Sediment monitoring and the European Water Framework Directive

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Summary. Sediment is an essential, integral and dynamic part of our river basins. A healthy river needs sediment as a source of life. Unfortunately, sediment also acts as a potential sink for many hazardous chemicals. Above a certain level of contamination this will result in negative impacts such a loss of biodiversity. This is deemed intolerable by society and hence the European Water Framework Directive (WFD) was developed. The WFD aims to achieve a good status of all European waters by the year 2015. The WFD does not specifically deal with sediment although it is clear that there is a link between sediment quality and achieving of this WFD objective. However, related to sediment monitoring there are some direct links in the WFD, which are further explained in this paper.

Key words: monitoring sediment, Water Frame Directive 2000/60/CE, aquatic ecosystem quality.

Riassunto *(Il monitoraggio dei sedimenti e la Direttiva Europea Quadro Acque)*. I sedimenti sono parte integrante, essenziale e dinamica dei bacini idrografici; essi costituiscono anche una fonte di vita necessaria per la salute degli ecosistemi fluviali. I sedimenti purtroppo possono essere anche siti di accumulo di molte sostanze chimiche pericolose, che a determinate concentrazioni possono causare impatti negativi, tra quali la perdita di biodiversità. Ciò risulta intollerabile per la società ed è anche per questo che la Direttiva Quadro Acque è stata emanata. La Direttiva Quadro sulle Acque 2000/60/CE ha l'obiettivo di raggiungere il buono stato di tutte le acque europee entro il 2015. Sebbene i sedimenti non siano esplicitamente trattati dalla Direttiva appare chiaro come la loro qualità e il raggiungimento di un buono stato siano strettamente correlati. In riferimento al monitoraggio dei sedimenti ci sono dei collegamenti diretti con la Direttiva Quadro Acque che vengono ulteriormente illustrati in questo articolo.

Parole chiave: monitoraggio dei sedimenti, Direttiva 200/60/CE, qualità degli ecosistemi acquatici.

INTRODUCTION

The Water Framework Directive

In Europe, adequate water quality is one of the most eminent concerns for the future. This is recognised by recent EU policies such as the Water Framework Directive (WFD) [1]. The implementation of the WFD sets the scope to integrated management of the "soil sediment water system" to the river basin scale. It aims to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and ground waters in Europe. It applies 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 coordinates 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 [2].

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" needs 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 good 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 [2].

Environmental cause-effect-response chain

The drivers pressures state impact response (DPSIR) approach *(Figure 1)* was developed by the Organisation

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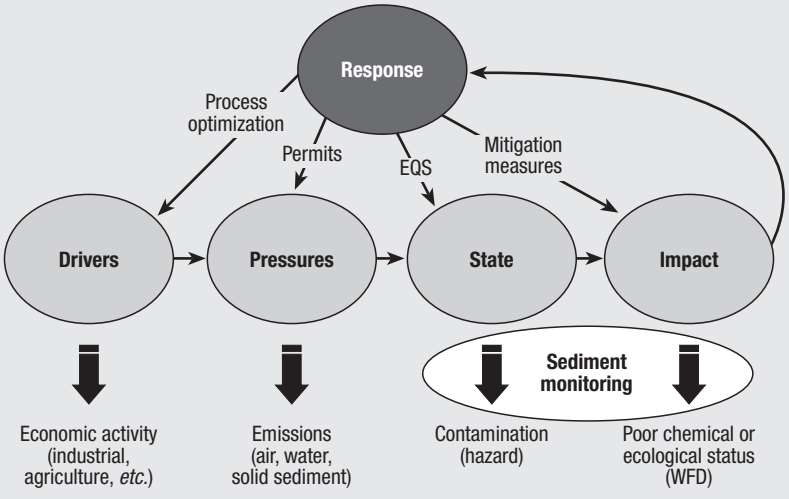

Fig. 1 | *The drivers pressures state impact response (DPSIR) approach including some examples of possible response measures and indicating the position of sediment monitoring (EQS: environmental quality standard; WFD: Water Framework Directive).*

for Economic Cooperation and Development (OECD) and extensively used by the European Environment Agency (EEA) to provide an insight into environmental processes and the links between human activities and their impact on the environment, such as river basins.

