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Sediment Dynamics and Pollutant Mobility in Rivers

An Interdisciplinary Approach

With 195 Figures and 52 Tables

Springer

Editors

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Preface

"Sediment management requires a solid mix of pragmatism and sound science"[1]

The actual discussion on the role of sediments in the European water legislation is a typical example, how the development of environmental policies mixes legal requirements with socio-economic aspects, issues of technical feasibility, and scientific knowledge[2]. In fact, the Sixth Environmental Action programme of 2001 has stipulated, namely, that "sound scientific knowledge and economic assessments, reliable and up-to-date environmental data and information, and the use of indicators will underpin the drawing up, implementation and evaluation of environmental policy"[3].

In the ten chapters of this book, a broad set of practical process knowledge is presented, comprising simulation techniques, laboratory and in-situ studies on the interaction between biological, chemical and hydrodynamic factors as well as models, for solving combined quality and quantity problems of riverine sediments. The underlying research on various types of particulate matter, risk analyses and problem solutions will also contribute to the implementation of the Soil Strategy and – in particular – Marine Strategy Directive in Europe.

Among the 24 original scientific papers of the present book (with 12 review articles and 8 short chapter introductions), 13 stem from the interdisciplinary Joint Program SEDYMO ("Fine *Se*diment *Dy*namics and Pollutant *Mo*bility in Rivers"), funded by the German Federal Ministry of Education and Research (BMBF), May 2002 to July 2006. The respective sub-projects were organized under the three headings "experimental techniques", "processes and properties", and "development and validation of models" (see Sect. 1.2).

The present scientific state-of-the-art overview on the wider area "sediment stability assessment" has been and will further be confronted with the world of policy and management. To characterize these interactions, achievements and deficiencies, the following paragraphs of our preface give a selection of ten sediment-related themes actually under discussion:

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[1] Krantzberg G, Hartig JH, Zarull MA (2000) Sediment management: deciding when to intervene. Environ Sci Technol 34:22A–27A.

[2] Quevauviller Ph (2006) Science-policy interfacing in the context of the WFD implementation. J Soils & Sediments 6(4):259–261.

[3] Anon (2001) 6th Environmental Action Plan 2001–2010. European Commission, rue de la Loi, B-1040 Brussels.

1. Quantity vs. quality – concept of sustainable sediment management[4]

Sediment management challenges and problems relate to quality and quantity issues. Quality issues relate to contamination, legislation, risk perception and assessment, source control and destination of dredged material. Quantity issues are related to natural processes causing erosion, sedimentation, flooding and the impact of engineering works such as dams, on the river morphology. The concept "sustainable sediment management (SSM)" of the European Sediment Research Network SedNet (www.SedNet.org)[4] is based on the integration of quality and quantity aspects involving typical hydrodynamic issues like erosion stability and transport in a broad spectrum of spatial and temporal scales (Sect. 1.1 *"Quantity and quality issues in river basin" by U. Förstner and P. N. Owens* and Sect. 2.1 *"Hydrodynamics and sustainable sediment management" by B. Westrich*).

2. Hydraulic processes as the driving force for dispersion of contaminated sediments

The quantification of flow rates including the transport of particle aggregates, microorganisms as well as dissolved and adsorbed substances requires an integration of various experimental techniques (flumes, turbulence columns, erosion chambers), to study the combined effects of sediment processes during resuspension, transport and deposition, and to describe these processes by models on different scales for the determination of hydrodynamic, chemical and biological parameters.

Sediment physical parameters are the basis of any risk assessment both on local and river basin scales. In the decision process, sediment stability should be considered a subset of an overall risk-management framework, using a tiered approach[5], which is characterized by a progressive increase in complexity – e.g., definition of key elements at the site, regional geomorphology to understand the sensitivity of the site to flood – associated flows, and definition of needs for sediment sampling, acoustic surveying and current measurements.

Application of the empirical methods used to assess the erosion characteristics of a cohesive deposit would benefit from a demonstration that, despite the relatively small size of most of the available experimental apparatus, the resulting flows represent a reasonable simulation of the flow conditions at the sediment-water interface in the field[5]. The SEDYMO-program included two subprojects using sediment stability tests which could bridge the gap between laboratory and field (no. 1 "Triad System" and no. 3 "Microcosm/Hot film anemometer").

