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Authors' Review

Assessing and Managing Contaminated Sediments: Requirements on Data Quality – from Molecular to River Basin Scale*

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Management of environmental risks in river basins needs to address quality aspects of sediment – both because of its storage capacity for contaminants and due to its potential function as a secondary source of pollution. Assessment of sediment quality, however, is still prone to a number of uncertainties and insufficient information with regard to regulation, analytical methods, risk assessment and risk management. The European Water Framework Directive (WFD), *e.g.,* has not come up with environmental quality standards for sediments. Lack of harmonization, representativeness and traceability of sediment data, not fully understood processes governing bioavailability of sediment-bound contaminants, all add up to the uncertainty that needs to be quantified. This paper details uncertainties ranging from the molecular to the basin scale level with regard to sediment quality assessment and its integration into management approaches, and it suggests ways of how to cope with a lack of data and insecure data while still developing an overview of basin wide risks.

INTRODUCTION

Sediment is an integral and dynamic part of river basins, including estuaries and coastal zones. Sediment originates from the weathering of minerals and soils upstream and is susceptible to being transported downstream by the river water. Sediments function as sinks for ongoing releases from many sources; these include wet and dry fallout from air emissions, runoff from farms, solid and dissolved inputs from mines, discharges from landfills, industrial plants, and sewage-treatment plants.[1] Sediment analysis, on a local and a regional scale, can be favorably used to estimate point sources of pollutants that upon being discharged to surface waters do not remain in solution but are rapidly adsorbed by particulate matter, thereby escaping detection by water monitoring.[2]

During recent years, two other functions of sediments came into the focus of researchers and practitioners: (i) sediments as a secondary source of pollution, when contaminated particles are mobilized and contaminants are released into the water phase after natural or artificial resuspension of sediments, and (ii) sediments as an intermediate or permanent depot, using the ability of a sediment body for long-term immobilization of potentially hazardous substances, which can be achieved, for example, by transfer into practically insoluble pollutant species.

With regard to the latter function, it has become clear that remediation techniques for contaminated sedi-

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* Dedicated to the memory of the late Professor Marko Branica.

** Author to whom correspondence should be addressed. (E-mail: u.foerstner@tu-harburg.de) ments are generally much more limited than for most other solid waste materials. The widely diverse contamination sources in larger catchment areas usually produce a highly complex mixture of pollutants, which is difficult to treat in a traditional way by chemical or biological procedures. On the other hand, geochemically engineered approaches such as subaqueous depots, active capping, and *in situ* stabilization are not only cheaper but also more flexible in their regional application.[3]

The two sediment functions – "storage medium", *i.e.,* development of technologies based on molecular information, and "secondary source", *i.e.,* assessment of river-basin wide effects of natural or man-made sediment relocation, reflect extreme positions regarding the sampling, analytical and experimental programs as well as the associated data quality requirements.

Sediment-related Issues in the European Water Framework Directive

The European Water Framework Directive (WFD), which focuses on the catchment scale, does not consider sediment quality and quantity as a major issue.[1] However, the strategies against chemical pollution of surface waters (WFD article 16), *i.e.,* implementation of monitoring programs until 2006 and establishment of a program of measures until 2009, have to consider sediment quality on the catchment scale. With respect to the latter date, the very 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 WFD monitoring objectives require compliance checking with Environmental Quality Standards (EQS) but also progressive reduction of pollution. The no-deterioration clause implies that trend studies should be foreseen for sediment and biota; this calls for further guidance under the Common Implementation Strategy (CIS), complementing the existing monitoring guidance. However, *compliance monitoring for sediment* is not yet appropriate because of the lack of definition of valid Environmental Quality Standards (EQSediment) in the European context, analytical limitations and anticipated costs involved to obtain full spatial coverage.[4]

Sediment *trend monitoring* may be both spatial and temporal, and may be related to the chemical and ecological status of a water body. Sediment monitoring may also play a part in *risk-assessment*:

– in cases where the good-ecological-status/potential is not met or water quality is adversely affected by the bedded and/or resuspended sediments also in order to prioritize sites where actions can take place and/or where monitoring should be intensified with respect to its effects along the river basin;

– to address the issue of sediments as potential carriers of long-lived bio-accumulative toxicants, bioavailability and combination toxicity;

– to assess the extent of organisms affected by sediments on less than "good ecological status" examined locations;

– to apply EDA (Effect Directed Analysis) to determine whether contaminants could be a causative factor and which these are.