Economic activities (driving forces) such as industry, agriculture, tourism etc., lead to increasing Pressures on the natural environment as these activities result in use of natural resources and/or emissions (accidental or controlled) of waste to (ground) water, soil and sediment. The use of resources and/or emissions will change the state of these environments in quantity and/or quality: sediment (see next section), water and soil resources are depleted (erosion) and/or they are loaded (contaminated) with hazardous substances originating from the economic activities. Above a certain level of depletion and/or contamination the environment may be impacted, *i.e.*, loss of biodiversity, vulnerability to floods and landslides, decreased chemical and/or ecological water, soil or sediment quality and/or a shortage of these resources. Several response measures prevent this from happening or mitigate impacts to a level deemed acceptable or tolerable by society [3]. For example *(Figure 1)*, by optimization of industrial manufacturing processes less resources will be used and less waste may be produced. Through stricter permits for emission of waste water the pollution of surface water maybe reduced. The setting of environmental quality standards (EQS) may help to prevent that the environment will be "overloaded" with specific hazardous substances. And through mitigation measures the impacted environment may be restored.

SEDIMENT

Its role

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 floodin 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 resuspension and resettlement. In estuaries, sediment transport occurs both downstream and upstream, mixing fluvial and marine sediment as a result of tidal currents [2].

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 *(Table 1)* [2].

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

Table 1 | *Overview of sediment as a resource [4]*

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

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 [2]. 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 [2].

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 [2].

THE POSITION OF SEDIMENT IN THE WFD

The WFD does not specifically deal with sediment although sediments are a natural and essential part of the aquatic environment and their management has to play an important role in water legislation. However, it is clear that the implementation of the WFD will shift the scope from local sediment management (*e.g.* dredged material) to river basin scale sediment management [2].

The European Sediment Network SedNet (www.SedNet.org) successfully raised attention to this issue by underpinning that it is essential to integrate sustainable sediment management [2] in WFD River Basin Management Plans (RBMP). Some major European river basins commissions now took up this challenge to work towards a transboundary Sediment Management Plan as part of the RBMP (*e.g.* the Rhine and Danube commissions).

Also the European Commission (Stravros Dimas, Commissioner for the Environment) recognises the importance of sediments now [5, 6]: "The Commission is aware that polluted sediments are a problem for water quality across the EU. Unfortunately, there is no comprehensive overview from current monitoring data in the Member States yet. The most extensive set of monitoring data on pollutants in aquatic sediments of rivers was collected in the context of the Commps project (combined monitoring-based and modelling-based priority setting; http://europa.eu.int/comm/environment/water/water- framework/preparation_priority_list.htm). More than 68,000 individual monitoring results from 10 Member States for 221 different pollutants have been collected by the Commission. Based on this compilation, several substances (*e.g.*, brominated diphenylethers or flame retardants) which are particularly polluting sediments have been included in the list of priority substances under the WFD. The list was finally established by Decision No 2455/2001/EC [7]. Currently, the Commission is preparing a proposal to set EQS for the priority substances in accordance with Article 16 [7] of the WFD. It is expected to come forward with such a proposal in the first half of 2005 (this deadline was not met. It is expected that EQS will be proposed by the Commission in December 2006 and then solely for surface water and not for biota and not for sediment (personal communication, Brils).

