COMMON IMPLEMENTATION STRATEGY
FOR THE WATER FRAMEWORK DIRECTIVE
(2000/60/EC)

Integrated sediment management Guidelines and good practices in the context of the Water Framework Directive

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Meuse river – photo from Jos Brils

Policy summary

Why this document and how was it developed

Building on an evaluation of the Water Framework Directive (WFD)[1] (Fitness Check[2]) and on lessons learnt after two cycles of implementation, the importance of properly managing sediment to reach the environmental objectives of the WFD, but also of many other EU policies, has been now well recognised. The Water Directors agreed in particular to include this topic in the CIS work program of ECOSTAT for 2019-2021. In April 2019, an ECOSTAT workshop took place in Dubrovnik which concluded to the need to develop a CIS document to share a common understanding and good practices on the management of sediment in the context of the WFD. In order to achieve this, a core group of experts was nominated to coordinate the drafting of this document, which involved the participation of experts from different fields.

This document, and the approach it promotes, are also fully aligned with the goals of the European Green Deal[3], and in particular of the EU Biodiversity Strategy for 2030[4], of the Zero Pollution Action Plan[5], of the EU Adaptation Strategy[6] and of the EU Soil Strategy for 2030[7].

Sediment relevance for the WFD and other EU legislations

Sediments are key components of aquatic ecosystems. They consist of solid particles of various sizes, which form the bed and bank of rivers and their floodplains, of lakes, estuaries and coastal ecosystems. Sediments acts as host for all categories of aquatic species, including aquatic and riparian plants, which use it as a substrate, fish that use sediment as spawning sites, and different benthic organisms (e.g., invertebrates) which use it as their habitat. It plays therefore a vital role for ecosystems. **In addition, sediments provide important ecosystem services, such as balancing riverine and coastline morphology, contributing to the connection between surface water and groundwater, increasing soil fertility, contributing to natural water purification, mitigating the negative effects of extreme flow events, etc**. Sediments mostly enter river systems through erosion and delivery in the river catchment, and are transported from the headwater to the sea. Sediments enter coastal ecosystems from rivers, from coastal cliff erosion or from marine sources. Dynamic processes shape both rivers and coastlines, and determine their morphology.

Where human activities interfere with sediment quantity or quality, sediment management becomes necessary. Human activities in the river basin can affect these natural processes and may create unbalances due to a deficit or surplus of sediments, which can compromise the integrity of aquatic systems and the multiplicity of ecosystem services provided by them. In addition, discharge of pollutants in the environment can lead to sediment contamination which may represent a threat for decades. **In the EU, past sediment, land and water management practices have led to widespread hydromorphological and contamination impacts,**

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[1] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

[2] Fitness Check of the Water Framework Directive and the Floods Directive. SWD(2019) 439 final: https://ec.europa.eu/environment/water/fitness_check_of_the_eu_water_legislation/documents/Water%20Fitness%20Check%20-%20SWD(2019)439%20-%20web.pdf

[3] Communication from the Commission. The European Green Deal. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

[4] EU Biodiversity Strategy for 2030 Bringing nature back into our lives. COM(2020) 380 final : https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF

[5] Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'. COM(2021) 400 final :https://eur-lex.europa.eu/resource.html?uri=cellar:a1c34a56-b314-11eb-8aca-01aa75ed71a1.0001.02/DOC_1&format=PDF

[6] Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. COM(2021) 82 final: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0082&from=EN

[7] EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate. COM(2021) 699 final : https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0699&from=EN

which have impaired the ecological as well as the chemical status of most water bodies. Addressing sediment related pressures is therefore one of the pre-requisite conditions to the protection and enhancement of aquatic ecosystems and consequently to the achievement of good status for the WFD. Although there is little direct reference to sediment in the WFD, **hydromorphological conditions and most biological quality elements depend on sediment processes** to a greater or lesser extent. In addition, **many substances (including in particular chemical substances, metals, and nutrients) can accumulate in sediment over time and be released in water or contaminate aquatic species, thus potentially negatively affecting ecological or chemical status**. Furthermore, flood events as well as human interventions can remobilize deposited sediment and by that result in down-stream, and cross-border transport of sediment associated contamination.

The effective management of sediment pressures is also important for certain uses or activities, and integrated management can contribute to reduce costs associated to them (e.g. reducing maintenance costs, improving efficiency of measures). This is particularly relevant in the context of other environmental legislations (e.g. Floods Directive[8], Habitats Directive[9], Marine Strategy Framework Directive[10]), as well as sectoral policies (e.g. agriculture, energy, transport).

Recommendations for addressing sediment in the context of the WFD

Considering their natural dynamics and interactions with many uses in a river basin, sediments need to be addressed at the appropriate scale and in an integrated way. To achieve this, **it is recommended to apply the concept of “integrated sediment management planning”**, which is defined in the context of this document as an approach that recognises the system (source to sea) scale at which sediment-related processes operate, and aligns these, in a consistent way with the objectives of environmental policies as well as those stemming from socio-economic activities (e.g., navigation, flood risk mitigation, hydropower production, irrigation). This approach should result in the definition of appropriate management objectives for sediment, in line with the objectives and requirements of the WFD and other relevant water and biodiversity Directives, while integrating different use-related needs. Such planning should be either part of, or well aligned with, the preparation of River Basin Management Plans.

Applying “integrated sediment management planning” requires a preliminary analysis of the sediment dynamics in the river basin. It is generally recommended to **start by setting objectives at the catchment scale, and then derive them at more local scales**. Identifying measures at local scale without assessing both the cause of the problem and the effects of the measures at the larger scale risks being counter-productive as measures may not bring the expected benefits. It is also recommended, where relevant, to address both sediment quantity and contamination aspects as these may be closely linked.

In addition, identifying sediment related measures in an efficient way involves following some key principles, including to **prioritise as much as possible measures aiming at reducing pressures at the source, to apply nature-based solutions and to apply the principles of adaptive management** (e.g. evaluating measures to possibly adapt them regularly).

Finally, a **good governance system and the involvement of relevant actors or stakeholders** is essential as sediment is a cross cutting issue and requires coordinated actions.

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[8] Directive 2007/60/EC on the assessment and management of flood risks. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32007L0060

[9] Council Directive 92 /43 /EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31992L0043&from=EN

[10] Directive 2008/56/EC establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0056&from=EN

This document was developed with Member States in the year before the finalisation of the draft RBMPs for the 3rd cycles. Member States are expected to consider the extent to which the recommendations in this document can be included in the context of this cycle and in subsequent steps. The topic of sediment has been included in the work program of ECOSTAT for 2022-2024.

Scope

This document aims to establish a common understanding on the role of sediment in achieving the objectives of the Water Framework Directive, and to provide guidance on how to address pressures on sediment quantity and sediment contamination, in the context of the River Basin Management Plans, and also other policies' planning instruments. It covers, in particular, the different steps where consideration of sediment is needed. Due to the nature of sediment as integral, natural component of aquatic systems, and its interlinkages with multiple water uses, functions and services, this document builds on the concept of integrated sediment management, considered as the most appropriate approach to manage sediment, and provides practical methods, tools and examples to apply it.

The target audience consists of policy makers responsible for drafting RBMPs and local plans, as well as implementers/practitioners, specialists and scientists supporting the implementation of the WFD. As this document promotes an integrated approach which addresses all sediment related issues and related uses, the target audience also includes policy-makers responsible for other policies such as energy, navigation, agriculture, flood and drought risk, biodiversity, climate change, contaminated site management (including consideration of soil and groundwater) as well as other environmental policies.

Structure of the document

The document includes a policy summary targeted at policy makers which summarises all key messages further elaborated in the main body of the document.

The document addresses all aspects of sediment management in the context of the WFD. The main body of the text is organised in four chapters complemented by annexes:

Chapter 1 (sediment dynamics from the headwaters to the sea) is the introductory chapter. It describes the main concepts needed to understand the role of sediments in aquatic ecosystems and to fulfil the objectives of the WFD and other related policies. It describes, in particular, the processes of sediment transport at the catchment scale, the importance of sediment for aquatic ecosystems, as well as the requirements of the WFD and other related policies regarding sediment quantity and sediment contamination.

Chapter 2 (sediment quantity) provides the necessary information and tools to assess and address potential pressures and impacts of different types of pressures on sediment quantity, in the context of the WFD. Sediment quantity includes aspects related to sediment supply, continuity, the lack or excess of sediment required to support natural processes and characteristic habitats, and changes in sediment size ratio and composition, at different spatial and temporal scales. It helps the reader in assessing what are the alterations on sediment quantity, describes the main tools and methods for such assessment and for sediment monitoring, and helps in defining the most appropriate measures for optimizing the dynamics of sediment quantity.

Chapter 3 (sediment contamination) provides the necessary information and tools to assess and address potential pressures related to sediment contamination in the context of the WFD. Sediment contamination includes, in this context, all substances[11] (particularly toxic substances & nutrients) excluding micro-plastics, which can negatively affect aquatic ecosystems. It helps the reader in assessing pressures associated with sediment contamination, in understanding what are causes of the contamination, and helps in defining the most appropriate measures to prevent pollution at the source and to address already contaminated sediments.

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[11] Micro-plastics are not addressed in this document

Chapter 4 (Integrated sediment management planning) aims at helping those responsible for water management ("water managers") or involved in water management, to develop and implement integrated sediment management planning in view of addressing the pressures on sediment quantity and contamination at the most appropriate scale, in the context of the River Basin Management Plans (RBMP). It provides, in particular, a methodology to develop integrated plans, as well as recommendations to implement them. These concepts and recommendations have been developed on the basis of experience and cases studies in sediment management in different part of Europe.

Cases studies related to sediment management in Europe have been gathered in the process of development of this document. These case studies are summarised in boxes in the main text, and in addition full case studies are provided in annex A.

Contents

Chapter 1: Sediment dynamics from the headwaters to the sea

Key messages

- Sediments (both coarse and fine fractions) represent a crucial element in riverine, estuaries and coastal environments. Preserving or restoring their near-natural transport regimes is key for the goals of WFD as well as other EU policies (e.g. EU Habitats and Birds Directives, Floods Directive, Marine Strategy Framework Directive, Biodiversity Strategy, Climate Change Adaptation Strategy)
- Past sediment, land and water management practices have led to widespread hydromorphological and contamination impacts which have impaired the ecological status of most European water bodies
- Alterations of sediment transport processes and sediment quality at the catchment headwaters determine ecological impacts along the whole channel network as well as on the associated estuarine and coastal environments
- A change of paradigm is now needed regarding sediment management, as its environmental and socio-economic sustainability is fundamental to achieve the goals of the WFD as well as of other EU legislations.

1.1 Background and key concepts

1.1.1 Sediments as key component of rivers and estuaries

Until a few decades ago, both scientists and practitioners in the field of freshwater, estuarine and coastal ecosystem health were primarily concerned with water quality, and the assumption was that unpolluted water would correspond to healthy rivers and coastal areas. Indeed, chemical and bacteriological contamination was a major issue in many European water bodies. This led to the widespread implementation of modern, efficient water treatment plants, which took place in the 1980s-1990s (Tockner et al., 2022). Since the 1950s and 1960s, the importance of sediment contamination by anthropogenic sources in aquatic ecosystems has also been recognized (Von Züllig, 1956) and remains an issue today.

Meanwhile, scientists – mostly geomorphologists and physical geographers – started to report and publish papers on morphological changes occurring in and along some European rivers and coasts. While anthropic disturbances and consequent adjustments of most European river systems have a pluri-centennial history – mostly due to deforestation at the basin scale and diversion and channelization of the main rivers – major morphological changes occurring after the 1950s and 1960s involved dramatic riverbed incision and narrowing, as well as a rapid coastline regression in most regions (Petts et al., 1989). Such widespread erosion (Comiti and Scorpio, 2019) has resulted not only in huge economic damage related to the collapse of fluvial hydraulic structures and increased coastal flood risk, but also profound alterations of riverine and coastal ecosystems (Habersack et al., 2016). At the same time, in central and northern European countries, an increasingly diffuse presence of contaminated fine sediments in river systems and estuaries spurred increasing concern about their transport processes (Salomons and Brils, 2004), as did the consequences of ill-planned reservoir flushing operations, which caused severe impacts to riverine ecosystems (Kondolf et al., 2014; Espa et al., 2019).

In the 1990s (ASCE, 1992; Allan, 1995; Brookes and Shields, 1996) it became clear how the environmental quality of water bodies heavily depends not only on water quality and quantity (hydrological regime), but also on the quantity and contamination status of their sediments, and on the processes by which those sediments interact with water flow and vegetation (Fig. 1). These processes create the physical habitats upon which biological communities establish (e.g. Madsen et al., 2001). Riverine and coastal habitats at both the micro- (<0.5-1 m) and the meso- (1-100 m) scale are shaped and maintained by the interactions of water, sediment and vegetation (Figure 1). Nonetheless, other organisms (bacteria, animals) may be important geomorphological agents in specific ecosystems. The geomorphological characteristics of river basins and of their water bodies exert a first-order control on their biological communities (Gurnell et al., 2016), mostly at the meso-habitat scale (Belletti et al., 2017), whereas the size characteristics of sediments influence biota at the micro-habitat scale (e.g. Milan et al., 2000).

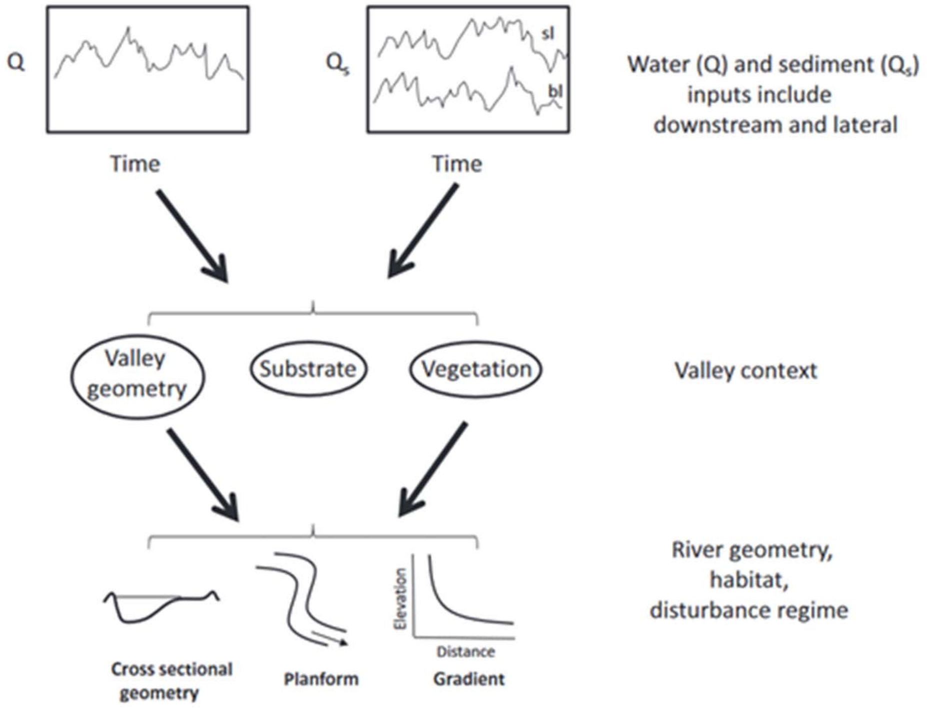

Figure 1.1: Schematic illustration for river systems of how the hydrological (Q) and the sediment transport (Qs) regime are mediated by valley geometry, substrate sediments and vegetation to determine river morphology at different spatial scales, shaping habitat distributions and their temporal dynamics (from Wohl et al., 2015). sl: suspended load; bl: bedload.

Geomorphological characteristics of rivers and tidal channels, as well as their connections to floodplain wetlands, salt marshes and tidal flats, are important to riverine and coastal ecosystems and their biodiversity (e.g. Schofield et al., 2018). The maintenance of species migration routes is important in avoiding habitat fragmentation and maintaining the capacity for populations to self-recover after natural (e.g. large floods) and/or anthropic disturbances (e.g., high-concentration sediment release from reservoirs). At both the micro- and meso-scale, sediments and their dynamics represent key factors for ecological status as they determine the quality of the structure and functioning of aquatic ecosystems associated with rivers and coastal waters, thereby affecting the biological quality elements (fish, benthic invertebrates, macrophytes and diatoms) foreseen by WFD. Nonetheless, although causal links between sediment transport, river morphology and ecology are evident, it should be noted that certain species are more sensitive to habitat changes than others (Fredorenkova et al., 2013).

Fish species depend on sediments in several ways. For example, the coarse sediments moving in rivers as bedload (see section 1.2) form spawning sites and habitats for juveniles and adults (Hauer et al., 2007). The proportion of fine sediment in gravel beds should be low enough to ensure sufficient water flux within the gravel layer to remove waste products and supply oxygen for several fish species (e.g. salmonids, Milan et al., 2000). Some other fish species (e.g. Brook lamprey) require fine sediment deposits for spawning. Moreover, the extent and timing of bedload transport is important for specific life stages of fish and of benthic invertebrates (Wohl et al., 2015), and sediments may also be important for the provision of food where invertebrates depend on allochthonous[12] energy sources (Billotta and Brazier, 2008). Sediment transport and deposition also play a key role also for plants, in terms of dispersal and habitat creation for many riparian plant species, as well as by providing the rooting substrate and nutrients for instream macrophytes, microphytes and phytobenthos[13] (Jones et al., 2012). Additionally, bed sediments play a crucial role in hyporheic[14] water exchange taking place between surface and subsurface compartments, thereby influencing water quality as well as fish habitat. In fact, thermal refuges for fish may be provided by cool upwelling groundwater associated to coarse riverbeds which are not clogged by fine sediment deposition. For a detailed description of the links between abiotic factors and biotic elements in rivers please refer to Allen (1995).

In estuaries, salt marshes are vulnerable ecosystems where balanced sediment processes are vital. As the rate of sediment deposition is a key factor for their development, the fate of salt marshes and their species, and the ecosystem services they provide, partly depends on the supply of fine sediments. Other coastal environments thrive when fine sediments are absent or nearly absent, because the turbidity that results from fine sediments hinders photosynthesis. Seagrass meadows are particularly sensitive to an abundance of fine sediments. For more details, see Day et al (2012).

Since 2000, morphology, bed substrate as well as vegetation (this latter being founding elements of riparian, intertidal, and shore zones) are fully recognised in the WFD as key aspects of water bodies, as they determine their ‘hydromorphological’ characteristics. The inclusion of hydromorphology in EU environmental legislation represented a turning point in how water bodies are to be characterised, monitored and managed. Twenty years of WFD application have now shown the key role of hydromorphology – and thus of a near-natural sediment regime – in achieving the environmental objectives set by the WFD (CIS ECOSTAT hydromorphology, 2018). However, sediment transport regimes in rivers have been altered within the EU territories by multiple human activities (including the construction of hydropower plants, expansion of agriculture, large scale river regulation and dredging for navigation, aggregate extraction and flood prevention). Consequences include reduced coarse sediment fluxes (e.g. in water bodies downstream of dams and/or major flood control works), and increased fine sediment transport (e.g. in lowland, agriculture-dominated river catchments - Grabowsky and Gurnell, 2016).

Besides their ecological impacts, imbalances in sediments are also recognised for their importance to other sectors. For example, with respect to flood risk, excessive sediment deposition in river channels may reduce their potential to convey floodwater and thus increase flood hazard (Mazzorana et al., 2013). Long-term channel aggradation also makes the maintenance of a safe navigable depth more challenging (Garcia, 2008) increasing the costs associated with dredging, and sedimentation in

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[12] Allochthonous - denoting a deposit or formation that originated at a distance from its present position

[13] Phytobenthos - plants of the seabed, both intertidal and subtidal, and both sedimentary and hard

[14] Hypoheric - region of sediment and porous space beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface

European reservoirs is steadily decreasing their available storage volumes (approaching 1% per year, Schleiss et al., 2014). Conversely, bed incision - resulting from reduced coarse sediment supply, in-channel gravel mining and/or increased transport capacity due to channelization – not only has profound impacts on aquatic and riparian ecosystems (Gurnell et al., 2016), but also undermines hydraulic structures (e.g. weirs, bank and shore protections) and infrastructure (piers, bridges), as well as lowering groundwater levels, with severe consequences for water abstraction at wells. Also, both flood-related and long-term degradation trends in rivers are highly hazardous for their impact on anthropogenic structures due to bank erosion (Krapesch et al., 2011; Rinaldi et al., 2015).

The reduction of sediment supply to coastal environments from fluvial sources as a result of the construction of hydropower plant and river network regularization works is an important factor for sediment starved coastal areas, promoting coastal erosion and loss of habitat. At the coast, erosion control works reduce sediment input to the system, and structures such as groynes and breakwaters often interfere with natural longshore transport, potentially leading to a supply deficit for sensitive coastal habitats such as sand dunes, salt marshes and mudflats. In contrast, habitats such as seagrass beds might be smothered by excessive fine sediments delivered by riverine inputs and deposited in the nearshore marine environment.

