Improved sediment-management strategies for the sustainable development of German waterways

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Abstract Apart from the coastal waters, the German waterway system consists of large navigable rivers and of canals connecting the individual basins. The main arteries are the Rhine River and the tidal Elbe River. In the impounded section of the Upper Rhine, relocation of sediments causes major problems as the fine-grained deposits are contaminated by hexachlorobenzene (HCB). Furthermore, an increasing frequency and intensity of extreme events might increase the sediment input into the impoundment chains and enhance deposition there. Hence, new strategies to reduce maintenance costs and to minimize ecological risks are required. Due to sediment retention in the impounded section, the free-flowing Rhine is subject to severe bed degradation. Here the goal is to achieve a dynamic stabilization of the river bed by combining training works with bed-load management measures, such as artificial sediment supply. In the estuaries of north-western Germany, regulation and deepening of the fairways have enforced tidal pumping leading to enhanced upstream transport of sediments and to increasing dredging volumes in the inner parts of the estuaries. In the tidal Elbe River, the strategy is to accomplish measures to damp the incoming tide and to optimize relocation of dredged sediment from both ecological and economic aspects.

Key words Rhine; tidal Elbe; contaminated sediments; relocation; bed-load management; residual transport

INTRODUCTION

Every year, about 240×10^6 tons of goods are transported along the 7700-km long German inland waterway system. The main artery of this transport system is the River Rhine connecting western Germany, eastern France and Switzerland with the North Sea. In the coastal areas of Germany the most important routes are the Elbe Estuary, serving as access to the Port of Hamburg, and the Nord-Ostsee Canal shortening the waterway between the Baltic Sea and the North Sea (Fig. 1). To enable secure navigation for the ever-larger vessels, the major rivers have been deepened, regulated and partly impounded. These impacts have disturbed the sediment flow to such an extent that additional sediment management measures are necessary to maintain the fairway and to avoid ecological damage. In this paper, the strategies for sustainable development of the German waterways, considering both economic and ecological aspects, are exemplified by the sediment management in the impounded section of the Upper Rhine, by the bed-load management of the free flowing Rhine, and by the sediment management of the tidal Elbe.

SEDIMENT DEPOSITION AND MANAGEMENT IN THE IMPOUNDED SECTION OF THE UPPER RHINE

The southern part of the Upper Rhine was impounded during the 20th century, starting after the end of World War I with the construction of the Grand Canal d'Alsace, and ending with the implementing of the Iffezheim barrage some 170 km downstream in 1977 (Fig. 2).

Quantitative aspects

Sedimentation in the impounded section of the Upper Rhine causes the rise of the bed and water levels. To ensure high flood discharge and the security of the dykes, the sediments have to be removed from time to time. Dredging activities in the impounded Upper Rhine are mainly concentrated on the sediment accumulations upstream of the weirs and on those forming in the outlet channels of the hydropower stations. Figure 2 gives an overview of the impounded section and the annual amounts of material dredged between 1990 and 2006 (WSD Südwest, 2007). The mean annual dredging volume amounted to 330 000 $m^3\,year^{-1}$, of which about 85% were dredged in the two final impoundments, Gambsheim and Iffezheim. These two barrages cross the whole

