

# Risk management of sediments

**Susanne Heise**

*Consulting Centre for Integrated Sediment Management (BIS),  
Technical University Hamburg-Harburg, Hamburg, Germany*

**Summary.** Sediment management nowadays is often concerned around sediments that have been polluted in former times, posing the following questions: what risks remain after time has passed concerning the persistence, ageing and bioavailability of the polluting substances; where does the risk apply regarding the transport of contaminated sediments and the management objectives in the different zones of a river basin; how can solutions be found; who is responsible for paying the management measures. This publication reflects on the discussions in the SedNet Working Group on “risk management and communication” claiming that sustainable sediment management needs to be risk based and oriented towards the river basin scale. Results of two case studies are recounted, which roughly followed the site prioritization approach that was suggested by the participants of the working group and gives an example on a decision making module that could help in communicating interests and the resulting priorities of measures, after areas of risks have been identified in a river basin.

*Key words:* sediments, risk management, polluting substances, SedNet.

**Riassunto** (*Gestione del rischio dei sedimenti*). La gestione dei sedimenti riguarda generalmente l'inquinamento del passato e su tale aspetto si pongono diverse questioni: quali sono i rischi riguardo alla persistenza, all'età ed alla biodisponibilità delle sostanze inquinanti; dove è necessario applicare la valutazione di rischio in relazione al trasporto dei sedimenti contaminati e gli obiettivi di gestione in relazione alle differenti zone di un bacino idrografico; che tipo di soluzioni possono essere trovate; chi è responsabile delle misure di gestione. Questo lavoro riflette le discussioni del Gruppo di Lavoro SedNet per “la gestione del rischio e comunicazione”, in cui si afferma che una gestione del sedimento sostenibile debba essere basata sulla valutazione del rischio e orientata su scala di bacino. Vengono riportati due casi studio in cui è stato seguito l'approccio della prioritizzazione del sito suggerito dai partecipanti al gruppo di lavoro e offre un esempio di uno schema decisionale che potrebbe supportare, dopo aver identificato le aree di rischio su scala di bacino, l'individuazione delle priorità delle misure.

*Parole chiave:* sedimenti, gestione del rischio, sostanze inquinanti, SedNet.

## INTRODUCTION

The term “Anthropocene” has been suggested for the current era, indicating the enormous influence that humans have on the earth surface system [1]. Most of the risks that people have to face in connection with sediment – whether they centre on humans and society, the water phase or the sediment biotope itself – support this observation: if we talk about risks, we also have to talk about our motivations or objectives that put us or the environment at risk, and about those actions that will lessen the effects of our recent or past deeds. Two criteria of sediment cause risks: the quantity of sediment, which may increase (sedimentation) or decrease (erosion) with potential adverse economic and environmental consequences, and its quality, which has been reduced through anthropogenic activities and which – despite trends of improving water quality in Western Europe – is still poor in many rivers. But when talking about

risks, this implies an assessment of a situation that is largely uncertain and unstable, one that presents a danger for organisms that have not yet adapted to the present or future conditions.

## SEDIMENTS AND EXISTING ENVIRONMENTAL REGULATION

Risk due to erosion of contaminated sediments and their potential impacts downstream is not covered by existing regulations. Existing regulations focus on local impacts of the relocation of contaminated sediments and do not take the whole catchment into account. On the other hand, the Water Framework Directive (WFD), which focuses on the catchment scale, so far does not consider sediment quality and quantity as a major issue [2]. However, the strategies against chemical pollution of surface waters (WFD Article 16), *i.e.* implementation of monitoring pro-

grams until 2006 and establishment of a program of measures until 2009, have to consider sediment quality at the catchment scale. With respect to the latter date, already the first step – screening of all generic sources that can result in releases of priority substances and priority hazardous substances – will include the specific source/pathway “historical pollution from sediment”.

### THE NECESSITY TO ADDRESS THE RIVER BASIN SCALE [3]

Sediments along rivers are of a dynamic, complex and interconnected nature, linking terrestrial and estuarine/marine environments. Risks posed by these sediments (environmental, economical, societal) therefore require a basin scale approach that takes the entire sediment cycle, time and space dimensions, into account rather than one unit of sediment at a time. A basin-scale risk management framework has been suggested by [4] and should be comprised of two principal levels of decision making; the first being a basin-scale evaluation (prioritisation of sites for further evaluation and/or management) and the second being an assessment of specific sites for risks and management options (site-specific risk ranking and management) [5]. Such a basin scale decision framework will help focus limited resources to maximize the achievement of management objectives, including basin scale risk reduction.