It is still open to what level the various sediment monitoring approaches will become reality in the course of the WFD implementation process. In principle, it has been recognized that harmonization of sediment monitoring is particularly relevant at the river basin level. Different objectives (trend monitoring, compliance monitoring, risk assessment and source control) will be involved and subsequently also different sampling strategies. However, technical issues such as sediment collection, sample treatment, sediment analysis and reporting results will have to follow a common level of quality requirements. An example is the application of the traceability concept in chemical sediment analysis (section on types and quality of chemical sediment data).

QUALITY CONTROL IN SEDIMENT MONITORING DATA

Data quality control is a complex and time-consuming activity, which must be undertaken continuously to ensure meaningful water quality assessments. Experts agree that 10 to 20 percent of resources, including manpower, should be directed towards ensuring the quality of analytical determinations for common water quality variables.[5] When trace pollutants (*e.g.,* pesticides and trace elements) are measured, the resources required for quality control may reach 50 percent.[6] Similar efforts are needed for assessment strategies involving sampling and analysis of particulate matter.[7]

In the framework of an integrated decision-making process, the systematic approach starts with a critical examination to establish whether environmental measurements provide a suitable basis for monitoring and other assessment strategies. Major problem areas have been identified and discussed by the European thematic framework "Metropolis" (Metrology in Support of Precautionary Sciences and Sustainable Development Policies):[8]

– lack of harmonization of the procedures applied by laboratories (starting with the sampling procedure, but also including the approach adopted for the calculation of uncertainty); this lack of harmonization makes the data obtained from different sources difficult to compare;

– lack of representativeness: data that do not reflect the reality that we want to represent are simply not fit for the purpose;

– a too high level of uncertainty associated with the data collected makes the process of decision-making critical (in some cases the uncertainty is not expressed at all!);

– lack of metadata: information about the data (which, how and when measurements were made, who owns the data, *etc.*) and the way they are reported/used is an essential requirement for allowing the use of the data for other purposes (*e.g.*, compilation of databases);

– lack of traceability: The concept of traceability implies that measurement data are (i) linked to the stated references (ii) through an unbroken chain of comparisons, (iii) all with the stated uncertainties.[9]

In the following, implications of the traceability concept for the quality control of chemical sediment analysis will be demonstrated with special reference to the study of historically contaminated sediments on the river basin scale.

Types and Quality of Chemical Sediment Data – Traceability Concept

As mentioned in the introduction, sediments have different functions in natural and technical systems, and these differences are derived from their role in management plans, in assessment schemes, and in methodological – sampling and analysis – concepts. From a practical viewpoint of the river-basin management, three functions of aquatic sediments can be distinguished (Table I):

– Memory effect, mainly in dated sediment cores from lakes, reservoirs and marine basins, as historical records reflecting variations of pollution intensities in a catchment area.

– Life support, *i.e.*, sediment as an ecological, social and economic value, as an essential part of the aquatic ecosystem by forming a variety of habitats and environments.[10] A system approach is needed that involves biotests and effect-integrating measurements due to the inefficiency of chemical analysis in the assessment of complex pollution.