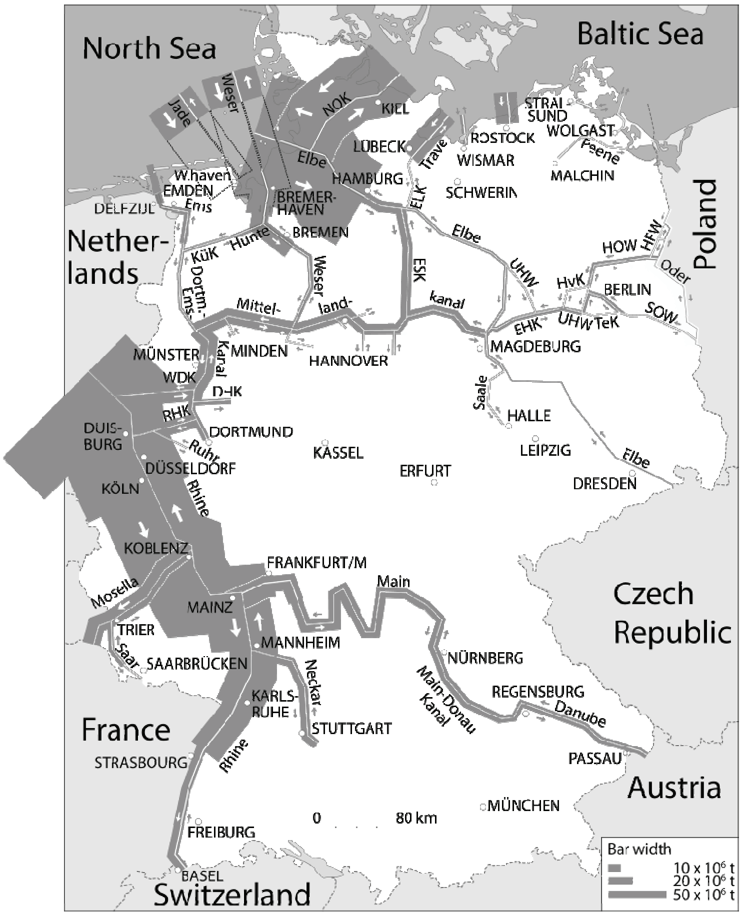

Fig. 1 Goods-traffic density (t) on German waterways.

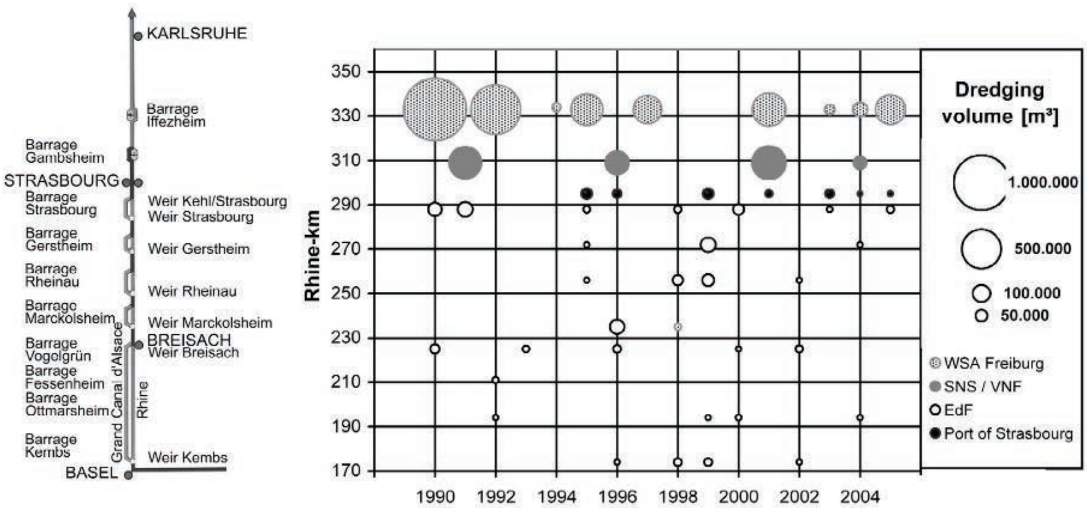

Fig. 2 Dredging volumes in the impounded section of the Upper Rhine, 1990–2005.

river as one structure. They consist of two locks, a dam, the hydropower station, and a flexible weir. Both impoundments are laterally bordered by high dykes between which the whole flow of the river has to be discharged (Fig. 3).

In the first years after construction the dredging volumes of these two barrages were considerably higher, but could be reduced by building moles in the backwater serving as hydraulic structures