In addition to impacts associated with physical modifications, sediments are also important vectors of chemicals that may have direct deleterious impacts on riverine, lake and coastal ecology. Fine sediment particles (<63 µm) are the most chemically active (Collins et al., 1997) and effectively transport nutrients, metals and organic contaminants. Nutrients often play an important role in maintaining river ecosystems (e.g. Jones et al., 2012) but when in excess and in the case of contaminants they may have detrimental effects in both riverine, lake and coastal environments.

In summary, sediment management has become an important issue across the EU countries for its key role in guaranteeing the sustainability of economic activities (e.g. navigation, renewable energy production, water supply) and human safety (e.g. flood conveyance and slope stability) while maintaining or enhancing the ecological functionality of riverine, estuarine and coastal environments. Indeed, it has become evident how the sustainable management of such ecosystems and their restoration requires sound and integrated sediment management plans (Wohl et al., 2018).

1.1.2 Definition of sediments

Sediments include both mineral and organic particles that vary in size from very fine material (leading to colloidal dynamics) to boulders (see Wentworth classification, Wentworth, 1922). Sediment particles are subject to erosional (initial dislodgement and successive remobilization), transport (displacement), and depositional (settling) processes, depending on the local forces – both gravitational and related to surrounding fluid flows – acting on them. Mineral particles may be generated by rock weathering and by biological processes alike. Biologically-derived, inorganic sediments (e.g. carbonates, as shell fragments) are known to exert particularly important morphological and ecological roles in estuarine and coastal dynamics.

Organic particles (mostly fragments originating from plants) are often referred to as particulate organic matter (POM), which can be fine (FPOM) or coarse (CPOM) depending on particle size (finer or larger than 1 mm). A large fraction of FPOM is associated with fine mineral sediments (i.e., clay and silt) due to organic mineral complexation. The transport of organic-mineral aggregates and colloids dominates the transport of suspended sediments in many river systems (e.g. Hoffman et al 2020). In addition, large wood pieces (very large CPOM, > 1 m in length and >0.1 m in diameter) have recently emerged as key elements in riverine and coastal ecosystems for their capacity to control morphological patterns, to provide unique habitats and to regulate carbon fluxes. (Gurnell et al., 2002; Wohl et al., 2019)

1.2 Sediment transport in fluvial systems

1.2.1 The long – and intermittent – journey of sediments in rivers

Most river sediments are generated on the hillslopes of their basins (Figure 1.2), where the bedrock substrate is subject to chemical and physical weathering which leads to progressive rock fragmentation. Large rocks as well as fine soil particles are then transported downslope by gravitational (colluvial) and surface runoff-driven processes. Subsequently, sediments may then enter the channel network, either at the headwaters or directly into higher order reaches if these are confined by hillslopes. Within the channel network, during their downstream transportation by fluvial processes, sediments are subject to further fragmentation as well as to abrasion and sorting, resulting in a progressive reduction in sediment size. In addition, along the river system, sediments may be deposited and remain stored within the channels and in the floodplains for highly variable timescales, up to millions of years. Sediments arriving at a river outlet may then be partly deposited in the estuary or delta (i.e. the coarser fraction), whereas the finer fractions can be readily captured by coastal sediment transport processes (see 1.3). In addition, in estuarine and coastal environments, sediments may be derived from the local erosion of coastal cliffs or seabed features and transported by longshore or onshore-offshore processes.

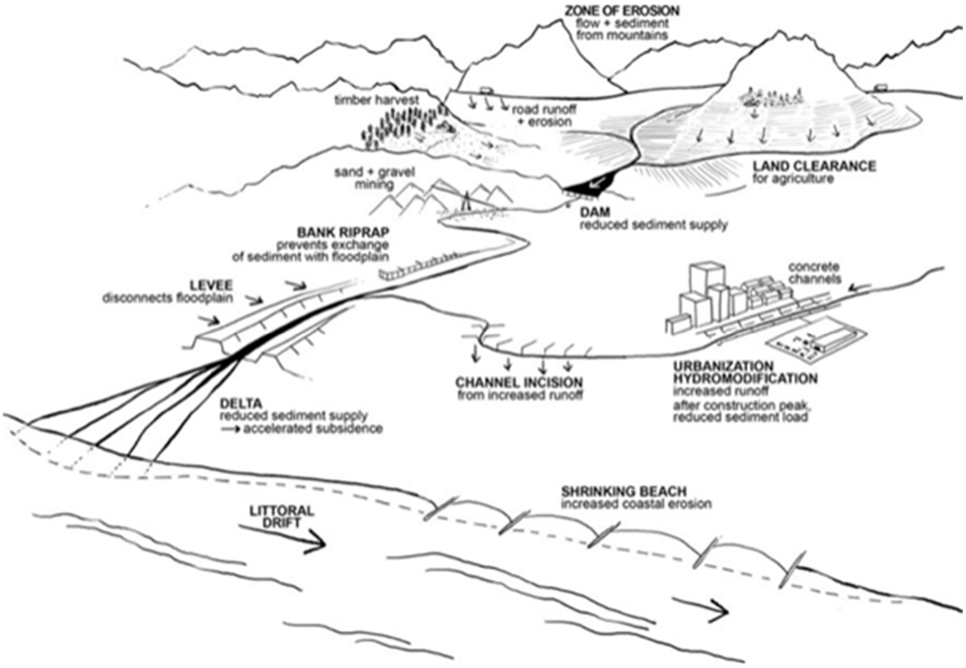

Figure 1.2: Sediment transfer from the headwaters to the sea has been widely impacted by anthropogenic activities (Kondolf and Podolak, 2014)

The chain of processes from the source of a given sediment to its sink (lakes, oceans) is called a "sediment cascade" (Burt and Allison, 2010). The quantitative knowledge of sediment fluxes along a sediment cascade permits the establishment of sediment budgets (Slaymaker, 2003) at desired spatial scales (e.g., river, river reach, delta). In turn, sediment budgeting – through the comparison of sediment inputs and output within the analysed system – leads to a determination of whether the system is in dynamic equilibrium or prone to sediment surplus (and thus to net aggradation or deposition) or to sediment deficit (i.e., to net degradation or erosion). Detail on the application of the sediment budget approach is given in Chapter 2.

Human activities have severely altered (as shown in Fig. 1.2) the fluxes within sediment cascades in river catchments and coastal and transitional environments worldwide (Eurosion, 2004; Hoffmann, 2015; Wohl, 2019), including Europe. This has been a response to sediment source reductions (e.g. stabilization of hillsides, riverbanks and channels) or increases (e.g. conversion of forested areas to crops), as well as by the disruption of sediment connectivity within rivers basins (Fryirs, 2013; Figure 1.3) and with coastal systems. In coastal and transitional waters, human interference at various scales (e.g. by breakwaters and storm-surge barriers) has similarly resulted in modifications in sediment transfers, causing local sediment surplus or deficit (Habersack et al., 2019). Consequently, the present structural and functional dynamics of riverine and coastal ecosystems in Europe are quite different from what they were before human alteration (Haidvogl, 2018).

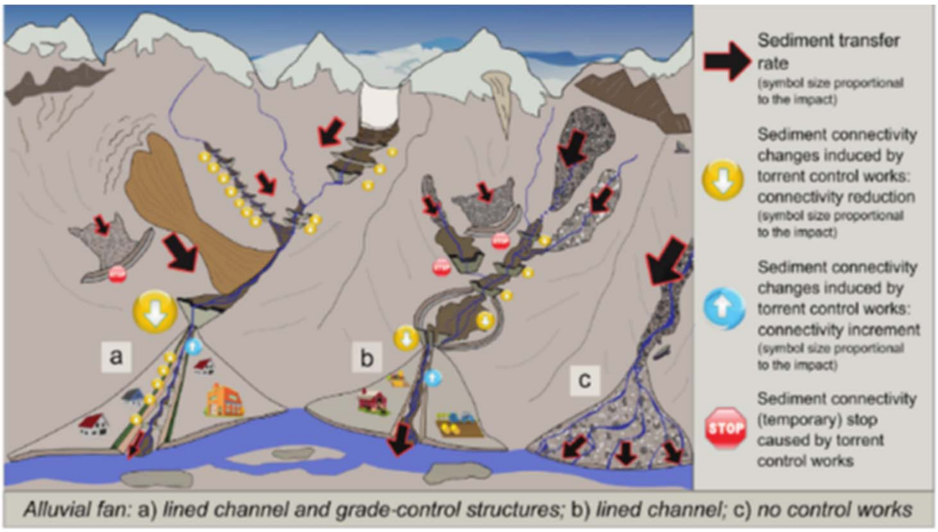

Figure 1.3: Sediment connectivity within European river basins is severely reduced by the presence of several structures built for mitigating natural hazards, beside dams and road infrastructures which also represent widespread sediment disconnection (from Marchi et al., 2019).

It is also fundamental to highlight how every river catchment, transitional water and coastal cell features a unique set of sediment cascades, characterized by their own temporal dynamics as influenced by local geological and climatic conditions as well as historical alterations by humans. Therefore, sediment transport processes show an enormous degree of site-specificity and temporal variability, which should be always taken into account when establishing sediment management strategies. Furthermore, a comprehensive knowledge of sediment transfer processes at the whole system scale is crucial for understanding and predicting local changes in rivers and coasts, and thus to successfully implement management measures to achieve the targets required by the WFD.

1.2.2 Sediment transport modes in river systems

In riverine environments sediment particles are transported as bedload and suspended load (Figure 1.4). Bedload refers to particles dragged by the fluid forces along the riverbed, and which move by sliding, rolling and/or saltation. Bedload consists of the coarser sediment fraction moving within a channel. This can range from coarse sand in lowland rivers to gravel, cobbles and boulders in steep mountain streams. In contrast, suspended load refers to particles transported downstream across the entire water column – and thus not in contact with the bed – as they are maintained in suspension by the flow turbulence. The suspended load usually consists of the finer sediments (clay, silt and sand), although coarser particles may be suspended for short distances in highly turbulent flows (i.e., during extreme floods in steep channels). Sediment particles featuring density lower than that of water – typically fragments from plants – can be transported at or near the water surface by flotation. Nonetheless, such organic sediments may also travel at or near the riverbed (Ruiz-Villanueva et al., 2019). In addition, the chemical weathering of rocks produces mostly ions which are transported in solution within the water column and constitute the so-called dissolved load.

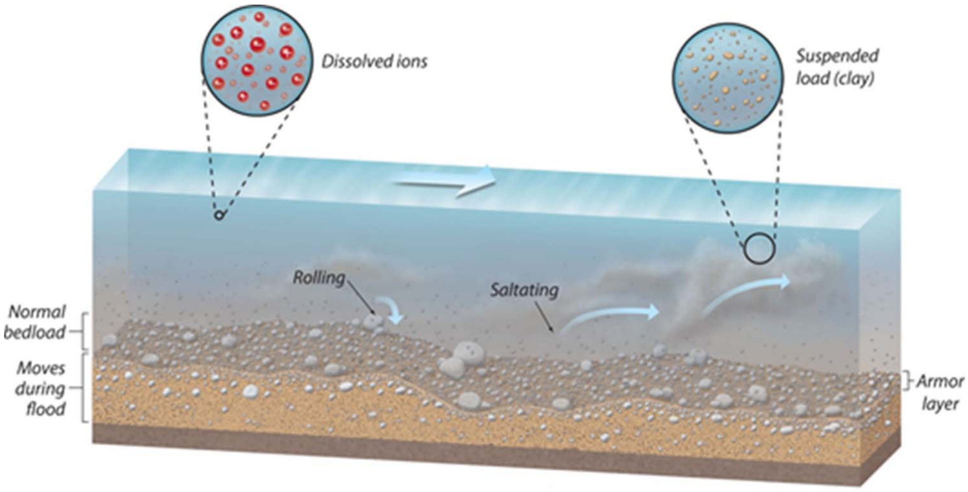

Figure 1.4: Illustration of the different sediment transport processes in river channels (from Bierman and Montgomery, 2013).

Even during competent flows (i.e., flows able to entrain and move sediments along riverbeds), particles transported as bedload exhibit a wide range of velocities, and may be subject to relatively long resting times – especially in gravel bed rivers – which separate periods of transport often triggered by turbulent bursts (Schober et all, 2020) as well as by impacting clasts moving from upstream (Ancey, 2020). Conversely, suspended particles are transported downstream at about the same velocity of water, and the average turbulent characteristics of the flow are responsible for determining the maximum grain sizes that can be maintained in suspension (Garcia, 2008). Local scale, short-lasting turbulence events may also prove important for suspended sediments (Tsai and Huang, 2019). Suspended sediments may also be deposited on riverbeds – and contribute to bed variations in sand-bed rivers, beside being responsible for floodplain vertical accretion in all types of rivers – and experience intermittent transport (often over seasonal timescales), and seasonal cycles in macrophyte growth and decay can exert a strong control on the mobility of fine sediment (Gurnell, 2014).

Indeed, a distinction can be made in terms of short-term sediment origin between bed-material load and wash load. The former includes sediments eroded from riverbeds, which can be transported as bedload or in suspension depending on their size and flow turbulence. In fact, in gravel- and cobble-bedded channels bed-material moves as bedload only, whereas – as already mentioned above – in sand-bed rivers part of the bed-material may be transported in suspension during high flows. Wash load describes instead the finer sediment fraction - transported always in suspension - which is supplied to the channel network directly by hillslope erosion processes, and which do not deposit in significant quantities on channel beds being characterised by very low settling velocities.

Bed-material transport and bedload process are thus fundamental factors in determining the morphological development of alluvial river reaches, with the exception of cohesive-bed channels in estuaries where bedload is practically null as all the sediments move in suspension. Bed–material transport shows a large spatio-temporal variability, and changes in river morphology in both space and time are determined by magnitude, timing and size of bed-material supply and by its interaction with flow and vegetation dynamics. Indeed, changes in bed-material supply can cause profound transformations in the channel pattern (Figure 1.5), e.g. a braided morphology can quickly evolve into a single thread pattern following supply reduction.

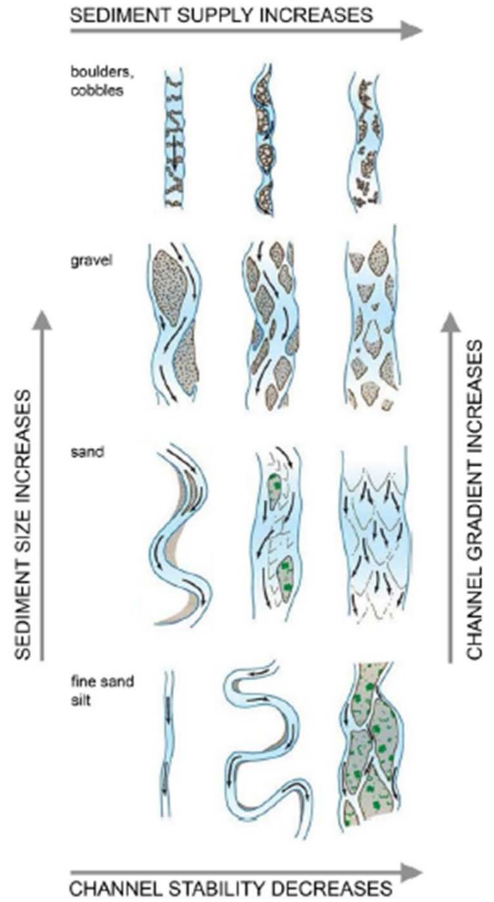

Figure 1.5: Relevance of bedload transport for river morphology (based on Church, 2006)

Therefore, the bedload fraction in rivers presents the most direct linkages with aquatic habitat dynamics – through the formation, maintenance and disruption of sedimentary and morphological units (Belletti et al., 2017) – and with the disturbance regime of benthic and fish communities (Allan, 1995; Milner et al., 2013). Nonetheless, flow events characterized only by very high suspended sediment concentrations may represent natural (e.g., ordinary floods) or human-induced (e.g., flushing operations) disturbances for river biota as well (Quadroni et al., 2016; Folegot et al., 2021).

The relative importance of suspended sediment and bedload transport

Most of a river's annual sediment yield is transported in suspension, with bedload typically making up a relatively smaller proportion, from <5% (in large sand-bed rivers) up to 30-40 % (in steep, glacier-fed streams, Mao et al., 2019). In large gravel-bed rivers, bedload can be assumed to be in the range 10-20% of the total sediment yield (Turowski et al., 2010). However, these figures are based on quite a limited number of field measurements, most of them taken during short periods and thus not including important flood events. Indeed, the continuous monitoring of bedload fluxes – in association with suspended sediment monitoring – has been carried out at very few sites worldwide. Such scarce knowledge on the actual temporal dynamics of the shaping of riverbeds is a great limitation to our understanding of river systems and thus of their ecosystems.

It has become evident during the last two decades how the prediction of bedload transport rates, by means of bedload transport capacity equations and their implementation in numerical models, may lead to overestimates (Rickenmann, 2001) or underestimates (Habersack et al., 2002) of up to 1-3 orders of magnitude. The higher errors are observed in mountain channels, which are typically bedload supply-limited during ordinary flows (Comiti and Mao, 2012), and thus ordinary bedload rates are largely overestimated in such systems. However, most rivers in Europe are nowadays supply-limited in terms of their bedload fraction mostly due to direct human alterations (e.g., dams and erosion control works such as check-dams and bank protections, in-channel sediment mining), and thus the use of transport capacity-based models to estimate the annual bedload sediment transport is expected to provide unreliable results in many cases. Large uncertainties are also present in the prediction of suspended sediment transport volumes by means of equations and models (see chapter 2), but the more the system is transport-limited (i.e. the less the availability of sediments dictates transport rates) the more accurate predictions are, as observed for bedload as well.

1.2.3 Sediment regime in rivers

River ecosystems have evolved over millennia in response to the environmental forcing exerted by their catchments, including their flow (Poff et al., 1997), sediment (Wohl et al., 2015) and wood transport regimes (Wohl et al., 2019). Differences in climate, geology, soils, topography, vegetation, and available sediment sources give rise to highly spatially variable responses of sediment transport to rainfall or snowmelt, which are strongly catchment-specific.

The sediment transport regime in a specific river reach can be defined as the typical variation of sediment transport rates (both in terms of bedload and of suspended load) over the year, in analogy to the flow regime. Similar to the flow and wood regime– several metrics can be used to quantitatively characterize such temporal variations (e.g., in terms of average and min-max magnitudes, frequency of sediment transport events, duration curves, seasonal occurrence of high transport events, rate of change of sediment transport rates).

Occasional (e.g., intense rainstorms), daily (e.g., ice melt cycles in glacier-fed rivers) and seasonal variations (e.g., snowmelt and cyclonic rainfall periods) occur naturally in sediment supply and hydrological conditions in rivers, thus impacting sediment transport rates. Such forcing, coupled with the non-linear nature of the physical relationship between flow stresses and sediment transport rates, determine a very complex temporal pattern of sediment transport in rivers (Aigner et al., 2017; Habersack et al., 2017; Mao et al., 2019). Such a complexity and its further dependence on the occurrence of large events with legacy effects lasting several years (Rainato et al., 2017) makes sediment transport rates highly variable at multiple time scales, ranging from few minutes to several decades.

Indeed, sediment regimes of rivers are characterized as being much more irregular over time than their hydrological regimes. The high variability of sediment transport within and between catchments is exemplified in Figure 1.6, where suspended sediment load data are presented for three rivers with contrasting climatic and geomorphic settings. In addition to this natural variability, several human pressures have impacted on sediment transport processes and thus modified the natural regime in most rivers worldwide, and especially in Europe (Chapter 2).