However, the consultation of experts in preparation of the proposal concluded that it is currently not possible to set quality standards for sediments since the considerable lack of ecotoxicity data for benthic organisms (*i.e.* fauna living in the sediment) and the scientific uncertainties in relation to the exposure as part of the risk assessment in sediments. On this basis, the current position of the Commission is that it will be left to the Member States to identify sediments where remedial action is needed on the basis of the results from the ecological monitoring under the WFD. Benthic organisms are one quality element to determine the "good ecological status" under the Directive. If the sediment quality is too poor to achieve "good ecological status", Member States are required to initiate appropriate actions in line with Articles 4 and 11 of the Directive. This applies also to cross-border pollution from sediments, since such measures need to be coordinated in an international river basin management plan as set out by Article 13. Irrespectively of these effective provisions under the WFD to enable the Member States to tackle the pollution of sediments, the Commission will continue its efforts to overcome the lack of knowledge on sediment quality in the EU. To this end, the Commission will continue discussions with the EEA to overcome this deficit. In

addition, the Commission will consider whether an appropriate research project in the action on support for policy under the 6th Framework Programme may be another possibility to address this issue. In that respect the research projects carried out in the context of the European Sediment Research Network (SedNet) activities have been very valuable".

SEDIMENT MONITORING UNDER THE WFD

Sediment in the WFD

The WFD [1] contains provisions that call for assessments of contaminated sediments. Firstly, Article 16 [7] of the Directive states: "The Commission shall submit proposals for quality standards applicable to the concentrations of the priority substances in surface water, sediments or biota". If quality criteria were to be defined for sediment, then monitoring would be required to establish compliance with such criteria. Secondly, it is clear from the WFD that sediment monitoring can play a role when assessing impacts on environmental quality, while monitoring trends in pollutant levels and compliance with the WFD no-deterioration objective (Annex V 2.4.) [4]), and in any investigative monitoring of pollutants' fate and behaviour [8, 9].

In order to address these requirements of the WFD, the Working Group on Analysis and Monitoring of Priority Substances (AMPS) has considered the technical implications of sediment monitoring. AMPS intended to summarise the key issues and give technical expert advice to the EC on analysis and monitoring aspects, in order to justify the choices made in the forthcoming proposal for a daughter Directive on priority substances. The document could provide: a) suggestions for drafting proposals on sediment monitoring for the daughter Directive and b) recommend areas of sediment assessment to be further developed in the near future, to yield annexes to legislation or a separate guidance document [8, 9].

AMPS proposes the following definition for sediment: particulate material such as sand, silt, clay or organic matter that has been deposited on the bottom of a water body and is susceptible to being transported by water [8, 9].

Aim of sediment monitoring under the WFD

The purpose of analysing the levels of priority substances in sediments under the WFD might be: a) to monitor the progressive reduction in the contamination of priority substances and phasing out of priority hazardous substances and b) to demonstrate conditions of "no deterioration" in sediment quality. This is implicit in the need to ensure adequate provision of pollution prevention and control [8, 9].

Four types of sediment monitoring relate to the WFD:

- risk assessment;
- trend monitoring;
- spatial monitoring;
- compliance monitoring.

Risk assessment

The presence of contaminated sediments might be one of the obstacles to achieving "good ecological status" for a waterbody. One widely accepted way of obtaining an initial indication of the likely causes of a waterbody's poor ecological status is the sediment quality triad [10] *i.e.*, the simultaneous observations of sediment chemistry, sediment toxicity tests and, in the field, the benthic community [8, 9]. The observed concentrations of sediment-associated chemicals can be compared with sediment quality guidelines, if these are available. 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 meet 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. This demonstrates our need to better understand the relation between sediment contamination (a hazard) and its actual risk to the functioning of the ecosystem (ecological status) in order to be able to take effective measures to restore the ecological status of a given water body [11]. Complementary tools that are useful for improving this understanding include AVS/SEM extraction, bio mimetic extraction (POM, SPME, TENAX, etc.), functional monitoring techniques (suspended particulate matter grazing, organic matter mineralisation, etc.), effect directed analysis or toxicity identification evaluation and model ecosystems [12, 13].

TREND MONITORING

Trend monitoring will provide an indication of temporal changes over a prolonged period, *e.g.*, increases or decreases in concentrations of contaminants over time. The ICES Working Group on the Statistical Aspects of Environmental Monitoring in the marine environment has developed statistical methods for trend detection, including trend detection in sediments. These studies might contribute to a sound basis for the future development of statistical methods for sediment monitoring under the WFD [8].