The first step (site prioritisation) will make use of existing information on location of river sites, their potential (hydrodynamic) energy within the catchment, the quality and quantity of the sediment (*e.g.*, from monitoring programmes) [6, 7]. However, the information on water (and even more so sediment) data often shows deficiencies which have been identified by the European thematic framework programme “Metropolis” (Metrology in Support of Precautionary Sciences and Sustainable Development Policies; [8] as to impede a Europe-wide comparison of water quality data and the integrated decision processes required to achieve improvements along whole water sheds. These are:

- the lack of standardised investigation and evaluation methods;
- the lack of representative data: those available today are not representative of the reality of the situations found in the field;
- the lack of specifications on quality and uncertainty of the data used for decision-making II-2;
- the lack of so-called “meta-data”: How and when have measurements been carried out? Who do these data belong to? In what way have the data been used? Such information is essential, if data are supposed to be used also for other than the original purpose;
- the lack of traceability. The fundamental concept of traceability requires that environmental measurement data allow backtracking: i) to defined references (material and methods); ii) via a

continual chain of comparabilities and; iii) with assessed uncertainties [9].

A quantification of uncertainties and the consideration of best case and worst case scenarios is hence of uttermost importance in order to assess robustness and reliability of the conclusions.

### SEDIMENT MANAGEMENT NEEDS TO BE RISK BASED

#### *The concept of risk in environmental management*

Although there is no commonly accepted definition of the term risk, all concepts have one element in common: the distinction between reality and possibility. Renn [10] proposes as a general definition: “Risks refer to the possibility that human actions or events lead to consequences that affect aspects of what humans value”.

This definition has some important implications: 1) a risk can theoretically have adverse or desirable outcomes; 2) it is strongly connected with a value for humans. The risk of extinction of a polychaete population in estuarine sediment will concern less people than the reduction of the seal population in the Northern Sea.

Risk management refers to the process of reducing the risks to a level deemed tolerable by society and to assure control, monitoring and public communication [11]. Risk management decisions are based on the outcome of the scientific risk assessment process, but they also have to include social, economic, cultural, political and legal considerations as well as the technological feasibility.

Key drivers include [12]:

- *economics*: cost-effectiveness of various risk reduction or mitigation alternatives and the benefits derived from each;
- *societal factors*: public perceptions, risk communication, stakeholder involvement, environmental justice, and competing economic concerns (*e.g.* jobs, crime, education);
- *policy and politics*: environmental laws and regulations; federal, state, and municipal policies; and associated processes by which they are developed;
- *technology*: availability of engineering capability to support various risk management options;
- *public values*: regulations, case law, market analyses, public influence, quality of life, clean environment, good health, good jobs, and public perceptions, etc.;
- *science*: the state of knowledge pertaining to the risk and its attendant uncertainty and variability.

The foundation of risk assessment is the scientific evaluation of information. The purpose of risk assessment is to summarize and present scientific knowledge so that it can be used to make sound management decisions. It is commonly also expressed by the product of the magnitude of possible adverse effects and the probability of exposure.

In this formulation there is no reference to possible interest of the public. On the opposite, in order

to ensure the scientific integrity of the risk assessment process, risk assessment and risk management procedures were conceptually separated by the NRC [13]. Recently, however, this concept has been questioned as it too easily resulted in risk assessments that lacked relevance for the risk management process. A clear formulation of management goals has been found necessary and an early interaction between risk assessment and management has been suggested [12, 14].

Four objectives of risk management have been identified [15]. They comprise: 1) the need to meet regulatory criteria such as the WFD; 2) the willingness to maintain economic viability; 3) the assurance of environmental quality; and 4) the obligation to secure quality of human life. They are all based on either human and societal risk (the economic situation, health or quality life) or environmental ethics, claiming that nature has a right to exist in and of itself. By managing the environment and by following the WFD, it is recognized that most of the damage that has been done to the environment has been done by human activities, directly or indirectly. So by terminating or reversing the process, management aims to improve or maintain living conditions for humans and society and the world we live in.

To consider the temporal scheme is one of the main differences between hazard assessment and risk assessment, as has recently been pointed out by Tannenbaum [16] and whatever objective is followed, for successful sustainable management it needs to be understood that the timescale of sediment is different from water. Sediments have a much longer residence time in the aquatic environment, their dilution rate with uncontaminated material, is much lower than that of water. This needs to be taken into account when planning management actions to prevent or reduce risks posed by sediments and when planning actions that may put sediments or the environment at risk.

#### *An approach to risk-based sediment management*

Industrial development along rivers over the last 150 years has left us in many places with a legacy of contaminated sediments and sites which are still being transported downstream, carrying contaminants adsorbed to particulate matter to other river stretches, finally settling in harbour basins.

Sediments can be regarded as the “memory” of the environment, as they will store those contaminants for a long time. The hexachlorobenzene (HCB) contamination of the sediments of the High Rhine, for example, goes back to a German pentachlorophenol producing plant until the 1980s [17]. HCH- and dioxin contamination of Elbe sediments derive from industrial sites at Bitterfeld in the former GDR [18]. For all those site, no institution or person can be held responsible anymore, as owners and/or political systems have changed since these extensive emissions took place. High dioxin contamination in sediments at the Port of Hamburg, increased HCB contami-

nation in suspended matter at the Dutsch-German Border after a flood event in 1999 give evidence to the fact, that contaminated sediments from upstream are transported with the current, especially after flood events, and can pose a risk to sites much further downstream. As pointed out above, sediment management accordingly has to be addressed on a river basin scale. The number of contaminated sites, however, is often too high for all of them to be managed. A prioritization of sites has to be carried out according to the risk that they pose to the environment of the river basin. Thereby not the extent of contamination alone is sufficient to indicate such a risk. A highly contaminated site, which is fairly stable and not eroded during floods may pose a local risk, but none to the river stretches downstream. An unstable site can hence lead to a much larger risk to the river, even if it is less contaminated but causes higher exposure. The area which may be exposed by this sediment is larger, the further upstream the contaminated site is. Babut *et al.* [7] defined the criteria which determine the risk of a site in the river basin as such:

- *location* along the up- to downstream gradient; for long-term protection of a harbor, for example, location could be defined as distance to the harbor; for more short-term and local impacts one might consider using distance between two sediment sites; for cumulative downstream risk one might use distance of a site from the river source;
- *energy*, *i.e.* potential energy [6], is also a component of the overall transport risk: the higher the energy, the higher the risk that upstream sediments be deposited downstream. The potential energy could best be represented by the slope between points of interest, or as a surrogate by the elevation difference. Some confounding factors such as barriers might interfere. The energy criteria is primarily related to the management goal of reducing sediment loads in water, and downstream, but it can also be related to the quality function;
- *quantity* encompasses three inter-related aspects all of which could be used as criteria: volume of contaminated sediment available for entrainment, sediment budget [19] represented by the balance between eroding and depositing material, and mobility, which describes the ease with which sediments may be entrained into flow. Mobility will be affected by the grain size distribution of sediment deposits, the length of time sediment has been deposited and the shear stress exerted on the sediment by flowing water [20]. In the Netherlands the concept of a stability constant has been used [21];
- *quality*, which could be represented by indices of hazard, such as [22] or by using sediment quality guidelines (SQG). These could be expressed as sums or means of a hazard quotient (HQ; ratios of chemical concentrations to SQG) or bio-

logical measurements, such as acute or chronic toxicity. It should be noted, however, that for a basin-scale study, if available data are limited, screening-level chemical and biological measures can be used. Clearly, quality is linked to the goal to either control toxicity or control contaminant levels;

- *expected risk or benefit* of a specific sediment unit to downstream sediments. This can be expressed as a combination of the likelihood of sediment moving from its current site to a site of concern and the relative quality of the two sites. At a screening level this can be expressed as the ratio of the difference in quality and the distance (horizontal or vertical) between sites.

### THE CASE-STUDIES RHINE AND ELBE

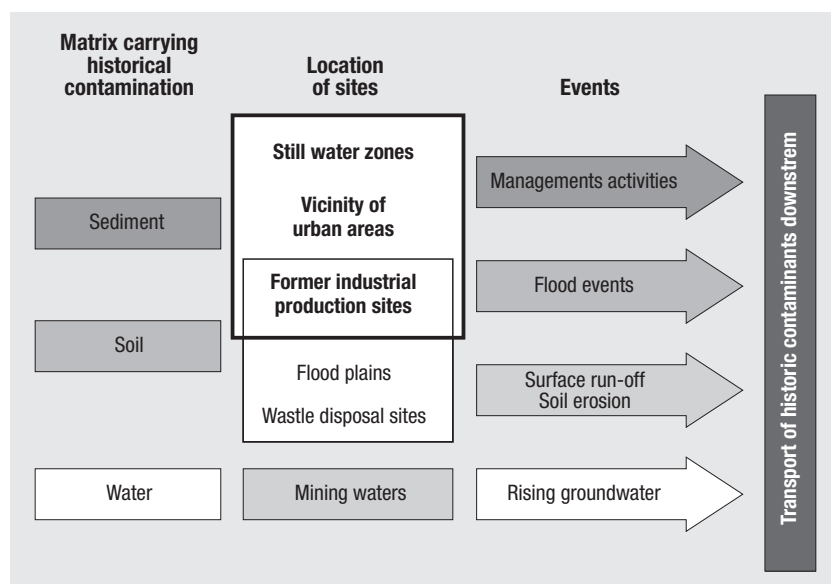
This approach was applied to a prioritization of sites in the Rhine catchment according to their risks for downstream areas [17], and a similar study has begun for the Elbe river. Both case studies have been financially supported by the port authorities of Rotterdam for the Rhine and of Hamburg for the Elbe river. Many ports have in parts highly contaminated sediments in their harbour basins which need to be dredged to ensure economic liability and then have to be carefully and expensively managed in order to comply with environmental regulation. In The Netherlands each year 25-30 million m<sup>3</sup> partly contaminated dredged material has to be removed. More than half of this amount comes from maintenance dredging for the main port Rotterdam. In Hamburg, where the volume of dredged material has increased 3-fold from about 3 mio m<sup>3</sup> to 9 mio m<sup>3</sup> since 1999 [23], the necessity to dispose the material is achieved at high costs – also in environmental terms, as relocation of contaminated sediment to the North Sea was considered to be the only short-term solution to this

sudden increase. A dilemma exists, as the ports themselves are often not fully and in some cases even to a minor degree responsible for the contamination of the sediment ending up in their harbours. One long-term possibility for them to reduce the financial expenses necessary to manage contaminated dredged material is a river basin approach which leads to reduction of transport of contaminated sediment downstream with the river current.