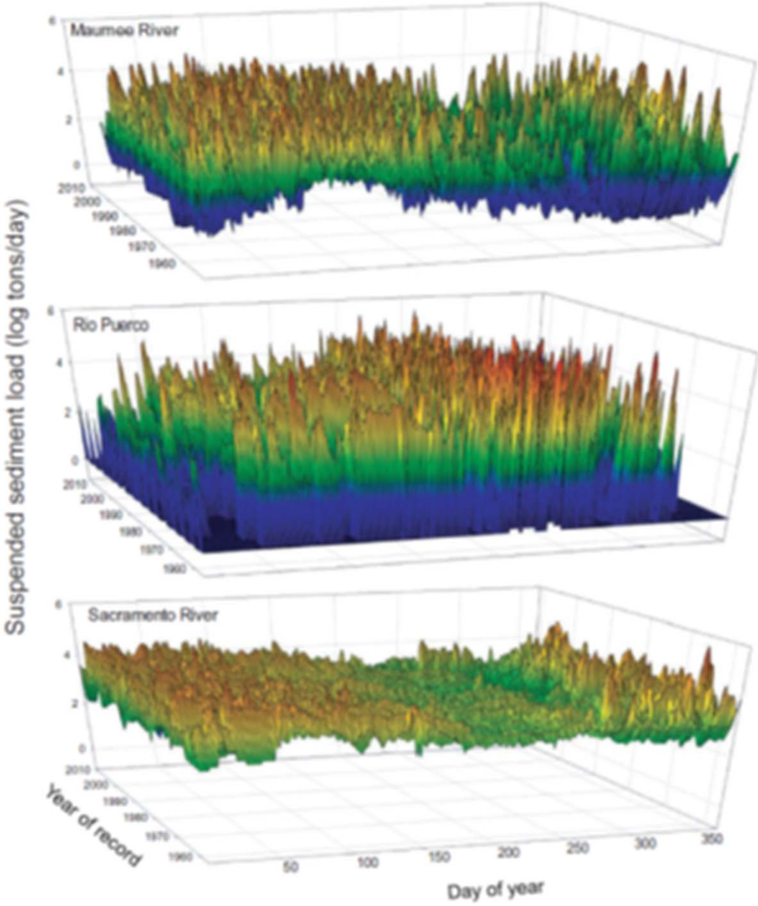

Figure 1.6: Intra- and inter-annual variation of suspended sediment load in three rivers featuring different climatic and geomorphological settings. The sediment regimes are markedly different (from Wohl et al., 2015).

Effective river management measures, aimed at maintaining or increasing the ecological value of water bodies, are best built on the quantitative knowledge of sediment regimes (Wohl et al., 2015). On the one hand, the quantitative understanding of the ’natural’ (i.e., in absence of the most impacting human pressures such as dams, erosion control works and gravel mining) bedload regime of a specific river is a prerequisite to designing interventions to achieve multiple objectives, such as ecological amelioration and flood risk mitigation. Habitats for fish, benthic invertebrates and riparian vegetation strongly depend on minimally altered bedload (and wood) transport regimes, via the formation of geomorphic units such as bars, riffles, steps, pools, islands and floodplains. On the other hand, the knowledge of the natural suspended transport regime – i.e. peak sediment concentrations, durations, timing – could guide the selection of the most rational thresholds to be pursued during operations that imply the remobilization of fine sediment fractions (e.g., during flushing/sluicing operations at reservoirs). Indeed, the acknowledgment that periodic disturbances such as moderate and large floods – which feature very high sediment concentrations and flow velocities able to ‘reset‘ ecosystems – are indeed natural and fully contribute to the ‘natural river conditions‘ pursued by the WFD is a key step forward for an effective, science based river management.

1.3 Sediment transport in coastal and transitional waters

Longitudinal sediment transport in rivers is unidirectional in downstream direction. In transitional and coastal waters, the respective influence of rivers and of tides and waves can result in sediment transport in opposite directions (Carter, 1988). This may result in bidirectional transport (downstream and upstream in estuaries and other tide-influenced environments) and multidirectional transport (in two longshore directions and two cross-shore directions). Furthermore, transport directions can also vary for sediments with different grain-sizes and can change under different conditions (seasonal, storms, climate oscillations). Therefore, a sound understanding of sediment pathways is required before attempting sediment budgeting, and thus sediment management.

In coastal research and management, the term ‘coastal (sediment) cell’ is used to describe the (largely self-contained) segment of the shore within which the movement and the exchange of sediments occurs (Figure 1.7). Input of sediment into the coastal sediment cell can take place from fluvial sources, the erosion of headland or cliffs and from the sea floor. Output can take place in offshore direction, to the sea floor, or onshore, to tidal basins or estuaries. A coastal cell can be connected to a river basin. The spatial scale of coastal cells can vary from tens of metres for beaches bordered by rocky promontories to tens of kilometres (Cowell et al., 2003). Large coastal cells may exceed the administrative boundaries of the WFD-water bodies.

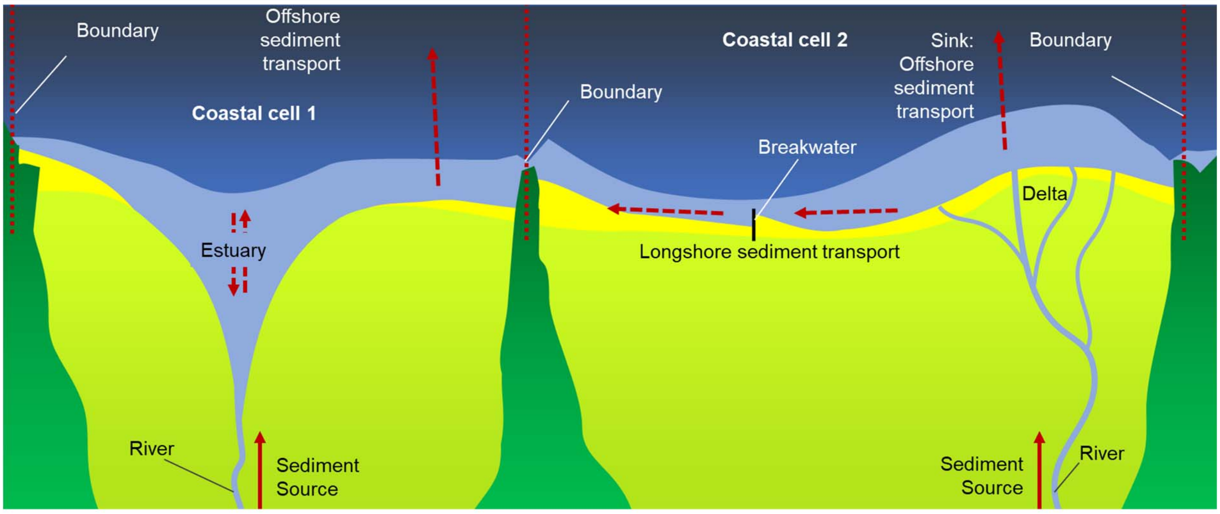

Figure 1.7: Two coastal sediment cells in a schematic map.

1.3.1 Forcing mechanisms for sediment transport in coastal and transitional waters

Waves, tides and currents are the natural ‘forcing mechanisms’ that combine to move sediments to shape and reshape the sea or estuary bed and intertidal areas. The absolute and relative contributions of these forcing mechanisms vary tremendously between the seas and ocean that border the coastlines of the EU member states. And even along the shorelines of one of the seas there are large differences in the waves, tides and currents and their contributions to sediment transport (Woodroffe, 2003).

Different types of waves affect the transport of sediment in the coastal and marine environment (Carter, 1988). Wind waves are generated by local winds. When wind generated waves then travel some distance from their source, at their destination they are known as swell. Long period waves are generated through the grouping of local wind waves and longer-distance swell waves. As waves travel into shallower water they interact with the seabed and the waves can potentially move the seabed sediments. Finally, as waves travels further into shallow water they break. In water depths less than the shoaling depth, waves will determine sediment transport. The direction of the sediment transport depends amongst others on the direction of the incoming waves. The direction wave induced sediment transport has an alongshore component and a cross-shore component. There can be large differences between the wave-induced sediment transport at short timescales and the long-term transport. For sediment budgeting at the scale of the coastal cell, the long-term transport is mostly relevant (Cowell et al., 2003).

When waves meet an obstruction such as a headland, breakwater, reclamation, or island they may get reflected, passing back through the incoming waves, increasing their height where crests become superimposed. Where waves pass around the end of the obstruction, they will spread, or diffract into the area in its lee, losing height in the process. The introduction of such an obstruction, for example the construction of a new breakwater, has the potential to greatly change the waves in its vicinity. Because the direction of the sediment transport is in part determined by the direction of the incoming waves, changes in the refraction and diffraction may have a major impact on the sediment transport.

For sediment transport, the tide-induced currents can be very important. High current velocities can result in significant transport of silt and clay, sand and even gravel. Because tidal currents alternate between flood and ebb direction, the direction of sediment transport also switches. As a result, the net sediment transport direction in transitional waters can be in either the upstream or downstream direction (Swart and Zimmerman, 2009). The net sediment transport direction can even differ for coarse (sand) and fine (silt and clay) sediments. In addition to tides, local currents are influenced by permanent ocean currents, atmospheric forcing and local effects such as run-off or density currents.

In estuaries, freshwater from the river meets the sea saltwater. In some cases, the fresh and saltwater become well mixed. In others the fresh and saltwater do not mix, and freshwater discharge remains at the surface while denser seawater remains underneath, forming what is called a saltwater wedge. The interaction of the freshwater and salt water in estuarine environments results in complex three-dimensional currents which affects the sediment transport. Combined with biological and chemical processes the sediment transport in estuarine environments may result in local enrichment of fine sediments (Dronkers, 2005).

1.3.2 The relationship between sediment dynamics and coastal evolution

Knowledge of the pathways, sources and sinks of sediments as well as their overall budget is key to understanding the evolution of coastal and transitional waters. The overall responses of coastal systems to changes in sea level are largely dictated by the balance between sediment sources and sinks (Nichols, 1989). Coastal systems, including estuaries, tidal basins and deltas in natural conditions adapt to long-term sea level changes by changing aggradation rates. If the result of the change in aggradation rate is an overall surplus of sediment this will result in progradation, while a deficit will result in retreat of the coastal system. Other factors which control the progradation or retreat of coastal systems are the subsurface subsidence and peat formation and decay (Syvitski, 2009). Figure 1.8 illustrates progradational (regressive) coastal environments with a surplus of sediments in the lower half of the diagram in the form of deltas, broad tidal flats and strand plains. The retreating (transgressive) environments with a sediment deficit are illustrated in the top half of the diagram in the form estuaries, narrow tidal flats and barrier lagoons.

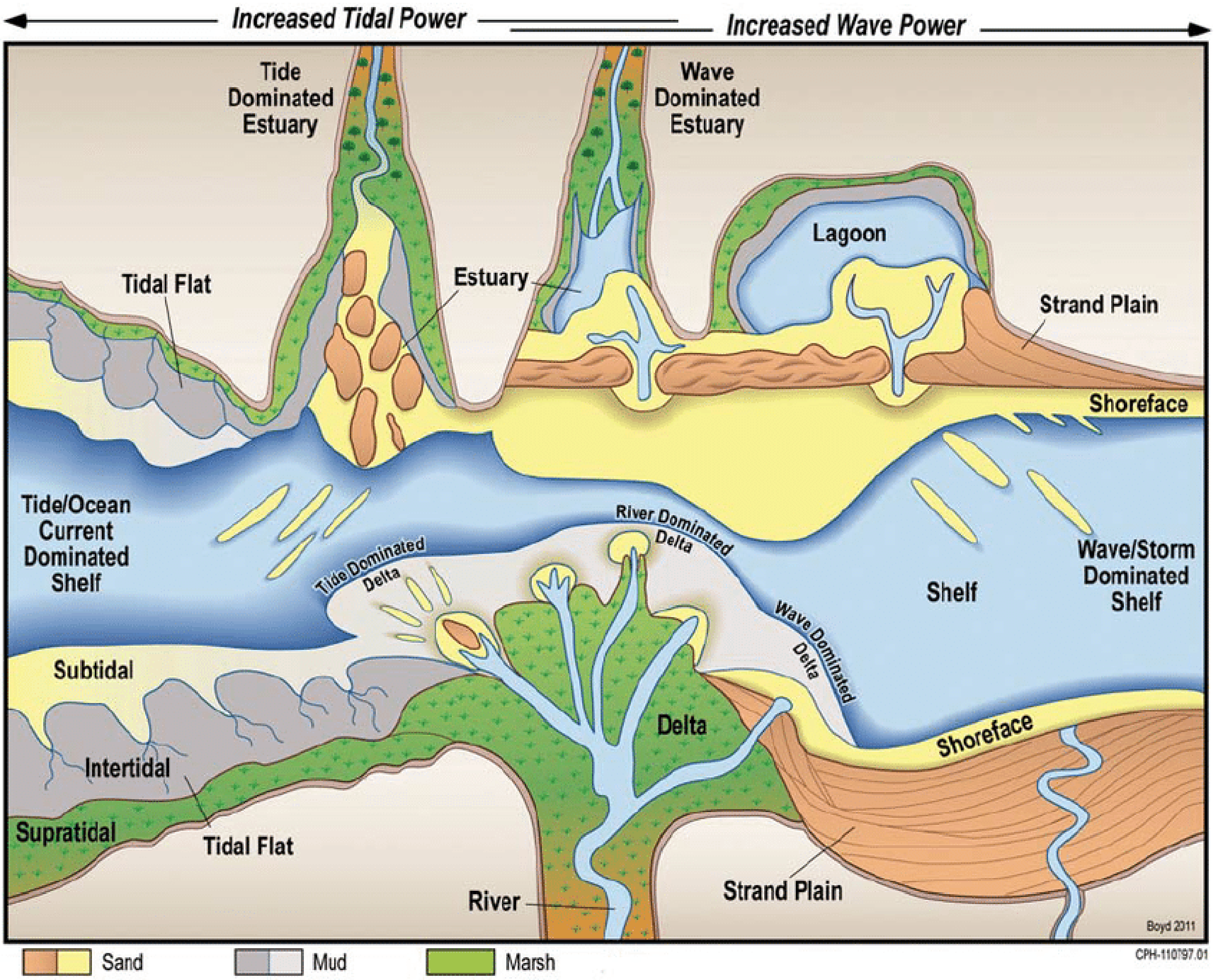

Figure 1.8: Shallow-water coastal depositional systems based on the ration of tidal to wave power (Boyd et al., 1992 updated by James and Dairymple, 2010) Source: Steel and Milliken (2013). Upper half shows retreating (transgressive) environments, while the lower half shows progradational (regressive) coastal environments.

Sediment excess/deficiency conditions in estuaries and deltas can differ for different size fractions, for instance an excess of fine-grained sediments and a lack of coarse grains. Sand is the building material for coastlines and an important part of tidal flats. A deficiency of sand required to maintain/protect coastlines and for sedimentation on aggrading tidal flats may be a consequence of decreased upstream sand supply. Different human activities will result in such a decrease, for instance sand mining, damming of river systems and construction hindering longshore transport. A lack of sand frequently results in increased flooding potential of coastal areas, when limited aggradation rates of estuaries and deltas are outpaced by accelerated sea levels rise, in response to climate changes during the last decades. Enhanced subsurface subsidence due to groundwater or hydrocarbon extraction may have a similar effect as accelerated sea-level rise (Syvitsky et al., 2009). And human activities in peat filled parts of coastal environments (i.e. peat digging, drainage and agricultural use) may also result in an imbalance in the sediment budget and thus in coastal retreat. The persistence of tidal flats and other nearshore environments in the face of rising sea level and subsiding subsurface depends on a sufficient supply of sediments with an adequate grain size and transport processes that disperse sediments from river or marine sources.

1.3.3 Sediment dynamics within coastal systems

The previous paragraph is dedicated to sediment dynamics at the scale of the coastal cell and the overall response of the coastal environment. The sediment dynamics within coastal systems are also of major importance for the various functions and ecosystem services they provide. For instance, an increase in high water levels combined with decreased freshwater inflow may intensify tidal transport in landward direction and thus will lead to higher concentrations of fine-grained sediments in the upper part of estuaries (Winterwerp and Wang, 2013). This process is known as tidal pumping and is the result of fairway deepening and the loss of tidal flats. Tidal pumping may lead to the formation of mud layers showing a thickness of several meters and with suspended sediment concentrations in excess of 100 g l^{-1}. In these hyper-turbid conditions, oxygen consumption prohibits the occurrences of aerobic organisms and high turbidity prevents the growth of photosynthetic plants, resulting in an extreme decline of biomass exchanges and strongly degraded ecology of affected estuaries.

Dredging in many estuaries and other transitional and coastal environments aims to remove the excess of sediment in order to maintain navigable water depths. Depending on the regional and local setting the required depth may vary throughout tidal phases and during seasonal low discharge conditions. The dredges sediment volumes in transitional and coastal water exceeds the dredged volumes in inland waterways by several orders of magnitude, with typical annual dredged volumes in large river estuaries (e.g. Ems, Elbe, Scheldt, Rhine-Meuse, Seine) of several millions cubic meters per year. The large amounts of dredged sediments in coastal and transitional water make this a major management challenge. One of the challenges relates to the contamination of sediments, which limits relocation options of dredged sediments within the system. Contamination is discussed in Section 1.4 and chapter 3. If possible, uncontaminated sediment from dredging activities should be relocated within the same coastal cell, be used for beach nourishment or be placed nearshore of beaches with erosion problems, thus maintaining the cell sediment budget. Suitable relocation sites ideally result in limited sailing times to reduce emissions, hindrance and costs, restricted additional dredging due to circular dredging and ideally the development of sought-after habitats (Baptist et al., 2019) and other benefits, for instance for flood protection. Nature-based solutions should guide dredging and relocation strategies in these environments in compliance with the objectives of EU legislations (Bridges et al., 2021; Manning et al., 2021).

Dredging and relocation may also be required as mitigation measures for constructions which hinder alongshore coastal sand transport. A permanent mitigation system is known as a 'by-pass' and this is considered for the Aveiro inlet in Portugal (Coelho et al., 2021). Sound dredging and relocation concepts should, in addition to the local requisites, also account for the (long-term) impact of accelerated sea level rise and the reduction in sediment supply due to human activities (i.e. sand mining, upstream damming).

1.4 Sediment associated contamination

Contaminants can reach surface waters via point and diffuse sources, via airborne deposition, via ground-water and potentially in the form of inadvertent spills. These contaminants and nutrients can associate to sediments in two ways. Firstly, contaminants directly emitted to surface waters as a result of human activity can become attached to suspended particles. Secondly, contaminants may become associated to particulate matter such as soils and dusts and then enter surface waters through processes such as soil erosion and urban/road runoff (Lerat-Hardy et al., 2021) and via airborne deposition in case of dust. If resistant to degradation or remobilisation, contaminants may remain attached to, and thus be transported with sediment particles for considerable periods of time. In general, the finer the particles, the larger the active surface, and thus the higher the sediment contaminant concentration per unit mass of sediment (Langston et al., 2010).

The fate of persistent, sediment associated contaminants is thus closely linked to the sediment cascade. Over long periods of time at depositional sites, contaminated bed sediments may get covered by lesser or un-contaminated, fresher deposits, reducing the availability of the deeper contaminants to organisms. However, bed sediment associated contaminants can become remobilised into the water column at depositional sites, due to e.g. the impact of physical disturbance such as severe flood and storm events and anchoring of vessels (Rapaglia et al., 2015). Downstream transport of sediments may disperse contamination a considerable distance from its source. This process may repeat itself over hundreds of kilometres (in the largest river basins), leading to an accumulation of contaminants in sediments when further contamination sources are passed. Periodic inundation of floodplains, tidal flats and saltmarshes can result in deposition and resuspension of fine sediments. If the incoming sediments are contaminated, this may result in gradual contamination of floodplain top-soils, with potential risks not only to the soil ecology but also to livestock and (via food consumption) to humans (Rinklebe et al., 2019).

Some sediment processes that are not directly linked to the overall sediment cascade can influence the impact of sediment associated contamination, these are processes that influence the degree to which sediments may release contamination into the water phase. Changes in the chemistry of bed sediments (for example between oxic and anoxic status) influence the solubility and hence the availability to organisms of metals and metalloids such as copper, zinc and arsenic (Tang et al., 2019). Bioturbation, the disturbance of sedimentary deposits by living organisms (plants and animals), can also induce release of contaminants into the water phase (Bosworth and Thibodeaux, 1990).

Owing to the persistence of many contaminants in sediments and Europe’s history of industrialisation and environmental contamination, many European sediments now contain a mix of legacy and present-day contaminants (European Environment Agency, 2011). Despite regular sediment contamination assessment by member states, a reliable estimation of the overall amount of contaminated sediment in Europe is hard to provide. The main reason for this is the absence of uniform sampling methods, analytical techniques and application of sediment Quality Standards or Guideline Values. This causes a lack of inter-comparability. Countries with areas in the same river basin typically use different methods (SedNet 2004).

Some contaminants are of concern because of their potential for bio-magnification, (including their transfer and accumulation in the food chain). Sediments can have a very important role in this context. It is, for example, well known that inorganic (less toxic and bioavailable) mercury is transformed (methylated) into organic mercury by sediment microorganisms, given the right conditions (Compeau & Bartha, 1985), thus becoming highly toxic, bioavailable, and bio-magnifiable. Some benthic organisms, such as shellfish and flatfish, which directly depend on (clean) sediments are consumed directly by humans. Others are consumed by pelagic organisms, of which some (fish) also serve as an important food source for humans. Thus, protecting the benthic community (flora and fauna, including also microorganisms) from sediment associated contamination is of vital importance to the rest of the aquatic ecosystem and to protect our ecosystem services, such as the food source it provides, directly and indirectly.