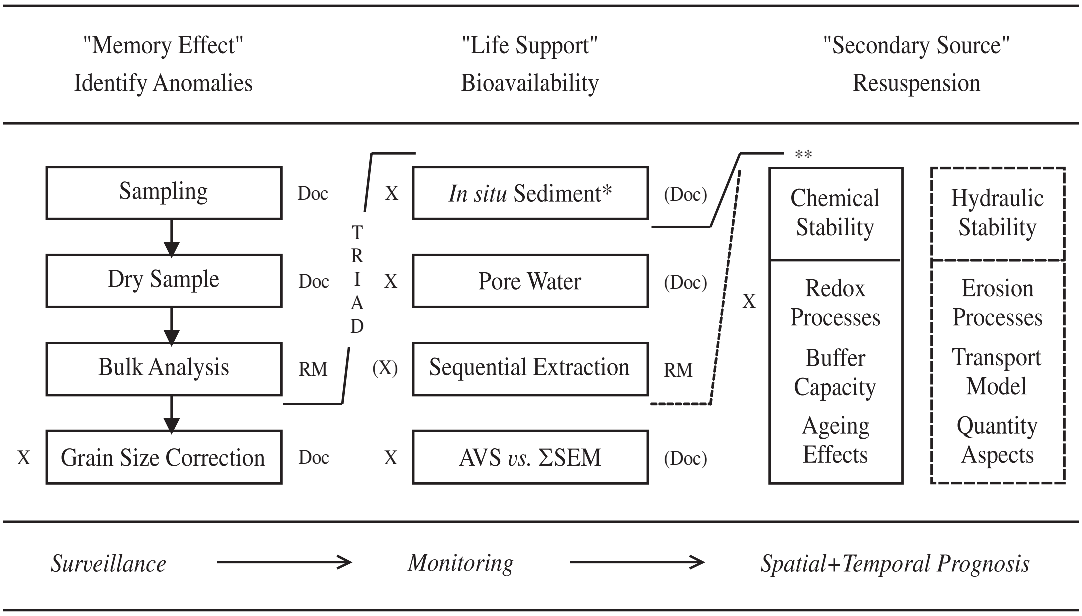
– Secondary source, mobilization of contaminated particles and release of contaminants after natural or artificial resuspension of sediments (see above).

In the present context, memory effects (1st column) are involved both in the assessment of source material, *e.g.,* from historically contaminated sediment in upstream areas, and in the measurement of pollutant concentrations in target sediments, *e.g.,* in dated sediment cores from downstream harbors or coastal areas. Resuspension effects (3rd column) will be estimated from source materials and this information will form the input term for the transport calculations, which will eventually lead to a prognosis of both mass deposition rates and trends of pollutant concentration in downstream harbor sediments (*e.g.,* Rotterdam harbor).[14]

Surveillance Investigations (1st column, Table I)

Surveillance is "continuous specific observation and measurement relative to control and management";[15] the

TABLE I. Overview of traceability aspects of chemical sediment analysis[11]



X = Sediment-specific Property; RM = Reference Material; Doc = Documented Procedure; TRIAD = Chemical Proportion of Triad Approach; AVS/ΣSEM = Acid Volatile Sulfide/Sum Simultaneously Extractable Metals; [12] *Wet Sample:[13] Sub-sampling for tests under oxygen-free atmosphere (pore water, sequential extraction, *etc.*); **Depth Profile: Coupling of chemical/ecological risk data with critical shear stress (erosion probability) data.

primary objective is to trace and observe sources and pathways of specified hazardous substances.[16] If the simple aim of a study is to determine the presence or absence of a specific contaminant in bottom sediment in a given area, then the sediment can be sampled at one or a few sampling stations at fine-grained sediment deposition sites. However, after confirmation of the presence of the contaminant in the sediment, the study may be expanded to determine the extent of sediment contamination by the specific compound or element with the area, the contaminant's sources, history of the loading of the contaminant, its transport, bioaccumulation, *etc.*[17]

As regards the traceability concept, the basic sequence of measurements consists of three steps, which can be considered as an unbroken chain of comparisons:

Sampling and Sample Preparation. Project planning, sampling stations, sampling devices, handling and storage, and quality control are not standardized, but well-documented in all aspects.[17]

Analytical. Reference sediment materials are commercially available. While direct species analysis is still limited, standardized extraction schemes for metals and phosphorus in sediments as well as certified reference materials for comparisons were developed under the auspices of BCR/IRMM.[18]

Grain Size as a Characteristic Sediment Feature. Sampling of fine grained sediment[19] and grain size normalization with "conservative elements" such as Cs, Sc, Li and Al (all reflecting clayey material content) are recommended as a standard approach.[20]

Uncertainties. Minor uncertainties, which will not affect the general applicability of the present approach, could arise from variations of typical matrix constituents and can be narrowed down by analyzing parameters such as organic matter, carbonate and iron oxide contents.