Accordingly, management measures must be carried out upstream in the catchment area. The high number of contaminated sites, scarce financial resources, absence of responsible institutions for historical point sources make this a highly difficult and politically complex task. Support comes from European Legislation: The European Water Framework Directive (EC 2000) for the first time required the cooperation of different institutions and stakeholders along rivers, independent of national and administrative boundaries, for achieving an overview over the environmental status of rivers in Europe. By 2009, a programme of measures needs to be suggested by the European states for the various catchments, aiming at achieving a good ecological status of all waters in Europe by 2015. Therewith, this regulation fosters catchment scale thinking and the awareness, that only joined efforts and measures can be successful in reducing impact of historical sites on river basins. These, however, have to be directed to specific areas with the highest environmental impact.

The prioritization of those sites in a catchment with regard to the risk that they pose for downstream areas should apply a three-step approach [5]:

- *identification of substances of concern* and their classification into “hazard classes of compounds”. These classes are assigned depending on the chemicals persistence, their partitioning to sediment and their environmental risk;
- *identification of areas of concern* and their classification into “hazard classes of sites”. Areas are



**Fig. 1** | Pathways and processes for the transport of historic contamination downstream.



defined to be of concern, if the surface sediment data exceed the sediment quality criteria that are valid in the downstream region of the river e.g. in downstream harbours. The classification into 4 classes, differing in the extent of hazard and the degree of uncertainty, was based on the confidence in the sediment data for the specific area (e.g. only one sample taken as compared to frequent sampling over years), the extent of contamination and the hazard class of those substances that exceeded the target thresholds;

- *identification of areas of risk*. The risk assessment for the downstream sediments due to those “substances of concern” that could derive from the identified “areas of concern” requires estimating resuspension, transport probabilities, and determination of transported quantities. As floods frequently occur in main river and tributaries, the final assessment of “areas of risk” has to take into account the impact of increasing discharge levels.

An indication of the potential for an “area of concern” to lead to an exceedance of the target threshold in the downstream area if it becomes resuspended and transported downstream is derived from taking into account dilution by suspended matter originating mainly from the tributaries:

$$XA = X * G_{KB} / Q_A$$

(where “ $X_A$ ” is the concentration at location “A” which needs to be exceeded at a certain location in order to have a potential to exceed the respective target value at the downstream area after resuspension; “ $X$ ” is the target threshold for the respective substance; “ $G_{KB}$ ” is the suspended matter load at the downstream area; “ $Q_A$ ” is the suspended matter load at location “A”).

This information is regarded as separate lines of evidence, from which at the end the final conclusions are drawn and sites classified as bearing “no evidence of risk”, “evidence for risk”, “evidence for high risk”, or as those sites, for which a risk could not be excluded.

### Substances of concern

In the site-prioritization process for the Rhine, those substances were chosen for further evaluation, that were of concern for the management of the Port of Rotterdam as they frequently exceeded or reached the new Dutch “Chemistry toxicity tests (CTT) levels”. These substances of concern were then assigned to hazard classes 1 or 2, whereby the higher hazard class 2 represented bioaccumulative, persisting and sediment adsorbing substances (Table 1).

In the application of this approach to the Elbe river, inorganic substances that are of concern along the Elbe basin also include arsenic.

### Areas of concern

Sites for the accumulation and potential exposure of contaminated sediments in the catchment area which are a potential area of concern are:

**Table 1** | Substances of concern in the Rhine study and their ranking

Substances of concern	Hazard class
Cadmium	2
Chromium	1
Copper	1
Mercury	2
Nickel	1
Lead	1
Zinc	1
DDT+DDD+DDE (SUM)	2
Dioxins and Furans	2
Hexachlorobenzene	2
Polycyclic aromatic hydrocarbons	2
Polychlorinated biphenyls	2
TBT	1
Aldin (Dieldrin, Endrin)	1
$\gamma$ -hexachlorocyclohexane	1
Nonyl-phenol compounds	1

- river reservoirs and barrages where sediment is accumulated and which can release the contaminants during floods events;
- inland harbours with wide openings to the main river;
- groyne fields that may contain a large volume of contaminated material along a river;
- tributaries and bypass channels which historically were industrially used but which have not been maintained by continuous dredging;
- industrial areas which are located within the potentially flooded area and which contain waste deposits;
- the vicinity of larger cities (and emissions from municipal wastewater plants);
- contaminated soil during surface during run-off or erosion events.

Existing sediment analysis data from the last 10 years were used to identify those areas in the Rhine and its tributaries, and in the Elbe which show increased concentrations of these substances of concern above the target level – the CTT level in the Netherlands and the target value class II of the IKSE Classification of the Elbe river (IKSE: International Commission for the protection of the Elbe) – and therewith could potentially provide a danger of increasing concentration levels at the downstream ports. In the Elbe river, e.g., with the exception of lead, which there is of least concern among the heavy metals and only shows increased levels in parts of the Mulde and the Saale, all heavy metals as well as organic substances like PCB, HCH, dioxins, DDT and HCB show highest concentrations in the sediments between Magdeburg, sometimes even further upstream, and Hamburg [24].