1.5 Sediment management in the WFD and other EU environmental legislation

Sediments are a fundamental component of rivers, lakes and coastal systems but their natural dynamics are altered because of socio-economic uses. Therefore, specific measures have to be developed to comply with EU legislation. This requires a deep understanding of sediment dynamics, (sources, transport, sinks), quantity and contamination status at various scales. Several EU environmental legislations address the issue of sediment management directly or indirectly: the WFD, the Floods Directive, the Habitats Directive, the Marine Strategy Framework Directive and also the Waste Framework Directive.

1.5.1 Overview of WFD requirements relevant for sediment

The WFD indeed recognizes the role of sediments as basic component of aquatic ecosystems (supporting elements) and as a relevant matrix for assessing water bodies status. Therefore, sediments and their dynamics are central to all stages of the WFD planning cycle (Table 1.1).

Table 1.1: Sediments in the different stages of the WFD planning cycle.

WFD PLANNING STAGE	ACTIONS REQUIRING SEDIMENT CONSIDERATION AND RELATED INFORMATION	ARTICLES	CIS GUIDANCE
Characterization	Definition of water body types (Geology; slope; forms and shape of river bed; substrate composition) Identification of sediment sources, sediment transport paths and sediment sinks Characterization of sediments (physical, chemical)	Art. 5 Annex II	1,2,10,19,25,28
Segmentation in water bodies; Risk analysis	Analysis of pressures and impacts (sediment budget; possible contamination paths; impacts of structures or sediment/water/vegetation management actions on sediment dynamics and consequent impairment of habitat conditions)	Art. 5 Annex II	3,35
Reference Conditions	Unaltered hydromorphology; "functioning processes" (e.g. natural sediment transport regime; channel morphology character and habitat assemblages)	Art. 4 Annex II	10
Monitoring strategies	Programme of monitoring (monitoring sediment contamination and quantity, habitat quality, morphology)	Art. 8; Annex V	7,19,25,35
Status/Potential assessment	Hydromorphological status; ecological status / potential (e.g. absence of significant pressures on sediment transport; consideration of sediment related measures to evaluate MEP); physio-chemical/chemical status (in sediment matrices)	Art. 4 Annex V	4, 13, 19,25,35,37
Design and implementation of measures	Many measures related to sediment management (river restoration; sediment replenishment; restoring sediment connectivity etc)	Art. 11 Annex VI	31,35
Designation of Heavily Modified Water Bodies	Identification, evaluation of environmental better alternatives (modelling effects of different alternatives on sediment dynamics)	Art. 4.3.	4, 35,37
Exemptions	Evaluation of restorability of hydromorphological impacts and/or remediability of contaminated sediments	Art. 4.	19,20,35,36

At the basis of WFD classification lays the identification of water body typologies to allow the comparison of like with like. The rationale behind these typologies, as defined in annex II of the WFD, is to have characterization information on the intrinsic behaviour of aquatic systems (rivers, coasts, etc.). Sediment dynamics are accounted for here, both indirectly (e.g. geology and slope, valley confinement, coastal sediment cell, structure of the intertidal zone, substrate) and directly (e.g. morphology, sediment size and assemblage, sediment transport). This information, together with those on pressures on the aquatic system (e.g. presence of structures disrupting sediment connectivity, mining, dredging, pollution) drives a further segmentation into 'water bodies'.

The water body is by definition a management unit showing a homogeneous response to the pressures it undergoes, with a uniform ecological and chemical conditions. Ecological status and potential need the consideration of supporting elements, which include hydromorphology, and to ensure coherence between their conditions and the biological response (the Biological Quality Elements; Chapter 2 Table 2.2). The WFD provides a definition of hydromorphological quality elements, which requires indeed the consideration of any modifications to flow regime, sediment transport, morphology, and lateral mobility, which depends on sediment regime (WFD All. V; Rinaldi et al. 2013).

The WFD requires identification and assessment of all relevant pressures. This includes hydromorphological pressures (e.g. abstractions, damming) and, through the filter offered by water body type, estimation of their impacts on water bodies (alteration), and in particular the risk of not achieving good status or potential. Such analysis should consider pressures and impacts associated to sediment regime disturbance, or to sediment pollution.

Sediments and their dynamics are crucial components of the hydromorphological quality elements (Table 1.2), which range from sediments to their assemblages in the form of structure and substrate of water bodies bottom, to the geometry of water body sections (Table 1.2). According to the type of monitoring the elements to be monitored and the frequency of monitoring will vary, with the requirement to apply at least the minimum frequencies specified in annex V of the WFD, and an obligation to report to the Commission data on the status of water bodies every six years.

Table 1.2: WFD sediment-related supporting quality elements[15]

WATER CATEGORY	SUPPORTING ELEMENTS (HYDROMORPHOLOGICAL AND PHYSICO-CHEMICAL)	SUB-ELEMENT
RIVERS	River continuity	Sediment transport
	Morphological conditions	River depth and width variation Structure and substrate of the river bed Structure of the riparian zone
LAKES	Morphological conditions	Lake depth variation Quantity, structure and substrate of the lake bed Structure of the lake shore
	General physicochemical elements	Transparency
TRANSITIONAL WATERS	Morphological conditions	Depth variation Quantity, structure and substrate of the bed Structure of the intertidal zone
	General physicochemical elements	Transparency

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[15] The table describes the quality elements explicitly containing or being formed by sediment. As explained in this document, other supporting elements can influence sediment transport such as tidal regime, hydrology, etc.

COASTAL WATERS	Morphological conditions	Depth variation Structure and substrate of the coastal bed Structure of the intertidal zone
	General physicochemical elements	Transparency

Sediment contamination may adversely impact the attainment of the environmental objectives of the WFD, although the relationship between water body status/potential and sediment contamination is complex. There are factors that may limit the impact of sediment contamination on water quality, such as burial of contaminated sediment by clean material, low bioavailability of the contaminants to benthic organisms, or the lack of an exposure pathway to pelagic organisms. It is however important to note that such limiting factors may be only temporary as sediment contaminants may be remobilised and released into the environment due to different processes or events.

Sediment contamination may impact either chemical or ecological status/potential, or both, of a water body, and the resultant status is considered in either chemical or ecological condition:

1. Chemical status is considered impaired (not good) if measured concentrations of one or more contaminants exceed the Environmental Quality Standards (EQSs). EQS is defined as the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment. There is no absolute requirement for EQSs for the sediment compartment to be set, although Directive 2008/105/EC does provide Member States with the option to apply sediment EQSs for priority and other substances (Annex 1 of Directive 2008/105/EC, as amended by Directive 2013/39/EU). In this case, Member States should derive EQSs for sediment according to the methodology described in CIS 27. In addition, according to the EQS Directive Article 3(6), Member States shall also analyse the long-term trend of concentrations of priority substances listed in Part A of Annex I that tend to accumulate in sediment and/or biota.

2. Ecological status can be considered impaired (moderate status or below) due to the presence of sediment contamination in different ways. The Biological Quality Elements may be affected, in particular the benthic invertebrate fauna by excess of nutrients/lack of oxygen in sediment (which can be detected in by the supporting physico-chemical quality element “nutrient concentration”). One or more of the River Basin Specific Pollutants accumulated in sediments may be present at concentrations above their EQS. River Basin Specific Pollutants are part of the physicochemical quality elements and the member states may develop EQSs for substances of relevance according to WFD Annex V and CIS 27.

In cases where sediment contamination is suspected to be adversely affecting water body status, Chapter 3 provides guidance on understanding and confirming the nature of the problem, and selecting appropriate mitigation measures.

Many restoration/mitigation measures are aimed at enhancing connectivity and habitat conditions or to mitigate the effects of contamination, thus they necessarily address sediment conditions and transport. This means that information and appropriate tools to evaluate sediment quantity and contamination are needed, to design and select measures, and are required for the designation of Heavily Modified Water Body (HMWB) and the definition of their ecological potential, or where relevant to confirm the possibility of using exemptions.

1.5.2 Other EU environmental policies relevant for sediment management

Sediment management has an inter-sectorial character and needs to be harmonized across policies, through an "integrated sediment management" strategy (see chapter 4). This section aims at describing, without being exhaustive, the main environmental policies which are relevant for sediment management.

The Floods Directive (Dir. 2007/60/CE – FD) aims to reduce and manage the risk of flooding on human health, the environment, cultural heritage and economic activity, through the implementation of combinations of different measures envisaged by Flood Risk Management Plans (FRMP). According to art.9 FD, priority should be given to the identification and implementation of those measures that can deliver on the objectives of both WFD and FD. This is only possible where room for natural expansion of floods is made available, otherwise, structures aimed at preventing or reducing the detrimental effects of floods (flood defences), including actions on vegetation and sediments, need to be implemented. Such measures deliberately modify sediment transport and thus impair ecosystems with an extent and severity that can only be evaluated if appropriate data and models are available. Such measures can also be linked to sediment contamination. In particular, when making available room for flooding to occur naturally, consideration needs to be given to the likelihood and risks of (i) floodplain soil contamination via the deposition of contaminated sediment during flooding events, and (ii) erosion of historically contaminated flood plain soils and return of floodplain sediments to the main river channel for downstream transport (cf chapter 3).

The Habitat and Birds Directives (Dir. 92/43/EEC and Dir. 2009/147/EC) aims to promote the maintenance of biodiversity by the conservation of natural habitat, and of fauna and flora, at a "favourable" conservation status. Annex I of the Habitats Directive[16] explicitly protects a number of habitats, notably estuarine and coastal habitats, that depend for their quality and integrity on an adequate supply of the right type of sediments (e.g. sandbanks, mudflats, sand dunes, shingle or stony beaches). Sediment-dependent vegetation types are also mentioned in the Directive (e.g. *Salicornia* and other annuals colonizing mud and sand; shifting dunes along the shoreline with *Ammophila arenaria*). Measures to restore or maintain such status involve sediment management, as basic component of habitats, and have to be contextualized at the relevant sub-catchment scale in order to select the most efficient and also beneficial ones, across policies. In addition, sediment provides habitat as well as food for invertebrates and thus sediment associated contamination may impact these species. Hence, in accordance with the overall aims of the Directive and the role of sediment management in achieving these aims, the role of sediment associated contamination and its management must be considered, and be contextualized.

The Marine Strategy Framework Directive (Dir. 2008/56/EC MSFD) aims to achieve "Good Environmental Status" in the marine environment by applying an ecosystem-based approach. The spatial extent of the MSFD is broader than the WFD, as it encompasses the coastal zones and the Exclusive Economic Zone (EEZ) of the EU marine waters. There is generally an overlap in coastal areas between the areas covered by the WFD water bodies and by the MSFD. The Marine Strategy Framework Directive[17] (MSFD) similarly recognises the critically important role of sediments through multiple references to seabed structure and substrata, subsoil, seabed habitats and seafloor integrity (Preamble 12, in the Annex I Descriptors and in Annex III, Table 1). In the light of sediment management the

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[16] See consolidated version, Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora

[17] See consolidated text, Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy

objective of sea-floor integrity in the MSFD is of specific importance as this relates to the extraction of sand and gravel from the sea floor. In addition, the general need to ensure that sediment management measures do not adversely impact the attainment and/or maintenance of Good Environmental Status (GES) in marine waters includes those GES descriptors (Annex 1 of the MSFD) which may be adversely impacted as a result of transport of contaminated sediment from inland, transitional and/or coastal waters into marine waters. The most clearly pertinent descriptors are: descriptor 8 “Concentrations of contaminants are at levels not giving rise to pollution effects” and descriptor 9 “Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards”.

The Waste Framework Directive (Dir. 2008/98/EC WD) lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste. Article 2.3 of the WD excludes sediments from WD scope if they are “relocated inside surface waters for the purpose of managing waters and waterways or of preventing floods or mitigating the effects of floods and droughts or land reclamation […], if it is proved that the sediments are non-hazardous”. Otherwise, sediments are considered as waste or hazardous waste and as such have to comply with all the requirements of WD. This can have serious repercussions when selecting different management options and needs to be accounted for in decision-making.

The restoration of degraded habitats is a key objective of the EU Biodiversity Strategy for 2030[18]. The target to restore river continuity and to restore at least 25,000 km of EU rivers to a free-flowing state, for example, relates not only to facilitating fish passage but also to restoring sediment transport, in turn enabling and supporting the reinstatement of natural habitat functions.

In addition to these, the sustainable management of sediment is also of particular relevance for meeting the objectives of the EU Strategy on Adaptation to Climate Change[19], as sediment related problems can reduce the resilience of ecosystem to such changes as well as the ecosystem services they provide (see chapter 2 section 2.2.2).

Finally, the EU soil strategy for 2030[20] also recognises the key interactions between soils, sediments and water and call Member States to better integrate soil and land use management in their river basin and flood risk management plans where possible by deploying nature-based solutions such as protective natural features, landscape features, river restoration, floodplains restoration, etc.

All these different policy objectives need to be considered in the framework of River Basin Management Planning. The WFD provides the legal framework to integrate multiple objectives through the application of the DPSIR approach (Driver-Pressure-State-Impact-Response). The WFD requires a profound knowledge of catchment processes, seen as interactions between ecosystems and human pressures at the different scales, and the status of water bodies results from such interrelations, in a systemic view of causes and effects.

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[18] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380

[19] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

[20] EUR-Lex - 52021DC0699 - EN - EUR-Lex (europa.eu)

Chapter 2 – Sediment quantity

Key messages

- Achieving good ecological status/potential can depend on having the right amount of sediment of the right type (size, shape), in the right place at the right time
- Indicators suggesting a possible human-induced sediment quantity problem may include biological quality element (BQE) failures; evidence from the hydromorphological assessment; and/or the outcomes of the catchment pressures assessment (potentially useful when the BQE or hydromorphological data are not available)

2.1 Introduction

2.1.1 Aim and focus of this chapter

This chapter addresses the relevance of sediment quantity (supply, transport, delivery, deficit or surplus, at reach, catchment or coastal cell scales) and sediment type (size distribution of particles) to WFD ecological status/potential objectives. It highlights how achieving good ecological status/potential can depend on having the right amount of sediment of the right type (size, shape), in the right place at the right time, and some of the typical problems that can compromise such achievement (Sections 2.2 and 2.3). It goes on to introduce methods to assemble and assess sediment budgets (Sections 2.4 and 2.5) before concluding by considering measures to address pressures at different scales and the value of following the mitigation hierarchy during their selection (Section 2.6).

This Chapter will help the reader answer the following questions:

1. Does the water body of interest have a sediment quantity problem that may be impacting its ecological status? (Section 2.1.2)
2. What are the important pressures on sediment quantity in the water body of interest, and what are the consequences? (Section 2.1.2)
3. How is sediment quantity relevant to the WFD ? (Section 2.2)
4. What is the nature of the sediment problem in the water body of interest? (Section 2.3.1)
5. How can a sediment budget help understand sediment dynamics in a catchment? (Section 2.4)
6. What are the WFD requirements for monitoring sediment quantity? (Section 2.5.1)
7. When and where is it relevant to monitor sediment quantity? What should be measured and how? (Section 2.5)
8. What measures are available to facilitate effective management of sediment quantities given the identification of certain issues? (Section 2.6.1 and 2.6.2)

   What guiding principles may be followed in the selection of measures? (Section 2.6.3)

In addition, if there is a sediment quantity problem accounting for coastal erosion issues, the above questions should, according to the strategic guidance provided by the WFD and the Floods Directive, be incorporated to the integrated management and planning of sediments (cf chapter 4), for which the potential of catchment areas in supplying sediment to the coast should be calculated and compared with the costs and benefits inherent to the use of sediment from other sources, namely from the adjacent continental shelf.

2.1.2 Does the water body of interest have a sediment quantity problem?

The ecological status of water bodies may be impacted by a system-level, human-induced imbalance in sediment quantity or by hydromorphological modifications that interrupt or modify natural sediment continuity and transport processes which themselves are characterised imbalances. Present or past sediment extraction activities may also determine local/reach/catchment sediment deficit. In cases where a sediment quantity problem is suspected, this chapter will provide guidance on understanding and confirming the nature of the problem and selecting appropriate mitigation measures.

Depending on the type of data available, a sediment quantity problem might be identified via one or more of the following indicators. It should be noted that the focus here is on information that should be available through WFD data collection or monitoring, but data from other sources can also be very useful.

- Biological quality elements
- Hydromorphological quality elements
- Evidence of certain pressures within the catchment

Biological quality elements

Chapter 1.1.1 introduces how sediments play a critical role in supporting many of the biological quality elements used in the assessment of ecological status. Examples of the mechanisms of impacts are given in Section 2.2.1. Failure to achieve good status for fish, invertebrates, macrophytes and/or phytoplankton can be indicative of too much or too little sediment, of a suitable size to sustain ecology, at system level or locally within a water body. Some member states have ecological indices that are sensitive and specific to sediment pressures. However, given that the interrelationships between hydromorphological pressures and biota are often uncertain, consideration of hydromorphological indicators is strongly encouraged to properly assess physical anthropic pressures (see next section). This was proposed, among other sources, in the deliverables of the FP7 project REFORM (REstoring rivers FOR effective catchment Management), which underlined the need to develop new biota sampling methods which could be more sensitive to hydromorphological impacts, including sampling of habitats (e.g. the riparian) particularly impacted by hydromorphological degradation. The application of hydromorphological indicators could be thus oriented as supporting elements to BQEs, or as tools to better understand the effect of human activities on river biology in a wider sense (e.g., including complementary biological groups, or particular ecological fluxes or processes).

Hydromorphological quality elements

Hydromorphological quality elements can take several forms (see Section 1.5 – Table 1.2); mechanisms of impact are given in Section 2.2.1. If a process-based hydromorphological assessment has been undertaken and the hydromorphological supporting elements including river continuity, morphological status and flow characteristics have been considered (Kampa and Bussettini, 2018), this may confirm the presence of a sediment quantity problem. Also the analysis of the trajectories of geomorphological changes of the river (e.g. diachronic analysis of aerial photographs, maps, sediment records, riverbed elevation change, etc.) could also support the identification of sediment quantity-related problems. However, even in the absence of such an assessment, in some cases visual evidence might give a first initial indication of such problems, which should be later confirmed by experts. An inspection or walkover survey may identify atypical scour or erosion; areas of accumulated sediment/smothered habitats or instances of a recent change in sediment type; or an absence of characteristic habitat types. As such observations may indicate a sediment imbalance, either locally or at catchment scale, it is advised to undertake an expert assessment.

Catchment pressure assessment

A proxy for sediment imbalance is the presence within the catchment of certain types of pressure(s) associated with changed sediment contributions (or extraction), disruptions in the continuity of the sediment system, or changed transport capacity as a result of modified channel morphology and/or flow characteristics (volume, velocity). Examples of catchment pressures and their potential consequences are included in Table 2.1.

Table 2.1: Sediment related pressures and consequences (examples, list not exhaustive)

Sediment related pressure	Consequences for sediment quantity
Land management (agricultural intensification):	Increased sediment supply; increased suspended sediment load in river, coastal and transitional water bodies
Land use change (construction, deforestation):	Increased sediment supply; increased debris flows, landslides, bedload and suspended sediment load in river, coastal and transitional water bodies
Land use change (afforestation)	Decreased sediment supply; reduced suspended sediment load in river, coastal and transitional water bodies
River or coastal engineering (dams; weirs; torrent control structures, impounded waterways; reservoir construction; breakwaters; groynes; or other shore parallel structures) and port infrastructures	Disrupt sediment continuum and reduce sediment supply downstream or down drift
Sediment mining (or dredging for other purposes where sediments are removed from the aquatic system for disposal)	Decrease in available sediment; loss of balance between particle sizes; bed incision, alteration of the geometry of sections, longitudinal profile and local slopes
Dredging & disposal	Change in sediment composition at dredging and disposal sites (depends on current velocities and source material); change in physico-chemical features at both sites
Increased transport capacity (reduced river bed width, increased bed slope, river bank protection)	River bed erosion in affected reach
Deepening, widening, or other modifications of water body morphology (increased river bed width, decreased bed slope, decreased river flow)	Decreased transport capacity leading to river bed aggradation
Deepening, widening, or other modifications of tidal channel morphology	Increase in tidal incursion and increased transport capacity, potentially leading to increased turbidity
Engineering works to prevent or control erosion and morphodynamics	Decrease available sediment and increase in channel or down drift erosion
Water body straightening or physical modification of their margins	Increased velocity, reduced sheltered or low flow areas where sediment may be deposited; reduced habitat diversity
River channelization	Loss of lateral erosion, floodplain morphodynamics, increasing of sedimentation of fine material, prohibition of erosion
Construction of flood embankments/roads leading to disconnection of floodplains/hillslopes, salt marshes and tidal flats	Increased in-channel erosion, loss of flood retention and associated sediment deposition on floodplains, salt marshes and tidal flats
Accelerated climate change (permafrost degradation)	Increased sediment supply

Accelerated climate change (increased or modified vegetation cover)	Modified sediment supply

2.2 Sediment quantity in a policy context

Key messages

- Many aquatic habitats are sediment-dependent. Surplus or deficit of sediment due to human activities can compromise or prevent effective ecological functioning, and as a consequence, hinder the achievement of Good Ecological Status or Potential or other environmental objectives.
- Likewise, important dependencies between hydromorphological conditions and biological quality elements can be compromised if sediment supply is interrupted

2.2.1 Sediment quantity in the context of the WFD

As described in chapter 1, sediment is an integral component of aquatic ecosystems. Whereas the WFD recognizes the role of sediments as basic component of aquatic ecosystems, there is relatively little direct legal reference to sediment quantity in the WFD and other relevant policy instruments. Rather, it is included indirectly through several requirements and quality elements. Effective management of sediment quantity and dynamics is critical to meeting the objectives of the WFD, and several other EU environmental Directives and Strategies in both the freshwater and marine environments (see chapter 1 Section 1.5.2). Chapter 1 lists the WFD requirements which are relevant for sediment generally (see chapter 1 Section 1.5.1); the following points highlight in more detail how sediment quantity in particular is relevant to these instruments.