Monitoring (2nd column, Table I)

Many national assessment schemes are based on a Triad approach, combining physical-chemical, biological and ecotoxicological assessment methodologies. Chemical parameters, which are included in the physical-chemical part of the Triad approach in many countries, are (example of the Netherlands[21]): mineral oil, chlorobenzenes, organochlorine pesticides, PCBs (standard group of 7 congeners), PAHs (16 of EPA) and heavy metals Cd, Cr, Cu, Ni, Pb, Hg, Zn and As.

Bioavailability: Limitations and Empirical Relationships.[22] – Since the form in which a compound or element occurs can effect its exposure, and thus toxicity, accurate estimates of the effects of toxicants and nutrients require a knowledge of both the short-term and long-term exposure, which is a function, in part, of bioavailability. However, the utility of bioavailability in decision making is limited by the fact that there is little uniformity in the operational techniques.

Empirical relationships have been developed using scientific judgments and field and laboratory data; Table II summarizes some of these relationships with their understanding of mechanisms, uses, problems or exceptions, and research needs.

Additional information that can be used to bridge the gap between chemical analyses and biological effects:

Porewater. Tests on porewater (interstitial water) were considered suitable for several types of regulatory frameworks, but unsuitable for others, *e.g.,* as stand-alone pass/

TABLE II. Examples of empirical relationships in bioavailability[22]

Empirical relationship	Understanding of mechanism	Use(s)	Problems or exceptions	Research needs
K_{oc} partitioning describes interactions with sediment and water	Good	Estimate exposure concentrations	All organic carbon not equal	Define sorption/desorption kinetics and add classes of compounds
Free metal ion controls bioavailability	Poor	Predictive	Ion pair small organic ligands	Activity should be used instead of concentration
Photochemical, redox, hydrolysis processes generally detoxify organic chemical	Limited	Regulation, EPA requires product studies across all species	Some	Compilation of compounds that are photochemically active
Activities should be used instead of concentrations	Good	Used in research and modeling	Some	Availability of activity coefficients for organics
All metals cycle with Fe and Mn	Good	Prediction	Not always correct	Better empirical data needed
AVS control metal availability in sediments	Good	Prediction, potential regulations	No evidence from intact sediments	Better empirical data needed

fail methods or as a substitute for a solid phase test. Determination of chemical concentrations in pore-waters is recommended, in addition to the regular contaminant measurements conducted in the whole sediment, as a means of providing information on the routes and levels of exposure, and aiding in the interpretation of test results.[23]

The *leachable fraction* does not necessarily correspond to the amount available to biota. Studies on the prediction of the trace metal levels in benthic organisms have shown that the prognostic value of sequential extraction data is improved when the trace metal concentrations are normalized with respect to the iron (hydrous oxide) and/or organic content of the sediments.[24]

Traceability/Uncertainties. Standing alone or for a particular sample, the physical-chemical portion of the Triad does not seem to involve major practical problems. "Sampling", "sample preparation" (using wet sediment) and "chemical analysis" (use of bulk or fractionated reference material; normalization to grain size and organic carbon) widely follow a standard sequence similar to the surveillance approach described in the relevant section. However, with a differentiated approach, *e.g.,* when applying the BCR fractionation scheme,[18] the question how to preserve the original physicochemical forms of both matrices and critical contaminants becomes crucial. This question also relates to the way and extent to which the findings within the chemical portion can be compared with the results of the biological studies.

Spatial and Temporal Prognosis – Resuspension – Secondary Source (3rd column, Table I)

On a river-basin scale, *i.e.,* when applied in a conceptual river basin model (CBM), chemical and ecological information needs a strong basis of sediment quantity data. In a dynamic system, this assessment should include not just those materials that are currently sediments, but also materials such as soils, mine tailings, *etc.* that can be reasonably expected to become part of the sediment cycle during the lifetime of a management approach.[25]

Sampling. In both erosion risk and chemical mobilization risk studies, the chains of comparison are broken at early stages of sampling and sample preparation. Sampling of flood-plain soils and sediments is affected by strong granulometric and compositional heterogeneities arising from the wide spectrum of flow velocities at which the sediments were eroded, transported and deposited. These heterogeneities can be reduced by subsequent normalization procedures (section on Surveillance); however, the overall comparability of the samples will be significantly lower than in the applications described in sections on Surveillance and Monitoring for surveillance and monitoring tasks, respectively. Sampling and sample preparation of *in situ* sediments should primary avoid any modification of labile phases, in particular access of oxygen, which will inevitably change redox-sensitive minerals such as metal sulfides. For physical sediment property analysis, especially for erosion tests, undisturbed samples should be taken in order to ensure the best possible *in situ* conditions and thereby avoid disturbance of the sediment matrix and escape of gas.