These areas of concern were classified with regard to the quantity of contamination and available data to give an overview over the distribution of persisting hazards in sediments along the rivers. A survey on information about historic emissions followed in order to: a) clarify the sources of the sediment contamination; b) validate the possibility of persisting contamination at these sites; c) gather information on management options due to the potential persistence of sources and the distribution of contamination. An example for historical sources and areas of concern along the Elbe river are presented in *Table 2*.

### Areas of risk

In this last step of the site-prioritization, the areas of concern are examined with regard to the actual risk that they present for the downstream areas. In the case of the Rhine, a number of 12 “areas of concern” along the Rhine basin was reduced to five “areas of risk” of which 2 were classified as areas presenting a “high risk with high certainty” under certain levels of water discharges (*Figure 2*):

- 1) the *Ruhr river* was assessed to represent a risk at increased water discharges. High concentrations of polycyclic aromatic hydrocarbons (PAH) but also of the other substances that are of concern in that river, especially cadmium, are likely to be resuspended and transported downstream;
- 2) the *barrages in the Upper Rhine* were the only sites in this study, that may already present a risk dur-

ing business as usual conditions (average water discharge, no management activities): already at normal discharges, increased concentrations of HCB have been measured in suspended matter at Iffezheim. With increasing discharges HCB (and possibly mercury) becomes resuspended and transported downstream. With the continuous inflow of contaminated sediments from the barrages further south, the existing sediment disposal sites reaching their upper limits, combined with still high HCB concentrations in the sediment and significant gaps in the understanding of its transport processes, this area becomes an important challenge for future sediment management.

For the Elbe river, the identification of the areas of risk at this moment has begun. It will be carried out by BIS on behalf of the Hamburg Port Authority, the “River Basin Community Elbe” (FGG: Flussgebietsgemeinschaft Elbe) and the Federal Institute of Hydrology. This co-operation expresses the common aim of the different institutions in sediment management of the Elbe river, despite different objectives.

### SELECTING MEASURES. THE USE OF DECISION MAKING TOOLS IN SEDIMENT MANAGEMENT

The consequent next step after the areas of risk have been prioritized is the decision about what measures

**Table 2** | Substances of concern, their historic sources and current areas of concern in the Elbe river (compiled in Förstner et al. *J. Soils & Sediments* 2004;4(4):247-60, from [24, 25])

Substance of concern	Historical sources	Areas of concern
Arsenic (As)	Browncoal mining	Mulde
Cadmium (Cd)	Browncoal mining smelting processes metal processing	Mulde (Havel) (Elbe downstream Magdeburg)
Copper (Cu)	Artificial silk production Copper-processing industry	Elbe Saale
Mercury (Hg)	Chlor-alkali electrolysis (amalgamation process)	Saale Mulde downstream of Bitterfeld
Lead (Pb)	Mining Smelters	Saale Freiberger Mulde
Zinc (Zn)	Industrial and municipal Wastewater Mining industry Smelters	Saale Mulde Weiße Elster Havel (Elbe downstream of Magdeburg)
Halogenated organic compounds (AOX)	Pulp and paper mills (Mulde)	Mulde Saale
Trichloromethane	Chemical industry, pulp and paper mill waste water	Mulde
Insecticides e.g. DDT, $\gamma$ -HCH	Production facilities	Bilina (Czech Republic), Mulde
Hexachlorobenzene (HCB)	Chemical industry	Karlsberg and Luznice (disposal sites) Bilina (Czech Republic)
Polychlorinated biphenyls (PCB)	Chemical industry	Bilina (Czech Republic), Mulde, Saale, Weiße Elster
Polycyclic aromatic hydrocarbons (PAH)	By-product during incomplete incineration of organic material	Schwarze Elster Mulde