Many aquatic habitats are sediment-dependent. A surplus or deficit of the right type (size(s)) of sediment can compromise or prevent effective ecological functioning, and as a consequence, the achievement of Good Ecological Status or Potential. The WFD recognises this, both directly and indirectly through the supporting hydromorphological quality elements (see chapter 1 Table 1.2).

For rivers, the Annex V definition (1.2.1) states that river continuity at high status (from which good status is derived) must allow undisturbed migration of aquatic organisms and sediment transport.

- For all water body types (rivers, lakes, coastal and transitional (estuaries)), the morphological conditions contain an implied reference to sediments, in the requirements for substrate condition (including bed quantity, structure and substrate) and the structure of the riparian zone, shore or intertidal areas to ‘correspond totally or nearly totally to undisturbed conditions’ at high status. For reaching good status, according to annex V it is necessary that the hydromorphological conditions are consistent with the achievement of good status for the biological quality elements sensitive to hydromorphology.
- For lakes and TraC water bodies, the importance of sediments is further referenced via the requirements of the physicochemical supporting elements. Specifically, for these water body types, there is a requirement that transparency should “not reach levels outside the ranges established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements” for good status. Since water column transparency is reduced by suspended sediment, this requirement clearly is for

suspended sediment concentrations to be sufficiently low so as not to adversely impact transparency.

Important dependencies between hydromorphological conditions and biological quality elements can be compromised if sediment supply is interrupted (e.g. riparian/shore/intertidal zones or rivers beds suffer net erosion because of an insufficient 're-nourishing' sediment supply) or if areas are smothered because of an excess of (particularly fine) sediments. For more details and examples on specific links between hydromorphological conditions and species refer to chapter 1.1.1.

Further consideration of the effects of sediment on each of the quality elements of the WFD is included in Table 2.2. This provides an appreciation of how sediments may impact on biological and hydromorphological quality elements and thus affect the ecological status of water bodies.

Table 2.2: Examples of the impact of a sediment imbalance on biological and hydromorphological quality elements used in the assessment of ecological status

Quality Element	Quality Indicators	Classification of ecological status	Mechanism of impact (Example 1: Excess sediment)	Mechanism of impact (Example 2: Deficit in sediment)
Biological	Fish fauna	Assess composition, abundance and age structure	-Smother eggs -Fill interstitial spaces used by emergent fry -Reduced feeding success -Damage to gills -lack of oxygen	-Loss of spawning substrate -Incised river with lower river-floodplain connectivity
	Benthic invertebrate fauna	Assess composition and abundance Use scoring methodologies (e.g. PSI)	-Loss of suitable habitat -Increased drift -Reduced food quality – limited photosynthesis	-Loss of gravel substrate for refuge -Reduction in intertidal area used for feeding
	Macrophytes and phytobenthos	Assess composition and abundance	-Abrasion of leaves -Erosion from substrate -Burial -Reduced photosynthesis	-Loss of rooting substrate -Loss of nutrients
	Phytoplankton	Assess composition and abundance Use scoring methodologies (e.g. diatom indices; see Bahls (1993) and Jones et al. (2017)).	-Burial -Erosion -Shading	-Habitat alteration

Hydromorphological	River Continuity	Free downstream movement of sediment		Barrier to sediment continuity can lead to downstream deficits
	Morphological conditions	Consideration of the physical characteristics of the river (e.g. channel shape/width/depth, and the structure of the bed/banks/riparian zone)	Rapidly aggrading rivers may result from an excess sediment. River bed substrate may be affected by excess fine sediment.	Rapidly incising rivers are a consequence of a sediment deficit
	Hydrological regime	Consideration of river flow	Increased inundation frequency of floodplains Alteration of flow paths Modification of spatio-temporal patterns of hydraulic variables (flow depth, flow velocity) affecting meso and micro habitats	Decreased inundation frequency of floodplains Alteration of flow paths Modification of spatio-temporal pattern of hydraulic variables (flow depth, flow velocity) affecting meso and micro habitats

2.2.2 Key role of sediment for ecosystem resilience and climate change adaptation

Having the right amount of sediment of the right type (size distribution), in the right place at the right time to support the natural functioning of habitats is not only important to the WFD. Many other EU policy instruments strive to protect natural habitats, species and ecosystems that depend, directly or indirectly, on sediment quantity and its dynamics (see in chapter 1.5 a list of relevant environmental policies).

Even in the absence of the changes in seasonal precipitation, sea level, periods of heat or drought, and other parameters induced by the warming climate, natural habitats have been under pressure as a result of a deficit or surplus of sediments, for example:

- Sediment discontinuity causes river bed erosion in many rivers in Europe. As a consequence the river morphology is transformed from a dynamic system into an eroding, degrading, single thread channel. This leads to a loss of gravel and sand bars, reduced width, depth and flow velocity distribution as well as an increase in river bedgrain size. There is a deterioration or loss of habitats (e.g. spawning places for fish and invertebrate habitats). Groundwater levels adjacent to the river may be lowered, leading to a "drying up" of floodplains and related wetlands.

- River channelization for flood protection and gaining land for agriculture lead to a reduction of channel length combined with an increase of slope, a loss of sinuosity and bank erosion and other channel forming processes. Thereby, instream morphological features, bars and meso- and micro-habitats decline or disappear. Thus, habitats for spawning, refuge, juvenile but also adult species will not be available, especially when river bed erosion is caused by river regulation with sediment discontinuity (see above).
- Dredging leading to a lack of sediments in the river can negatively impact sediment balance, intensifying habitat loss or degradation, even more if sediment input is reduced from upstream and the river is regulated. At dredging locations habitats are locally impacted.
- Sea walls and embankments, built to protect land from tidal flooding, prevent the natural landward-migration of saltmarshes, mudflats and other coastal habitats. These sediment-dependent habitats are often protected under the Birds and/or Habitats Directives. The effects of sea walls can be compounded by the construction of up drift breakwaters, groynes or similar structures that interrupt longshore sediment transport processes, reducing the natural supply of sediment to coastal and estuarine habitats.
- Levees and other artificial river defences reduce lateral connectivity of rivers (and their sediments) with their floodplains, particularly in medium- and low-gradient reaches. Reduced lateral connectivity of sediments hampers the dynamics and regeneration of aquatic and riparian habitats, and progressively contributes to their homogenization and decay. In parallel, flow acceleration through laterally constrained river reaches (e.g. due to river defences) typically induces channel incision, riverbed narrowing and further disconnection with river margins and floodplain. Sediment deficits in incised river channels degrades aquatic habitats.
- Changes in the amount of sediment reaching the coast from rivers can affect estuarine and coastal seabed habitats. For example, sediments that historically supplied estuaries or deltas may be trapped behind impounding structures upstream, or agricultural land-uses may be associated with an excess of fine sediments in run-off waters, in both cases potentially impacting on local sea floor integrity and hence Descriptor 6 of the MSFD.

All these changes do not only negatively impacts habitats and species, but can also reduce their resilience and the ecosystem services that they would naturally provide, which can be detrimental in light of climate change impacts.

There is increasing acknowledgement, internationally, of the important role of nature-based solutions in both mitigating carbon emissions[21,22] and adapting to the changing climate, both in the context of the forthcoming EU Adaptation Strategy. Nature-based solutions, whether they are intended to contribute to or capitalise on nature's resilience (i.e. with regard to ecosystem services such as flood protection and natural water quality improvements) sometimes depend on a sufficient supply of the right type of sediment. For example, choosing to enhance a degraded intertidal area to provide a natural buffer against storms and wave action rather than construct a concrete sea wall may rely on

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[21] Ocean-based mitigation options could reduce the "emissions gap" by up to 21 percent on a 1.5°C pathway, and by about 25 percent on a 2.0°C pathway, by 2050. See https://www.wri.org/blog/2019/09/turning-tide-ocean-based-solutions-could-close-emission-gap-21-percent

[22] Turrell, W.R (2020). A Compendium of Marine Related Carbon Stores, Sequestrations and Emissions. Scottish Marine and Freshwater Science Vol 11 No 1, 70pp. DOI: 10.7489/12261-1

the reinstatement of longshore sediment transport processes to ensure the sustainability of the solution. In other cases, the sustainability and maintenance requirements of natural flood mitigation and water quality improvement features (such as ponds) will be determined by the magnitude of incoming sediment fluxes and their trapping efficiencies.

The following case studies provide examples of how sediment quantity management measures can contribute to a multiple environmental objectives, and uses, and can thus help better integrate different EU policies. It is important to emphasise that when adopting such sediment quantity management measures, even if local measures will result as the most appropriate the problem should first be studied at the system level to identify the cause and most appropriate solution (see Mitigation Hierarchy in section 2.6). Preferred measures target the cause of an issue at the catchment scale as opposed to targeting the consequence of an issue at the local scale.

Case study 2.1: Beneficial relocation of dredged sediment in the Mersey Estuary (UK) - Working with Nature

Suspended fine sediment from the Mersey Estuary enters the Liverpool and Birkenhead Dock system via the pumps and lock entrances. This requires regular dredging to maintain safe depths for navigation. Until recently, Peel Ports, operator of the Port of Liverpool, disposed of this dredged sediment 20km offshore in Liverpool Bay. Investigations were conducted by the port involving stakeholders, and tracer studies/hydrodynamic modelling, to develop more sustainable alternatives. As a result, a new disposal site, only 1km from the Docks, was found as a better alternative as it would benefit the natural up-estuary transport of fine sediments, while reducing costs for the port. More specifically this supported improvements in the WFD benthic invertebrate BQE and enabled protected saltmarshes (under the EU Nature Directives) to accrete to accommodate sea level rise. In 2018, the 'Beneficial Placement of Dredged Sediment – Mersey Estuary' project received PIANC's Working with Nature Certificate of Recognition, confirming the success of this Peel Ports' initiative. 'Working with Nature' is aimed at changing the way port and waterway operators think about construction and maintenance activities by working in a more integrated way.

For more detail, the detailed case study is presented in annex A.

Case study 2.2: Restoration of the Aragon River (Ebro basin, Spain) harmonises several policy objectives.

The Aragon river has been degraded through incision in response to past dredging and regulation. Sediment augmentation along with floodplain reconnection and habitat restoration for vulnerable or endangered communities and species was conducted in an attempt to harmonize WFD, FD and BHD objectives.

For more detail, the detailed case study is presented in annex A.

For recommendations on integrating policy objectives see Chapter 4 (section 4.4).

2.3 Sediment quantity imbalance

This section will help water managers and river basin authorities developing RBMPs gain a fuller understanding of the nature of their problem. Examples are given to illustrate problem types.

All processes identified in sediment cascades and the fluxes accounted for in sediment budgets may be impacted by natural and anthropogenic drivers. Rivers, coasts and their ecosystems adjust to natural changes over long timescales but anthropogenic changes typically occur over shorter timescales and affect processes such that sediment deficits and surpluses occur, with implications for hydromorphology and ecology.

Key messages

- Sediment quantity problems may be manifested at different scales, and are often inter-related
- Seven categories of sediment quantity-related problems are distinguished, covering the overarching pressures of sediment supply into, and continuity through, the system; widespread deficit or surplus; local deficit or surplus linked to transport capacity; and sediment discontinuity.
- Pressures and consequences are both included within these categories because both of these are important in selecting the most appropriate sediment management measures

2.3.1 Types of sediment quantity-related problems

There are a number of types of sediment quantity-related problems. In Chapter 1, the principles of catchment-scale sediment dynamics were introduced to illustrate how the achievement of good ecological status or potential may be compromised by problems related to sediment supply and/or by sediment transport, not only downstream mountain-to-sea continuity but also locally where transport capacity is compromised by morphological alterations. Sediment quantity problems may be manifested at different scales, and are often inter-related.

This section helps water managers and river basin authorities developing RBMPs, supported by experts where relevant, understand the nature of these problems. Seven categories of sediment quantity-related problems are identified and briefly described. Pressures and consequences are both included, but they are distinguished from the outset to facilitate the eventual identification of appropriate mitigation measures (see Section 2.6).

Problems 1 and 2 represent the main overarching pressures of sediment supply into, and continuity through, the system. Problems 3 and 4 illustrate two of the main widespread consequences of interrupted continuity or imbalanced supply. Problems 5 and 6 are more local consequences associated with morphological constraints affecting the local sediment transport capacity, while Problem 7 is a consequence of sediment discontinuity. These distinctions are elaborated in Figure 2.4, later in the document, which relates to the process of identifying problem-specific mitigation measures.

Furthermore, it is important to be aware of the possibility of multiple stressors leading to combinations of these problems. These can result in complex, sometimes contradictory, indicators that present challenges to the water/sediment manager or river basin authority developing the RBMP (see, for example, Dépret et al. (2017) or Vázquez-Tarrío et al. (2019)). Nonetheless, it is worth putting effort into untangling the issue to ensure that – wherever practicable – mitigation measures tackle the underlying problem cause(s) rather than only the symptoms.

Problem 1: Unbalanced sediment input into system

(Examples: Land-use change & erosion-management infrastructure)

This problem arises when there is an imbalance in the sediment supply to the system from within the basin or from coastal/marine sources. Problem 1 occurs when there is a catchment based surplus or deficit; when there is too much or not enough sediment entering the system (catchment, coastal sediment cell - see Figure 1.7) to support the characteristic morphology and ecology. This is different from local issues that may occur due to interruptions to sediment conveyance through the system.

Increased inputs of fine sediment occur in river basins across Europe where natural landscapes are modified by human activities such as agriculture (notably from arable land, but also from forestry operations (including deforestation) or overgrazed landscapes) or from urbanisation (notably from construction activities, but also from surface water or sewer discharges). In some cases, excess sediment may originate from upstream eroding channel banks or river bed stores (e.g. Walling and Collins, 2005, Collins and Walling, 2006). The growing of crops such as winter cereals leaves arable fields effectively bare in winter and as a result excessive fine sediment inputs to river systems can occur. This problem is often exacerbated where sediment delivery ratios are enhanced by increased connectivity caused by land drainage systems, removal of hedgerows or the presence of farm tracks. Extensive areas cleared for other reasons, such as construction, can have similar effects, but this tends to be a local rather than system level issue.

Decreased sediment inputs often occur due to catchment erosion control measures or modifications such as channel bank protection works. In Alpine and Pyrenean regions protection measures such as torrent control works have been implemented above settlements and commercial/industrial areas to reduce the effects of debris flows and flash floods. In many regions of Europe, modification of grazing pressure due to rural abandonment is having significant effects on sediment supply (e.g. the upper Drôme, France; Lallia-Tacon et al., 2017). In the Pyrenees, (e.g., Llena *et al.*, 2019) land use changes and associated transformations of land topography have shown to have an important role on the alteration of sediment yields. Reductions in sediment inputs in coastal systems may similarly occur where erosion control measures are put in place or where sediments are removed from the system, for example by aggregate extraction.

Problem 2: Interrupted continuity of sediment transport

(Examples: Dam or another type of barrier)

This problem occurs when structures such as dams, check-dams and other erosion control works, breakwaters, groynes or similar structures trap sediment, limiting or preventing its downstream or 'downdrift' transport[23]. Changes in river, estuary or coastal form or connectivity may similarly hamper sediment transport. In both cases, the discontinuity and the associated lack of sediment in the system can have adverse consequences downstream or downdrift. Sediment-dependent habitats and species, not only in rivers and lakes but also mudflats, saltmarshes and sand dunes on the coast, may be starved of their sediment supply, causing deterioration and, in some cases, preventing the achievement of good ecological status or potential. Discontinuity in sediment transport can also have implications for morphological processes such as erosion (see Problem 3 below).

In addition to the lack of sediment downstream or downdrift, the sediment retained behind structures such as dams can reduce reservoir capacity or compromise the use of structures (e.g. weirs and flumes for flow gauging). Sedimentation of reservoirs is one of the key future issues for sustainable hydropower and dam development and management. According to Basson (2009), an estimated 0.8% of the worldwide storage capacity will be lost annually by sedimentation, with the highest average sedimentation rates to be found in arid regions as in the Middle East, Australia, and Oceania as well as

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[23] 'Downdrift' refers to the direction of net longshore transport in coastal locations

Africa. In Europe and Russia, 80% of the useful reservoir volumes for hydropower production could be lost due to sedimentation by 2080, and 70% of the reservoirs' volumes for other uses by 2060. Reservoir sedimentation not only affects the reservoirs themselves and their suitability for producing electrical energy, but also gives rise to issues of dam safety and downstream sediment deficits and river bed erosion (Habersack et al., 2016).

Problem 3: Widespread deficit of sediment

(Examples: Bed incision; large scale erosion; beach lowering)

This problem relates mainly to bed lowering and its many possible projections, such as bed incision or erosion pits. It is typically caused by a reduced sediment input (particularly coarse material), either at catchment level (Problem 1) or downstream of an artificial structure such as a dam (Problem 2), or by disequilibria in erosive processes due to lack of river lateral space, decrease of channel width, bank protection prohibiting lateral erosion, increase of bed slope due to channel straightening, changes in flow patterns/sediment transport, or changes in median grain size. Such discontinuity in supply may result in changes in river morphology from braided to a narrower, single thread eroding channel (Comiti et al., 2021). Mining or dredging sediments from river beds typically have similar downstream effects (e.g. Rinaldi et al., 2009; Surian et al., 2009). On some occasions as an aftermath of current active extraction activities, and on others as part of the legacy effects of such activities developed in the past. A combined effect of past and present mining/dredging operations may also be found during the assessment of sediment quantity dynamics (Comiti and Scorpio, 2019).

An example of this problem is provided by the Po River in Italy where river bed incision resulted from the sediment discontinuity produced by an upstream power plant and river bed sand mining (Bizzi et al., 2015). Along many Alpine rivers a so-called 'riverbed breakthrough' may occur in response to extreme situations of sediment deficit (Figure 2.1, Habersack & Piegay, 2007). River bed erosion is particularly important for bridge stability; e.g., this issue led to a bridge-collapse accident in Portugal, 2001, killing 70 people (Sousa & Bastos, 2013). In such cases, the glacial gravel deposits are eroded, resulting in a canyon type erosion as the braided river transforms into an eroding single thread river. Lack of sediment supply is followed by self-acting river narrowing and straightening and leads to a lack of aggradational features, thus limiting lateral erosion and morphodynamics. Excessive river channel erosion may also occur downstream of urban developments where impervious surfaces increase total runoff and response times giving rise to higher more erosive peak flows.

Figure 2.1 Excessive river bed erosion (a) and (b) undermining structures; and (c) incising the river bed and causing river breakthrough (sources : (a) Fernando Magdaleno Mas ; (b) Hervé Piegay ; (c) Habersack & Piegay, 2007)

At the coast, reduced sediment delivery from the river catchment or from alongshore can similarly lead to bed lowering. For example, progressive reductions in the quantity of longshore transport of sand along the Lincolnshire coast in eastern England led to increasingly regular exposure of the clay substrate when sand was moved offshore during winter storms (Zwiers et al., 1996). Prior to a major sediment management scheme involving beach nourishment being implemented, rates of erosion of this clay foreshore were increasing, with consequential lowering of both the substrate and beach. As a result, not only were the ecology and human uses adversely impacted, but the natural flood defence function of the beach was compromised, increasing the risk of inundation of an extensive, heavily populated low-lying coastal area. The Danube River provides another example: in this case, reduced catchment sediment delivery to a delta has resulted from a hydropower development which led to major coastal erosion issues (Habersack et al., 2016).