All sediment tests and analyses should be performed for a single sample. However, this is technically impossible in most cases. Hence, at least two sediment cores must be taken at the same sampling spot, one for the physical erosion test, and the other for the chemical and biological tests. Since neighboring samples always show some different properties (known as the nugget effect in geostatistics), there will be no full correspondence of the physical and chemical/biological parameters for the same sediment depth,which implies a systematic uncertainty.

Reference Materials. Sediment reference materials should be applied for erosion risk studies in a similar way as described in the section on surveillance investigations. Harmonized fractionation schemes and respective reference materials can be useful for studying ecotoxicological aspects, *i.e.,* in the framework of comparative investigations of erosion stabilities and bioavailability of pollutants in sediment core samples. As regards chemical mobilization studies, fractionated reference sediments, even if the chain of direct comparability has been broken, may offer some advantages in providing secondary information on the contents of calcium, iron and sulfur, from which the matrix parameters such as "acid producing potential" and "acid consuming capacity" can be calculated and predicted.[26]

Uncertainties regarding the interpretation of findings both from the combined erosion risk and chemical mobilization studies mainly arise from the fact that the reliability of proper chemical analyses is masked by a high variability of influencing factors such as granulometric and compositional heterogeneities. Anoxic sediment/porewater extraction and preservation requires special experience; thus far, lack of pore-water reference material has been a significant drawback with respect to chemical mobilization studies.

Hydraulic Data Quality[27]

Hydraulic processes form the primary input factors for large-scale dispersion of historically contaminated sediments. Unlike problems related to conventional polluted sites, the risks here are primarily connected with the depositing of contaminated solids on soils in downstream regions.[28] Therefore, sediment physical parameters and techniques form the basis for all risk assessment in this field.

For contaminated sediment resuspension risk assessment *different sources of uncertainties* must be considered. The most significant contribution to the uncertainty is due to discharge hydrology, which is known as the hydrological risk. Additional uncertainties originate from the imperfection of the model concept and in particular from the erosion related sediment properties, which at least include the threshold of sediment erosion and the erosion rate as depending on different geochemical and biological factors.

Different experimental methods have been developed for *cohesive sediment erosion tests*; however, there is no inter-comparison of the different methods available for quality assessment. Furthermore, it is still an open question how to upscale laboratory erosion tests, which were usually performed at low flow Reynolds numbers and in boundary flow conditions different from the real riverbed situation. The upscaling problem is currently pursued at the Institute of Hydraulics, University of Stuttgart, by using a combined experimental setup that, on the one hand, allows comparing the results of the erosion tests with different sizes of sediment testing areas exposed to the flow and, on the other hand, comparing laboratory tests with *in-situ* tests.

Numerous *models* have been developed to describe the effect of flood events on river morphology and sediment transport, but most of them are deterministic and cannot account for the uncertainties involved in the input variables and model parameters. In most stochastic approaches, probabilistic distributions of the input variables and model parameters are used for uncertainty assessment. Often, however, the dataset is not sufficient to determine the probability distribution, or the data cannot be described by a distribution function. Integration of the stochastic concept into a deterministic model provides a useful alternative to cope with the most important uncertainties.[29]

No figures have been reported for *data accuracy*, neither for the hydraulic parameters nor for sediment parameters. The key quantities, *e.g.,* the initial concentration of suspended particulate contaminants or the total mass of resuspended contaminants, are a specific function of several independent variables such as the discharge, the actual bed shear stress *versus* the critical erosion shear stress, the erosion rate parameter, and the particulate contamination of the sediments, which all have an uncertainty and therefore all the uncertainties of the parameters have an impact on the uncertainty of the resulting objective quantity. At this point, with the objective of risk estimation for target areas in the downstream reaches of large river basins, it is clear that a new approach is needed beyond the strict traceability concept as described in the relevant section.