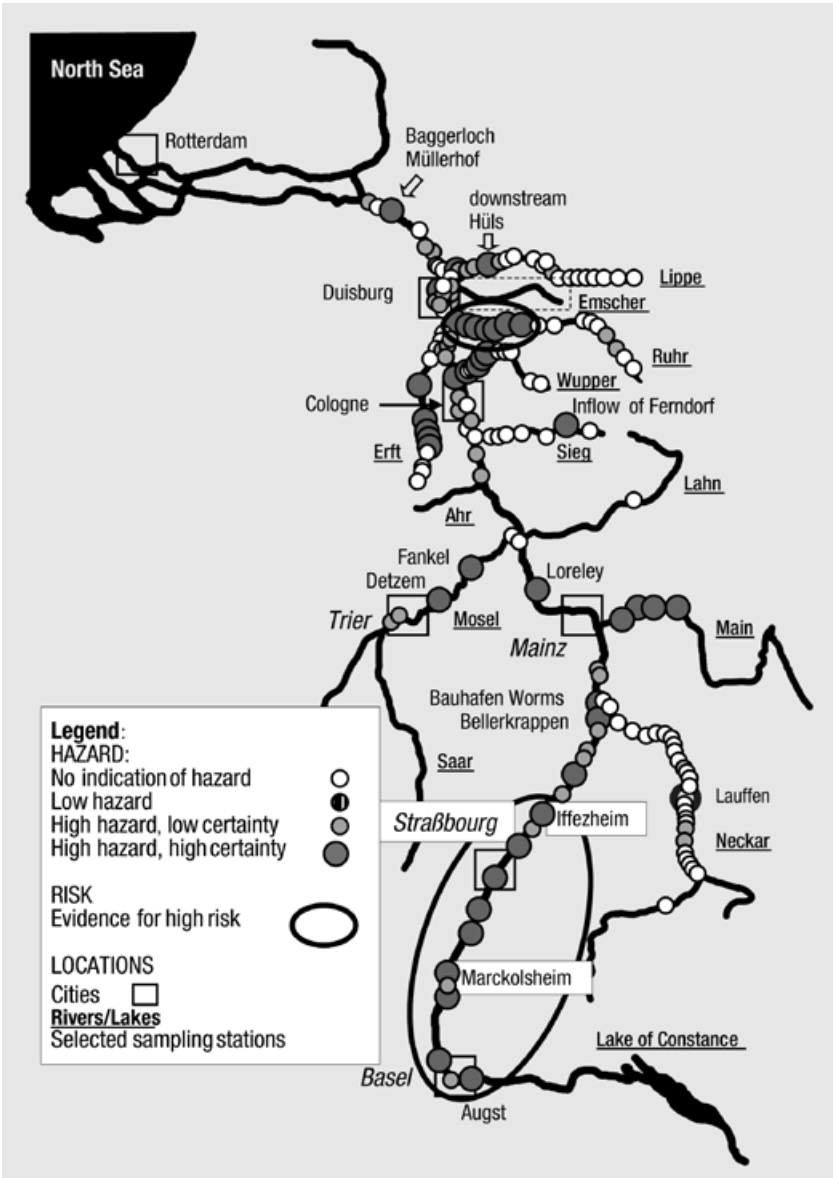


Fig. 2 | Areas of concern and areas of risk in the Rhine Basin (modified from [17]).

need to be applied where. The decision on sediment management measures is complex and multivariate, namely, because the decisions need to look for compromises between socio-economic, environmental, and economic impacts. The criteria for selecting appropriate remedial techniques for contaminated sediments (e.g. cost, risk, safety, environmental impact) cannot easily be converted into the same value, and that complicates the integration problem inherent to making comparisons and trade-offs. Research in the area of multi criteria decision analysis (MCDA) has made practical methods available that can be used to solve multi-criteria problems. However, these methods have not been formalised into a framework readily applicable to environmental projects dealing with contaminated sediment sites where risk assessment and stakeholder participation are of crucial concern.

Analytical hierarchy process (AHP) is a one decision support tool that has been applied to recom-

mend a sediment management measure at Sepetiba Bay in Brazil [26] and to analyse potential measures for a highly contaminated site in the Elbe catchment area [27]. Within AHP, elements of a problem are hierarchically structures [28]. It can support decision making by providing a quantitative comparison of alternatives by breaking down the problem into its smaller parts and evaluating relative strength of each element. The method uses pairwise comparisons of criteria and sub-criteria, where the evaluator sets priorities through a scale of preference. The steps to be followed when assessing the relative risks associated with application of sediment management methods included problem formulation and determination of objectives, determination of alternatives and selection of criteria, followed by the evaluation of criteria with respect to alternatives, and finally, decision analysis, which included hierarchical structuring of objectives, criteria and

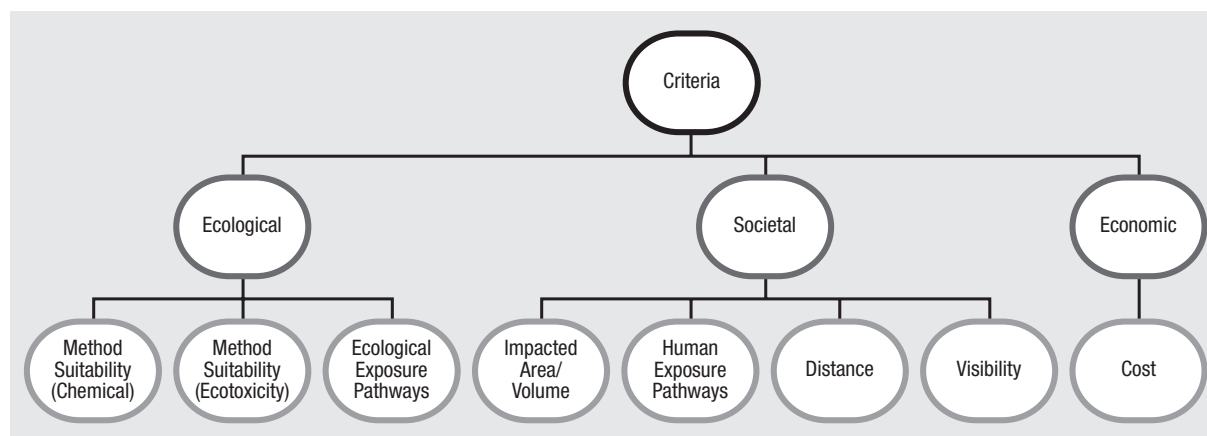


Fig. 3 | Criteria for analytical hierarchy process.

alternatives, determination of weights with AHP, normalisation of criteria, synthesis of results, sensitivity analysis and making a decision.

