and the temporal storage of upstream pollutants in deposited sediment (legacy of the past), with the consequence of further transport downstream through erosion events
- flood control measures, including controlled flooding of areas adjacent to the river, impacting sediment budgets

Last but not least, climate change and its impacts on the hydrology at the river-basin scale will affect sediment fluxes and should be anticipated in a sediment management plan.

Management options

Costly end-of-pipe solutions may be unavoidable for sediment and dredged-material management. Solutions like relocation into the aquatic system or placement on river embankments are the first options to consider, since they bring the sediment back to where it belongs. But these solutions are only acceptable if the contamination is below given standards. Depots for contaminated dredged material can be an option in this situation, but they are expensive, often lack public acceptance and are subject to complex legislation.

Alternatives include treatment for beneficial use and controlled (confined) disposal. Treatment and re-use is politically encouraged, but is currently applied only at a small scale because of the higher costs compared to disposal and the lack of product markets. However, in some cases treatment and beneficial use may be a competitive alternative for confined disposal. Confined disposal will remain the first choice solution for the time being. For the realisation of new confined disposal sites (both upland and sub-aquatic), public involvement and support are needed. In many cases the procedures are very time consuming (10-15 years) and/or the lack of public acceptance can complicate matters and their implementation.

Recommendations

The main recommendations resulting from the SedNet activities[2] towards European policy development, sediment management and research, respectively, are:

- Further develop and eventually integrate sustainable sediment management into the European Water Framework Directive
- Find management solutions that carefully balance social, economic and environmental values and are set within the context of the whole river system
- Improve our understanding of the relation between sediment contamination (hazard) and its actual impact to the functioning of ecosystems (ecological status) and develop strategies to assess and manage the risks involved

More specific recommendations are given in Chapter 6.

[2] Top-level scientists and major stakeholders contributed to the 17 workshops and 3 conferences organised by SedNet. These network events were used to identify and review the current state-of-the-art in knowledge, to identify practical recommendations and to review research needs related to specific sediment-management issues. New scenarios and concepts were debated and are currently being further underpinned. The complete results will be published in 2005 by Elsevier as a series of four books.

1. Sediment

1.1. Introduction

Sediments originate in the catchment through erosion processes and are transported in river systems in the direction of the coast, with oceans being the final sink. As such land use, hydrology, geology and topography determine erosion and transport processes. In the river system temporary deposition can take place. Important in this respect are floodplains and lakes. In many regulated rivers, sediments are trapped behind dams and reduce sediment supply downstream.

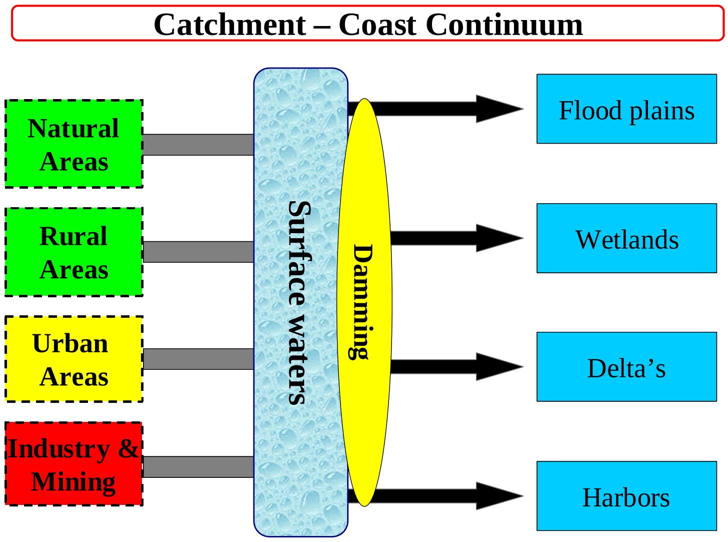

Figure 1. The Catchment-Coast continuum. Flow of contaminants, water and sediment from land, through rivers to impacted areas downstream

Important areas downstream are wetlands, deltas and harbours. The amount and the quality of sediment in the low-lying areas of the river system and in the estuary, delta and coastal zone depend on the processes in the contributing catchment. Hence, impacts on and functioning of these areas have to be considered as being part of the catchment-coast continuum (Figure 1). This section deals with erosion, transport and deposition of sediments. In addition, the function of sediment as an economic and ecologic resource and its specific role in wetlands and floodplains are discussed.

1.2. Erosion and transport

Erosion

Natural erosion is generally the dominant source of sediment in rivers. However, changes in land use, started centuries ago, have increased the rate of many erosion processes. Increased soil erosion causes an increase in sediment supply to rivers, and is also of concern for the sustainable use of soils for agriculture. Soil erosion affects large areas of Europe and it is estimated that about 17% of the total land area in Europe is affected (Oldeman *et al.* 1991). However, large differences exist in Europe, which reflect climate, land-use, topography and hydrology. In fact enhanced erosion due to deforestation, agricultural activity, urbanisation and other land-use changes is one of the most important changes occurring globally at the Earth's surface. In Europe this process has been very gradual over the last few hundred years and in most regions this additional flux is currently limited. In the most extreme cases, soil erosion, coupled with other forms of land degradation, have led to desertification in some areas of the Mediterranean. In a sense, open-pit mining is human-made erosion, since it generates loose particulate matter (tailings) likely to be disposed of in river systems, stored on land or in tailings ponds where it may be eventually remobilised. Since the rate of soil formation is very slow, any soil loss of more than 1 tonne/ha/year can be considered as irreversible within a time span of 50–100 years (EEA 1998).

Transport in the river system

As soon as soil particles are mobilised and transported, they can be deposited at the plot scale, on slopes and piedmonts. A major proportion of the coarse material (> 2 mm) derived from mechanical erosion from the upper river course does not travel very far from its source except in mountain catchments or during extreme floods. As such there is a difference in the amounts eroded from soils as well as a time delay before the actual delivery to the main channel. In channels the incision of the river bed can be a major secondary source of river sediment. Also, within the river system there is a continuous remobilisation of deposited material from the lateral erosion of alluvial deposits.

Natural sediment traps include lakes and floodplains during high water discharge. River bed deposition occurs during low flows but is not permanent. It may last for a few years, particularly for successive dry years in Mediterranean regions, but this deposited material is eventually remobilised and transported further downstream.

Sediment transport depends on the water discharge of the river system. However, for a given river catchment size there is often a large temporal difference in the amount of sediment transported. Often sediment transport occurs in pulses. This effect is most pronounced for smaller catchments (up to 500 km^2), where 50-90 % of the annual sediment flux is transported during periods of days to weeks. In the largest basins (exceeding 100,000 km^2), this effect still occurs, but is far less pronounced. Hence small basins or tributaries of larger basins are more subject to pulses of sediment flux compared to the total sediment flux from large basins. This feature has to be taken into account for the transport of contaminants.

Transport in estuarine and coastal environments

In the estuarine zone most of the river-borne sediment is deposited, and only a relatively small proportion of the fine sediment load eventually reaches the open sea, where it finally settles. In areas with limited tidal range and little or no offshore currents (such as the Mediterranean and Baltic) most of the sediment in estuaries and deltas are of river origin.

In estuaries with large tides this balance of sediments is reversed and there is a very little export of fluvial material, but on the other hand there is a net trapping of material originating from coastal and seabed erosion. This net trapping of sediment from the marine environment results in major dredging activities to allow for continued access of waterways for shipping. These estuaries can be divided in three parts, based on the dominance of fluvial or marine processes.

In the fluvial or upper part, fluvial sediments dominate. Although sediment quantities to be removed for navigational purposes may be low, in the case of emission sources in the catchment their contamination is comparatively higher. In the middle part of the estuary is a deposition area with a mixture of (uncontaminated) marine and fluvial sediments. The ratio of marine to fluvial sediments in this area depends on the discharge characteristics of the river. Hence, as a result the quality of sediments in this part of the estuary can change seasonally. During periods of low discharge (such as summer), the marine sediments with their lower contaminant load dominate, although with higher discharge the fluvial sediments are transported further into the estuary and hence the contamination in the middle estuary increases. The deposition (trapping) of marine sediments is predominantly in the lower or marine estuary. The outer part, where most of the dredging takes place, receives mainly clean sediments from the sea. The regional classification of estuarine dredged material in contamination categories reflects this natural process of the mixing of marine (relatively clean) and fluvial sediments (contaminated). Figure 2 shows this regional classification for Rotterdam harbour.

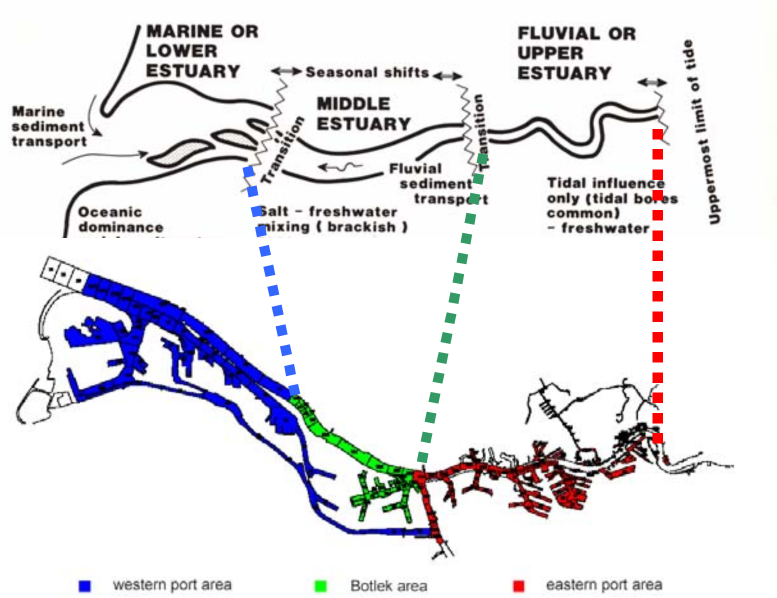

Figure 2. The classification of estuaries and the corresponding classification of dredged material (example Rotterdam harbour).

In the Humber estuary most of the estuarine sediment is not derived from the contributing rivers but instead derives from the marine environment. In fact this situation is predominant in many of the estuaries and harbours bordering the North Sea.

Impacts of damming on sediment transfer

Damming has become a practical necessity and has provided huge benefits to agriculture, industry and urban development. The report of the World Commission on Dams (2000) has highlighted the scale of human intervention of ecosystems by the construction of large dams. Dams, inter-basin transfers and water withdrawals for irrigation have fragmented over 60% of the world's rivers and changed the sediment load of rivers to the coastal sea.

In Western and Northern Europe reservoirs can be found in many catchments depending on their main purpose: hydroelectric reservoirs are common in Scandinavia and in the Alpine range from France to Slovenia, as well as in medium-high mountains (Tatra, Carpathian). Reservoirs of various sizes have been constructed in the Vistula, Elbe, Seine, Danube and Humber catchments. However, the greatest density of reservoirs is found in the Mediterranean basin (Spain, southern Italy, Sicily, Greece). New reservoir cascades are planned in Greece and on the lower Vistula. In the African or Asian parts of the Mediterranean basin (Algeria, Tunisia, Turkey) reservoirs are also very common.

These reservoirs are human-made sediment traps in which more than 90% of the sediment transport of an incoming river can be stored when the residence time of the water exceeds two months. For the impact of damming on the global water and sediment flux, quantitative estimates have recently been made. Globally, large reservoirs intercept more than 40% of global water discharge, and approximately 70% of this discharge maintains a sediment trapping efficiency of more than 50%. It is estimated that about 25 to 30% (4-5 Gt year $^{-1}$) of the sediment flux to the coastal sea is trapped behind dams. One of the positive environmental effects is the trapping of contaminants associated with sediments and thus the protection of downstream areas. An example is the Vistula catchments, where damming traps contaminants from upstream industrialised areas.