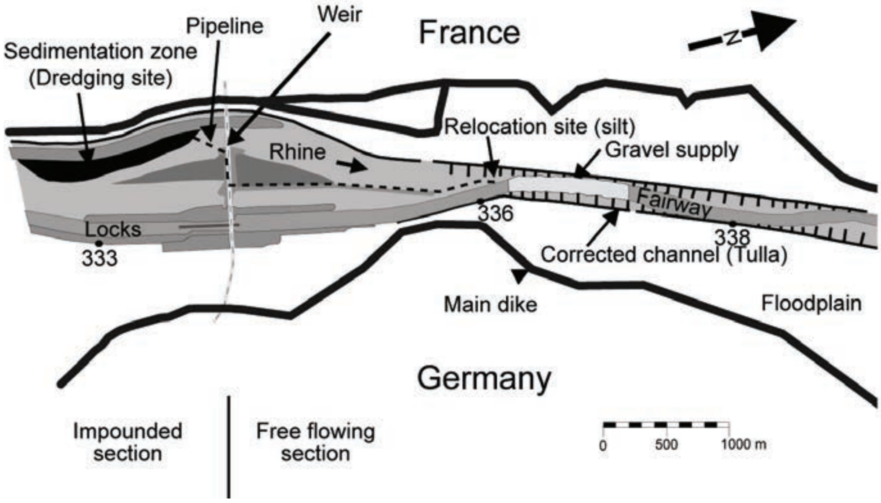

Fig. 3 The Upper Rhine near the Iffezheim barrage.

and as disposal sites for the dredged material. Meanwhile, the capacity of these disposal sites as well as the capacity of an additional mole in the tailwater of the Iffezheim barrage, is nearly depleted. Depending on the hydrology it must be expected that every year 150 000–200 000 m^3 of fine-grained sediment settle in the backwater of the Iffezheim barrage and have to be dredged to guarantee the safety of the dams and the discharge of floods.

Sediment quality

Dredging and disposal, however, are a major problem as the sediments are contaminated by hexachlorobenzene (HCB). Although the HCB-emissions reduced to negligible levels many years ago, HCB-contaminated sediments are still present in the impoundments and move downstream when they are resuspended by floods (Witt *et al*., 2003) or mobilized by dredging operations (Koethe *et al*., 2004). Thus contamination of freshly-settled sediments in the backwater of the Iffezheim barrage is the result of mixing of recent, relatively clean, suspended matter with re-mobilized old, contaminated sediments. The detailed transport mechanisms of the HCB-load from one barrage to the next, and finally to Iffezheim, are very complex and not fully understood yet.

In the future, due to climate change, the frequency and magnitude of high floods could increase (Asselman, 1997; Kempe & Krahe, 2005) and might influence sedimentation in the impounded section (Vollmer & Goelz, 2007). Thus the development of strategies both to reduce dredging of sediments and to dispose of them in an ecologically sound and economically acceptable manner, is one of the important tasks of sediment management for the Rhine waterway.

Economic aspects

Considering the costs, there are two main options to solve the problem. The first is to reduce sedimentation by means of hydraulic measures; the second is to relocate the sediments from the backwater to the tailwater by appropriate techniques.

In 2004 the Waterways and Shipping Office Freiburg (WSA Freiburg) tried to flush about 300 000 m^3 of dredged sediment through a pipeline across the Iffezheim barrage into the free-flowing river (Fig. 3). The relocation of such a huge amount of fine-grained sediments within a few months has never been practised on the Rhine before, but it was clear that this measure would increase the concentration of suspended matter in the free-flowing Rhine downstream of the barrage over many kilometres and for a long period. Therefore the relocation was accompanied by comprehensive monitoring of both sediment transport and HCB-concentration. In addition, faunal and sedimentological investigations were carried out in the groyne fields and the accompanying bayou system.

Besides an increase of suspended sediment concentration up to five times the mean concentration, no negative impacts caused by sedimentation were observed (Vollmer & Gölz, 2007). Yet during flushing, the HCB-concentration of the sediment exceeded an upper limit that was predefined by the authorities responsible for water and sediment quality according to the recommendations of the International Commission for the Protection of the Rhine (ICPR, 1997). Consequently, WSA Freiburg stopped the relocation of the dredged material although only half of the volume scheduled had been relocated. The remaining 150 000 m^3 had to be deposited in residual containment facilities near the barrages of Iffezheim and Gambsheim. This practical experience and a major political intervention by the Dutch government led to the conclusion that an improved strategy is necessary to handle the contaminated sediments of the Rhine basin in an appropriate manner.