RIVER BASIN SCALE – THE THREE-STEP APPROACH OF THE RHINE STUDY[14]

The objective of the Rhine study was to produce an inventory of historically contaminated sites along the Rhine and its tributaries and to identify the sites that constitute a risk for the Port of Rotterdam with respect to the possible exceeding of the sediment quality criteria that decide the fate of dredged material: open water or the more expensive upland disposal (CTT thresholds).[30]

Here, a three-step approach was followed:

– Identification of substances of concern (s.o.c.) and their classification into "hazard classes of compounds" (HC_c);

– Identification of areas of concern (a.o.c.) and their classification into "hazard classes of sites" (HC_S);

– Identification of areas of risk (a.o.r.) and their assessment relative to each other with regard to the probability of polluting the sediments within the Port of Rotterdam.

Conclusions regarding "hazards" and "risks" were differentiated. A hazard describes the potential danger of a substance or a specific site without referring to actual exposure. The risk is the magnitude of hazard multiplied by the probability of exposure.

A potential risk to regions through sediments upstream depends on the sediment quality, the probability of its becoming resuspended and transported, the amount of the sediment of a certain quality, and the location or distance of the contaminated material relative to the potentially exposed area.[31] The aforementioned traceability aspects should form the basis for the analyses of risk criteria. Accordingly, also the major problems mentioned in the section on quality control have to be dealt with in the practice, adding to the level of uncertainty connected with the assessment of molecular information.

Monitoring programs of suspended matter and – where it is done at all, of sediments – are carried out in Germany by the different Federal States. Sampling data, the grain size fraction analyzed and monitoring periods are often not consistent, which hampers the analysis and conclusions for effects along the river basin.

Challenges in quantifying the probability and degree of resuspension have already been described. The volume of contaminated sediment is seldom known. The location of a site within a catchment is a rough indication of the size of the potentially exposed area downstream.

Uncertainties in this study were dealt with by

– quantifying their extent where possible;

– following a weight-of-evidence approach when drawing conclusions.

Hazards, which in this report are the hazards of "substances of concern" and of "areas of concern", can be determined with higher certainty than the risks, since they lack the additional exposure assessment, comprising resuspension and transport phenomena, which are part of a later risk assessment.

Assessing Uncertainties

Quantifying Uncertainties. – Uncertainties with regard to the hazard of a certain site were quantified on the basis of the number of contaminants that exceeded the sediment quality criteria used in that study and on the basis of the number of samples either in the following years or taken during one survey showing this exceedance.

Choosing a fuzzy logic tool facilitates consideration of these uncertainties when calculating the hazard index of areas of concern. The fuzzy set theory[32] has been commonly recommended for the assessment of ecological data because it makes it easy to integrate information from different fields.[33,34] It can reflect natural variability, ambiguity and lack of quantitative data in environmental prediction.[35] It presents an interesting alternative to stochastic analysis since fuzzy logic models reflect very well how humans think and make decisions.[36] The big difference from stochastic models is that it is easy to include uncertainties in the data and that the whole information of a dataset is sustained throughout the calculation, since no early decisions need to be made *e.g.* in black or white, but "shades of grey" can be worked with.

Reducing Uncertainties by Following a Weight-of-Evidence Approach. – Different lines of evidence were discussed before drawing a conclusion on the risk of a site with regard to the situation in the Port of Rotterdam:

– the hazard class of the site;

– the capability to exceed CTT values in the Port upon resuspension of the sediment;

– the indication for resuspension.

The indication for resuspension was considered in dependence on the hydrological situation and was based on measurements of erosion potentials and observations of increased contaminated suspended matter downstream of the site.

Quantifying Hazards

Hazard Classes for Substances of Concern. – Contaminants that frequently exceeded the CTT thresholds upstream of the Port of Rotterdam were identified as "substances of concern" in the Rhine Basin with respect to the objective of this study. The hazard class was calculated based on their significance as sediment-bound contaminants (quantified by the partitioning coefficients), their persistence in sediments and their ecological effect (*e.g.*, bioaccumulative potential). Uncertainties in this hazard classification are comparatively small, since data for these criteria are available and processes are partly well understood. (see Table II).