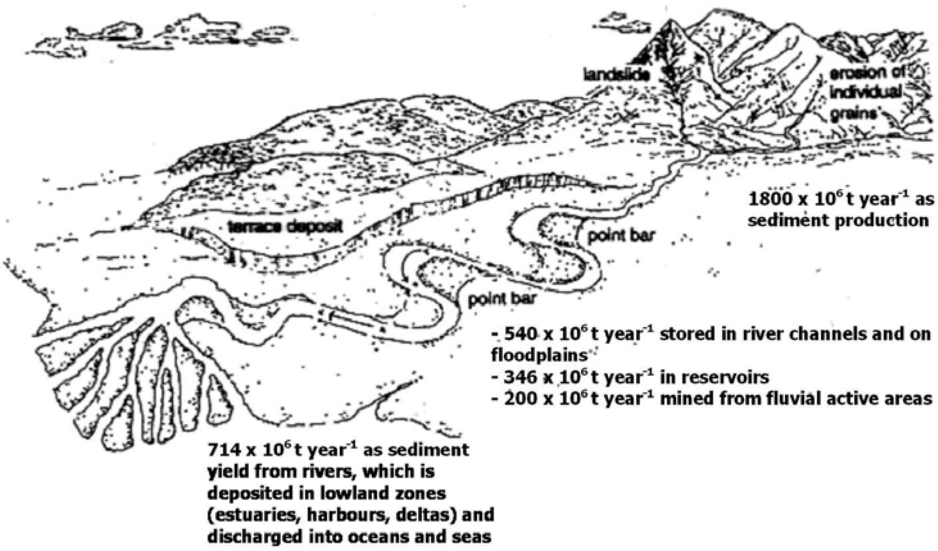

Figure 3. Tentative sediment budget for Europe (Owens and Batalla 2003)

However, damming affects the hydrology and morphology of the river downstream. The sediment-starved water causes rivers to degrade (downcut) into the river bed until a new equilibrium has been reached. The decrease in sediment supply also causes coastal zones to change from accretion to erosion, which affects coastal morphology. Resources like floodplains and wetlands are similarly affected.

1.3. Deposited sediments

Introduction

Once sediments become deposited in wetlands, floodplains, deltas and also in the bottom of lakes and reservoirs, they have important ecological, social and economic value (i.e. the functions of sediment). In the case of navigable waterways and harbours, deposited sediment can have a severe impact on shipping and may require dredging.

Too little or too much sediment in the catchment-coastal sea system has impacts on its functions. Table 1 gives on overview on the functions of sediment and possible impacts of changes in sediment delivery. In the next sections some of these functions will be highlighted.

Table 1. Overview of sediment as a resource (Martin 2002).

Too much sediment	Too little sediment	Sediment as a resource
Obstruction of channels	Beaches erode	Construction material
Rivers fill and flood	Riverbanks erode	Sand for beaches
Reefs get smothered	Wetlands are lost	Wetland nourishment
Turbidity	River profile degradation	Agricultural soil enrichment

Biology of sediments: Ecological function

The bottom sediments of lakes, streams, ground waters and wetlands host an enormous diversity of biota (Palmer et al. 2000). Global biodiversity is estimated at more than 100,000 benthic invertebrate species, 10,000 species of algae and more than 20,000 species of protozoans and bacteria. Biodiversity in aquatic sediments is poorly known, particularly for the smallest biota. This group is difficult to sample, as it is microscopic and often lives deep within the sediment. Species richness of freshwater sediment biota varies considerably between wetlands (locally up to 1500 invertebrate species), lakes and streams (locally approximately 80 – 1000 species) and ground waters (locally 0 – 150 species). Local diversity also varies over time, with, for example, low diversity in streams during flood season and high levels of diversity across the entire year.

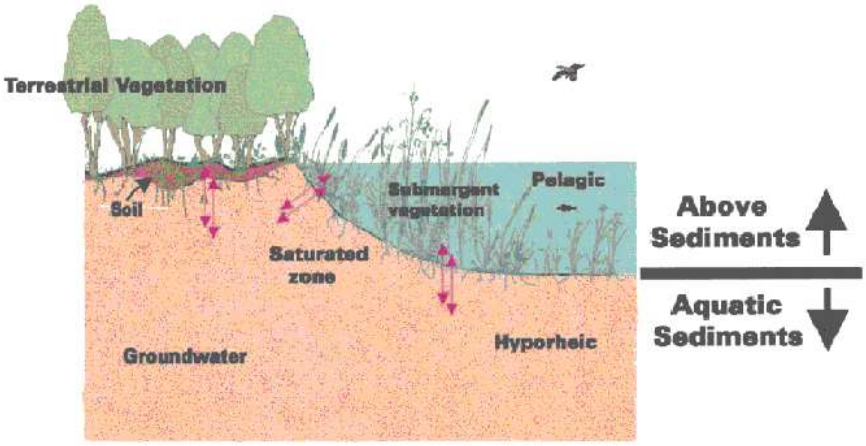

Figure 4. Location of above sediment and aquatic sediment habitats (pelagic = living in the water column, hyporheic = saturated sediment zone) (Palmer et al. 2000).

Figure 4 illustrates the location of habitat types that are considered above sediment and those considered as aquatic sediments. Sediment biota may be defined as those organisms living within, on or closely associated with aquatic sediment at some stage of their life. The distribution between 'above' and 'within/on' sediment, is not as obvious, especially not in high-energy streams and rivers where the distinction between the water column is less clear and more variable in time.

Because species-specific information is typically lacking for sediment biota, a functional group approach is useful for examining the interactions among aquatic sediment organisms and those living above sediment. Many aquatic sediment species are likely to play important functional roles in freshwater ecosystems. Sediment biota not only mediate biogeochemical transformations of global significance, but are essential for the maintenance of clean water, the decomposition of organic material (often added in excess to our water bodies), the uptake and transfer of materials including sediment-bound contaminants and primary production.

The species composition and distribution of sediment-dwelling organisms are influenced by several factors. Important factors are: water flow, sedimentation rate and water oxygen content (reduced flow, enhanced sedimentation and lowered oxygen content may reduce diversity), presence of aquatic plants (plants increase species richness and abundance), the quality and quantity of water input of plant litter (i.e. a food resource for benthic life), pelagic predators (e.g. by bottom feeding-fish and predatory invertebrates), planktonic algae and bioturbation (as it alters the flux of nutrients and oxygen in the water column).

Upland sediments: Wetlands

Rivers act as "sediment conveyor belts" (Morisawa 1985), which start from the erosion of soils, landslides etc., towards their ultimate transfer to the coastal sea. In the river system itself sedimentation leads to a temporary but often long-term loss of suspended matter from the flowing water to the floodplain. Changes in land use, mining, urbanisation and industrialisation in the upstream river basin strongly affect the quantity and quality of the sediments delivered to river channels. Sediment throughput along a river stretch is a function of sediment load, flow conditions and retention in the river corridor, which together result in a substantial variability among and within rivers in Europe.

Sediment retention in the main channel of a river is often limited, and flooding events are more important and often lead to reduced annual sediment transport due to sedimentation on floodplains. Depending on the extent of the flooding and the topography of the floodplain, sorting of the grain size of the deposited sediments takes place. Laterally, increasingly fine matter settles in backwaters and lower marshes and at greater distances from the main river channel. Longitudinally, finer particulates travel the furthest downstream. Vertically, graded soil profiles on floodplains show successive flooding events with fine material overlying initially deposited coarser gravels. This sorting generates spatial patchiness and gradients in soil structure and fertility, and hence creates a wide variety of habitats for biota in an attractive, heterogeneous landscape scenery.

Sedimentation also brings nutrients to the floodplain. Phosphorus is mainly carried in particulate form, but also nitrogen is delivered in different forms to floodplain habitats. Dissolved forms of

Managed realignment (new coastal wetlands) and its role in management at the catchment level: The Humber Case

Wetlands are composed of sediments and require for their functions a continuous supply of sediments. Apart from their role as important habitats they provide a filtering function for nutrients (denitrification) and contaminants (heavy metal immobilisation through sulphide formation) as well as a role in coastal protection (soft defence). A detailed study in the Humber investigated their role as part of the catchment-coastal sea continuum. This study looked at the cost of upgrading wastewater treatment plants, cost to farmers (loss of income) for implementing the Nitrate Directive versus the cost of creating additional wetland areas in the Humber estuary, which can also provide nutrient retention. In addition, the creation of wetlands will bring down the cost of additional hard defences (dikes) in the estuary against sea level rise. The criteria for nutrient reduction were the OSPAR guidelines.

The main outcome of this three-year research study was:

✓ Managed realignment, if implemented on a reasonably large scale, could be an effective way of improving the water quality of the Humber estuary. In the scenarios outlined above, farming practices throughout the ca. 25,000 km^2 of the catchment would have to be radically changed in order to achieve reductions in concentrations of nutrients throughout the estuary comparable to those realised by creating 75 km^2 out of a total floodplain area of 900 km^2 of new intertidal area around the estuary and tidal rivers by realignment of flood defences.

✓ Measures to tackle diffuse nutrient pollution from agriculture are more cost-effective than upgrading/construction of tertiary treatment. This is particularly the case for nitrogen and may also apply to phosphorus.

✓ Managed realignment has a number of environmental benefits (habitat creation, carbon sequestration, etc.) the value of which can more than offset of the costs associated with this option and can result in substantial positive net present values.

This research study shows that sediments play an important role in the catchment-coast continuum, and understanding their functioning is an integral part of its management. In this case cost-benefits could directly be assigned to: nutrient reduction, coastal defense and carbon sequestering. Apart from that, other values include the creation of valuable wetlands as well as a recreational area.

nitrogen will only be retained in stretches where flow is sufficiently low to allow for plant and algal uptake or denitrification. However, in certain systems like the Rhine, nitrogen is mainly carried as dissolved nitrate, and retention is negligible.

The highest sediment deposition rates are generally found where flow is reduced, such as in reed marshes (high surface roughness) or in deep ponds. Marshes, ponds and other depressions in floodplains therefore silt up comparatively rapidly, leading to vegetation succession and adding to spatial heterogeneity. On the floodplains of the River Rhine in the Netherlands contemporary sedimentation rates of overbank fines are estimated to be in the order of 0.5 – 3.5 mm per year (Middelkoop 1997).

River floodplains have attracted humanity well before the Neolithic because of the ample availability of natural resources, especially fertile soils and relatively flat land for agriculture. Early in history, river corridors also became pathways for trade, and at least since the Roman era engineering works have been carried out to improve flow for navigation and provide an increase in safety from flooding. In The Netherlands, for example, a closed system of dikes existed along the branches of the River Rhine since about 1350 AD.

Large-scale embankment, however, concentrates flow and sedimentation into a narrow floodplain strip and aggravated flood consequences after dike failure. In addition, the main channel of the Rhine and many other large rivers have been engineered extensively to maximize navigability as well as aid the transport of high water peaks. This has generally increased flow rates and hence the proportion of sediment that remains suspended.

Together with sediments, floodplain wetlands also receive particle-bound pollutants such as heavy metals. Middelkoop (1997) estimated for 1993 that 10% of the annual heavy metal load of the Rhine was deposited on its floodplains. A historical heritage of more heavy industrial pollution from the past is present in the soils of most central European river floodplains. This has led to concern for the breeding success of top predator birds such as the little owl (*Athene noctua*, Van den Brink *et al*. 2003) that largely feed on earth worms and voles.

In conclusion, sediments in river floodplain wetlands (a) serve as an important template for habitat differentiation through spatially variable sorting and settling, (b) contribute to the necessary nutrients to maintain a high floodplain productivity, and (c) allow for rapid autogenic succession and transitions between habitats.

Sand and gravel extraction

In lower and medium river courses the alluvial plain is the main source of sand and gravel extracted for the construction of roads and buildings. This river material, which often corresponds in European catchments to sediment deposited some 10,000 to 6,000 years ago after the end of the last glacial period, is not regenerated today in most river catchments. In some catchments the present excavation of fossil sand is more than 50 times greater than the present river sediment flux, as for the Seine River (50 million tons excavated per year versus 700,000 tons transported by the river to the coast).

The total market for Europe has been estimated to vary between 2000 and 3000 million tonnes/year (Harrison 2003). This amount is in the same order of magnitude as the natural sediment delivery to rivers in Europe of 1800 million tonnes/year (Figure 3). Not all the sand and gravel is from recent deposits, and older sedimentary deposits in particular will often be mined. SedNet estimated that roughly 200 million tonnes is mined from active fluvial areas (Figure 3), which accounts for about 10% of the total of sand and gravel mined in Europe.

Apart from its use as construction material for off-shore construction such as airports or harbour extensions, sand is also used for beach nourishment.