Approach and strategy

Various German and French administrations and organisations are responsible for the maintenance of the impounded section of the Upper Rhine. On the German side, this is the Federal Water and Shipping administration (WSV) represented by the Waterways and Shipping Office Freiburg (WSA Freiburg); in France these are the Service de la Navigation de Strasbourg (SNS/VNF), the Port Autonome de Strasbourg and Électricité de France (EdF). Water and sediment quality is controlled by the State of Baden-Wuerttemberg (Germany) and by the Agence de l'eau Rhin-Meuse (France). As sediment-management measures at the Upper Rhine may have an impact on sedimentation and sediment quality in the middle and lower part of the waterway down to the Port of Rotterdam (Netherlands), the finding of a sustainable solution is a truly transboundary problem, which needs to be solved with a basin-wide sediment management approach (Joziasse *et al*., 2007).

In this context, the international working group SEDI was established by the ICPR with the aim to evaluate and classify the risks arising from the contaminated sediments and to establish a management plan comprising proposals for how to deal with the contaminated sediments in specific situations. Looking at the HCB-pollution of the Upper Rhine, the working group came to the conclusion (Keller, 2008) that the highly contaminated sediments mainly occur on the impoundments of Marckolsheim and Rheinau (Table 1). A local remediation of these sites would considerably reduce the HCB-flux along the Upper Rhine. As a consequence the HCB-concentrations in the sediments of the Iffezheim and Gambsheim impoundments would decrease with time to such an extent that dredged material can be relocated without exceeding the limits set by the recommendations of ICPR (1997).

Meanwhile, a bilateral working group (SuBedO) established by the French and German authorities has checked the possibilities to reduce sedimentation by installing an additional hydraulic structure and to improve the dredging and/or relocation process by applying appropriate techniques, e.g. hydrosuction (Hotchkiss & Huang, 1995). Although the study results, which also includes chemical aspects, have not been presented yet, together with the proposals of SEDI they will help to improve sediment management on the Upper Rhine in both economic and ecological respects.

DYNAMIC BED STABILIZATION AND SEDIMENT MANAGEMENT IN THE FREE FLOWING RHINE

Due to the impounding of its upper course and of its main tributaries, the River Rhine downstream of the Iffezheim weir is characterized by a general bed-load deficit. Together with a non-uniform

Table 1 HCB-concentrations in the sediments of the impoundments of the Upper Rhine.

Impoundment	Mean (mg/kg)	Maximum (mg/kg)
Iffezheim	158	910
Gambsheim	127	400
Strasbourg	223	2 300
Gerstheim	135	1 520
Rheinau	1 110	3 400
Marckolsheim	609	4 100

bed-load distribution, this leads to severe bed degradation whereas other reaches are stable or slightly aggrading. As water levels tend to follow bed level trends (Droege *et al*., 1992; Brinke ten & Goelz, 2001), ecological damage in the flood plain, serious navigation problems in the main channel, and economic disadvantages for water management, agriculture and forestry are well known negative consequences. To solve these problems, a strategy has been developed which allows stabilization of the river bed by combining conventional training measures with bed-load management measures (Goelz, 1994). The latter aims to balance the bed-load budget of the river by artificial bed-load supply, as well as by dredging and redumping of bed sediment. In addition, local river training works and scour prevention measures are required to support this sort of dynamic bed stabilization.

Bed-load supply

Artificial supply of bed-load material for the stabilization of river reaches has become an accepted method in river engineering and is being applied increasingly on German Federal waterways. To avoid bed degradation immediately downstream of the Iffezheim barrage (Fig. 3) the river has been supplied with gravel since 1978 when the weir was put into operation (Kuhl, 1992). The material to be added is dumped from hopper barges forming a thin mobile gravel carpet on the river bottom (Fig. 4). Stabilization of the river bed and of water stages immediately downstream of the impoundment weir is the primary aim of this measure, as the unhindered access to the ship locks of the impoundment must be ensured. Moreover, this bed-load supply at Iffezheim is the only major source of the free-flowing Upper Rhine since the impoundment weirs upstream and the dam regulation of the main tributary, the River Neckar, inhibit the natural supply of bed load to a high degree. In the long-term, an average 180 000 m^3 of gravel are dumped each year.