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[4] Anon (2002) SedNet Demand driven, European Sediment Research Network, Description of Work, Final Version. EC Proposal No EVK-2001-00058; Salomons W, Brils J (eds) (2004) Contaminated Sediments in European River Basins. SedNet 'Booklet'; SedNet Work Package books (Elsevier Publ 2007): WP2 (PN Owens) Sediment Management at the River Basin Scale; WP3 (D Barcelo) Sediment Quality and Impact Assessment, WP4 (G Bortone) Sediment and Dredged Material Treatment, WP5 (S Heise) Sediment Risk Management and Communication.

[5] Bohlen F, Erickson MJ (2006) Incorporating sediment stability within the management of contaminated sediment sites: A synthesis approach. Integr Environ Assess Manag 2:24–28.

3. Problems with model approaches for fine-grained sediments

Analytical and numerical models are indispensable for both connecting and integrating the interdisciplinary study of individual processes and for transferring the findings from laboratory experiments to a natural aquatic system where processes take place on extremely variable scales both in space and time. Coupling of field data to model formulation requires particular attention when dealing with cohesive sediments; due to the complex nature of the transport processes, designs would benefit from a degree of standardization that does not exist at present[5].

In the SEDYMO-program, special emphasis has been given to fine-grained sediments and to a typical set of factors commonly influencing solution/solid equilibrium conditions. Examples are the delayed release of metals from resuspended anoxic sediments (subproject no. 10) and the relationship between sediment-associated phosphorous entrainment rates and bed shear velocities, which were studied in subproject no. 11 for a series of in-situ experiments for the river Spree, Germany.

4. "Is the site erosive or depositional?" – conceptual site model[6]

The sediment manager's work begins with a conceptual site model (CSM), a description what is known about the contaminant source areas, as well as the physical, chemical, and biological processes that affect contaminant transport from the sources through environmental media to potential environmental receptors[7]. With respect to sediment-associated contaminants, questions that should be asked during selection of management options include: *(i)* Is the site erosive or depositional? *(ii)* Will management options change that, and how will that impact other sites downstream? *(iii)* Can the normal sedimentation process in the area solve the problem through burial and mixing? Or as the principle question[8]: Should we wait for the natural recovery mechanisms to reduce the risk due to sedimentation, degradation or other natural attenuation processes, or does the situation require removal of the contaminated sediments?

5. Sediment management strategies – appropriate selection criteria?

In practice sediment management strategies can be categorized according to typical problem solutions like monitored natural recovery, in-situ containment, in-situ treatment and dredging or excavation[5]. The information required to evaluate or compare each of these options is fundamentally different[9] and the realization of the optimal solution is a difficult, not only technical task. This is because the complexity of sedi-

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6 Apitz SE, White S (2003) A conceptual framework for river-basin-scale sediment management. J Soils Sediments 3:132–138; see also Apitz et al. (2005) Integr Environ Assess Manag 1(1):2–8.

7 Anon (1995) Standard Guide for Developing Conceptual Site Models for Contaminated Sites. In: Annual Book of ASTM Standards, vol. 04.08, E 1689-95 American Society of Testing and Materials. West Conshohocken, Pa.

8 Wim Salomons, personal communication.

9 Apitz SE, Power EA (2002) From risk assessment to sediment management. J Soils Sediments 2:61–66.

ment transport processes and associated uncertainties in most cases is fostering application of the precautionary principle, with removal as a presumed conservative but more expensive approach over in-place options.

6. "How best to incorporate sediment stability assessment results when managing risks at contaminated sediment sites?"

In order to give in-situ options such as monitored natural recovery (MNR)[10] a real chance, a shift of emphasis would be needed towards the use and communication of results from the analyses of multiple lines of evidence, e.g., through detailing the potential impacts of large, low-probability events or combinations of probabilities (e.g., the 100-year flood and the probability of erosion to a specific depth) on exposure and risk, and the associated uncertainties.