2. Sediments and contaminants

2.1. Introduction

Contaminants enter the river system through various pathways. A distinction can be made between rural areas, urban areas and direct inputs. Input from rural areas is through erosion of soils, channel bank erosion, waste dumps and indirectly from atmospheric deposition on soils. Urban areas contribute through leaching from building material and from sewer systems. Direct inputs are derived from industry, shipping etc. (Figure 5).

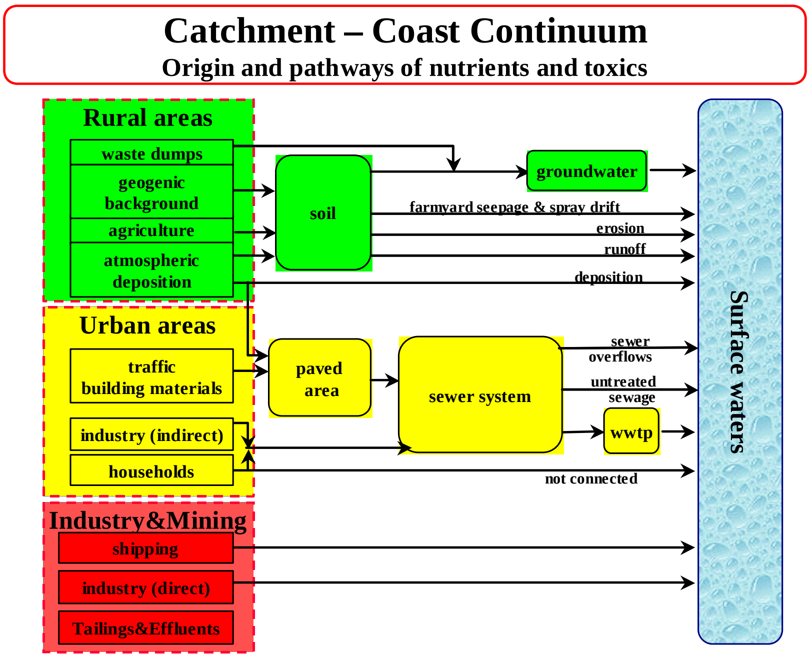

Figure 5. The Catchment-Coast Continuum: a generalized overview of land use and pathways of contaminants 9wwtp = waste water treatment plant)(Vink and Berendt 2001, Vink 2002).

In this section an overview is presented on the various sources of contaminants, their transport, and their relationships with hydrological conditions. In particular, the latter determine the contribution of the various sources and whether contaminated sediments remain in the riverbed or become more widely distributed over floodplains and wetlands. Furthermore, examples of the impacts of contamination are given and the assessment of contaminated sediment is addressed.

2.2. Sources of contaminants

A common distinction is between point and diffuse sources of pollution; a distinction which reflects their behaviour under changing meteorological conditions (Vink and Berendt 2001):

- **Point sources** are identifiable points that are (fairly) steady in flow and quality (over the time scale of years). The magnitude of pollution is not influenced by the magnitude of meteorological factors. Major point sources under this definition include municipal wastewater effluents and industrial wastewater effluents.
- **Diffuse sources** are highly dynamic and widely spread pollution sources and their magnitude is closely related to meteorological factors such as precipitation. Major diffuse sources under this definition include surface runoff (load from atmospheric deposition),

groundwater, erosion (load from eroded material), and diffuse loads of paved urban areas (atmospheric deposition, traffic, corrosion) including combined sewer overflows since these events occur discontinuously in time and are closely related to precipitation.

Both point and diffuse sources contribute to the total contaminant load of rivers. A distinction between them is necessary for the planning of restoration actions and for the determination of the effects of past control measures at industrial sources. In rivers in Western Europe the contribution of point sources to total loads has decreased over the past decades and this reflects the efforts of industry in combating pollution discharge. As a result the contribution from diffuse sources is becoming (relatively) more important. As an illustration of this trend, the point and diffuse sources of mercury and lead in the River Elbe are shown in Figure 6.

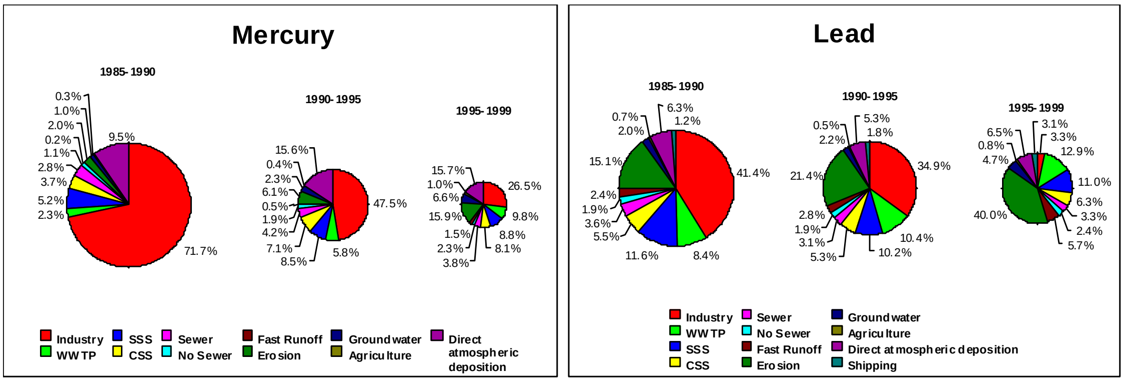

Figure 6. Decreases and changes in the sources of mercury and lead in the Elbe basin (Vink 2002).

2.3. Transport of contaminants

Transport in solution versus attached to the sediment

Riverine material is characterised by a continuum of sizes from pebble (or larger) to purely dissolved forms. The conventional definition of the “dissolved state” is that amount which passes a filter with a pore size of 0.45 μm.

‘Dissolved compounds’ are transferred across aquatic systems together with the water, while the ‘particulate compounds’ are transferred differently: they may settle and be remobilised, according to flow velocity, particle size and shape, river bed morphology, etc. In river systems the pathways and transport characteristics of dissolved material and particulate material are therefore very different.

The fine and medium-sized particles, i.e. below 63 microns, are the most important. All the clay minerals, as well as the organic matter and fine-grained common minerals like quartz, feldspar and carbonates are found in this fraction. Coatings of iron and manganese (hydro-) oxides are common. The properties of these fine particles (e.g. large specific surface areas, high ion exchange capacities) enable them to act as efficient scavengers of contaminants discharged into the river system. When total suspended solids concentrations (TSS) exceed 100 mg/L, more than 90% of the most toxic metals, such as cadmium, copper, chromium, mercury, lead and zinc, and of major Persistent Organic Pollutants (POPs) such as the polychlorinated biphenyls (PCBs) and the polyaromatic hydrocarbons (PAHs), are present in river particulates. Below 10 mg/L of TSS the dissolved fraction of these contaminants may equal or exceed the particulate fraction.

In European rivers the average TSS levels commonly range from 5 mg/L to 100 mg/L or more. In the so called turbidity zones of estuaries, TSS contents naturally reach levels of 600 mg/L or more. During floods these levels are commonly multiplied by one or two orders of magnitude, which means that most metals, POPs and an essential part of organic carbon and nutrients are transported in association with the suspended particulate matter.

Relationship with hydrological conditions

The transport of contaminants is not constant with the discharge of a river system. Most data in this respect are available for heavy metals, and cadmium will be used to illustrate the relationship with discharge in the River Rhine.

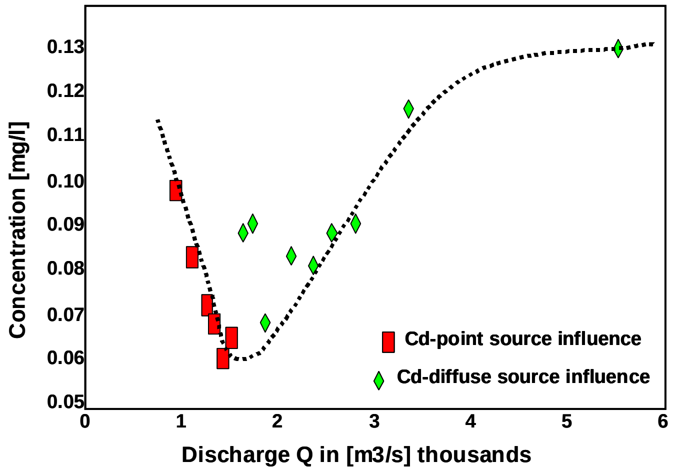

Figure 7. Relationship between discharge and cadmium (Cd) concentrations in the Rhine(Vink and Behrendt 2001).

The concentrations of Cd in the sediment show a complex relationship. At first the concentration in the suspended matter decreases, which reflects the dilution from relatively uncontaminated eroded material. This type of relationship was commonly found in the monitoring data of 1970-1980 when the point sources were still highly dominant. Sediments deposited on the floodplains during high discharge had lower sediment contaminant concentrations compared to the concentrations in the river itself during normal discharge. In later years, the curve shows the relationship as depicted in Figure 7. With increasing discharge the Cd concentrations in the sediment also increases. This is caused by the contribution of sediment from eroded contaminated areas, which contribute and now overshadow the input from point sources. It reflects the increasing importance of diffuse sources to sediment contamination in the river system.

2.4. Impacts of sediment contaminants

Introduction

Contaminants can be degraded or irreversibly bound to the sediment, thus decreasing their bioavailability. Above this level, contaminants in sediment will impact the ecological or chemical water quality status and nearly always complicate sediment management. In this section some examples of such impacts are given.

Effects on living organisms (ecological water quality)

Research on several European rivers has demonstrated that sediment-associated contaminants can have adverse effects on sediment dwelling species. The abundance of certain species may decrease as a result of sediment contamination while other, more susceptible species may disappear completely, resulting in a decreased biodiversity. A decreased abundance results in a decrease in food availability for higher organisms and, thus, a disruption of the aquatic ecosystem. Furthermore, through the consumption of 'contaminated organisms' the level of contamination can increase in organisms with each step in the food-chain. Food-chain transfer and bio-magnification may result in effects on reproduction or health of fish-eating birds and mammals such as cormorants and otters. Consumption of severely contaminated fish (e.g. eel) or consumption of meat or milk from livestock on severely contaminated flood plains could also have an impact on human health. There are examples of floodplains where use by livestock has been restricted.

Effects to water resources (chemical water quality)

Even if we manage to significantly reduce or even stop the discharge of hazardous chemicals to rivers, substantial historic sediment contamination still remains. Through release of these contaminants to the surface and groundwater, these sediments remain potential sources of adverse affects on water resources (Figure 7). The present knowledge, however, is not sufficient to adequately predict the actual risks at specific sites.

Effects on management

Ports and channels need to be dredged regularly in order to keep them open to shipping, to allow a proper functioning of locks and dams (maintenance dredging), to prevent flooding and occasionally to restore or improve the quality of the ecosystem at a specific site (environmental dredging). Although the water and 'new' sediment quality is improving in some European rivers, a great deal of the older, deeper layers of sediment is contaminated to such an extent that disposal of dredged material to open water or land is not allowed and the beneficial use of this material, e.g. for the construction of dikes and soil improvement, is restricted. The dredged material must be disposed of in confined disposal facilities at much higher costs, or, when feasible, transformed into non-hazardous material, subjecting this sediment to costly treatments. Due to the enormous volumes involved, especially in the case of maintenance dredging in ports, minor changes in the management, or demands made upon dredged sediments, can result in dramatic changes in costs. More on sediment and dredged-material management can be read in chapter 3.

2.5. Assessment of contaminated sediments

Introduction

Contaminants in sediment may impact the ecological or chemical water quality status. Some contaminants have the intrinsic possibility to cause such negative impacts and thus are hazardous. However, the actual risk of contaminants is to a large extent determined by their bioavailability. Strongly and in some cases irreversibly sediment-bound contaminants are hazardous, but their risk is negligible. Furthermore, even if 'loosely bound' sediment contaminants are or become available, e.g. due to bioturbation (i.e. resuspension of settled sediment due to activity of biota), or due to a flooding event, then there still is not a 1 to 1 relationship with impact to chemical or ecological quality. Thus it is very hard to predict whether or not a certain level of contamination will result in adverse effects on chemical or ecological water quality.