In [26], the most adequate sediment management alternative was defined as the option with the least economic, societal and ecological impact. AHP was employed to organize and weight criteria and provide scores for the impact of each of four potential management options for the case of Sepetiba Bay, Brazil. Figure 3 shows the criteria for the AHP, divided into ecological, societal and economic sub-criteria, following roughly the approach of [29]. Method suitability and exposure pathways were used as indicators of the potential ecological impacts of the sediment management alternatives. Impacted area/volume, human health exposure pathways, distance, visibility provided quantitative measure to the public acceptance of the alternatives. The costs were taken to evaluate the economical burden of the proposed options.

In a scenario in which all criteria were regarded as equally important, confined aquatic disposal in this specific case presented the lowest ecological, societal, and overall impact (Figure 4). In a scenario, in which the economic criterion would be considered

strongly more important than the other criteria, in-bay disposal of contaminated sediments would become an option. However, ecological impact would need to be accepted.

## CONCLUSIONS

Sustainable sediment management is a complex issue due to the different objectives involved, due to the challenging measures and due to the environmental regulations which are mostly not sufficiently defined for sediment purposes. Concepts for risk based sediment management on river basin scale have been suggested, but there is still a need for case studies to further develop and elaborate on these concepts.

With the implementation of the WFD, basin scale thinking has become more accepted. The interlinking character of sediment that has been polluted in historic times but may still present a problem at river stretches far away from the original source has made it necessary to overcome administrative and political boundaries if solutions are to be found and measures adopted. Where no polluters can be held responsible, a circumvention of the polluter pays principle can seem advisable, in which those institu-

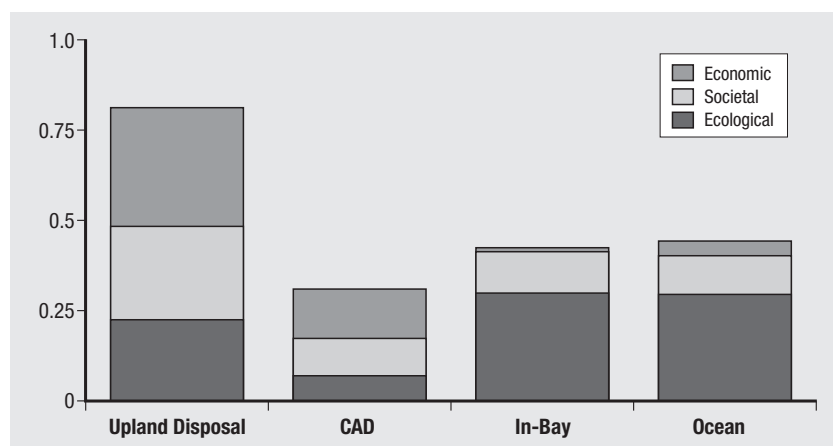


Fig. 4 | Relative risks of 4 management options for the case of Sepetiba Bay. All criteria were equally weighted (from [26]).



tions with an interest in the sediment contamination cooperate, also on financial terms.

Even though the aim to sustainably manage sediments may be common among the actors of such a cooperation, the weighing of different interests and criteria will surely be different. If, however, it is claimed, that only a cooperation of stakeholders on river basin scale can achieve a sustainable sedi-

ment management, the challenge of communicating these interests among stakeholders and among the public and of finding compromises needs to be approached. One step in this can be the application of decision support models.

Submitted on invitation.

Accepted on 3 June 2008.