These lines of evidence should include a range of accepted and independent methods, such as historical review of site characteristics, past usage, and storm events; careful consideration of regional geomorphology and implications regarding the evolution of sediment deposits; detailed geochemical analysis of sediment cores obtained at carefully selected locations; and field measurements to characterize hydrodynamic forces[5]. This approach provides the basis for the development of a conceptual site model – paragraph 4 – that includes a numerical model for prediction potential impacts of rare events on the resuspension of sediments.

7. "Water Framework Directive – the river basin scope also for sediments?"[11]

Since 2000 remediation methodology as well as the preceding risk assessment are part of the holistic river basin approach according to the European Water Framework Directive (WFD), which is aiming to achieve a good ecological potential and a good surface water chemical status in European river basins until the year 2015 by a combined approach using emission and pollutant standards. Although there are immense quantitative and qualitative problems with sediments, the WFD did not take sediments explicitly into its implementation scheme. In particular, lack of information on the role of sediments as a long-term secondary source of contaminants may easily lead to unreliable risk analyses with respect to the – pretended – "good status".

8. Risks due to erosion of contaminated sediments and their potential impacts downstream are not covered by existing regulations …

The Water Framework Directive monitoring objectives require compliance checking with Environmental Quality Standards (EQS) but also the progressive reduction of pollution. The no-deterioration clause implies that trend studies should be foreseen

[10] Magar VS, Wenning RJ (2006) The role of natural recovery in sediment remediation. Integ Environ Assess Manag 2:66–74. Schwartz R, Gerth J, Neumann-Hensel H, Bley S, Förstner U (2006) Assessment of highly polluted fluvisol in the Spittelwasser floodplain based on national guideline values and MNA-criteria. J Soils & Sediments 6(3):145–155.

[11] Förstner U (2002) Sediments and European Water Framework Directive. J Soils & Sediments 2:54.

for sediment and biota; this calls for further guidance under Common Implementation Strategy[12], complementing the existing monitoring guidance. However, *compliance monitoring* for sediment is not yet appropriate because of lack of the definition of valid Environmental Quality Standards ($EQS_{sediment}$) in a European context[13]. One can, however, find certain links of this important issue to present and future activities in the European Water Framework Directive. For example, the strategies against chemical pollution of surface waters (WFD article 16), i.e. establishment of the program of measures until 2009, must consider all potential pollution sources at the catchment scale. 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"[14].

9. Pragmatic approach – two case studies on historical contaminated sediments in the Rhine and Elbe River basins

The first study in the Rhine River catchment by Heise et al.[15], on behalf of the Port of Rotterdam, presented a three-step strategy, by the identification of *(i)* substances of concern, *(ii)* areas of concern and *(iii)* areas of risk with regard to the probability of polluting sediments in downstream reaches. The final assessment of the "areas of risk" had to take into account sediment erosion thresholds and the hydrological exceedance probability. The pragmatic approach provided initial evidence, that sediment-associated hexachlorobenzene (HCB) from the Higher and Upper Rhine has a significant effect on the quality of material dredged from Rotterdam Harbor and that this historical HCB source can contribute to a failure of the objectives of the WFD in the Rhine basin and may require additional measures for its control. Similar results were obtained from the study of Heise et al. on the Elbe River basin[16]; here, the transfer of dioxins and furans from the sediments and soils of the former Chemical Triangle at Bitterfeld can be considered as the most critical process involving historical contaminated sediments in this catchment area.

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[12] Anon (2003) Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Carrying forward the Common Implementation Strategy for the Water Framework Directive. Progress and Work Programme for 2003 and 2004, as agreed by the Water Directors, 17 June 2003, 52 p, Brussels.

[13] Anon (2004a) WFD Expert Group on Analysis and Monitoring of Priority Substances (AMPS), Sediment Guidance Discussion Document, AMPS and SedNet, Draft Version 16 April 2004. See also: Proposal for a Directive of the European Parliament and of the Council on environmental quality standards in the field of water policy and amending Directive 2000/60/EC (WFD-Daughter Directive), Brussels 17.7.2006; e.g., Article 2 (2) "*Member States* shall ensure, that concentrations of substances listed in Parts A and B of Annex I do not increase in *sediment* and biota".