For assessment of contaminated sediment, there is not one 'best' method available. Each specific management question requires a tailor-made solution:

- Chemical analysis can be used to determine concentrations of selected, hazardous chemicals and then it can be checked if the concentrations exceed pre-defined standards or guideline values

- The toxic effects of sediment on organisms can be tested by using bioassays
- Through a field inventory the long-term impact on sediment biota can be investigated

These assessment methods (chemical, bioassay, field) are complementary by giving a unique answer that cannot be given by any of the individual methods themselves. But each method also has its own unique drawbacks and uncertainties. A simultaneous application of these three, complementary assessment methods (Figure 8) is commonly referred to as the Triad-approach (Chapman 1996).

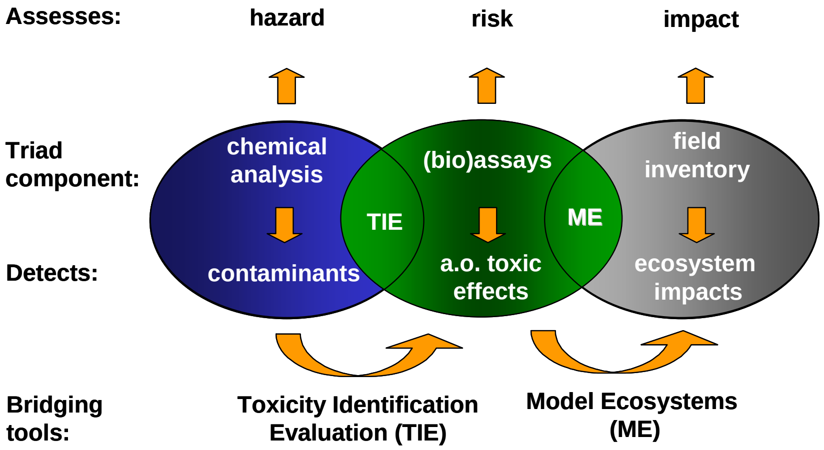

Figure 8. An elaboration of the sediment Triad-approach, positioning hazard, risk and impact assessment and positioning the bridging tools Toxicity Identification Evaluation and Model Ecosystems.

Chemical analysis (hazard assessment)

A major advantage of chemical assessment is its specificity. When a generally accepted standardised analysis procedure is followed, such as ISO, CEN, AFNOR, BSI or DIN (see glossary), the result will be an exact and reproducible amount for the analyses aimed for. By application of extraction techniques it is also possible to indicate the amount present in certain sediment fractions, such as the freely dissolved concentration in the sediment pore-water. Concentrations in such fractions may relate better to the amount that can impact the chemical or ecological water quality status. For such reasons it is also common to normalise data for organic matter or clay content, as it is well known that these decrease the availability of hydrophobic organic compounds and of metals, respectively.

If pre-defined quality standards are available (see for instance Den Besten *et al*. 2003) it is then very easy to check if they are exceeded and follow their implications for management. A very simple standard, for instance, relates to the ‘non-deterioration’ objective of the WFD: water, and thus also sediment quality should not deteriorate further. For the WFD priority hazardous substances that have a strong preference to stick to sediment, such as hydrophobic organic compounds, it makes more sense to monitor their trend or status in sediment instead of in the water phase. Trend monitoring provides an indication of temporal changes over a prolonged period, e.g. increases or decreases in concentrations of contaminants over time. Spatial monitoring will provide an indication of the status and variation of contamination over an area. Such monitoring is necessary to detect the spread of a contaminant over a river basin, and possibly to locate its source. It will provide basic information for appropriate sediment management. Historic contamination at hot spots is often reflected in the deeper sediment layers. The spatial variation in sediment contamination is influenced by differences in sedimentation rate of newly formed particulate material, as it influences the degree to which historic contamination is covered-up. Consequently, the choice of sediment sampling depth is a critical issue in mapping the status of sediment quality (Stronkhorst *et al*. 2004).

There are also some major disadvantages to chemical analysis. Results are only obtained for the contaminants aimed for, and the use of quality standards has serious technical flaws. While the negative effects of some chemicals are relatively well-characterised, such as the toxicity of lead, others are not well understood, or may not even have been identified. Toxicity data are mostly derived from total concentrations in water tests only. It is well known that the bioavailability of contaminants in a whole water sample is profoundly decreased by the presence of suspended sediments. Furthermore, ecosystems may be able to adapt to additions of toxic chemicals, or changes in their environment.

Bioassays (risk assessment)

Over the years, research has demonstrated that contaminated sediments that exceed sediment quality guidelines do not always result in toxic effects in sediment toxicity tests or in the benthic community as a result of decreased bioavailability of the sediment-associated contaminants. Sometimes the opposite has been observed, i.e. sediment that meets a suite of sediment quality guidelines has caused adverse effects to the benthic community in the field or in laboratory toxicity tests because of combination toxicity or the presence of unidentified compounds. Therefore, in a growing number of European states, authorities are considering heading towards the implementation of bioassays in sediment or dredged-material quality assessment procedures (Den Besten *et al*. 2003). Some countries already have implemented this, as is for instance the case in the Netherlands.

A bioassay may be defined as a laboratory or field experiment in which a selected aquatic species is exposed to sediment. If enough contaminant is available to the test species this exposure will result in a toxic effect. A toxic effect could be a reduced reproduction or growth or, in its most dramatic form, mortality (Brils *et al*. 1997). To date, several well-standardised bioassays are available. Bioassays can range from using only a certain cell-type (or even part of that) of a test species to using several species in one test system.

As with chemical assessment, there are also disadvantages to bioassay assessment. A local sediment ecosystem is unique and comprises thousands of species. It is impossible to test for effects on all of them, and the degree to which tests on selected species can be extrapolated to others, or the ecosystem as a whole, is perhaps as difficult as extrapolating effects from chemical analysis. Furthermore, besides the effects mentioned above, there are numerous other effects that might occur, such as carcinogenicity, mutagenicity, endocrine disruption, changes in metabolism or role in ecosystem, etc. The mechanisms for these effects can all be different, but they can all have an impact on ecosystem health and function. It is impossible to test them all, so mostly a ‘battery of complementary bioassays’ is used in order to aim for different types of effect and/or use different test species. However, each addition to this battery means extra costs, so in most cases the number of different assays applied is limited to between 2 to 5.

Another complicating factor in applying bioassays is that whenever a toxic effect occurs the question of its cause will arise. An answer to that question is often required to be able to take the right measures, such as for instance to be able to address the source of contamination or to be able to select the appropriate remediation technique. For this purpose Toxicity Identification Evaluation (TIE) procedures have been developed. The goal of any TIE is to identify quickly and cheaply, as far as possible, those contaminants causing toxicity (Burkhard and Ankley 1989), thus TIE bridges the gap between the Triad components chemistry and assays (Figure 8). However, there are several examples where even an elaborate, and thus costly, TIE procedure was not successful to identify the true cause of toxicity. On the other hand, several examples also exist where TIE was successful. For example, the endocrine disrupting compound TBT, that causes imposex at snails, was detected through such an approach. The mitigation measure taken is the global ban on the use of TBT on ship hulls (TBT is the toxic ingredient in anti-fouling paint, which prevents barnacles and other organisms to stick to ship hulls and thus increase fuel consumption).

Field inventory (impact assessment)

The third component of the Triad approach is field inventory, i.e. an assessment of taxonomic composition and abundance of benthic invertebrate fauna. These organisms, together with algae, serve as the most common biological water-quality assessment indicators. The EC funded research project AQEM (AQEM 2002) has developed a benthic invertebrate-based assessment system for European rivers.

However, if a field inventory reveals a 'poor or moderate status' of benthic invertebrate fauna, e.g. indicated by a low diversity and abundance, then the question arises if and to what extent this status is due to an impact of sediment contaminants. This is a very challenging question, as the benthic invertebrate fauna status is to a large extent also determined by variables other than contaminants, such as habitat characteristics, the interaction between biota present, or the level of adaptation of benthic species to the contaminants present. Furthermore, what a field inventory reveals today is the result of what happened in the (near) past. Thus it could be the case that the sediment contaminant that actually caused the impact has already disappeared from the sediment due to degradation or erosion.

In order to help to bridge the gap between the Triad components assays and field inventory, use can be made of model ecosystems (Figure 8). However, model ecosystems incorporate both advantages and disadvantages involved with these extremes in terms of spatial and temporal scale. The main advantage of model ecosystem experiments compared to a field inventory is the opportunity to use replicated systems to test the response of perturbations. In contrast to a field inventory, the effects of a perturbation can be simultaneously studied and compared to an undisturbed system under similar environmental conditions. As is the case with all type of experiments, an optimal size of the test system and experimental duration should be chosen based on the hypothesis to be tested and on the desired level of complexity and reproducibility (Jak 1997).

3. Management of sediments

3.1. Introduction

Sediment quantity has been managed for centuries, mostly by dredging. This was, and still is, very much needed in order to keep waterways, that tend to silt up, open to the flow of water. This ensures a proper drainage capacity for precipitation and melting snow and ice, so it aids in flood prevention. But it also ensures water supply for drinking and irrigation purposes and for shipping. However, the natural hydrodynamic conditions of many waterways have been altered: directly by hydraulic constructions, such as dikes, dams, seawalls, and artificial drainage; and indirectly by changes in land cover and use, such as deforestation and urbanisation. These changes have resulted in the accumulation of sediment at places where the sediment impedes economic activities. The removal of sediment for the maintenance of waterways and water quality from locks, floodplains, harbours, navigation channels and river stretches is a high capital cost for responsible authorities and agencies.

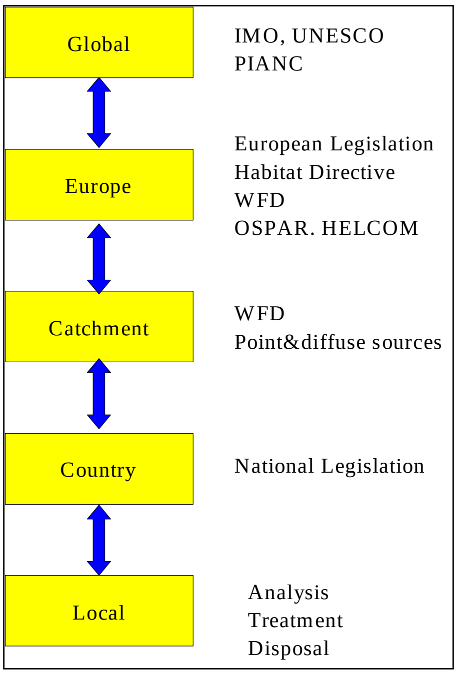

Figure 9. Spatial scales related to sediment issues and regulations

These changes at the basin level are a major challenge to river-basin managers and to the coastal zone managers who are 'at the receiving end' of the basin. Notable are the issues faced by port authorities, which have to deal with the sedimentation of riverine suspended solids in their ports. At the local scale the "dredged-material manager" has to deal with navigability of water ways, which requires dredging, and with disposal issues, in particular for those cases where the sediments are contaminated and exceed contaminant levels set by national regulations.

As a result, the management of sediment operates at different spatial scales (Figure 9). The local managers (port authorities) have to deal with analysis, treatment and disposal aspects, which are guided by local regulatory guidelines, but also increasingly with European guidelines (Köthe 2003). Both PIANC[3] and CEDA[4] have developed guidelines for disposal of dredged material. In a wider context the local managers benefit from regulatory efforts for point and diffuse sources. Most often the point and diffuse sources are upstream from the dredging sites, and hence control of these requires management at the basin level. Point sources are direct discharges into the river systems by industrial activities, sewage treatment plants etc. Diffuse sources include agricultural activities, runoff from paved areas, erosion of (contaminated) soil and sewage overflows (Figure 5). Hence, European and national regulations on soil quality, prevention of erosion, implementation of sewage treatment, control of industrial point sources, indirectly are of benefit to sediment quality downstream. Sometimes contaminant

[3] International Navigation Association (www.pianc-aipcn.org), see 'Read more' section.
[4] Central Dredging Association (www.dredging.org), see 'Read more' section.

control has to be carried out at the global level, which is the case for anti-fouling paints on ship hulls (TBT), for which measures have been implemented by the International Maritime Organisation (IMO).

Hence, sediment management follows different categories based on the spatial scale. At the small scale, regulators have to deal with the removal of sediments from waterways to, for example, allow safe navigation. At the basin scale, sediment management deals with both sediment quantity and quality. As such it is part of and benefits basin management schemes by dealing with the reduction of point and diffuse sources of contamination and erosion control. With regard to the quantity of sediments, the impacts of damming on sediment fluxes are well studied. However, the impact of the decrease or increase in sediment loads downstream on wetlands, floodplains and riparian systems should be an important part of sediment management at the basin scale. In preceding sections this issue of quantity has already been addressed. A special case of sediment management deals with “environmental dredging”, which means the removal of contaminated sediment solely for restoration of impacted aquatic ecosystems.