Problem 4: Widespread surplus of sediment

Examples: Elevated suspended sediment concentrations; large scale aggradation/accumulation of bed or bank structure or habitat change

A widespread excess of sediment in the catchment (or coastal cell) (Problem 1) can have a variety of ecological and economic consequences along the river, tidal and coastal areas. Problem 4 is typically associated with a surplus of fine sediments, but it is also possible for problems to arise when human activities (certain land uses) result in a surplus of larger sediments entering the system.

Increased rates of sediment accumulation behind structures such as dams may adversely impact river bed or lake bed substrate and the associated habitats and species, in turn affecting the achievement of the WFD ecological status or potential objectives. Furthermore, such accumulations can compromise the operational effectiveness and sometimes the integrity of the structure. Another problem can arise if, in the event of a flood, the accumulated sediment is mobilised and can lead to major damage in the surrounding area of the river. More generally, a consequence of an excessive load within a catchment or coastal cell is widespread temporary or long-term accumulation, sometimes smothering characteristic habitats or species. The Ems estuary is an example of a transitional water where, exacerbated by dredging-associated tidal pumping, fine sediments have accumulated up to levels where the ecological quality is severely reduced (De Jonge et al., 2014). Once it reaches the coast, an excess of sediment, particularly fine sediment, from the catchment can cause problems when it settles out in the nearshore marine environment. Habitats such as seagrass beds are particularly susceptible to damage from smothering.

The ecological problems associated with excessive (fine) sediment input are not limited to those associated with accumulation or smothering (i.e. when the sediment is deposited). Higher than natural level of suspended sediments in the system can also adversely impact on species directly or indirectly, for example by impacting on foraging effectiveness or by creating a ‘barrier’ (plume) to migration for certain fish species. These potential effects are foreseen by the WFD in lakes and TraC water bodies by the ‘transparency’ physico-chemical supporting element. There is no equivalent in river water bodies, but sensitive riverine species may still be adversely affected by excessive suspended sediment levels.

Problem 5: Local scale sediment deposition deficit (linked to transport capacity)

Examples: Modified flow regime; local erosion, degradation or absence of characteristic habitat

Problem 5 relates to the local loss or degradation of characteristic habitats (riparian, shore or intertidal), usually as an indirect consequence of a physical modification (e.g. channel straightening). Such modifications can increase flow velocities, preventing or limiting deposition and thus resulting in net erosion derived from issues with local sediment transport capacity. It is not a problem of system level sediment supply or continuity/availability per se.

Several types of riparian or intertidal habitat depend on a balance between sediment accumulation (deposition and retention) and the occasional removal of sediments due to erosion. Some such losses and gains are broadly seasonal (losses from the river channel and gains for the floodplain due to overbank deposition in times of high flow, with gains for the river channel in periods of low flow); others are more frequent. Estuarine habitats such as mudflats, experience small losses and gains on a daily basis associated with tidal movements, while natural changes in some vegetated habitats including river margins and saltmarshes may be almost indiscernible in well-balanced systems.

In addition to causing direct physical habitat loss, water body modifications such as channel straightening, flow training, watercourse realignment or dredging, can lead to long term hydromorphological changes with potential indirect consequences for these sediment-dependent habitats, an example being the middle Ebro river in Spain (Magdaleno and Fernandez, 2011). In particular, the local increase in flow velocity and shear stresses associated with these physical modifications may reduce or prevent the deposition of sediments, tipping a previously balanced sediment regime into one of net erosion. These problems can be exacerbated by climate change, for example sea level rise.

It is important to be aware that such changes to the natural regime can take place irrespective of whether the catchment/coastal cell is functioning effectively in terms of system level sediment supply and transport through the system. Problem 5 can therefore be experienced in water bodies where neither Problem 1 nor Problem 2 apply. This possibility, combined with the predominantly local scale of both cause and effect (which may be important when mitigation options are considered), distinguishes this Problem 5 from Problems 1 to 3.

Problem 6: Local scale sediment accumulation surplus (linked to transport capacity)

Examples: Smothering of characteristic habitat or local absence of sensitive species

This problem relates to the local degradation of characteristic habitats due to the (excessive) deposition of typically, but not always, fine sediments. Local fine sediment accumulations or substrate smothering are the most common manifestations of this problem, but any change in sediment size can result in the degradation or change of existing habitats. Problem 6 may result when physical modifications such as channel over-widening/deepening (e.g. for flood conveyance or in response to river bank erosion), water abstraction (for water supply or hydropower), excessive instream vegetation growth, or the installation of groynes (to retain beach material) reduce flow velocities or volumes, causing (part of) the in-transit sediment load to be deposited. It is not necessarily caused by an over-supply per se.

For example, in the UK (River Lambourn, Berkshire, southern England) macrophyte growth has been observed to obstruct river flow and in doing so increase its depth and reduce its velocity, increasing the likelihood of local sediment accumulation. The ability of a stream to transport sediment is directly related to its stream power, and, where this is low, sediment accumulation can occur even where supply is relatively low. The importance of stream power on river bed siltation was identified by Naden et al. (2016) who demonstrated, using data from 230 streams from across England and Wales, that it was the most effective explanatory variable, being more significant than sediment supply.

In addition to local sediment accumulation associated with physical modifications or in-stream obstructions (including vegetation growth), activities that lead to the release of large quantities of fine sediment can have similar effects when this material is re-deposited. For example, the runoff of fines from beach nourishment activities has been documented as causing the smothering of sensitive sea grass (*Posidonia*) beds (González-Correa et al. 2008). In rivers, excess river bank erosion may lead to local sediment contributions and be caused by activities such as cattle poaching or riparian tree removal.

As with Problem 5 (local deposition deficit), Problem 6 can be evident even if there are no issues with system level supply or transport through the catchment. Rather, a modification or activity that reduces flow velocities locally may result in the deposit of the sediment that would otherwise be transported through/past the site in question. Both this scenario and the possibility of a failure being caused by an excess of locally generated fine material may be important when possible mitigation measures are considered. Problem 6 is therefore distinguished from Problems 1, 2 and 4.

Problem 7: Unbalanced sediment size distribution

Example: Modified substrate type

This problem happens when the sediments available in the system (or locally) are not supporting local biological processes (e.g. fine sediments are available but a supply of coarse sediments is needed to maintain spawning sites). Alternatively, it may be that the problem results from hydromorphological alterations changing energy fluxes or modifying the shear stress necessary to promote morphodynamics.

The problem is often a consequence of a discontinuity in sediment transport (Problem 2). There are many examples of river bed gravel being absent as a result of upstream sediment transport being interrupted by dams or definitively removed from the system by gravel mining. Furthermore, river gravels may contain excessive levels of fine sediment. For example, on the Ain River in France, a diagnosis of sediment deficit impact downstream of a dam identified a causal link between sediment deficit and channel bed degradation (paving) impacting on riparian and floodplain fish communities (Rollet et al., 2013). As a consequence of river bed erosion a coarsening of grain sizes can occur, whereas in aggradation conditions finer grain sizes are to be found.

2.3.2 Assessing and addressing problems through sediment management

Where one or more of the previously described problems is identified, sediment management plans at river basin scales should be developed and implemented to restore sediment balances or mitigate the imbalances, and consequently support aquatic (including TraC) ecosystems (see Chapter 4). As discussed in Section 2.6 and elaborated in Chapter 4, sediment management measures may target either the pressure (e.g. the surplus or deficit of sediment supply or interference with continuity) or the consequence (e.g. incision, erosion, habitat degradation). Best practice generally involves prioritising measures that target the pressure - tackling the cause of the problem rather than its symptoms. However, this depends on developing an understanding of both:

- how the system should be operating at the level of the catchment or coastal sediment cell level in terms of sediment regime, dynamics and sediment budget, and;
- how this is being affected by modification(s), human activities and so on either at system level or locally

Section 2.2.1 described how the different quality elements may be affected by disturbed sediment conditions.

The next sections in this chapter therefore provide information and guidance on how to assess sediment dynamics with the aim of understanding the processes and disturbances on the water system (section 2.4), as a necessary step to address sediment problems in the context of the WFD. The concept of sediment budget is in particular proposed as an appropriate tool for such assessment. Monitoring of sediment quantity in relation with the WFD is also a crucial aspect which is described in section 2.5. Finally, section 2.6 provides good practices to set and implement appropriate measures to address these problems and reach the objectives of the WFD and of other related policies.

2.4 The sediment budget approach: a tool for understanding sediment in the context of the WFD

The balance and dynamics of sediment quantity may be assessed in a well-structured and clearer way by means of the construction of sediment budgets (for different extents, and spatial and temporal scales). The aim of this sub-chapter is to introduce the concept of sediment budget and describe possible application in the context of the WFD. It also describes the different approaches and methods available to establish sediment budgets. The next section (2.5) provides guidance and best practices on monitoring and collecting data on sediment quantity, which are in particular required to establish the sediment budget.

Key messages

- Sediment budget may be a consistent approach to understand the balance and dynamics of sediment quantity
- Sediment budgets may be developed with the support of a wide range of model types, whose adequacy must be pre-assessed for an optimum selection
- Conceptualisation of the budget, data collection and analysis, and budget quantification are some main steps of the approach

2.4.1 Sediment budget in the context of the WFD

As presented previously in this document, sediment dynamics at the catchment scale influence and are influenced by hydrologic and geomorphologic processes, including those at water body scale. In order to properly address pressures on sediments, it is necessary to have a sufficient understanding of sediment dynamics processes in the relevant river catchment. This can help identify the main sources of pressures, their impacts on water bodies and take decisions on the most effective measures. Sediment budgeting is a methodological approach which can be used in this context.

Sediment budgets identify the magnitude of sediments sources, transport pathways and stores in a catchment, for any given period of time (Reid and Dunne, 2016), allowing the sensitivity of the catchment sediment yield to perturbations to be appreciated. Sediment budgets reflect a large array of anthropogenic and non-anthropogenic factors, such as geology, climate, topography, catchment size and land and river uses in different sub-catchments or areas. As such, they are frequently represented in the form of sediment cascades that link various sediment storage compartments via sediment transport processes along a topographic gradient (Hoffmann, 2015). Figure 2.2 provides an example of a sediment budget for two catchment in southern England, UK where the budgets are clearly represented by many cascades. A sediment budgets may also be represented as an equation (see Equation 2.1). Sediment budgets importantly illustrate the sediment delivery ratio (the ratio of the soil eroded to sediment delivered at the catchment outlet) (Walling and Collins, 2008). Given the very different levels of connectivity in catchments delivery ratios are highly variable. For instance delivery ratios of ~1% have been reported for UK chalk streams (Walling et al., 2006) indicating that 99% of eroded material is subsequently deposited within the upstream catchment and does not pass the catchment outlet.

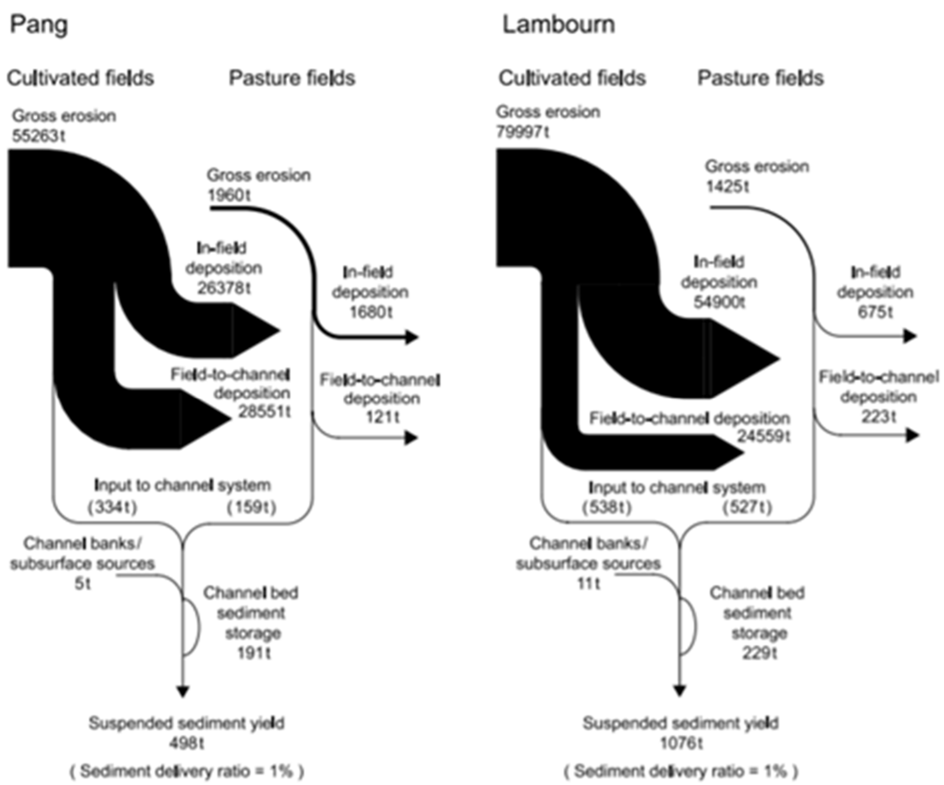

Figure 2.2 Sediment budgets for two catchments in southern England UK represented in the form of sediment cascades (source Walling et al., 2006).

Equation 2.1 Representation of a sediment budget by an equation (Hillebrand & Frings, 2017).

$$I_u + I_t + I_a - O_d - O_{dr} - O_{fgp} - O_a = \Delta S$$

I_u = sediment input from upstream
I_t = seiment input from tributaries
I_a = artificial sediment input
O_d = sediment output to downstream
O_{dr} = dredging
O_{fgp} = sedimentation on floodplains
O_a = abrasion
ΔS = change in bed elevation

The sediment delivery ratio for a given catchment has important management implications. Where delivery ratios are low, land management practices that reduce soil erosion rates are unlikely to affect sediment in watercourses owing to their limited connectivity. Furthermore, if connectivity is increased through management then considerable effects on sediments in water courses could result. Sediment budgets thus provide an important conceptual, methodological and modelling framework providing water managers and river basin authorities with rigorous, quantitative information on sediment dynamics as a basis for decision-making (Slaymaker, 2003).

Developing sediment budgets requires appropriate data, as described in 2.5. In particular spatio-temporal data representing the nature of sediment routing through the catchment, statistical robustness and good coupling with management objectives and with the particular targets of the ongoing assessment. Sediment data are usually scarce (particularly for coarse sediments), spatially and temporally disconnected and sometimes not shared in open-access formats. These challenges, and other difficulties inherent to the creation of sediment budgets limit their calculation in many river basins and coastal cells. Other obstacles relate to the accessibility of sampling sites and the difficulties for data collection, the heterogeneity of sediments´ sinks and sources, or the integration of data to sediment budget models. Most of these barriers may be overcome by a solid design of data collection, representing the structure of the specific sediment budget and the temporal and spatial scales of the involved processes. A good understanding, selection and inter-comparison of analysis and modelling tools, and an appropriate combination with other relevant (hydrologic, geomorphic, ecologic, social) data from the river catchment, reach, coastal cell or study site is also desirable.

Sediment budgets should be solution-oriented. This means that they should be designed to provide answers to specific scenarios, such as long-term river response to human-induced impacts, or short-term river adjustments caused by a single flood-event.

2.4.2 Review of conceptual and practical approaches and tools to develop and interpret sediment budgets, balances and dynamics

Sediment budgets have been a significant tool, since the late 1950s, for the assessment of sediment dynamics in water-related environments (Jäckli, 1957; Rapp, 1960; Dietrich & Dunne, 1978). Although their obvious utility is appreciated, difficulties in assembling the information required to establish a reliable budget has meant that they have not previously been widely used in land and water management (Walling and Collins, 2008). However, through adopting a mixture of novel sediment tracing and traditional measurements, budgets may be developed (Cox *et al.*, 2021; Chalov *et al.*, 2017; Piqué *et al.*, 2017). Furthermore, Walling and Collins (2008) suggest how budgets may be developed for different catchments types and the knowledge transferred to other similar locations to avoid the high costs of constructing budgets from first principles in every situation. Sediment budgets involve logical uncertainties, associated with the data used to feed them, and to the assemblage of those data along the catchments and the drainage networks. Budget uncertainties can be progressively mitigated by improving data resolution and solving data connectivity issues between land patches.

Developing sediment budgets requires a three-step approach:

1. Conceptualising the problem: First develop a conceptual model to identify the major sediment sources, pathways and sinks of a given catchment or coastal cell. This could be based, for example, on a reconnaissance analysis of available geomorphic information (including aerial photography, earth visors and digital elevation models);
2. Collecting sediment data;
3. Analysing data and quantifying the sediment budget.

Depending on the size of the considered study site and the scale of sediment transport processes, sediment budgets may be calculated from the perspective of local, zero order catchments (i.e. <1km²) to large, continental river systems (up to 10^6 km² (e.g. Hillebrand & Frings (2017) for the Rhine) , or even larger) as well as for coastal sediment cells.

Different approaches exist for determining sediment budgets. Each of them requires different levels and volumes of information, of training and expertise, and of data treatment. No single method is considered an optimum in all situations. Rather researchers and water managers/river basin authorities developing RBMPs, supported by relevant experts, must decide on the optimal approach for a particular location once all the aforementioned issues have been considered. The main types of approaches to develop a sediment budget can be grouped, according to Chalov *et al.*, (2017) into three main categories: i. Field-based methods; ii. GIS and remote sensing approaches; iii. Numerical modelling approaches. While Hajigholizadeh *et al.* (2018) refers to their categorization into 4 widely-used types:

1. Empirical models (based on statistical observations, and on developed regression relationships);
2. Conceptual process models (which consider the conceptual structure of the physical processes of runoff generation and sediment transport) - Figure 2.3 illustrates this for a coastal cell;
3. Physically-based models (based on the governing equations describing overland or streamflow, and sediment flow);
4. Hybrid models (mixture of physically-based and empirical soil erosion evaluation tools).

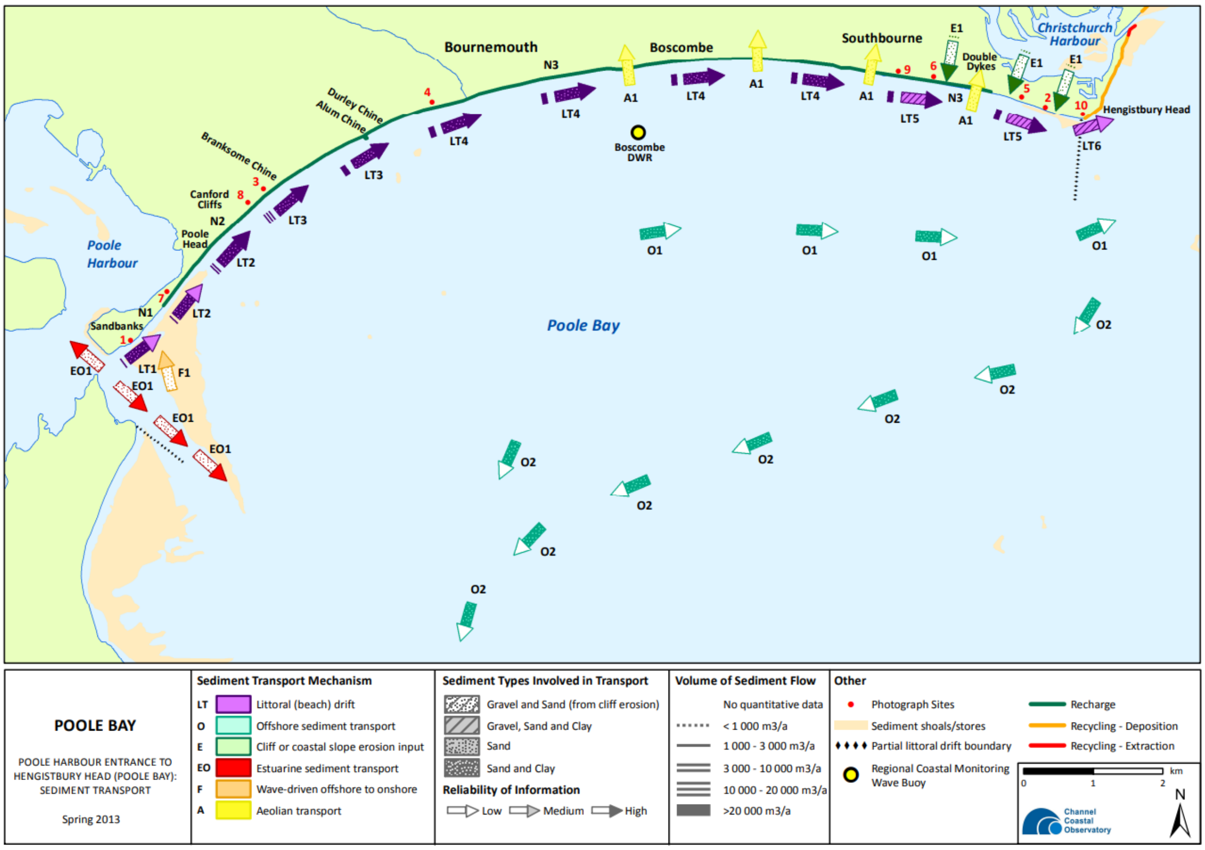

Figure 2.3: Conceptual Model for a Coastal Sediment Cell. Source: Standing Conference on Problems Associated with the Coastline (2004).