The AMPS suggestion for the WFD priority substances to be monitored in sediment and biota is described in *Table 2*.

Spatial monitoring

Spatial monitoring will provide an indication of the status of contamination over an area. Such monitoring is necessary to detect the horizontal 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 contamina-

Table 2 | *Analysis and monitoring of priority substances suggestion for Water Framework Directive priority substances for trend monitoring in sediment and biota [8]*

Priority substance	Sediment	Biota	Priority substance	Sediment	Biota
Alachlor	O	---	Naphthalene	O	O
Anthracene	P	O	Nickel and its compounds	O	O
Atrazine	---	---	Nonylphenols	O	O
Benzene	---	---	Octylphenols	O	O
Brominated diphenyl ethers	P	P	Pentachlorobenzene	P	O
Cadmium and compounds	O	O	Pentachlorophenol	O	---
C10-13-chloroalkanes	P	P	Polyaromatic Hydrocarbons	P	O
Chlorfenvinphos	O	---	Simazine	---	---
Chlorpyrifos (-ethyl, methyl)	O	---	Tributyltin compounds	P	P
1,2-Dichloroethane	---	---	Trichlorobenzenes	---	---
Dichloromethane	---	---	Trichloromethane	---	---
Di(2-ethylhexyl)phthalate	O	O	Trifluralin	O	---
Diuron	---	---	DDT (including DDE, DDD)	P	P
Endosulfan	O	---	Aldrin	O	O
Fluoranthene	P	O	Endrin	O	O
Hexachlorobenzene	P	P	Iosdrin	O	O
Hexachlorobutadiene	O	O	Dieldrin	O	O
Hexachlorocyclohexane[b]	O	P	Tetrachloroethylene	---	---
Isoproturon	O	---	Tetrachloromethane	---	---
Lead and its compounds	O	O	Trichloroethylene	---	---
Mercury and its compounds	O	P			

P: prefered matrix; O: optional matrix; ---: water is preferred matrix.

tion is influenced by differences in sedimentation rate of newly formed particulate material as it influences the degree by which historic contamination is covered-up. Consequently, the choice of sediment sampling depth is a critical issue in mapping the status of sediment quality [8].

Compliance monitoring

WFD environmental quality standards (EQS) for priority (hazardous) substances are currently being established for the water phase. EQS means the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment [1]. In cases where water quality standards have been violated, one of the sources of pollution might have been the emissions of contaminants from contaminated sediment to surface waters and groundwaters. This demonstrates the connectivity between the water and sediment phases. However, compliance monitoring of sediment quality is not yet appropriate because of the lack of valid sediment quality standards and the complexity of deriving such criteria in a European context. The limitations of sediment quality standards in assessing contaminated sediments have already been indicated in the section "The position of sediment in the WFD". A further obstacle is the anticipated high costs of obtaining full spatial coverage [8].

To keep in mind

Sediments have an impact on ecological quality because of their quality, or their quantity, or both. Therefore, sediment monitoring programmes should also address the basic physicochemical properties of sediments (grain size distribution, organic carbon content, etc.) as well as the geomorphological processes within each river system, including those operating in floodplains, wetlands and the coastal zone. The physicochemical quality of sediments is featured in the definition of good and moderate ecological status in rivers and lakes (Annex V 1.2) [1, 8].

GUIDANCE FOR SEDIMENT MONITORING

Current status

The AMPS discussion document [8, 9] indicates that there is a clear need to develop diagnostic and technical guidance for sediment monitoring. Such guidance should be made available in the year 2006 in order to support Member States in their effort to implement the WFD. First of all, there is the need to develop new monitoring programmes under the WFD. Secondly, analyses are under way to identify the necessary measures to meet the good ecological status and water quality standards.

SedNet recommendations

SedNet developed some recommendations towards guidance for sediment monitoring [2]:

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 contami-

nants. 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.

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 (PBDE). 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.

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