Bed-load withdrawal

Some 170 km downstream of the Iffezheim barrage, the hydraulic conditions of the river have drastically changed. Between Mainz and Bingen, water-level slope and flow velocity reach a minimum with the consequence that bed load transport slows down. The sandy sediment delivered from the Upper Rhine tends to form large dunes which obstruct shipping traffic, especially at low water conditions. Due to their mobility and limited dimensions, these obstacles are difficult to dredge. Thus other solutions had to be found to cope with the problem. In 1989, a huge bed-load trap was implemented near Mainz. A trench 160-m wide and 1.4-m deep was dug widthways into the bed. This structure collects the bed load delivered from the Upper Rhine. The sudden widening of the cross-section forces the bed load to settle in the trench. From there it can be easily removed by dredging. On average, about 100 000 m^3 of sand and fine gravel are dredged each year from the bed-load trap near Mainz. Due to this measure, navigation conditions have markedly improved within the last decade.

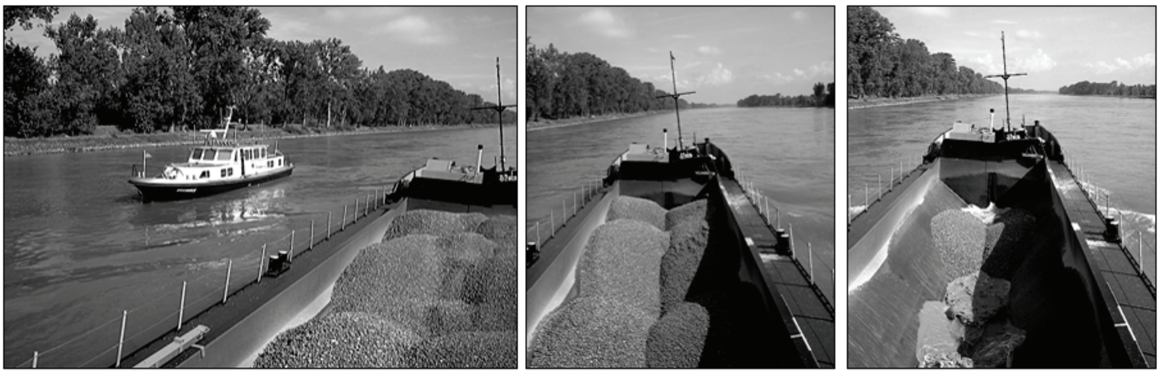

Fig. 4 Gravel supply downstream of the Iffezheim barrage.

Overall concept

Based on the positive experience with artificial gravel supply at Iffezheim and with bed load withdrawal at Mainz, an overall concept for the free-flowing section of the River Rhine was established aiming at achieving a dynamic equilibrium of the river bed (BMV, 1997). To avoid aggradation and erosion, sediment transport must be controlled in such a way that transport capacity and bed load are in harmony, both locally and at the larger scale. Accordingly, the concept must rely on the mutually complementary measures of river training (improving or construction of groynes, longitudinal dams, etc.) and measures of bed-load management (supply and withdrawal of bed-load material). Generally, large-scale deficits and excesses of sediment should be compensated by measures of bed-load management, whilst local imbalances should be counteracted by river training measures.

Besides local dredging and redumping activities, six major bed-load management measures provide the basis for a dynamic equilibrium over a length of 530 km between Iffezheim and the German–Dutch border (Fig. 5). In addition to the artificial gravel supply at Iffezheim, and to the bed load withdrawal near Mainz, another three sites for bed-load supply have been put in to operation along the Middle and Lower Rhine. All together, along the 500-km free flowing Rhine, each year about 500 000 tons of gravel-sized material is fed to the river.

At the Middle Rhine, where gravel exploitation is very limited, broken material from quarries has to be fed to the river. The same applies to some extent for the Lower Rhine. Therefore, the suitability of broken material as a substitute for gravel had to be tested by field tests (Goelz, 2002; Goelz *et al*., 1995).

By implementing the overall concept on the free-flowing Rhine, the German Waterways and Shipping authorities entered a partly unknown technical terrain. Therefore, a continuous performance review is indispensable. In this context, guidelines were elaborated containing a package of hydrological, sedimentological and morphological measurements by which water and bed levels are continuously controlled (PGEKG, 2005). Based on the measuring results, every two years a status report is produced describing the developments of the bed and water levels and identifying undesirable changes, so that individual management measures can be corrected or adapted in time.