Hazard Indices for Areas of Concern Based on Sediment Data. – Monitoring data of sediments and suspended matter were received from the environmental administrations in the various Federal States. For every sediment sample, the grain size distribution was provided and the calculation of the concentration in the whole sediment sample was performed on the basis of the <20 μm fraction in order to achieve a comparable dataset.

In the calculations done using fuzzy sets, the amount to which a compound exceeded the CTT threshold, the hazard rank of this compound, and the uncertainty of the data were used to categorize the hazard index of the area of concern.

In general, only few significant improvements in sediment contamination over the years were observed in the available data. Recent values often show high concentrations. Although sampling surveys did not specifically target floodings, these may well have affected the sediment data by exposing deeper and more contaminated sediments. This, however, does not corrupt the estimation procedure; if the sediment is exposed, it may also become transported towards the port.

In the Rhine Basin, 12 regions were identified as potentially hazardous and were classified into 3 classes: "Indication of potential hazard" (Class 1), "Indication of potentially high hazard" (Class 2), "High certainty that high hazard is present" (Class 3).

These hazard classes alone, however, give little information on the risk that may exist for areas downstream.

Estimating Risks for Areas of Concern

When taking into account the different hydrological situations, indications of resuspension, the probability to exceed the threshold values after being resuspended, and the degree of hazard to which downstream regions may be exposed, a risk was calculated for the areas of concern. The magnitude of hazard was quantified on the basis of the hazard class of the site and the concentration that the material may still have after becoming resuspended and transported to the Port. Probability of exposure was determined by calculations of erosion thresholds and indications that resuspension occurred. Probability of exposure was the most difficult parameter to quantify, since very little information was available about critical erosion thresholds and occurring shear stresses for different flood situations. Preferably, the probability of exposure should also include bioeffect data that can be related to the hydrological conditions and to resuspension events. Also these data are scarce.

Accordingly, conclusions needed to be drawn from indirect evidence rather than from concrete risk measurement data. The following classes were differentiated: "no evidence of risk", "presence of risk cannot be excluded", "evidence of risk" and "evidence of high risk".

From the 12 areas of concern in the Rhine Basin, 2 were finally assigned to the highest risk class: The Ruhr River during flood events with a return period of 100 years, and the barrages of the Higher and Upper Rhine at annual flood situations.

Reducing Uncertainties for Basin-wide Sediment Assessment

While it has been shown that uncertainties are high, when hazards and risks of areas in a river catchment are to be assessed, these can be handled to some extent by quantifying the uncertainties on the basis of data availability and by combining different lines of evidence.

It will be necessary, however, to reduce this degree of uncertainty if the assessment of risk is to be followed by concrete management measures. Hence, sampling and monitoring programs need to be much more focused on the objective of assessing basin wide risks, which implies better harmonization of sampling surveys, more intense sampling during flood events, and inclusion of data that have been barely acknowledged in regular monitoring programs to date – quantification and calculation of resuspension events.

CONCLUSIONS AND OUTLOOK

In the previous sections, requirements on sediment data quality have been described for their possible inclusion into the European Water Framework Directive (WFD) implementation process. It has been shown that there are two widely different sediment-based datasets for the assessment of chemical and biological quality in river catchment areas:

(i) Characterization of contamination sources, *in-situ* processes, pollutant concentrations and environmental effects on a molecular to microscopic scale. Data quality control, *e.g.*, in surveillance and monitoring activities, typically follows the traceability concept in sediment chemical analysis. Critical issues are grain size effects and the understanding of empirical relationships in bioavailability. Inclusion of mechanical effects, *e.g.*, resuspension of contaminated sediments, will significantly increase uncertainties relating to the interpretation of combined erosion risk and chemical mobilization data due to the large variability of granulometric and compositional parameters in the hydraulic term.