3.2. Local management: contaminated sediment treatment and disposal methods

Sediment management

Further source reduction is necessary to improve sediment quality thus helping to meet the water quality objectives of the Water Framework Directive. Furthermore, it helps to enable unrestricted relocation of dredged material, which should be the first option to consider because sediment forms an essential part of river systems. Hence, looking at a river-basin scale, investment in source control upstream is very often more favourable from an economic and ecological point of view than treatment of large amounts of sediment downstream. However, we still have to deal with historical contamination for which treatment and disposal are necessary as ‘end-of-pipe’ solutions.

Dredged material that is too contaminated for relocation, and cannot be used directly, is subject to treatment and/or confined disposal options. Many techniques for this have been tested and guidelines are available from organisations like CEDA and PIANC (see ‘Read more’ section). Technology is not the problem, but innovation towards more efficient techniques or applications is welcome. Sub-aquatic and more costly upland confined disposal are the main solutions in Europe for contaminated dredged material. Treatment is mainly done by low-tech methods such as dewatering, separation and stabilisation, often in combination with confined disposal. Confined disposal and treatment should not be considered as opposing options: they are complementary and both can be environmentally sound and acceptable solutions. More advanced techniques, such as thermal immobilisation to make bricks and lightweight aggregates, for example, are applied on a much smaller scale. The key problems for treatment are the costs and the lack of markets for beneficial use. Treatment is in general more costly than confined disposal but in some cases treatment can compete with disposal costs. Treatment of dredged material is only useful if it leads to beneficial use that is economically feasible and/or less disposal or less disposal costs. Confined disposal will remain a necessary and important option because treatment of all contaminated dredged material is not economically feasible.

Treatment and confined disposal options

The main objective of treatment is beneficial use, for example as a construction material. Other purposes of treatment can be to reduce the volume for disposal, the reduction, removal or immobilisation of contaminants and to improve handling characteristics of dredged material. A large variety of treatment and confined disposal technologies is available and well known in Europe. Treatment mainly refers to removed dredged material (*ex situ*), but in some cases treatment of sediments in place is also feasible (*in situ*). The main factors that determine the applicability of technologies are: dredged-material properties; technique performance; possibilities for beneficial use; and costs.

It is evident that by applying simple technologies such as sand-separation, land-farming, ripening and stabilisation, only a limited proportion of dredged material can be processed into usable products. In this situation, the major part of the non-relocatable dredged material and residues from sand-separation still have to be disposed. For logistical reasons simple treatment techniques are often located near a confined disposal site. By applying more advanced technologies, such as thermal immobilisation, more heavily contaminated sediments and residues from sand-separation can be processed.

Beneficial use

Beneficial use of products of dredged material is not common due to a number of constraints. Products from dredged material have to compete with primary materials and other secondary materials. Often there is a cost disadvantage for the treated material. Products from beneficial use, especially from low-tech methods, in general have a negative value: it costs money to apply them. Beneficial use is often hampered by legislation, for instance, adequate standards for building materials are lacking. The acceptance of the products can be problematic because of the negative perception of dredged material. Furthermore, there is no guarantee for a continuous supply of dredged material, which justifies high investments by the private sector. A possible solution is the combination with other waste materials, such as soil treatment residues.

In some countries measures have been taken to encourage beneficial use. Measures are, for instance: adaptation of standards on building materials; certification of products; application of dredged material in governmental projects, e.g. in road construction; prohibiting disposal of easily treatable dredged material; subsidising regulations on treatment and beneficial use; large scale pilots on treatment and beneficial use; and improving the perception of dredged material through communication campaigns.

Costs

Of great importance are the costs of different treatment options. Simple technologies such as sand-separation and land-farming / ripening are generally slightly more expensive than disposal, while costs for stabilisation and thermal immobilisation technologies are substantially higher. But, the costs depend very much on the site-specific circumstances such as characteristics of dredged material, amount of sediment, capacity of a disposal site, through-put of treatment facilities, transport and the revenues or costs for beneficial use, type of contract and legislation (see e.g. Netzband *et al*. 2002). According to these site-specific conditions large variations in costs occur, as described in Figure 10.

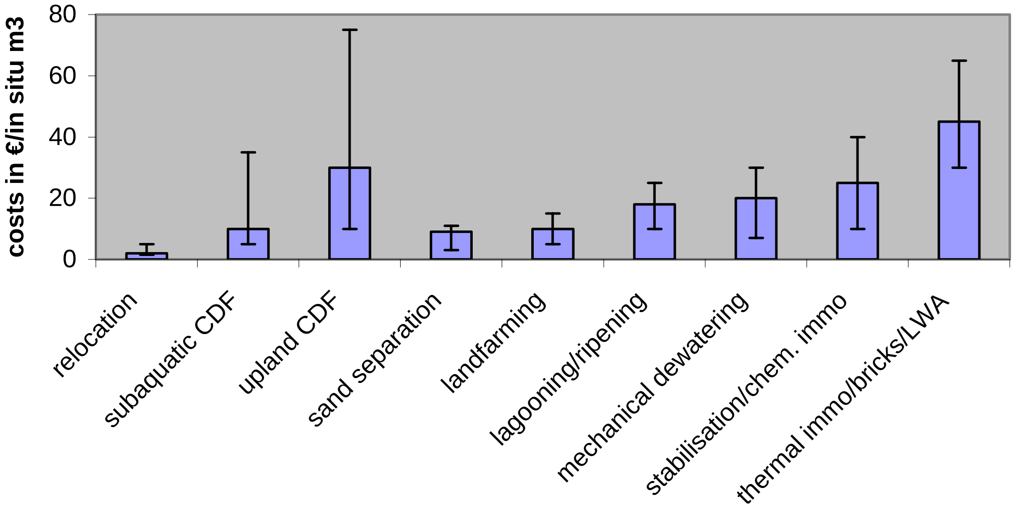

Figure 10 - Treatment and disposal costs. The height of the columns represent average and the bar shows the range of costs (Netzband et al. 2002; SedNet-Elsevier book "Sediment and dredged-material treatment"). Disposal options on the left and to the right treatment options vary in wide ranges due to different boundary conditions. (Note: Revenues or costs for application of the products are not included. The costs for sand-separation do not include dewatering and/or disposal; CDF = Confined Disposal Facility; LWA=Light Weight Aggregate; chem = chemical; immo = immobilisation).

Assessment and sustainability

There is no general outcome on the best treatment or disposal option because of site-specific conditions. The selection of the most preferred option is based on technical, environmental, economic and social criteria. It is of crucial importance to involve the public and other stakeholders in the decision-making process of treatment and disposal options. Communication is needed on actual risks of dredged material and the concept that dredged material should be considered as a resource rather than as a waste. Decision-making is mostly done by local or regional administrations, such as port authorities, but their actions often have consequences at the larger, river-basin scale. So co-operation between authorities along the river basin is necessary. Long-term effects over the time span of a generation or more have to be considered, e.g. the life-cycle assessment (LCA) of products and effects on mobility of pollutants with time. Assessment of treatment alternatives for dredged material should not be based on a single tool, e.g. a cost calculation or LCA, because no tool covers all fields necessary to be considered. In order to avoid unnecessary transport of sediments across borders between regions and countries in Europe applying different standards, harmonisation of those standards is needed.

3.3. Long-term sediment management: catchment approach

Sediments originate in the catchment through erosion processes and are transported in the river systems in the direction of the coast. Thus land use, climate, hydrology, geology and topography determine the amount and timing of sediment delivery to rivers. In the river system temporary deposition can take place. Important in this respect are floodplains and lakes. In many regulated rivers, sediments are trapped behind dams and reduce the supply of sediment downstream.

Important impacted areas downstream are wetlands, deltas and harbours. The amount and the quality of sediment in the low-lying areas of the river system and in the estuary, delta and coastal areas depend on the socio-economic activities and the biophysical conditions in the contributing catchment. Impacts on and functioning of these areas cannot be considered in isolation, but must be viewed as part of the catchment-coast continuum (Figures 1 and 11). Another important aspect is the delayed response of the downstream areas upon changes in sediment supply from upstream sources. In Europe the reduction of pollution through point sources and diffuse sources have also shown a temporal delayed response before this resulted in sediment quality improvement. Because of the slow and delayed responses of both sediment quantity and quality, sediment management by nature is a long-term process and has to be carried out at the catchment scale. Science has to provide the necessary tools for catchment sediment management which are able to answer "what-if" questions.

However, a catchment is a slowly responding geomorphologic entity, subject to socio-economic catchment activities which operate at a much faster pace, a combination which the dredged-material manager has to act on a daily basis to keep waterways navigable: a "spatial and temporal" challenge for management which requires adequate scientific tools.

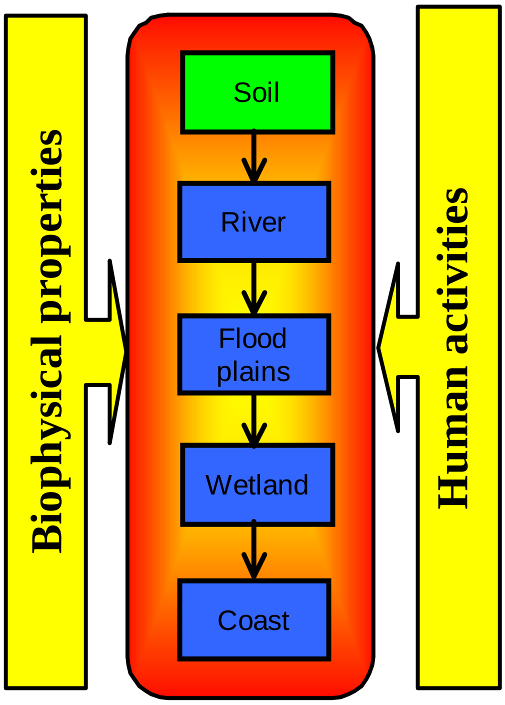

Figure 11. The Catchment-Coast Continuum and its biophysical properties and human activities with combined impacts on sediment quantity and quality.

Emphasis in the preceding sections has been on contaminated sediments at a specific site. Many tools are available to access their impact, and techniques are available for their disposal taking economic and environmental aspects into account.

Chapter 1 addressed the quantity aspects of sediment generation and subsequent transport to the important sedimentation areas. A major proportion of eroded sediment is temporarily stored in (human-made) lakes, weirs, locks and floodplains before being transported to the coastal zone (see Owens and Batalla 2003). Although no comparable data are available for Europe, it has been estimated for the large river basins in the US that the material transported by rivers is only 10% of the erosion in the 20th century. This demonstrates that 90% is temporally stored between the “soil and the coast” (Syvitski *et al*. 2004).

Hence, science has to deliver not just sediment transport models, but models which are able to interface with erosion models, deal with temporal storage effects and interface with morphological models. The latter is important with regard to depositional areas like floodplains and wetlands. The current GIS (Geographic Information System) based modelling approaches allow for this kind of integration.

Such a suite of coupled models makes it possible to predict changes in erosion, sediment transport, deposition and morphological changes. The next question to be answered is a “what-if” one in order to make future socio-economic activities and regulatory activities transparent. Figure 12 (Chapter 4) clearly shows that many regulations and policies exist and are planned which will have impacts on the quality and quantity of sediments in a given river basin. These regulatory activities deal with discharges of pollutants and hence affect the quality of the sediments. They have to be translated into inputs for the “GIS-based” models to assess the temporal delayed responses and show when they become effective. A further example is land use changes due to globally changing trade patterns and policies like the CAP (Common Agricultural Policy 2004) which indirectly affect erosion and the supply of sediments to the river system.

Climate changes are expected to change regional hydrology at the catchment scale and cause changes in erosion, transport and deposition of sediments. Tools for catchment management also have to incorporate the likely effects of climate changes on erosion, transport and deposition.

The discussion shows that many drivers and pressures have to be taken into account to predict the future quality and quantity of sediments in a given catchment: a prerequisite for setting up a sediment catchment management plan. Last but not least a socio-economic assessment will be necessary to identify and quantify any negative and positive impacts on the environment (wetlands, floodplains etc.), economy or society at large.