On the German Rhine, large-scale bed level changes proceed slowly at rates of about 1 cm/year (Goelz, 1994). As recently shown by a tracer test, the migration rates of gravel supplied at Iffezheim vary between 2 and 6 km/year (Goelz, 2002; BfG & WSA Freiburg, 2006). Due to the slow reaction of the system, the effects of bed-load management measures on bed and water levels might be recognized only after the course of several years or decades. Therefore, the positive impacts of the overall concept, whose individual measures have been implemented step by step since 2000, will mainly appear in future. Nevertheless the system has to be permanently

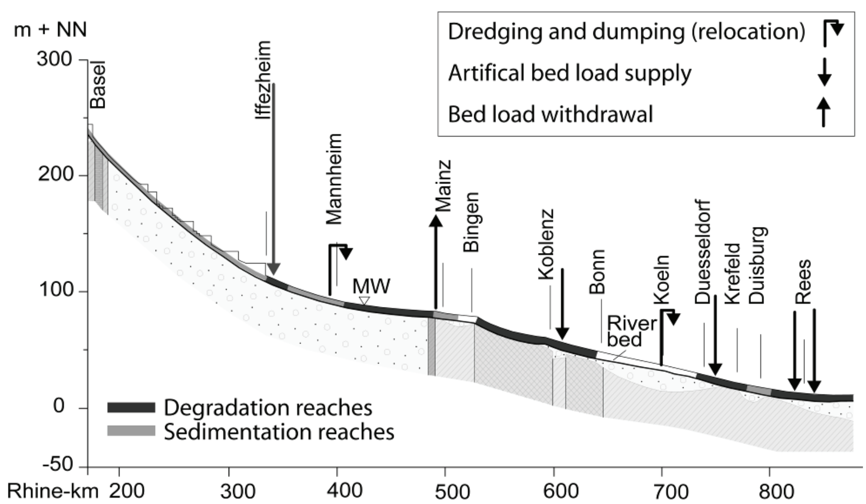

Fig. 5 Bed-load management in the free-flowing Rhine.

monitored, in order to recognize both positive and negative developments and to make corrections, if necessary.

SEDIMENT MANAGEMENT AND SUSTAINABLE DEVELOPMENT OF THE TIDAL ELBE RIVER

As a Federal waterway, the tidal section of the River Elbe is the seaward entrance to the Port of Hamburg. (Fig. 6). A description of the system, its physical processes, and most urgent problems of deepening, construction measures and sediment management is given by Eichweber (2006).

Anthropogenic impacts and hydrodynamic changes

Due to land reclamation connected with the embankment of the marshlands and with flood protection measures, the tidal Elbe has lost more than 90% of its natural flood plain since medieval times. Siefert & Havnoe (1988) showed that the combined effect of the dyking measures led to an increase of the maximum peak water level of almost half a metre in Hamburg during storm surges. As a result of industrialisation and the growing needs of a changing merchant fleet, river engineering measures were necessary. These included the construction of training walls, narrowing of cross-sections, and deepening of the fairway. Since 1860, the fairway of the Elbe River has been deepened in nine steps from 4.5 m to 14.4 m (Marušić & Iwens, 2008). The next phase of deepening, which aims at a fairway depth of about 16 m, is already in the licensing phase. The deepening of the fairway has led to a concentration of the flow on the deeper parts of the estuary, and to lower flow velocities in the mudflat and shallow water areas of the estuarine river system. The combined effect of training and deepening has increased the tidal energy in the inner parts of the estuary, where the weir at Geesthacht marks the tidal limit. The tidal wave is reflected at the weir as well as in some parts of the harbour of Hamburg, causing an increase of tidal elevation. These hydrodynamic changes all add to a deformation of the tidal curve towards a steeply ascending flood tide and more gently falling ebb tide in the upper reach of the estuary. Due to the expansion of the river mouth during the last decades, more tidal energy can enter the system.

Sediment dynamics

The hydrodynamic changes have resulted in an upriver transport of suspended sediment, which used to settle in the marshes and is now carried into the inner part of the estuary. An increase of the asymmetry of the tidal curve and an increase of the maximum flood current velocities is associated with the risk of enforcing the residual transport in an upstream direction, which is referred to as tidal pumping. This means that the ebb tide, in comparison to the flood tide, is not sufficiently strong to flush sediments which migrated upstream to Hamburg back downstream towards the North Sea. In periods of low freshwater discharge enhanced siltation occurs in the harbour reach.