## References

- Crutzen PJ, Stoermer EF. The "anthropocene". *IGBP Newsletter* 2000;41:17-8.
- Salomons W, Brils J (Ed.). *Contaminated sediments in European river basins. European Sediment Research Network SedNet. EC Contract No. EVKI-CT-2001-20002, Key Action 1.4.1 Abatement of Water Pollution from Contaminated Land, Landfills and Sediments*. Den Helder, The Netherlands: TNO; 2004.
- Förstner U, Heise S. Assessing and managing contaminated sediments: requirements on data quality from molecular to river basin scale. *Croatica Chimica Acta* 2006;79:5-14.
- Apitz SE, Carlon C, Oen A, White S. Strategic framework for managing sediment risk at the basin and site-specific scale. In: Heise S (Ed.). *Sediment risk management and communication*. Amsterdam: Elsevier; 2007. p. 77-106.
- Heise S, Apitz SE, Babut M, Bergmann H, Besten Pd, Ellen GJ, Joziassie J, Katsiri A, Vera Maaß, Oen A, Slob A, White S. Risk management of sediments and communication. Synthesis of the SedNet working group 5 outcomes. *J Soils & Sediments* 2004;4:233-5.
- Apitz S, White S. A conceptual framework for river-basin-scale sediment management. *J Soils & Sediments* 2003;3:132-8.
- Babut M, Oen A, Hollert H, Apitz SE, Heise S, White S. Prioritization at river basin scale, risk assessment at local scale: suggested approaches. In: Heise S (Ed.). *Sediment risk management and communication*. Amsterdam: Elsevier; 2007. p. 107-52.
- Evaluation of current gaps and recommendations for further actions in the field of environmental analysis and monitoring. Metropolis (Metrology in Support of EU Policies) Position Paper, March 2004. Verneuil-en-Halatte, France; 2004.
- Quevauviller P. Traceability of environmental chemical measurements. *Trends Anal Chem* 2004;23:171-7.
- Renn O. The role of risk perception for risk management. In: Douben PET (Ed.). *Pollution risk assessment and management*. Chichester: John Wiley & Sons Ltd.; 1998. p. 429-47.
- Kolluru RV. Risk assessment and management: a unified approach. In: Kolluru R, Bartell S, Pitblado R, Stricoff S (Ed.). *Risk assessment and management. Handbook for environmental, health, and safety professionals*. New York: McGraw-Hill; 1995. p. 1.3-1.41.
- Pittinger CA (Ed.). *A multi-stakeholder framework for ecological risk management: summary from a SETAC technical workshop*. Society of Environmental Toxicology and Chemistry (SETAC); 1998.
- NRC. *Risk assessment in the Federal Government. Managing the process*. Washington, DC: National Academy Press; 1983.
- Ferguson C, Darmendarial D, Feier K, Jensen BK, Jensen J, Kasama H, Urzelai A, Vegter J (Ed.). *Risk assessment for contaminated sites in Europe. Vol. 1. Scientific basis*. Nottingham: LQM Press; 1998.
- Joziassie J, Heise S, Oen A, Ellen GJ, Gerrits L. Sediment management objectives and risk indicators. In: Heise S (Ed.). *Sediment risk management and communication*. Amsterdam: Elsevier; 2007. p. 9-76.
- Tannenbaum LV. A critical assessment of the ecological risk assessment process: A review of misapplied concepts. *Integr Environ Assess Manag* 2005;1:66-72.
- Heise S, Förstner U, Westrich B, Jancke T, Karnahl J, Salomons W. *Inventory of historical contaminated sediment in Rhine basin and its tributaries*. Hamburg: on behalf of the Port of Rotterdam; 2004.
- Heise S, Claus E, Heininger P, Krämer T, Krüger F, Schwartz R, Förstner U. *Studie zur Schadstoffbelastung der Sedimente im Elbeinzugsgebiet*. Hamburg: Commissioned by the Hamburg Port Authority; 2005.
- Kern U, Westrich B. Sediment Budget Analysis for River Reservoirs. *Water Air & Soil Pollut* 1997;99:105-12.
- Haag I, Kern U, Westrich B. Erosion investigation and sediment quality measurements for a comprehensive risk assessment of contaminated aquatic sediments. *Sci Total Environ* 2001;266:249-57.
- Besten PJd, Schmidt CA, Ohm M, Ruys MM, Berghem JWv, Guchte Cvd. Sediment quality assessment in the delta of rivers Rhine and Meuse based on field observations, bioassays and food chain implications. *J Aquatic Ecosystem Health* 1995;4:257-70.
- Wildhaber ML, Schmitt CJ. Hazard ranking of contaminated sediments based on chemical analysis, laboratory toxicity tests, and benthic community composition: prioritizing sites for remedial action. *J Great Lakes Res* 1996;22:639-52.
- HPA. *Handlungsbedarf zur Sicherung der Unterbringung des Baggergutes aus der Stromelbe*. 2005, Hamburg Port Authority, Freie und Hansestadt Hamburg: Hamburg.
- Prange A, Furrer R, Einax JW. *Die Elbe und ihre Nebenflüsse - Belastung, Trends, Bewertung, Perspektiven*. 2000, ATV-DVWK Deutsche Vereinigung für Wasserwirtschaft, Abwasser, Abfall e.V: Hennef. p. 168.
- Spott D, Becker E. *Protokoll einer Wiederholungs-Meßfahrt auf der Mittelbe*. Hamburg: Arbeitsgemeinschaft für die Reinhaltung der Elbe; 2000.
- Barreto AR. *Evaluation of sediment management alternatives for dredging activities at Sepetiba Bay*. Department of Environmental Science and Technology. Hamburg: TUHH; 2006.
- Juurikas J. *Evaluation of environmental risks of sediment management measures in the river Elbe*. Department of Environmental Science and Technology. Hamburg: TUHH; 2005.
- Saaty TL, Vargas L. Modeling behavior in competition. The analytic hierarchy process. *AMHCBQ* 1985;16:1-92.
- Kane-Driscoll SB, Wickwire WT, Cura JJ, Vorhees DJ, Butler CL, Moore DW, Bridges TS. A comparative screening-level ecological and human health risk assessment for dredged material management alternatives in New York/New Jersey Harbor. *Hum Ecol Risk Assess* 2002;8:603-26.