One tool that can be used to answer these complex interactions and make them transparent is the use of scenarios at the catchment scale. Many global and European scenarios are available (IPCC, OECD etc.) which can be downscaled to the catchment level. Plausible land-use changes, hydrological changes, etc. can then be interfaced with natural science and socio-economic models to assess the impact on (changes in) sediment quality and quantity. Based on these results and in strong consultation with stakeholders (see section 5.3), choices can be made for implementing a river basin sediment management plan.

4. Policy and regulations

4.1. Current regulations and conventions

International conventions

International conventions for dredged-material management in Europe are:

- The London Convention (LC) on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. Dredged Material Assessment Framework - DMAF (2000)
- The Oslo-Paris (OSPAR) Convention on the Protection of the Marine Environment of the North - East Atlantic: Revised Guidelines for the Management of Dredged Material (2004)
- The Helsinki (HELCOM) Convention on the Protection of the Marine Environment of the Baltic Sea Area: HELCOM RECOMMENDATION Disposal of dredged spoils (1992)

Their purpose and primary aim is the environmentally sound disposal (relocation) of dredged material into the sea. Special national guidelines provide assessment criteria for the aquatic disposal (relocation or confinement) for inland and coastal waters. Whereas the coastal guidelines are in line with the guidelines of the international conventions, national guidelines and criteria may differ for the inland part of rivers. Owing to national implementation of international conventions and EU Directives, the European Member States have developed special dredged-material guidelines with different (limited) competences in practice.

European soil legislation

A European regulation for the protection of soils is under discussion as part of the EU Soil Thematic Strategy, which may include sediment-related issues. In addition, some European countries have already set Soil Protection Acts into force. For example, in The Netherlands, sediments (sub-aquatic soils) are part of the Dutch Soil Protection Act, in Germany they are excluded. The soils on the floodplains, often showing the same characteristic of contamination as the sediments in a river basin (due to flood events), are also under the scope of soil protection legislation. Furthermore, a goal of soil protection is the avoidance of soil erosion, which means the prevention of increased introduction of suspended matter into the river.

European Waste legislation

The European Waste Directive (Directive 75/442/EEC) defines in Article 1a: "*Waste* means any substance or object which the holder disposes of, or is required to dispose of, pursuant to the provisions of national law in force". This definition is independent of the contamination of the waste. The waste legislation follows the principle:

1. Avoidance of waste
2. Beneficial use (incl. treatment)
3. Safe disposal

All three options have to be part of an integrated sediment management plan. Several technical guidelines in waste legislation apply to sediments and differ to some extent on the national level.

The European Waste Catalogue (Decision 2000/532/EC) contains two waste codes for dredged sediment: 170505 "Dredging spoil containing dangerous substances" and 170506 "Dredging spoil other than those mentioned in 170505"

The European Landfill Directive (Directive 1999/31/EC) has to be applied if dredged material has to be disposed on land.

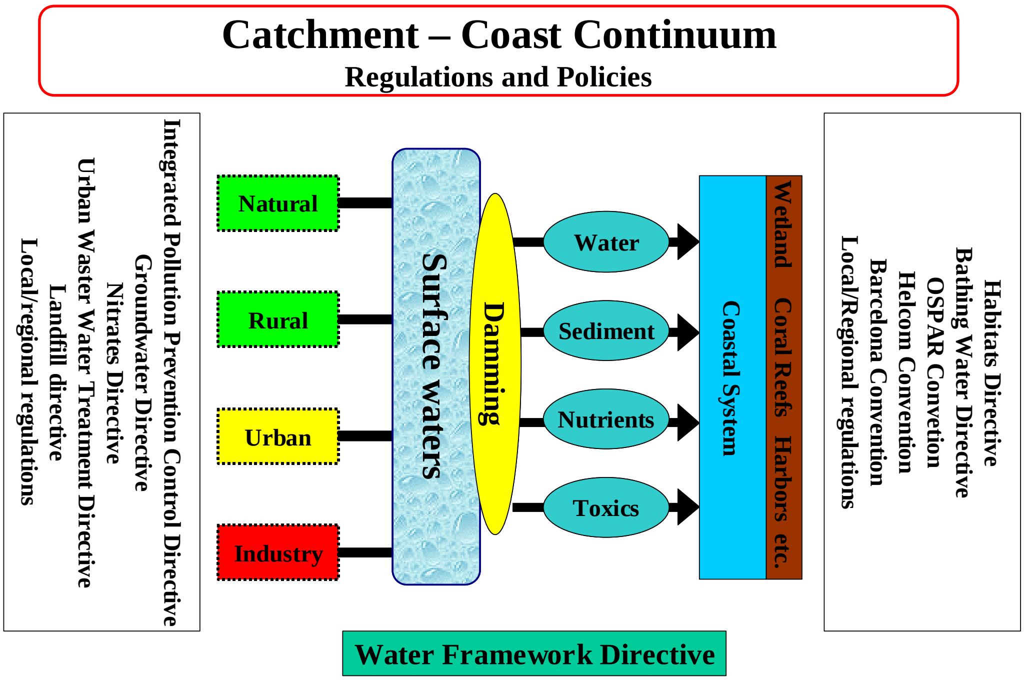

Figure 12. The Catchment-Coast continuum and some of the upstream and downstream regulations and policies affecting sediment quantity and quality as well as those relevant for impact assessment downstream.

4.2. The Water Framework Directive

The Water Framework Directive WFD (Directive 2000/60/EC) aims to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwaters in Europe. It will apply to all water bodies, including rivers, estuaries, coastal waters out to a minimum of one nautical mile, and artificial water bodies such as docks and canals.

The WFD provides for a new, global and integrated approach to water protection, improvement and sustainable use. It provides for a 'combined approach' of emission limit values and quality standards by setting out an overall objective of good status for all waters as well as providing for source controls. The WFD co-ordinates the application of all EU water-related legislation (e.g. Urban Waste Water Treatment, Nitrates, Integrated Pollution Prevention and Control, Seveso, Habitats Directives etc.) and provides a coherent management framework so as to meet the environmental objectives of these instruments as well as the WFD.

The Directive introduces a single system of water management by river basin - the natural geographical and hydrological unit - instead of according to administrative or political boundaries. Using river-basin management principles enables a coordinated, supra-national approach to achieve the set environmental objectives. For each river-basin district, a 'River Basin Management Plan' will need to be established and updated every six years, and programmes of measures will have to be coordinated for the whole basin district.

The WFD sets a very distinct time scale. All water bodies should be restored to ecological and chemical status by 2015 - the target 'good ecological status' means that only a slight reduction in water quality will be permitted when compared to the unmodified natural water body for that type. Less-stringent objectives are provided for water bodies affected by human activity than for natural/unmodified water bodies.

The WFD does not adequately deal with 'sediment' and 'dredged material', although sediments are a natural and essential part of the aquatic environment and their management has to play an important role within water legislation.

The inclusion of land-water transitions zones, like wetlands, is also not yet clear. Hence there is a clear need for a more integrated approach to manage land-water interactions through specific tailor-made policy at the catchment level, including river-basin – coastal-zone interactions.

Article 16 of the WFD provides for strategies against pollution of water. Article 16(1) requires the adoption of specific measures progressively to reduce discharges, emissions and losses of priority substances, and to cease or phase out discharges, emissions and losses of priority hazardous substances. This provision can be of help to tackle existing pollution sources in European River Basins to reduce ongoing sediment contamination.

5. Developments in sediment management

5.1. Introduction

The implementation of the WFD will shift the scope from local sediment management (e.g. dredged material) to river-basin-scale sediment management. In the opinion of SedNet this is a prerequisite and thus an important driver towards sustainable sediment management. It also drives other developments towards sustainable sediment management such as environmental risk-based management of sediments, the transition from hazard to risk-based management and stakeholder involvement.

5.2. Changing perspective on sediment as driver towards sustainable management

Building on the previous chapters, it is clear that sediments are an essential and integral part of river systems. Thus it is obvious that there is a direct link between sediment quality and the WFD focal points of ‘ecological potential’ and ‘surface-water chemical status’. Sediments, like water, are a highly dynamic part of river systems. Hence sediments are not tied to a particular area and are transported through countries in the same river basin. This changing perspective on sediment is an important driver towards a more sustainable management of sediments. Contaminated-sediment management issues and problems as addressed in the previous chapters should no longer be regarded as an ‘end-of-pipe’ issue, but as a common issue to all within a river basin who are responsible for that contamination. Thus trans-boundary management is needed for river systems that cross water bodies and national borders.

Hence, thinking should shift from dredged-material management to sediment management. To manage the cause of the local problem, it is first of all important to know where the sediment originates and what the dynamic processes are that transport the sediment to the dredging site. When the sediment is contaminated, the same procedure needs to be carried out for the contaminants. If you do not manage the cause of the problem, it will remain and the next time you need to dredge, the same situation may occur again. Respecting the fact that the elements in the system are connected and that efforts to maintain and improve the ecological status of water bodies need to be coordinated on that scale, risk management should be carried out and priorities should be set on that scale. It makes no sense when a downstream manager is extremely cautious while the upstream manager is very pragmatic and sets other priorities, or *vice versa*. Management constraints in the river basin and receiving coastal zone should be focused on actions that are most effective at the scale of the river basin, including that of the coastal zone. Then money is spent well and the environment is served most effectively.

Furthermore, stimulated by the WFD, the view of sediment is changing in recognition of the key role that sediment plays in the natural functioning of river systems. It is realised that the contamination issue cannot be viewed in isolation, but that sediment contamination has an impact on all parts of the soil-water system. Sediment management should fit in the holistic view on the role of sediment in river-basin systems. This is similar to the policy development for contaminated soil. There, development also started with the perception that soil, like sediment, is a vital part of our environment that deserves protection by proper management (Vegter *et al.* 2002). The big difference, however, is that contaminated soil is a site-specific issue, while the mobility of contaminated sediment makes it a river-basin issue.

5.3. Other developments related to sustainable sediment management

Environmental risk-based management of sediments: legacy of the past; changes in the future

Within SedNet the definition and objective of sediment risk-management was debated intensely. The following risk-management objective was agreed upon: "to reduce risk posed by contaminated sediments to humans and ecological receptors to a level deemed tolerable by society and to control and monitor sediment quality and ensure public communication with the final aim of complying with the EU WFD and Habitats Directive" (see Annex: synthesis report WP5 Sediment risk-management and communication). If by any process within the river-basin sites pose such a risk, reduction of that risk should be a vital part of an effective sediment management action-plan.

Long-term risk reduction requires a basin-scale decision framework that takes into account the entire sediment-cycle including the interactions between soil, sediment and suspended material. Figure 13 illustrates a conceptual diagram of the interrelationship between basin-scale and site-specific assessment and management actions (see Annex: Synthesis report of WP5, Sediment risk-management and communication). A basin-scale risk management framework should comprise two principal levels of decision making. The first being a basin-scale evaluation, comprising the development of a Conceptual Basin Model (CBM, Apitz and White 2003). CBM integrates an inventory and description of the mass-flow of contaminants and particles, and the prioritisation of sites considering their potential impact on other areas within the river system. The second level is a detailed assessment of environmental risks at specific sites, and the evaluation of the risks and benefits of management options (site-specific risk ranking and management).

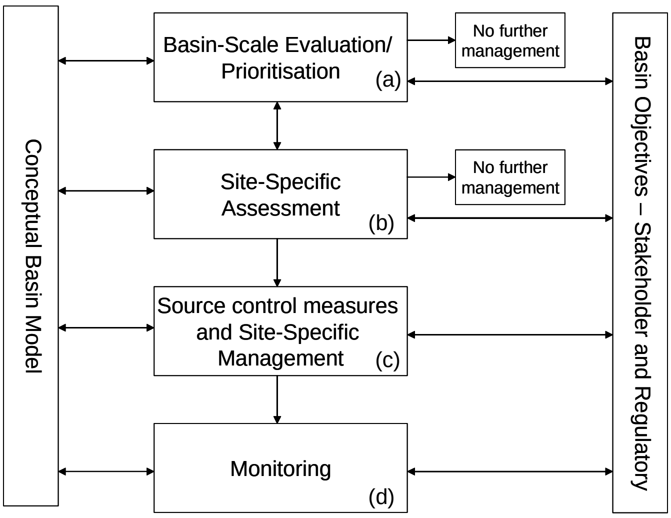

Figure 13. Conceptual diagram on the relationship between basin-scale and site-specific assessment and management in a river basin.