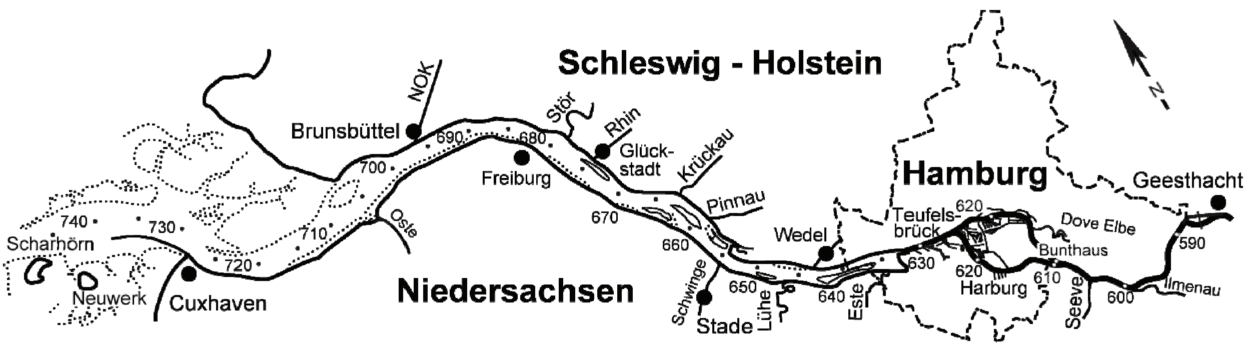

Fig. 6 The tidal Elbe River from the Geesthacht weir down to the mouth of the estuary. Numbers refer to river kilometres.

All together, the modification of the tidal system has resulted in a dislocation of the main siltation zone towards the harbour area.

Sediment pollution

In the 1980s, the River Elbe was known as one of the most polluted rivers in Europe. Since then the material dredged in the Port of Hamburg has been treated and deposited ashore. The annual cost for treatment and final waste disposal of approximately 10^6 m^3 of harbour sediment adds up to €25 × 10^6. As the capacity for treatment and disposal ashore is limited and only sufficient for another six years, a new landfill site within the Hamburg region is being established.

Due to the closure of many emitting companies and to the implementation of wastewater treatment plants, the pollution has been considerably reduced since the German reunification (Fig. 7). However, the amount of sediment that needs to be dredged has markedly increased. Therefore, as early as the mid 1990s, part of the harbour sediments were relocated within the tidal River Elbe inside the Hamburg State Boundary. Yet, after the last deepening of the fairway in 1999/2000, a further increase of the sedimentation rate led to a strong rise of the dredging volume in the harbour area (Fig. 8). To reduce sediment transport cycles and to avoid circuit dredgings, a

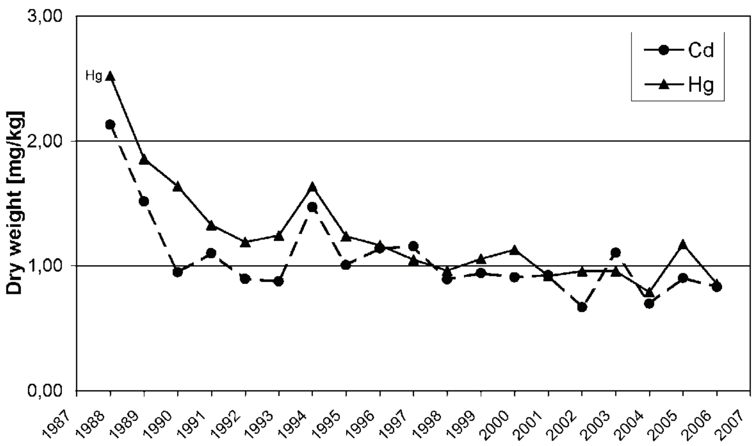

Fig. 7 Trends in heavy-metal concentrations in dredged material of the Elbe estuary between 1988 and 2006.