Hierarchical (arranged in a grading order of positions) and tiered (with a particular number of layers or levels) approaches can similarly be used to structure sediment modelling, and to combine existing models into specific tools which are of higher potentiality.

The choice of the correct model type strongly depends on the relevant spatial and temporal scales, the processes involved, and the data and resources available (Table 2.3). Recently, water managers, river basin authorities developing RBMPs, and their supporting experts increasingly recognize the need to consider catchment or coastal cell scale processes to plan and implement effective management strategies. Sediment budget approaches do not only focus on the magnitude of changes in certain parts of catchment, but also account for how these changes are routed through the catchment in terms of connected or disconnected sediment pathways. Given the many interacting processes and controls in river systems, river response is mostly complex and challenging to model. This is why reduced complexity models on sediment connectivity are increasingly applied in recent years.

Table 2.3: Examples of the selection made by different authors of particular types of models/approaches, according to their scope, and the main advantages and disadvantages found.

Specific model/approach	Type of model/approach	Usability	Advantages	Disadvantages	Reference
Sediment motion approach	Conceptual process model	Interpolate or artificially synthesize sediment motion	May allow an initial estimation of the overall routing of sediments	Lacks validation, could just be describing some sediment processes while leaving aside others	(Wilkinson *et al.*, 2014)
Connectivity approach	Conceptual process model	Identifies main drivers of system dynamics, supporting holistic models that simulate system dynamics at the catchment scale without excessive complexity	May contribute to an improved understanding of land and water processes related to sediments, and to create a foundation for a more successful management	Could leave aside relevant in-depth aspects of sediment motion while concentrating on the overarching connections which explain sediment activity in the catchment	(Keesstra *et al.*, 2018)
Empirical and specific models	Empirical model	Illustrate particular processes or sites	Require a smaller number of parameters	Need a sound site-specific calibration, which cannot be transferred to other regions or study sites. may ignore some relevant processes occurring in the contributing catchment	(Rovira *et al.*, 2005)
Catchment models	Physically-based model	Describe the main sediment fluxes and key processes at the catchment scale	Develop in-detail assessments of surface processes in the catchment	Do not correctly integrate fluxes and processes in the channel, even in those cases in which sediment fluxes are very relevant within the channel	(Wilkinson *et al.*, 2009)
Combinations of models	Hybrid model	Explores sediment processes by an optimized integration of existing models	Improve the spatial and temporal resolution of the results of each model, and cover various processes that are involved in sediment routing through the catchment	Uncertainties associated to integration of data and models which could have a different level of detail/accuracy, scope and target	(Brown *et al.*, 2009)

Beside numerical models, which are often limited by the accuracy of empirical sediment transport formulas, physical scale models are frequently used for specific sediment related studies (e.g. reservoir sedimentation).

A good balance between the different available approaches and a solid foundation of model calibration and validation on field-based measurements may be the key to overcome some of the disadvantages described for each. The feasibility of each will depend on how modelling is schemed and carried out, according to the particularities of field sampling and the informatics tools used. Most importantly, selection should consider the way in which modelling will be used to decide the specific set of measures which will be selected to improve sedimentary processes, as explained in more detail in the following section.

Furthermore, it is important that all variables or elements considered in a sediment budget are measured or (at least) estimated (e.g. Figure 2.1). Otherwise, keeping one single variable as an unmeasured residual (Kondolf and Matthew, 1991) might lead to misinterpreting physical processes of importance to address the points that motivated the sediment budget (Parsons, 2011). The next section (2.5) provides guidance and best practices on data collection, which is necessary to establish and quantify a sediment budget.

2.5 Sediment quantity data: monitoring and assessment in the context of the WFD

Once the sediment budget is devised to provide the context for the assessment of sediment transfers and stores (2.4), monitoring and assessment are necessary to complete the sediment scheme and to derive the results and conclusions necessary for a better interpretation of the sediment dynamics (in the basin, water body, reach or coastal cell), and for the adoption of specific measures (as shown in 2.6). Sediment monitoring may be approached from the perspective of the WFD requirements, but it may also incorporate further specific analyses to provide answer to additional requirements of other legislation.

Key messages

- A monitoring framework for sediment quantity data would cover the main purposes, type of data, and the frequency, technique and location for data collection
- Many data collection methods are available, which allows an optimal selection according to technical and economic factors
- Data collection approaches and protocols would ensure representation and exhaustiveness, fill existing gaps and be oriented to the identification of measures

2.5.1. Requirements of the WFD regarding sediment monitoring

Monitoring in the context of the WFD aims to establish a coherent and comprehensive overview of water status within each river basin district, as required by article 8. Annex V elaborates on the different purposes of monitoring, which include the classification of status, but also the characterisation of water bodies and the assessment of risks, as required by Annex II.

In order to support the assessment of ecological status in relation with sediment related processes, when biological indication delivers evidence for sediment quantity related deficits, monitoring could be designed or adapted to include sediment quantity components together with appropriate biological components discussed in Sections 2.2.1 and 2.2.2, with the aim of establishing relationship between the biology and flow & sediment regimes. Some monitoring and assessment methods and procedures already exist, e.g. in the Elbe context – see Heininger *et al.* (2015).

In other words, monitoring sediment and the own monitoring procedure should follow WFD guidelines, and also the support of expert decision, in order to concentrate monitoring in those water bodies which more clearly evidence sediment-related problems.

As presented in chapter 1.5, sediments are an intrinsic component of the supporting hydromorphological quality elements, which have to be monitored according to the WFD requirements (Annex V). Sediment is explicitly included as one component of the hydromorphological quality element “river continuity” and should consequently be monitored (Annex V). Sediment is also part of the quality element “morphological conditions” in all water categories as it forms the matrix of the bed and bank (even though the term “sediment” is not explicitly used in this context). The “morphological conditions” quality element is assessed at the scale of water bodies, however it is influenced by sediment dynamics occurring at the catchment level, which should be reflected in the “river continuity” quality element. It is therefore necessary to understand and monitor sediment dynamics in order to be able to define the good status / potential objectives for both “morphological conditions” and for “river continuity”. By definition hydromorphological quality elements aim to support the biological quality elements. As required by the WFD, biological quality elements should be monitored and their status classified in order to reflect the whole range of pressure on aquatic ecosystems. Consequently, it is necessary to ensure that biological quality elements reflect well hydromorphological pressure related to sediment. Hydromorphology can also be of relevance, under different conditions, to the physicochemical quality elements.

Monitoring sediment can also serve the characterisation of water bodies and the assessment of risks required by annex II. Understanding sediment dynamics and their budget at the catchment scale can in particular be used for the pressure and impact assessment of the RBMPs. Sediment monitoring would in this case be designed to provide input for the sediment budget tool described in section 2.4.

The following sub-chapters provides technical and scientific advice, methods and tools for the development of monitoring framework for sediment quantity and the collection of data. These can be used in the context of the monitoring of the WFD quality elements described previously, but also to support the development and quantification of sediment budgets as explained in sub-chapter 2.4.

2.5.2 Establishing a monitoring framework for sediment quantity in the context of the WFD

Establishing a monitoring framework starts by defining what are the purposes of the monitoring. Once this is set, designing the monitoring framework requires to establish what need to be monitored, when and where in relation with the objectives of the monitoring. This sub chapter provides support with respect to these different aspects.

Appropriate physical- and environmental-based approaches that consider the role of the different types of human-based alterations are recommended. Finding an appropriate balance between robustness of techniques and human and materials resources required for data collection becomes relevant when deciding on sediment collection, in order to avoid inefficient high cost or ineffective campaigns.

Water managers and river basin authorities developing RBMPs and their supporting experts should preferably focus on monitoring schemes which are both realistic and well suited to their targets, and which can be adopted during wide time horizons to guarantee consistency of the temporal data series. Monitoring schemes should also be coherent with other data collection initiatives throughout the river system, or catchment, to ensure strategic-based approaches are adopted.

Data collection and analysis must be based on a thorough understanding of the sampling sites. Despite river channels demonstrating general patterns of sediment supply, transport and retention along their course, local variability is usually observed, related to changes in channel width, slope, sinuosity, geology, confluence with tributaries, water abstraction, connection to groundwater and the structure of riparian vegetation stands. Thus, the local and wider environment should be assessed in parallel, also considering the temporal trajectory of water and sediment. Many examples could be given which substantiate this approach (e.g. in regulated rivers or in modified river channels/floodplains). This emphasises the importance of conducting hydro-geomorphic assessments and audits before any sediment schemes are selected. Success of the scheme design is so dependent on a full understanding of the hydro-geomorphic pattern of the river that the study of the latter should be recommended in all cases, with its scope being dependent on the issues in any place and time.

Purposes of monitoring

Sediment monitoring may be targeted at providing answers to specific requirements determined by the WFD, but also at evaluating different aspects of sediment dynamics for the integration of water and nature directives, or for connecting the WFD to other pieces of EU legislation (MSFD, for instance). As explained in chapter 1 (and later on in chapter 4), sediments constitute a valuable key aspect for diagnosing and interpreting land-water-biodiversity interactions, and also for the selection and design of management measures under different policies.

A detailed evaluation of sediment quantity (which may include the analysis of sediment loads and sediment physical characteristics such as particle size) may be crucial for the development of local restoration/mitigation measures in morphologically or ecologically degraded water bodies whether rivers, lakes, transitional or coastal in nature.

More specifically, the monitoring framework for sediment should be designed in order to meet the requirements of the WFD to:

- Assess ecological status / potential;
- Designate Heavily modified water bodies and Define Good Ecological Potential;
- Support the assessment of pressures and the gap analysis by providing initial information on the current situation an deviation to reference conditions;
- Facilitate the assessment of the effectiveness of the programme of measures.

Monitoring should adequately address the particular processes that need to be understood and managed in the context of each specific river or coastal system, and on the basis of the pressure analysis.

What to monitor

Despite the integrated character of sediment transport in river basins, data required to understand sediment quantity issues will mostly depend on the specific objectives pursued in the context of the WFD (section 2.2.1). The characteristics of the sites to sample, and the human and material resources available for the analysis could also play an influencing role, when complementary assessments are to be fulfilled. The monitoring framework should include components which are necessary to characterise sediment dynamics: the composition, structure and distribution of sediments over time. These three features should be assessed in order to have an appropriate understanding of the spatial and temporal sediment transport dimensions. These sediment dynamic components can in particular be used for the assessment of the hydromorphological quality elements such as 'river continuity” for rivers (which includes “sediment transport”) and “morphological conditions” for all water categories (channel patterns, width and depth variations, substrate conditions and both the structure and condition of the riparian, shore or intertidal zones) as defined by annex V of the WFD. The collected data can also be used to establish sediment budget, as described in the previous sub-chapter, which can be used for the different purposes described previously (including in particular assessment of pressures).

Sediment monitoring should be assessed and interpreted considering the different types of sediment transport along a river reach or section: i) bedload, ii) suspended load and iii) dissolved load. These different transport modes which are described in detail in chapter 1.1.1, are determined by the physical (size, shape) properties of sediment in the river basin, which also influences their biochemical properties. It is therefore important to monitor sediment size in relation with these transport processes.

The hydromorphological, physico-chemical and biological conditions throughout the catchment as well as in specific water bodies will greatly influence possibilities for data collection on the field, and should thus be considered when designing a monitoring framework. In hydromorphological terms in rivers, certain issues such as the wadeable character of the channel (i.e., the possibility of walking through the riverbed), the geometry of river reaches, water velocity, local slopes, or the heterogeneity and complexity of the riverbed may impose changes in the manner data must be collected. Equivalent limitations will exist in TraC water bodies. Physico-chemical characteristics, such as turbidity, or the presence of specific pollutants (or priority substances) modify data collection, in a direct or indirect way – in the case of pollutants, by potentially hampering the work of operators. Biology may also have significant effects during sediment analyses, particularly from the perspective of the distribution of aquatic and riparian plants. Additionally, the level of training of the sampling operators may also influence the type and quality of data collected, and the procedure applied.

Monitoring frequency and technique

The experimental design of the sediment quantity analysis should consider all the aforementioned aspects, and also the statistical robustness of the sampling, which require the selection of representative sites and sampling frequency. The WFD sets appropriate monitoring frequencies in order to establish a reliable assessment of the status of all water bodies. For surveillance monitoring, annex V states that morphological and river continuity should be monitored at least once every cycle (6 years) and for operational monitoring, the frequency of monitoring shall be determined by Member States so as to provide sufficient data for a reliable assessment of the status of the relevant quality element (and at least once every 6 years unless greater intervals would be justified on the basis of technical knowledge and expert judgement).

When assessing the sediment budget, the frequency should be set according to the needs of the problem being solved and the models or methods being used. In the case of suspended sediments in fluvial environments, Table 2.4 provides indication on the minimum sampling intervals for inland water bodies for different study objectives. Sediment rating curves (fitted relationships of river discharge and suspended-sediment concentration) are an appropriate measure to produce average sediment yield estimations for a cross section based on a dataset from long term sampling (several years), but the accuracy can be further improved if annual yields are estimated based on annually derived rating curves (as river sediment conditions are altered year by year) (Horovitz, 2003; Warrick, 2015). In many transitional and some coastal environments, the net changes in suspended load are a small fraction of the total amount of suspended sediments which tides and waves keep in motion. Sampling of the suspended load for the purposes determining the sediment budgets in these environments is not feasible.

Table 2.4: Indication of minimum sampling intervals for different purposes for inland waters (based on Horovitz, 2003).

Purpose of monitoring	Long term budgets (≥ 5 years)	Annual budgets	Study of sediment dynamics	Study of sediment composition
Sampling frequency	Bimonthly, hydrology-based sampling	Monthly hydrology-based sampling; weekly, biweekly calendar-based samples	Continuous measurement (automated samplers, flow proportional, turbidity probe)	Time integrated sampling, flow proportional, large volume sampling

Bedload sampling is to be repeated several times per year during different flow conditions so that bedload yield values are available for the whole discharge range, reducing the uncertainties from extrapolations. Having sufficient amount of measured data, relationships between discharge (Q) and bedload yield (QBL) can be established. These relationships need to be checked from time to time, since external (or even internal) effects can alter the transport patterns (BMLFUW, 2008; 2017, DanubeSediments, 2019). It is to be noted that bed load measurements can be more complex and costly than suspended sediments measurements.

Bed sediment condition may quickly change with time, for instance during a flood event which exceeded the transport capacity of the channel bed sediment. Thus, flow velocities (and from it, shear stresses) data should also be collected and interpreted at the same time, to better understand the past and current dynamics of sediments at the sampling site. It may also be relevant to consider the time lapsed from the last flood event and certain attributes of the flood hydrograph. Considering this variability, seasonal sampling may be advisable.

Where to monitor

A good understanding of the physical and environmental conditions of the sampling site and their interactions with sediment transport and channel hydraulic characteristics are most important before carrying out sediment sampling. Physical factors could include channel bed slope, channel bed composition, upstream catchment sources, channel sinuosity (e.g. meandering), biological factors include channel bed/bank vegetation, and anthropogenic aspects related to biology. That information is, alike, very relevant to decide the physical or mathematical modelling to be used in the prediction of future events or the measures to be taken to mitigate existing disequilibria.

In rivers, definition of the monitoring scheme should consider hydro-geomorphic patches for the definition of functional process zones (FPZs) – segments of channel with similar geological histories, flow and sediment regimes, as well as channel and floodplain morphologies (Collins *et al.*, 2014). These unique hydro-geomorphic zones represent a significant hierarchical organization of fluvial ecosystems, and may be a robust foundation to interpret the spatial and temporal trajectory of the dynamics of sediment quantity. In transitional and coastal waters, zonation normally considers some similar physical attributes to those applied in rivers, but in an adapted manner which integrates the particular structure and functioning of those water bodies.

Concerning channel sediments, sampling may have to be carried out in a wide area of the riverbed, about 5-7 channel widths long (Bunte & Abt, 2001), or be concentrated on a sequence of river forms (e.g., riffles and pools, or a continuum of meso-habitats). In terms of suspended sediment yields or load, cross-section integrated measurements are required (Annex B Table B1).

2.5.3 Data collection: approaches and protocols

Data collection is necessarily dependent upon the objective of the study and the site-specific environmental conditions (e.g. sediment composition, specific processes and features of the sampling site), and is thus based on a sampling strategy or scheme. Density, frequency, the specific location of sampling sites and the procedures decided for the monitoring are also of large relevance for data collection. Monitoring may be developed in the river channel, but also in the river floodplain, where alternatives exist for assessing the amount of sediment deposited during an extreme flood event, and the spatial variability shown by that deposition, such as the application of artificial grass mats (Asselman & Middelkoop, 1995).

In some cases, sampling particles will only be those exposed to the bed surface, while in others it will be necessary to sample the layer under the surface to a depth of 1 or 2 large particles, or make comparisons of sediments from different layers within the bed (Bunte & Abt, 2001). Subsurface sampling is particularly important in gravel-bed rivers with armor layers, i.e., surface layer formed by coarser material than that underneath.

Ensuring representative and exhaustive sediment monitoring

Two general criteria ought to be followed when sampling material from a riverbed: representativity and exhaustiveness. Concerning representativity, sediment samples need to represent the spatial heterogeneity of the deposits from which they are collected. In many cases this poses strong challenges on sampling designs, due to the large number of required samples and the limited accessibility as sampling locations. It should be noted that 1-3 substrate samples should be taken in a cross section and along the river at positions where characteristics are changing (e.g. width, slope, grain size), tributaries are entering, or structures are influencing the sediment transport process.

Regarding exhaustiveness, collection of particles will be fulfilled in a different way according to the level of heterogeneity of the riverbed. When sediment composition presents multimodality (for example, bed materials composed of fine sediments intermixed with coarser material), data collection procedure must be designed in a way that allows for the detection of the particularities of each sediment type. In particular, area covered by the different types of bed materials should be determined in order to extract relevant conclusions about the sediment dynamics in the river reach represented by the sampling site. In some cases, different collection procedures would necessarily be applied for data collection in representative sites of each area. For instance, when the sampling river or reach includes areas with very different physical attributes, or areas characterized by suffering very different human-based pressures.

Methods to collect sediments

Traditionally, sediment monitoring was conducted by analog (grab) sampling of water or sediment samples, using water bottles and various forms of sediment samplers (Table B1; Annex B). These traditional sampling methods are time consuming and mostly taken at inadequate, infrequent sampling intervals, given the high variability of sediment loads. During the last decades, various sensors were developed to obtain surrogate measurements. For instance, optical sensors have been developed to measure the turbidity of waters as a surrogate for suspended sediment concentration (e.g. Gippel, 1989). Sensor based measurements are able to measure at high frequencies, and therefore detect the temporal variability of sediment properties. However, the major limitation of sensors, is their need for calibration, which is mostly site specific and complicated by the control of sediment parameters. For instance, turbidity does not only depend on the suspended sediment concentration, but is modified by grain size, color, etc., introducing a variable amount of uncertainty to the calibration of the sensor data (Hoffmann *et al.*, 2017).