(ii) On a catchment scale, *i.e.,* assessing the risk for downstream areas such as harbors or coastal zone, the uncertainties of sediment data will further increase. Modeling pollutant transport on a river-basin scale requires extensive information on water volumes, sediment dynamics and processes at the interfaces. Apart from the quantification of man-made activities (dredging, reservoir flushing), which should be dealt with when addressing an advanced watershed management, prediction of the effects of large storm-water events and – even more pronounced because of its exponential increase – the accompanying sediment load are among the most challenging tasks. In the three-step approach of the Rhine study, the hazards of "substances of concern" and of "areas of concern" – for the latter using a fuzzy logic tool – could be determined with higher certainty than the risks of polluting sediments within the Port of Rotterdam. However, the combined information on critical erosion thresholds and indications that resuspension took place as well as the differentiation of four risk classes with regard to the exceedance of well-defined target values (CTT-values) provided "evidence of high risk" for the Port of Rotterdam of historical contamination of sediments in the barrages of the Higher and Upper Rhine even during annual flood situations

In the future, a significant increase of the weight of evidence for risks in downstream target areas could be expected from the precision of the term "indications that resuspension occurred". Under favourable conditions, *e.g.*, in areas exhibiting continuing sedimentation, the study of dated sediment cores has proven particularly useful since it provides a historical record of the various influences on the aquatic system by indicating both the natural background levels and the anthropogenic accumulation of substances over an extended period of time.[37]

Best locations for such historical records are within or close to the critical target areas (harbor basins, lakes, depressions, lowlands, flood plain soils and sediments, *etc.*). Additional information on the source areas of specific pollutants that are analyzed in the target sediment cores can be gained from indicator substances or from typical isotopes (*e.g.*, lead isotopes) and patterns of congeners (*e.g.*, for dioxins/furans).[38]

The study of sediment cores, as a tool to confirm significant downstream translocation of sediment-bound pollutants during flood events and dredging activities, can be seen as a bridge between the two extremes: (i) "molecular to microscopic scale" and (ii) "catchment scale". With respect to the requirements on data quality, interpretations using sediment profiles should be based on the traceability concept,[11] specifically addressing uncertainties that arise from redox variations and pore-water transfer of pollutants.

Sediment core studies can play a key role in the emission-immission relationships of a river basin.[39] Here, the big ports such as Rotterdam and Hamburg have a joint function with the 'catchment-coast continuum'.[40] On the one hand, as the owners of 'large-sediment traps', they are put at a disadvantage as they have to pay the expenses of all former, actual and future shortcomings in emission control within their entire catchment areas. On the other hand, they increasingly tend to get rid of part of their problems by using sea disposal as a relatively cheap procedure for less contaminated dredged sediments. In this situation, the question arises of the yardsticks for assessing quality of both types of sediments – ingoing from the catchment area and outgoing into the open water. For example, as already mentioned, decisions about the fate of dredged materials from the Rotterdam harbor are based on 'Chemical Toxicity Test' (CTT) values; Port of Rotterdam used the same set of data as target values of key substances during its actions against severe inputs from upstream sources.[41] This approach may be helpful in implementation of a program of measures under WFD article 16 until 2009 (see 'Introduction'). However, one may infer that the release of sediment-associated contaminants into the marine environment should be based on more specific criteria. In any case, the risk definition for both immission and emission functions will play a key role in further discussion about sustainable sediment management.

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SAŽETAK

Procjena kvalitete i upravljanje onečišćenim sedimentima: potrebna kakvoća podataka – od molekularne razine do razine riječnih bazena

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Upravljanje rizicima po okoliš u riječnim bazenima treba sadržavati i aspekt kvalitete sedimenata – zbog njihovog kapaciteta za pohranu onečišćivala, ali i zbog njihove potencijalne uloge kao sekundarnog izvora zagađenja. Međutim, procjena kvalitete sedimenata ograničena je nekim nepoznanicama i nedovoljnim brojem podataka koji se odnose na propise, analitičke metode, procjenu rizika i njegovo upravljanje. Europska direktiva za vode (European Water Framework Directive – WFD) nije još uvijek donijela standard za okolišnu kakvoću sedimenata. Nedostatak harmonizacije, reprezentativnosti i dostupnosti podataka za sedimente, kao i nedovoljno poznati procesi koji upravljaju biološkom dostupnošću onečišćivala sadržanih u sedimentu doprinose stupnju neizvjesnosti koji je potrebno kvantificirati. U radu su opisane neizvjesnosti, u rasponu od molekularne razine do razine riječnih bazena, s obzirom na postupak procjene kvalitete sedimenata i integriranje tog postupka u upravljačke sustave, uz predlaganje načina kako se usprkos nedostatku podataka ili njihovoj upitnosti mogu primijeniti metodologije procjene rizika na razini riječnih bazena.