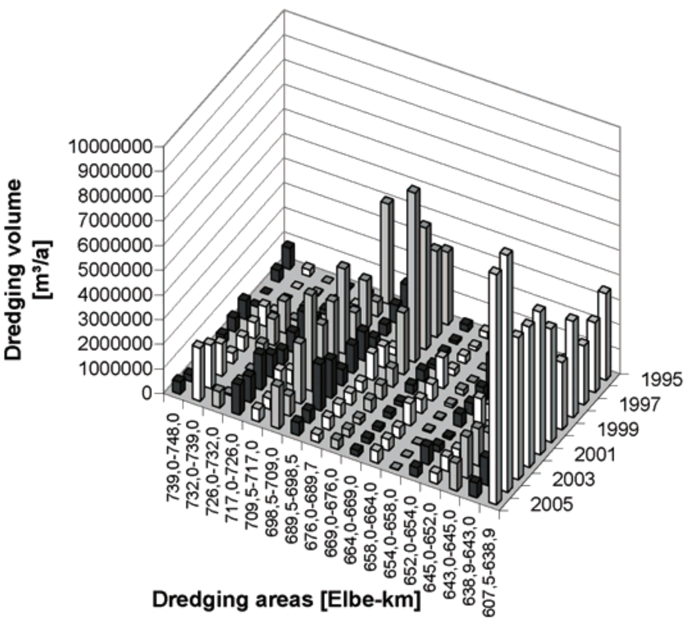

Fig. 8 Development of dredging activities in the Elbe estuary.

certain amount of sediment is now dumped in the North Sea close to Helgoland, where the bed-sediment composition is very similar to that of the harbour deposits.

Sediment management

Without appropriate measures, the siltation of the inner parts of the Elbe estuary will continue with negative effects for the ecology (silting of side channels and shallow water areas) and requiring an increasing effort to maintain the fairway and the berths of the Port of Hamburg. To achieve a sustainable development for the tidal Elbe River, the Hamburg Port Authority and the Federal Waterways and Shipping Administration (HPA & WSD Nord, 2006) see three main objectives for an action plan:

- dissipation of the incoming tidal energy by hydraulic engineering constructions, especially within the mouth of the estuary,
- establishing flooding areas in the middle and inner part of the estuary.
- optimizing sediment management by considering the whole system.

In a first step, a system study is being developed by the Federal Institute of Hydrology (BfG), which will be used to draw up an ecologically-optimal relocation strategy by defining and evaluating different relocation scenarios. The sediment management concept has to meet the overall goal to reduce maintenance dredging in the Elbe estuary. This can be achieved by relocating fresh, less-contaminated sediments in the outer parts of the estuary, where there is less possibility for them to return to the place where they were dredged. Sediments taken out by the ebb tide into the North Sea can no longer participate in the sedimentation process within the waterway, the port basins, the intertidal banks and the side channels.

Furthermore, whether subaquatic deposits in combination with hydraulic engineering measures could be part of the management concept to guarantee the water depths, in the tidal River Elbe and in the Port of Hamburg, is being examined.

At the mouth of the estuary the combination of hydraulic measures reducing the dimension of the mouth with the permanent and immobile localisation of fine silty sand below the low-water level could bring up new synergies.

Another main objective should be to improve sediment quality by cleaning up former sources of waste throughout the whole Elbe basin. This has to be done in cooperation with the other Elbe stakeholders and the Federal Waterways and Shipping Administration. Intensive efforts are required to improve the water quality further upstream, both in Germany and the Czech Republic, so that in future there will be no further need for contaminated sediment treatment in Hamburg.

CONCLUSIONS

For both coastal and inland waterways, the development of improved strategies for sediment management is an important task. In the long run, the measures described in this paper for three different types of waterway in Germany will not only reduce the maintenance costs of the transport system but also improve the ecological situation of the large rivers. This meets the objectives of the European Water Framework Directive (WFD) aimed at the enhancement of the ecological situation and ecological potential of the water bodies. Although sediments are not really addressed in the WFD (Casper, 2008), the realization of the sediment management strategies described above is an important contribution to the sustainable development of the navigable rivers because they reduce the amounts of pollutants, diminish siltation, and stabilize degrading or accreting channels. Furthermore, sediment management must be part of an integrated river management and should be incorporated into the management plans of the river basins (Owens *et al*., 2008). To be successful in implementing such improved sediment management strategies it is necessary to take into account the interests of the individual stakeholders along the river and to involve them in the developments of action plans at an early stage.

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