Site prioritisation at the basin scale should be done according to a number of criteria, preferably quantifiable at a screening level. Criteria are: the site's location along the up- and downstream gradient (e.g. how are downstream sites affected by contaminant and sediment sources upstream?), quantity of contaminated sediment (e.g. is the volume large enough to present a risk?), evaluation of sediment quality (e.g. how contaminated is the sediment?), sediment dynamics (e.g. is sediment transported downstream?) and the potential expected benefit of proposed management actions at a given site and for the river basin (to what extent can the risk to the site and the basin be reduced when the site is managed; to what extent do any management actions help meet socio-economic goals?). In those cases in which sediment-management decisions begin at the site-specific level (e.g., dredging for construction, small clean-up projects, etc.), it is essential that the impacts of these actions upon adjacent sites, and basin-scale quantity, quality and objectives are considered.

If a site is identified as high risk during the basin-scale prioritisation, then it should be subject to a management process, which includes site-specific risk ranking. Because evaluation at the basin scale may be at a screening level, or may be based upon generic criteria, risk-ranking at the specific sites comprises a more detailed risk analysis in the form of a tiered approach, comprising different methods such as chemical, ecotoxicological and sediment community data. The objective then is to assess the *in situ* risks and, if deemed necessary, to predict those risks that are connected with proposed management activities. The selection of risk management or disposal approaches requires a comparative risk assessment that identifies (and possibly compares) the risks to the environment due to proposed management options, such as dredging.

Transition from hazard to risk-based management

In the previous chapters it has already been addressed that contamination is a main problem when managing sediment and dredged material and that the relation between concentrations of chemicals (hazard) and their impact to water quality is complex and site-specific. Assessment methods form the basis for decisions on remediation. The WFD offers an opportunity to harmonise assessment methods on a river-basin scale.

In the opinion of SedNet, the actual impacts of sediment contamination on the chemical or ecological status should be the determining factor for deciding whether intervention in sediment quality is required. Thus SedNet also agrees with the EU WFD Expert Group on Analysis and Monitoring of Priority Substances (AMPS) (Stronkhorst *et al.* 2004) that compliance monitoring of sediment quality is not recommendable. International organisations such as the International Council for the Exploration of the Seas and the OSPAR Convention (the latter having jurisdiction landward as far as the freshwater limit on estuaries) have given consideration to the question of environmental criteria for sediments for more than 20 years. Indeed, the WFD itself recognises the importance of such initiatives. These international organisations have concluded that quantitative environmental quality standards, derived from limited toxicological data, should not be employed as compliance criteria in complex natural systems. Notwithstanding this, ‘guidelines’ can be effective as part of a tiered risk-assessment approach, e.g. to identify sites that need further/deeper investigation (see above).

Stakeholder involvement

Design and implementation of (sustainable) sediment management, whether at the local, regional or national level, requires input from stakeholders. The involvement of stakeholders in environmental policy development and implementation processes will become more and more important. In fact, it is legally required owing to the Aarhus-convention (UNECE 1998), the Water Framework Directive (Directive 2000/60/EC) and the Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003. In addition, resistance from stakeholders can prolong the decision-making process and increase costs and efforts on the long term. These negative aspects can be prevented if stakeholders are involved in the decision-making process at an early stage.

EU regulations are not the only argument for stakeholder involvement. Apart from the basic fact that some stakeholders have an impact on the quality and quantity of the sediments, the two most important arguments for involving stakeholders are:

1) The obstructive power that stakeholders have. To illustrate this, a disposal site for dredged material always alarms citizens living near the site: please “Not In My Back-Yard” (NIMBY). They can, and often do, protest against it, or take other actions. The early involvement of stakeholders reduces the risk of measures being delayed, or policies not being carried out.
2) The enrichment of the process, by inviting relevant stakeholders to obtain and apply knowledge and information supplied by them (Fischer 2000). No one can provide as much local insight to aid planning for the development of a disposal facility for dredged material as the local dredging companies, the people living in the vicinity of the site and the pressure groups that work to protect the natural and human environment in the area (Gerrits and Edelenbos 2004).

The United States Environmental Protection Agency (US EPA) has also embraced the concept of stakeholder involvement. When explaining their motivation for stakeholder involvement, the US EPA specifically refers to the OECD publication by Caddy and Vergeze (2001) which states that: "Engaging stakeholders in policy making is a sound investment and a core element of good governance. It allows governments to tap wider sources of information, perspectives and potential solutions, and improves the quality of decisions reached. Equally important, it contributes to building trust in government, raising the quality of democracy and strengthening civic capacity."

The ‘public’ is made up of numerous groups of people, not only citizens, but also of, for example, companies, governmental and semi-governmental organizations and pressure groups. Stakeholders may be described as “persons, groups and/or organisations that can affect or are affected by sediment management”. Stakeholder involvement is therefore "the early involvement of individual citizens and other organised stakeholders in public policy-making in order to explore policy problems and develop solutions in an open and fair process of debate that has influence on political decision-making" (Edelenbos 2000). The level of involvement can vary from informing the stakeholders about the decision-making process to co-production of solutions and co-decision made by the stakeholders.

Now the question raises how to mobilise the stakeholders? Too often, decision-makers feel that the majority of the potential stakeholders lack interest whereas some with strong, but specific interests dominate the agenda. So it is the duty of the manager to let stakeholders realise what is in it for them. Furthermore, awareness and urgency should be created. This can be done by pointing out the drivers behind sediment-related issues. Finally, the fairly technical nature of sediment-related problems such as contamination and morphological change need translation. Laymen cannot be expected to understand what it is about and therefore communication must be clear and free of jargon.

More on this issue, including rough guidelines for stakeholder involvement, can be read in the SedNet book on “Sediment management at the river-basin scale” that will be published by Elsevier in 2005 and also in the paper of Gerrits and Edelenbos in the Journal of Soils and Sediments (2004).

6. Recommendations

6.1. Introduction

SedNet has focussed on understanding river-system functioning and how to manage contaminated sediment and dredged material in a sustainable way, and has prepared a “Strategy Paper” (www.SedNet.org). Following this strategy, specific management issues were addressed by dedicated SedNet work packages (WP). Top-level scientists and major stakeholders contributed to the workshops organised by each WP. Those were used to identify and review the current state-of-the-art in knowledge, to identify practical recommendations and to review research needs related to specific sediment management issues. New scenarios and concepts were debated and are currently being further underpinned. A complete description, as well as proposed way forward, will be commercially available in four SedNet books, published by Elsevier in 2005.

The reports of the outcomes of the individual workshops can be found at the SedNet website. A synthesis of the WP discussions, and a list of the core-people that contributed to those discussions, can be found on the CD-ROM that goes with this document. Furthermore, three annual SedNet conferences (2002, 2003 and 2004) were used to put the WP discussions in a broader perspective and verify the WP conclusions and recommendations.

The main recommendations resulting from these SedNet activities are described in this section, and each recommendation is followed by a brief justification. Supporting background information can be found in the previous chapters and in the documents mentioned above. Recommendations are structured as follows:

- Recommendations towards EU policy development
- Generic recommendations towards sustainable sediment management
- Specific management recommendations:
  - towards river-basin management plans
  - towards sediment treatment
- Recommendations towards sediment monitoring under the WFD
- Research recommendations

6.2. EU policy development

Further develop and eventually integrate sustainable sediment management into the European Water Framework Directive.

At the level of the EU, sediment management is addressed fragmentarily and it is only covered by EU policies and directives for very specific issues. Effective protection and management of our sediment resources needs a more focussed attention. The WFD aims to harmonise water legislation in EU countries and focuses on the management of water at the river-basin scale. Thus it gives the best possibility for integration of a more direct and less fragmented focus on sediment management. The WFD, therefore, represents an enormous opportunity and stimulus to come up with guidance for sustainable sediment management (SSM). The current scope of the WFD does not yet clearly cover this subject. SSM should eventually become an integrated part of the WFD.

Other recommendations are:

- *Regulate the upland and in/under water disposal of sediment on an EU level.* Sub-aquatic confined disposal of contaminated sediments is not foreseen in the EU Landfill Directive.

The European Landfill Directive does not take into account the special properties of dredged material and the resulting requirements. Contrary to conventional waste disposal, dredged sediments should be stored in an anoxic, sub-aqueous environment. Very often, owing to the high content of fine-grained material, sediments have a very low permeability, thus ‘they seal themselves’.

- *Implement support to the beneficial use of sediments*. Beneficial use of sediments is a demand of EU waste legislation, but is hampered by costs and legal restrictions. The EU Landfill Directive asks for further elaboration of treatment techniques. If beneficial use of (treated) sediments has to be a future option, it has to get more support in legislation, for example by putting pressure on the use of natural resources, like clay pits. Furthermore, such use will also be promoted by more flexible standards for application of treated sediment.

6.3. Sustainable sediment management

Find solutions in the context of the whole river system that carefully balance social, economical and environmental values.

Sediment issues occur in temporal (geological and seasonal cycles) and spatial scales (catchment area, river foreland, polder) which cross political and administrative boundaries. Yet boundaries tend to scatter sediment management responsibilities and in the end no single stakeholder or country feels responsible. Planning sediment management at the river-basin scale will urge co-operation between agencies and even countries.

At that scale, joint methods and strategies should be developed for sediment and dredged-material management that link to the EU WFD and to pilot projects on trans-boundary rivers. Such methods and strategies should preferably be shared between different basins so that we can learn from each other. It will also help to recognise the differences between basins. This will underline the need to develop tailor-made, realistic solutions towards the environmental and socio-economic management issues (see above) that are at stake at that specific basin, or more detailed solutions at specific sites in that basin. For instance the type of dredged material, and the type of contamination, varies considerably between basins and between specific sites within a basin.

Thus sediment and dredged-material management needs to be integrated into existing frameworks at this scale, such as river-basin management plans (see further below under specific recommendations). An integrated approach is needed from inland (upstream) to coastal waters (downstream). This approach should respect the national and EU policy targets and comply with legislation.

Other recommendations are:

- *Find solutions in increase of the interaction with stakeholders.* The perception of sediment depends on a variety of roles, values and definitions and is influenced by stakeholder interests. In order to maintain a dialogue, definitions and terms used to describe sediment must be neutral and all-embracing, and sympathetic to stakeholder values and views.

- *Intervene in such a way that it does not result in unwanted impacts elsewhere in the river basin (up- or downstream), and should not have an adverse impact in the future.* A basic understanding of the water system, its dynamics and of the functions of the bordering areas (populations, industries, agriculture) is essential for an effective decision-making process.

- *Look for integrated solutions that embrace the whole soil-water system.* Sediment is part of the soil-water system. Management of sediments should be planned in the context of the soil-groundwater-water-sediment system.
- *Look for solutions that respect natural processes and functioning*. Management strategies for sediment should respect nature: working with nature, not against it. Thus it is crucial to use and improve our understanding of river system functioning and the role of sediment in the processes involved (see further under research recommendations). For instance, taking sediment out of the system can cause sediment deficits resulting in habitat loss and destabilisation of river system functioning. Therefore, sediment management must also consider the sediment balance and its dynamic role in the hydrological and geomorphologic processes operating within each river.

6.4. Specific management recommendations

River Basin Management Plans

Where necessary, supplement the River Basin Management Plan by a Sediment Management Plan based on simple and cost-effective approaches that are in line with the EU WFD.

The existing contamination of sediment may exceed the relevant quality targets and may lead to a widespread distribution of contaminants in rivers with a correspondingly widely increased sediment contamination level. This makes it necessary to concentrate (financial) efforts on the source of the problem, instead of undertaking costly measures provoked by sediment contamination. In general, source reduction measures would be overall the most economical and efficient solution. When the problem is not just local, or the source of contamination cannot be reduced immediately, long-term management solutions with interim arrangements have to be developed.