[14] Anon (2004b) Concept Paper on Emission Control from 8 June 2004 of the Expert Advisory Forum (EAF) on Priority Substances and Pollution Control. 7th EAF-Meeting at Brussels, 14–15 June 2004.

[15] Heise S, Förstner U, Westrich B, Jancke T, Karnahl J, Salomons W (2004) Inventory of Historical Contaminated Sediment in Rhine Basin and its Tributaries. On behalf of the Port of Rotterdam. October 2004, Hamburg, 225 p.

[16] Heise S, Claus E, Heininger P, Krämer Th, Krüger F, Schwartz R, Förstner U (2005) Studie zur Schadstoffbelastung der Sedimente im Elbeeinzugsgebiet – Ursachen und Trends. Im Auftrag von Hamburg Port Authority. Abschlussbericht Dezember 2005, 169 S.

10. Emission-immission relationships in the catchment-coast continuum

From their patterns of dioxin/furan congeners characteristic emissions from the Chemistry Triangle at Bitterfeld can be followed 350 km downstream to the sediments of Hamburg Harbour[17]. Such tracers, together with sediment core studies, provide an ideal tool for assessing the spatial and temporal development of pollution at critical sites in the "catchment-coast continuum"[18].

This, in particular, concerns the big river ports such as Rotterdam and Hamburg[19]. On the one hand, as the owners of 'large-sediment traps', they have to pay the expenses of former and actual shortcomings in emission control within their catchment areas. On the other hand, they increasingly tend to get rid of part of their problems by using sea disposal as a relative cheap procedure for less contaminated dredged sediments. In this situation, the question arises on the yardsticks for assessing quality of both types of sediments – ingoing from the characteristic emissions from the catchment area and outgoing into the coastal sea.

A majority of stakeholders at a SedNet round table[20] found environmental quality standards for sediments in the WFD not practicable, due to the highly variable hydrodynamic situations in riverine systems. Different from this, decisions about the disposal of dredged materials could be based on operational target values of key substances or ecotoxicological criteria, as in the case of Rotterdam Harbor, by application of 'Chemical Toxicity Test' (CTT)[21] values. Considering, however, the particular risks from sediment-associated contaminants in the marine environment, sustainable sediment management in coastal zones requires further science-based criteria, e.g., for assessing – in the wider area of this book – *(i)* pollutant loads (quality/quantity relationships) of extremely toxic substances like dioxins/furans, and *(ii)* specific dispersion and sedimentation patterns of "less" contaminated particles following the so-called "relocation" of dredged material.

The planned Marine Strategy Directive in the European Union[22] will follow the Water Framework Directive (WFD) in the stepwise implementation of elements that shall be reviewed every six years after their initial establishment: *(a)* the initial assessment and the determination of good environmental status, *(b)* the environmental targets; *(c)* the monitoring programs; and *(d)* the programs of measures.

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[17] Götz R, Steiner B, Friesel P, Roch K, Walkow F, Maaß V, Reincke H, Stachel B (1998) Dioxin (PCDD/F) in the river Elbe – investigations of their origin by multivariate statistical methods. Chemosphere 37:1987–2002.

[18] Salomons W (2005) Sediments in the catchment-coast continuum. J Soils & Sediments 5(1):2–8.

[19] Westrich B, Förstner U (2005) Sediment dynamics and pollutant mobility in rivers (SEDYMO). Assessing catchment-wide emission-immission relationships from sediment studies. J Soils & Sediments 5(4):197–200.

[20] "Sediment management – an essential element of river basin management plans", Venice, Nov 22–23, 2006. J Soils & Sediments 7(2):117–132 (2007)

[21] Stronkhorst J (2003) Ecotoxicological effects of Dutch harbour sediments – The development of an effects-based assessment framework to regulate the disposal of dredged material in coastal waters of the Netherlands. Dissertation Vrije Universiteit Amsterdam, 202 p.

[22] Anon (2005a) Proposal for a Directive of the European Parliament and of the Councel establishing a Framework for Community Action in the field of Marine Environmental Policy (Marine Strategy Directive). Brussels, SEC(2005), SEC (2005) 1290. Brussels 24.10.2005.