Sediment management is necessary to ensure that the requirements governing utilisation of waters are met, and at the same time also to protect sediment as a natural element of waters. Completely natural waters which are not subject to human influence or requirements do not need sediment management. The WFD promotes management of river basins according to uniform criteria. Where necessary, the River Basin Management Plan should be supplemented by a Sediment Management Plan. It should take into account the underlying needs and represents part of an agreed maintenance plan, linked to the measures necessary to achieve the sediment quality targets aimed for. Such a plan should fit to the basic objectives and requirements of the River Basin Management Plan. The components of a Sediment Management Plan for a particular river basin should include the following (in no particular order):

- Action to reduce point, and especially diffuse, sources. Following the WFD requirements source reduction is needed to phase out priority hazardous substances and/or to prevent further deterioration of the sediment quality. In the opinion of SedNet, it should also ensure unrestricted relocation of dredged material in the river basin, including coastal waters. Thus the WFD has to be compatible with the Marine Strategy of the EU. Furthermore, source control should ensure beneficial use of sediments or dredged material, be it on land, in water, or in coastal waters.
- Evaluation and/or monitoring of sediment quality, in order to make inventories and to enable prioritisation
- Action to reduce soil erosion and sediment delivery to rivers (and associated contaminant input) and control the sedimentation processes

- Action to provide and maintain water depths, discharge conditions, the maintenance of wetland areas, shallow water areas and retention spaces, and clean-up measures
- Framework for the disposal of sediments in the water, i.e. relocation, or possibly sub-aquatic confined disposal
- Options for beneficial use of removed, and if necessary treated sediment, including the use on land.

Sediment treatment

Innovation to more efficient treatment technologies and the stimulation of beneficial use need, at least temporarily, encouragement by financial incentives. This could be a subsidy from national governments or EU funds.

To date, treatment and (technical) beneficial use of sediments are too costly, especially when taking into account the often very large amounts of sediment that are required to be treated. In order to be economically viable, treatment and beneficial use need to be demand driven, in addition to be driven by legislation. The technology itself is not the problem, as a diversity of treatment technologies is already available, but innovation to more efficient technologies is welcome. If the (political) goal is treatment and beneficial use, additional funds have to be allocated and support is required. A (temporary) financial impulse is needed to stimulate the development of large-scale treatment and to stimulate beneficial use. An increase of the budget for dredging is needed in order to compensate for the higher costs of treatment.

Other recommendations are:

- *To make beneficial use possible, adequate and dedicated Europe-wide legislation is needed, such as standards for building materials*. Regulations on the side of demand for raw materials are needed in order to develop markets for products of treated dredged material
- *Long-term effects of treatment over the time span of a generation should be considered*, because potential effects of treatment can occur on a longer timescale than is often considered today.
- *Research is necessary to provide better tools to evaluate sustainability in order to improve decision-making*, looking at parameters like space consumption, landscape and the use of secondary materials.

6.5. Sediment monitoring under WFD

The actual impacts of contamination on the ecosystem rather than chemical assessment should be the determining factor for deciding whether remediation of contaminated sediment is necessary for environmental reasons.

Consensus is growing that contaminated sediment can be better assessed by looking at actual risks or impacts of the contamination, rather than on checking whether pre-defined sediment quality standards are exceeded. Sediment quality assessment methods should be based on the available contaminant fractions, on bio-assay results and/or on the results of a field inventory instead of total contaminant concentrations. Thus a transition should be made from hazard- to risk-based management.

Develop guidelines for monitoring contaminants in sediment in agreement with the EU WFD Expert Group on Analysis and Monitoring of Priority Substances (AMPS).

The frequency of sediment monitoring should be specified further, and could range from once or twice per year to once every 5 to 10 years depending upon the sedimentation rate. Sediment samples could be collected randomly at the designated sampling point and the location of each should be recorded. Samples shall be collected at the same time of the year for each sampling occasion, the time being chosen according to local circumstances, bearing in mind the aim of monitoring trends in the concentration of contaminants. The purpose of sediment monitoring guidelines is to assess long-term trends in impacts of anthropogenic pressures and to ensure no deterioration limit is reached and that comparable data are collected.

In case ecological criteria of the EU WFD are not met, a check may be needed on the role of sediment contamination. This requires sediment-quality assessment approaches (cause-impact analysis) that can be linked to the WFD.

Other recommendations are:

- *SedNet recommends criteria to select the target compounds to be monitored in sediments.* The selection of target compounds to be monitored in sediments should be based on: 1) Persistence; 2) Bioaccumulation/adsorption; 3) Toxicity; 4) Relevance at the large scale (river basin); 5) High fluxes (tendency to increase concentrations/fluxes on a long-term basis); 6) Addition or replacement of pollutants will be based on the results of present and future monitoring programmes and on the results achieved by RTD projects where the identification of new or emerging contaminants takes place.
- *Include sediments and/or suspended solids in river monitoring plans.* Substances which tend to accumulate in the geosphere and are transported bound to particles may better be measured in the suspended matter than in the water phase, which is particularly important for some new groups of compounds included in WFD, such as flame retardants (PBDEs). It is clear that transfer of contaminants from the sediments to the water column through processes of diffusion, advection and sediment resuspension is a major factor. SedNet recommends that a river monitoring plan should necessarily include monitoring of the suspended matter, in order to obtain a holistic picture of the contamination status of the whole river basin. In this respect, we should add that contaminants in suspended sediment generally represent “current” rather than historical pollution, as they will ultimately lead to “new” deposits of contamination, and newly settled material is the main food source for detritivorous benthic organisms.
- *Monitoring should include assessment of the bioavailable fractions of contaminants, in both the laboratory and the real field situations.* The relation between sediment quality and risks is complex and site specific, requiring assessment methods based on bioavailable contaminant fractions and bioassays results rather than on the traditional total contaminant concentrations.

6.6. Research

Improve our understanding of the relation between sediment contamination (hazard) and its actual impact on the functioning of ecosystems (ecological status) and develop strategies to assess and manage the risks involved.

Over the years, research has demonstrated that contaminated sediments exceeding standard or guideline values do not always resulted in toxic effects in bioassay testing or in the benthic community. This is due to a decreased availability of the sediment-associated contaminants. Sometimes the opposite has been observed: sediment that met a suite of standard or guideline values caused adverse effects to the benthic community in the field or in bioassays because of combination toxicity or the presence of unidentified compounds. This demonstrates the need to better understand the relation between sediment contamination (a hazard) and its actual impact on the functioning of the ecosystem (ecological status). Wherever a poor diversity and abundance of benthic invertebrates is observed, the question will arise to what extent this is due to sediment contamination. A proper answer to that question is needed in order to be able to decide whether sediment remediation might help to improve that status.

Other research recommendations are given and underpinned in the two dedicated SedNet documents that can be found at the SedNet website and on the enclosed CD-ROM. In summary, SedNet recommends:

- Especially in the context of perturbations due to climate change, improve our understanding, and thus also our capability, to predict or model, the fate of contaminants: from emission (upstream) to adherence to soil and/or suspended particles to sedimentation (also upland) and re-suspension (downstream).
- Improve our understanding of sediment transport processes (including erosion and sedimentation) at the river-basin scale as a function of land and water use and hydrological (climate) change in Europe.
- Investigate new architectures for policy processes with respect to sediment and soil issues that enable the interaction of several involved policy domains, interaction with stakeholders, new joint knowledge-production processes and joint actions.
- Investigate how the connection between the different involved policy levels and between strategy and implementation can best be established.
- Evaluate (social/economic/technical/environmental) source-control programmes, and perform a cost-benefit analysis of risk reduction through source control, including the management of historic contamination.
- Downscale global, European and country scale socio-economic scenarios to the river-basin scale and their effects on sediment quantity and quality and soil quality, and to stimulate research into the development of best management plans to comply with current and future EU regulations.

Annexes

Read more

SedNet recommends the following reports, books and other publications to obtain further information on the issues touched upon in this booklet:

SedNet books (published by Elsevier in 2005):

- "Sediment management at the river-basin scale", Editor: Philip Owens, National Soil Resources Institute, Cranfield University, UK, E-mail: Philip.owens@bbsrc.ac.uk
- "Sediment quality and impact assessment", Editor: Damià Barceló, IIQAB-CSIC, Dept. of Environmental Chemistry, Barcelona, Spain, E-mail: dbcqam@cid.csic.es
- "Sediment and dredged-material treatment", Editor: Giuseppe Bortone, Regione Emilia-Romagna, Bologna, Italy, E-mail: gbortone@regione.emilia-romagna.it
- "Sediment risk management and communication", Editor: Susanne Heise, Technical University Hamburg-Harburg, Hamburg, Germany, E-mail: s.heise@tu-harburg.de

International Guidelines:

- "Specific Guidance for Assessment of Dredged Material", adopted by the 22nd Consultative Meeting of Contracting Parties to the London Convention 1972 by resolution LC.22/5 (2000)
- "Revised OSPAR Guidelines for the Management of Dredged Material", OSPAR-Convention for the Protection of the Marine Environment of the North-East Atlantic (2004)
- "Revised Guidelines for the Disposal of Dredged Spoils", HELCOM-Baltic Marine Environment Protection Commission

PIANC International Navigation Association (www.pianc-aipcn.org)

- Managing Contaminated Dredged Material. PIANC's technical brief about the management of contaminated dredged material within the navigation community (2002).
- Special Report of the Permanent Environmental Commission "Dredged Material Management Guide"; Supplement to Bulletin no. 96. (1997)
- Working Group PTC I-17 "Handling and Treatment of Contaminated Dredged Material from Ports and Inland Waterways "CDM" Vol. 1" PIANC-Bulletin, Supplement to Bulletin no. 89 (1996)
- Working Group PEC 1: "Management of aquatic disposal of dredged material" (1998)
- Working Group ENVICOM 5 ‚Environmental Guidelines for Aquatic, Nearshore and Upland Confined Disposal Facilities for Contaminated Dredged Material' (2002)
- Working Group EnviCom 8 "Generic Biological Assessment Guidance for Dredged Material". In preparation
- Working Group EnviCom 10 "Environmental Risk Assessment in Dredging and Dredged Material Management". In preparation

CEDA Central Dredging Association / IADC (www.dredging.org; www.iadc-dredging.com):

Series Environmental Aspects of Dredging :

- Guide 1: Players, Processes and Perspectives (1996)
- Guide 2a + 2b: Conventions, Codes and Conditions: Land Disposal (1997)
- Guide 3: Investigation, Interpretation and Impact (1997)
- Guide 4: Machines, Methods and Mitigation (1998)
- Guide 5: Reuse, Recycle or Relocate (1998)
- Guide 6: Effects, Ecology and Economy (2000)
- Guide 7: Frameworks, Philosophies and the Future (2001)

Dutch-German Exchange on Dredged Material (e.g. www.htg-baggergut.de):

- "Sediment and Dredged Material Management - Relevance and Objectives" (2003)
- Part 1: "Dredged Material and Legislation" (2003)
- Part 2: "Treatment and Confined Disposal of Dredged Material" (2002)

Other documents:

- Apitz S.E., White S. A conceptual framework for river-basin-scale sediment management. *Journal of Soil and Sediments* 3(3):132–138 (2003).
- Den Besten, P., Deckere, E. de, Babut, M., Power, B., DelValls, A., Zago, C., Oen, A., Heise, S. Biological Effects-based Sediment Quality in Ecological Risk Assessment for European Waters. *Journal of Soils and Sediments* 3(3):144-162 (2003).
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- Directive 1999/31/EC. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste (European Landfill Directive). Official Journal of the EC, L182.
- Directive 2000/60/EC. Of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive). Official Journal of the EC, L327.
- Directive 2003/35/EC. Of the European Parliament and of the Council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC. Official Journal of the EC, L156.
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Annexes on CD-ROM

On enclosed CD-ROM	Also, free of charge, downloadable through:
This booklet	www.SedNet.org
Synthesis reports of the SedNet work packages (WP): - WP2 Sediment Management at the River-Basin Scale - WP3 Sediment Quality and Impact Assessment - WP4 Sediment and Dredged Material Treatment - WP5 Sediment Risk Management and Communication	 http://www.scientificjournals.com/sj/jss/Pdf/aId/7026 http://www.scientificjournals.com/sj/jss/Pdf/aId/7029 http://www.scientificjournals.com/sj/jss/Pdf/aId/7028 http://www.scientificjournals.com/sj/jss/Pdf/aId/7027
Presentations of speakers at 3rd International SedNet conference "The future of sediment management in Europe", November 25th and 26th , Venice, Italy	www.SedNet.org
Other, SedNet related publications (index included on CD-ROM)	www.SedNet.org
Glossary	www.SedNet.org