The preparatory, mostly scientific work in the Marine Strategy[23] focused notably on *(i)* the application of the ecosystem-based approach to management of human activities impacting the marine environment; *(ii)* monitoring and assessment issues; and *(iii)* the particular challenge of hazardous substances. Here, with the objective close to zero for man-made synthetic substances, primarily for dioxins/furans and PCBs, the pressure on emission control can be expected being more stringent than under the WFD.

From the start of the Marine Strategy Directive (MSD), sediments will play a more significant role than in the WFD. Referring to the quality aspects of sediments, the Marine Strategy of 2002 already stated: "as sediments act as sinks for many pollutants, these chemicals continue to be a public health concern and impede the use of marine resources for human use". In Annex II to the MSD the general state of chemical pollution is described, among others, by sediment contamination; the quantitative aspects of sediments refer to their role as bed substrate and potential physical damage due to siltation, abrasion and selective extraction.

In an internet consultation of the Commission[24], the objectives for the Strategy were considered of "high" importance by a large majority of respondents. There was strong support for the dual EU/regional approach and for the proposed methodology on monitoring. Finally, regarding the role of science in this complex approach, while not covered by the statistical evaluation, the statement of an anonymous respondent can be cited (conclusions no. 98):

> "Science-based decision-making must be the leading principle for consistent decisions."

[23] Anon (2002) Towards a strategy to protect and conserve the marine environment (Marine Strategy). Communication from the Commission to the Council and the European Parliament. Brussels 02.10.2002.

[24] Anon (2005b) Thematic strategy on the protection and conservation of the marine environment. Evaluation of the replies to the Internet Consultation, 15 March to 9 May 2005 (133 respondents from 22 Member States).

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For the investigation of contaminated sediment issues sampling campaigns in German rivers were conducted with logistic and technical support provided by various institutions. At the Rhine River it was the State Authority for the Environment Baden-Württemberg Karlsruhe, the German Waterways and Shipping Office Freiburg and the German Federal Waterways Engineering and Research Institute Karlsruhe. In cooperation with the International Commission for the Protection of the Rhine (ICPR), many experiments on sediment erosion were performed to provide basic information on the risk of mobilization of contaminants. Access to chemical and toxicological sediment data was given through the cooperation with the Federal Institute of Hydrology Koblenz thanks to Martin Keller and Peter Heininger. At the river Elbe. support was given by the Hamburg Port Authority, the Free Hanseatic City of Hamburg, the Consulting Centre for Integrated Sediment Management (BIS at the Hamburg University of Technology) and by UFZ Centre for Environmental Research Leipzig-Halle, Department Lake Research, Magedeburg.

First project results have been presented and discussed at the "Sedymo-Workshop" which was held at the University of Stuttgart in October 2004. The final presentation of the joint research project took place at the International Symposium in March 2006 at the Hamburg University of Technology. In addition to the "Sedymo"-Symposium – the proceedings are presented in this book – a special "SedNet"-day was organized in cooperation with the European Sediment Research Network. Two sessions, one focusing on "Sediments in European River Basins" with contributions from Susanne Heise, Axel Netzband, Philip N. Owens, Wim Salomons and Kevin G. Taylor and the other one on "Sediment Risk Assessment" by Marc Babut, Jos Brils and Sue White were devoted to the European perspective of sediment management (titles in the Appendix to this book). We are very grateful to SedNet and to the authors for this multidisciplinary state-of-the-art overview.

Thanks are given to all the reviewers of the submitted contributions, in particular to Johan C. Winterwerp for reviewing the "Transport Modeling" chapter. Special acknowledgment is paid to Dietrich Hammer from the University of Stuttgart for his enduring work on many details of the submitted papers to make them ready for printing. Mrs. Agata Oelschläger and Dr. Christian Witschel from the publisher Springer are gratefully acknowledged for their interest in publishing the present book.

Bernhard Westrich, *Ulrich Förstner*
Stuttgart, Hamburg, May 2007

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[25] See Appendix.

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