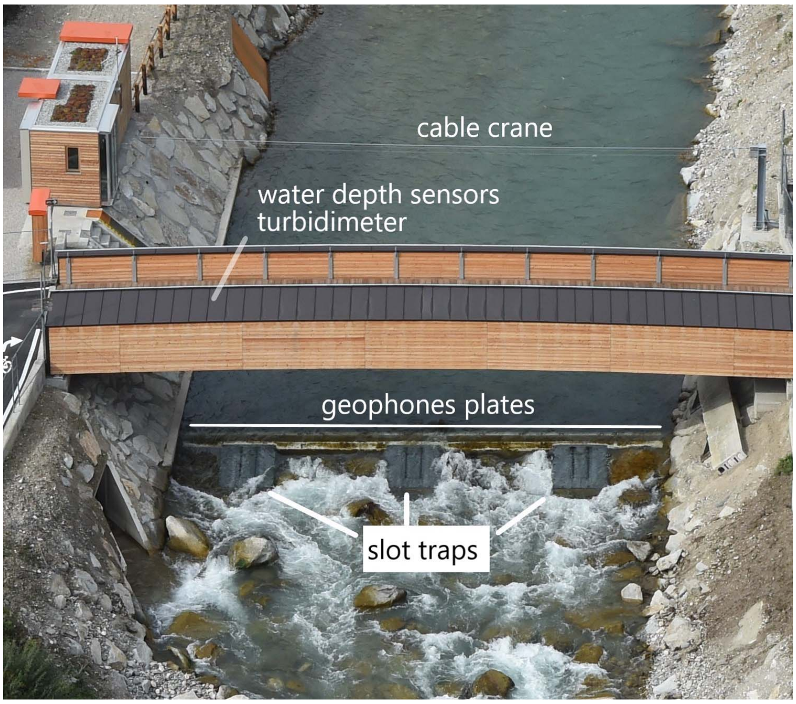

Figure 2.4: Example of a monitoring station for water and sediment fluxes, including both bedload and suspended transport, in a mountain river. The station is on the Gader/Gadera River in Montal/Mantana (South Tyrol, Italy). Photo by Luca Messina; station operated by the Civil Protection Agency, Autonomous Province of Bolzano - South Tyrol

Figure 2.5: Monitoring suspended matter and bedload at the Lower Rhine". Source, Copyright: BAW, Karlsruhe (Federal Waterways Engineering and Research Institute)

Annex B (Table B1) summarizes the methods for the collection and assessment of the suspended sediment and bed load, as well as channel bed sediments. In general there exist direct (e.g. basket samplers) and indirect bedload monitoring methods (e.g. geophones), and a combination of these can lead to an integrated bedload monitoring system (Habersack et al., 2017). Methods for the assessment of dissolved load are not included, since they typically require the combination of in-detail records of water discharge and solute concentration (as simply multiplying mean water discharge and mean concentration could lead to widely mistaken estimations).

The methods listed in Annex B (Table B1) refer to the measurement of sediment in the water systems. In many cases information about the sources and sink of these sediments are also needed. A range of methods for the estimation of erosion and sediment genesis in the catchments should be considered, since a good understanding of those slope and bank processes may be crucial for a correct interpretation of sediment quantity issues in river channels and coastlines. Due to the large areal extent of hillslope erosion in the catchments, this process is hardly measured with sufficient spatial coverage. Instead, in many cases soil erosion in the contributing catchment area is modelled using the Universal Soil Loss Equation (USLE, Wischmeier & Smith 1962; 1978) and its updates, RUSLE and MUSLE. The application of these equations is normally based today on GIS and remote sensing techniques. Other more recently developed techniques include the application of radioactive isotope tracers (Walling *et al.*, 2002), stable carbon or nitrogen isotopes, and also the utilization of process-based soil erosion models (e.g., SWAT, PESERA, WEPP, LISEM, EUROSEM) (Alewell *et al.*, 2008). There are also many techniques available to estimate rates of river bank erosion. Lawler (1993) provides a useful review of methods appropriate for various timescales including sedimentological evidence, botanical evidence, historical sources, planimetric resurvey, repeated cross-profiling, erosion pins and terrestrial photogrammetry.

Options to deal with data gaps

When data is lacking due to a scarce density of sampling points, gaps in temporal data series, uncertainties in the collection or treatment of sediment data, or to any other random or systematic source of error, new challenges may arise for water managers and river basin authorities developing RBMPs. In order to minimize them, different strategies are available:

- Increase and optimize the number and location of sampling sites during the new data campaigns or through the application of sensor data (compare Table 2).
- Benchmark with other data collected in upstream or downstream reaches, or in comparable neighbouring catchments.
- Carry out statistical operations to improve the quality of data series (e.g., simple and multiple regressions, or with geostatistical tools), when the number and size of existing gaps makes it feasible. These methods include sediment rating curves based on multi-annual records, or the improvement of the accuracy of the sediment yield data given by infrequent sampling by using daily discharge data (Walling *et al.*, 1992).
- Infer missing data from other direct or indirect (cartographic, imagery, eco-hydromorphologic) sources.

These information presented above on data-collection focuses on the monitoring of fluvial environments. The monitoring of transitional waters and the marine parts of the water bodies will in most cases require different strategies, because the sediment transport will be the result of different processes (tides and waves versus river flow) and physical conditions may limit the options for monitoring (in many cases an offshore monitoring vessel is required for even the simplest of measurements). Furthermore, in many tide-dominated transitional waters very large daily sediment-transports may occur which eventually result in limited net sediment-transport. When information on the net transport is important (as is the case when considering sediment budgets) monitoring of the daily transports is generally not the best approach. The 'coastalwiki' website provides an introduction to monitoring in coastal and marine environments:

http://www.coastalwiki.org/wiki/Category:Coastal_and_marine_observation_and_monitoring

2.5.4 Using the quantified sediment budget to identify measures

The WFD is aimed at accounting for how the objectives defined for the river basin can be reached under the specified timescale. RBMPs must include measures capable of addressing gaps in reaching those objectives. As explained in Section 2.2.1, effective management of sediment quantity and dynamics is critical to meeting the ecological objectives of the WFD: by implication therefore, the measures set out in the RBMPs should include any sediment management measures necessary to achieve these objectives. The following sub-chapter (2.6) describes, in a systematic way, the best practice measures targeted at addressing issues with sediment supply, continuity and local hydromorphological modifications.

Following the identification of a potential sediment quantity problem (section 2.1.2) support has been provided (section 2.3.1) for gaining a fuller understanding of the nature of the problem. The sediment budget approach, introduced in section 2.4, provides a structured way of obtaining a detailed understanding of sediment motion in a particular catchment. Using knowledge gained from modelling (section 2.4) and monitoring (section 2.5) the sediment budget can be quantified to identify or confirm the nature of the problem; importantly focusing on understanding pressures, risk and impacts. Once the nature of the problem has been confirmed, water managers and river basin authorities developing RBMPs, supported by relevant experts, can identify the appropriate broad measure category (section 2.6.1) and target their location and extent whilst also considering their cost-effectiveness.

2.6 Measures to manage sediment quantity

Key messages

- Interventions may be needed to address sediment quantity issues at the scale of the overall catchment or coastal cell, or only locally in certain water bodies, or both
- Before it can be decided which measures are appropriate, it is essential to understand both the generic issue type (supply, continuity and transport capacity) and the scale at which the problem is manifested/the solution is needed
- Measures to manage sediment dynamics and quantity can take many forms. Different measures may be suited to regulated vs. unregulated rivers; to urban vs. rural environments; to rivers, lakes, coasts or transitional waters; to coarse sediments/bedload or to finer/suspended sediments
- There are, however, also commonalities between different types of measures in terms of the purpose of the intervention. River basin managers should therefore consider generic and then specific measures addressing sediment supply; continuity (interruption); and hydromorphological modification/transport capacity, at different scales as appropriate.
- In addition to the measures summarised in this document, reference can also be made to the library of measures in CIS Guidance 37 as well as to Member States' own measures libraries

2.6.1 Need for Sediment Quantity Management Measures

If the analysis, described in previous sections, identifies that the achievement of good ecological status/potential or other relevant policy objectives is compromised due to sediment-related issues, the RBMP should include appropriate measures. This applies whether failures are experienced throughout the catchment/coastal cell and/or locally, only in certain water bodies.

The interventions needed to address such issues might comprise some or all of the following: mitigation measures in heavily modified or artificial water bodies; measures designed to contribute to meeting protected area objectives; or other measures in the RBMP Programme of Measures (WFD Article 11). Measures might also be included in FRMPs, Marine Strategies, and so on (see Section 2.2).

The previous sub-sections explain the circumstances in which achieving WFD good ecological status/potential depends on having the right amount of the right type (size, shape) of sediment, in the right place at the right time. In order to select mitigation measures that are appropriate to the particular circumstances, water managers and river basin authorities developing RBMPs, supported by relevant experts, will therefore need to understand:

1. The **scale** of the problem indicated by the biological quality indicators, hydromorphological indicators, catchment pressures assessment, etc. (Section 2.1)
    a. Is there a widespread failure to achieve GES/GEP throughout the catchment or coastal sediment cell, or in multiple locations, or
    b. Is the achievement of GES/GEP compromised only locally in a small number of water bodies or specific locations?
2. The different types of sediment quantity problem that may be encountered; the **nature** of such problems; and their linkages to specific water and biodiversity issues at catchment or water body level (e.g., biodiversity, connectivity or other nature conservation goals; management targets for protected ecosystems or habitats; risk management; etc.) (Sections 2.2 and 2.3)
3. Whether the investigations (Sections 2.4 and 2.5) have confirmed there are sediment **supply** issues i.e., the availability of sediment of the size and shape needed to support the ecological quality element(s) concerned
    a. Is there a surplus or deficit of the right type of sediment?
    b. If yes, is there evidence of a widespread sediment quantity problem or is it only manifested locally?
4. Whether the investigations (Sections 2.4 and 2.5) have confirmed issues with sediment dynamics, **continuity** or transport
    a. Is sediment continuity interrupted?
    b. If yes, does this affect a significant area (large parts of the catchment or coastal sediment cell, multiple water bodies) or are the effects only manifested locally (a small number of water bodies, effects within a water body)?
5. Whether the investigations (Sections 2.4 and 2.5) have highlighted issues with sediment **transport capacity** i.e., due to local hydromorphological modifications affecting flow velocity, depth, etc.
    a. Is transport capacity compromised?
    b. If yes, are the effects widespread (affecting large parts of the catchment or coastal sediment cell, multiple water bodies) or are they only manifested locally (a small number of water bodies, effects within a water body)?
6. Whether **additional investigations**, data collection, monitoring, etc. (Section 2.5) are needed to clarify or elaborate on the underlying cause of the problem(s), and whether these investigations have been undertaken.

Broadly speaking, the sediment quantity measures needed in RBMPs to help meet the Directive's ecological objectives can be grouped according to their main purpose as discussed in sub-chapter 2.3. They include seven measures needed to address:

1. Unbalanced sediment input into the system
2. Interrupted continuity of sediment transport
3. Widespread deficit of sediment
4. Widespread surplus of sediment
5. Local scale sediment deposition deficit
6. Local scale sediment accumulation surplus
7. Unbalanced sediment size distribution

These seven categories not only reflect the three generic issues (supply, continuity and transport capacity) but take into account the scale at which the problems are manifested or solutions are needed. The flowchart in Figure 2.4 illustrates how these seven problem categories can be mapped onto three generic issue categories.

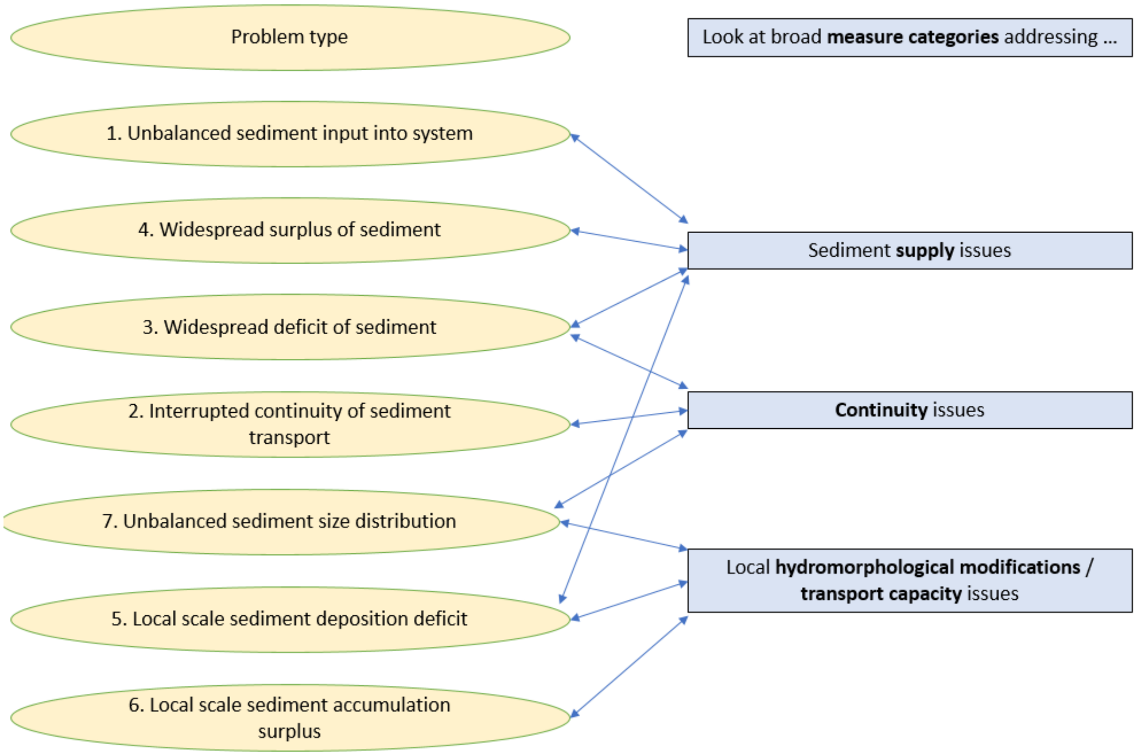

Figure 2.4: Flowchart linking problem types to more generic issue categories.

2.6.2 Types of Measures

Measures to manage sediment dynamics and quantity can take many forms. They can be applied in different situations and at different scales, from catchment to local (e.g. to individual or groups of water bodies, or even within a water body). Some measures may be more appropriate for regulated rivers; others for unregulated rivers. Some may suit urban environments, others rural. Some may be unique to transitional and coastal waters, others to rivers or to lakes. Some may address coarse sediments or bedload; others finer or suspended sediments. At a generic level, however, there are many commonalities between these different types of measures in terms of the purpose of their intervention. Table 2.5 below illustrates the types of generic measures commonly used to address sediment quantity issues (i.e. supply, continuity (interruption) and hydromorphological modification/transport capacity/flow velocities). Note that whenever such measures are applied, relevant good practice or guidelines may be followed when they are available.

Table 2.5: Measure types used to address issues with sediment supply, continuity and local hydromorphological modifications

Generic measure category and *measure objective*	Example measures*
Measure type: address change in sediment supply	
Reduce undesirable fine sediment input; manage excessive run-off Objective: to introduce management practices or infrastructure to reduce the	Soil sealing reduction Peak flow control measures Retention, detention or infiltration basins Other Sustainable (Urban) Drainage Schemes (SuDS)

flow of sediment-laden water into water bodies in areas of sediment surplus	Soil conservation practices Riparian buffers/buffer strips Other Natural Water Retention Measures (NWRMs) Select methods for maintenance works or dredging activities to avoid unnecessary sediment disturbance If necessary to protect river banks from erosion, use soft engineering techniques e.g. restore riparian vegetation buffer
Manage land-use **Objective**: to capitalise on the sediment-binding ability of vegetation and its root systems in areas of sediment surplus	Headwater afforestation No tillage or contour farming Cover crops Vegetation buffers Extensive sustainable agriculture Vegetated waterways Permanent vegetation cover
Minimise excessive debris flow/mass movement, soil erosion **Objective**: to avoid disturbance of potentially vulnerable soils, sealing, deforestation	Minimise urbanisation/construction on sloping terrain Spatial planning Forest protection and management Ecosystem-based practices in agriculture
Restore sediment input **Objective**: to increase the sediment input into the system when a deficit exists downstream in the river and coastal region	Remove artificial barriers and obstacles Restore the altered channel dimensions or pattern Establish fluvial erodible corridors where bank erosion is permitted Improve hydromorphological connectivity within rivers and with their margins and floodplains
Artificially introduce sediment **Objective**: to redress the sediment balance by introducing materials sourced from elsewhere in areas of sediment surplus	Sediment feeding to supplement sediment in system Ecosystem-based beach or foreshore nourishment
Manage activities that physically remove sediment **Objective**: to improve natural sediment supply processes and retain sediment in the system in areas of supply deficit	Prevent in-channel sediment extraction (mining)* Modify dredging activity (e.g. for navigation, recreation, flood conveyance)* Remove or modify cliff or bank erosion control structures (revetment, armouring, etc.) to allow managed erosion Ecosystem-based retention, disposal, reintroduction or augmentation of sediment within the system* (following relevant guidelines – e.g. SEPA 2010;2012)

	Reduce vegetation encroachment within the riverbed*
Measure type: address change in sediment continuity	
Remove, realign or modify retaining structures **Objective**: to modify infrastructure that is trapping sediment and thus facilitate natural sediment movement through the system	Remove redundant retaining structure Dam removal – total or partially Replace impermeable check-dams with permeable ones; convert ‘full body’ to ‘open’ check-dams; enlarge check-dam openings Minimise fixed weir sill height Modify weir fields Install large bottom outlets / gates for venting, sluicing or flushing Route sediments through turbines Realign breakwaters, groynes, etc. to optimise transport
Manage sediment flows **Objective**: to modify engineering measures and management practices that are interfering with natural rates of sediment transport	Sediment flows (s-flows; equivalent to e-flows)* Controlled/artificial floods** Frequent sluicing during flood events Venting of turbidity currents Environmentally friendly flushing Optimise flushing/sluicing strategies for dams in series Training walls Water injection or agitation dredging
Sediment bypassing **Objective**: to facilitate the movement of sediment from upstream/updrift of: a retaining structure and return it to the system downstream or downdrift	Sediment bypass tunnel or channel* Off-stream reservoir Physical transport using construction plant (e.g. from behind terminal groyne)*
Measure type: address physical modification (e.g. change of transport capacity)	
Hydromorphological restoration or diversification to reduce erosion or promote sustainable sedimentation **Objective**: to create or restore areas with low flow velocities and shear stresses to promote the deposition and retention of sediment in areas of deficit and to stop river bed erosion	Reinstate areas of low flow (creeks, backwaters, meanders, secondary channels, paleo-channels, river margins) Create islands, bars, reefs, breakwaters, etc. to reduce flow velocities or wave action River bank restoration; increase river bed width Increase river length to reduce slope (e.g. meander reconnection, re-braiding) Introduce large wood Other NWRM equivalent measures

Optimise engineering structures **Objective**: to modify flow characteristics to reduce (or increase) shear stress and transport capacity and promote deposition (or erosion)	Managed realignment/set-back/removal of flood defence structures; reopen polders Optimisation of river/coastal engineering structures to reduce erosion including use of vegetation and bio-engineering techniques
Use soft engineering techniques **Objective**: to promote sedimentation at desired, sustainable levels	Ecosystem-based beach or foreshore nourishment Plant pioneer species or place LWD to trap sediment (marshes, dunes, river margins) Initiate/create patches of riparian and aquatic vegetation
Measures to reduce excessive in-system accumulation **Objective**: to increase shear stress or otherwise promote the re-mobilisation of excess sediment	Remobilisation of consolidated gravel bars Remobilisation of accumulated fine sediment (e.g. mechanical remobilisation of clogged spawning areas) Management of instream vegetation to increase flow velocities and mobilise fine sediment deposits Management of discharges/flow to reduce sedimentation (e.g. Bussettini, Vezza, 2019 ; e.g. De Jalon et al, 2016) Optimisation of river engineering structures to reduce sedimentation (e.g. Halleraker et al,2016)

(*example measures may fit under more than one measure type; the closest fit has been chosen for the purpose of the table)

The table groups sediment management measures into generic categories according to their primary purpose or objective. In the context of the dynamic natural environment within which these measures apply, many such measures are types of nature-based solution (see Box 2.1) or green-blue infrastructure.

'Green-blue infrastructure' refers to strategically planned natural or semi-natural areas representing important enhancements of ecosystem services and biodiversity in both urban and rural environments. In sediment management terms, the strategic reinstatement of hydromorphological connectivity to facilitate a natural exchange of both water and sediments between a river and its margins/floodplain is one such example. The removal of a redundant structure or the realignment (e.g. of a series of groynes or breakwaters) to restore or improve natural sediment transport processes may be another. Nature-based solutions and green-blue infrastructure are not, however, listed *per se* as measures on Table 2.5.

Box 2.1 Nature Based Solutions to address sediment quantity problems

The term 'Nature Based Solutions' (NBS) refers to solutions that are 'inspired by nature'. NBS are typically sustainable management or restoration measures in natural or modified ecosystems that emulate natural functions. As such they can result in significant co-benefits, for example in terms of flood and coastal erosion risk management, strengthening resilience to climate change, or ensuring fuel, food or water security[24] (https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en).

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[24] https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en

NBS measures can include, among many others (Environment Agency, 2021[25];):

- Restoring connectivity, between a river and its floodplain, or an estuary and its former intertidal habitats to facilitate the natural exchange of water and sediments, and enhance both biodiversity and carbon sequestration. Examples of such solutions are the floodplain restoration on the River Elbe in Germany (Deltares, 2021[26]) and the Medmerry coastal managed realignment scheme[27] in the UK, which was recently recognised under the International Union for Conservation of Nature (IUCN) Global Standard for Nature-based Solutions[28]
- Restoration or enhancement of sediment-dependent habitats such as saltmarshes, mudflats, dunes, beaches and riparian areas that naturally reduce and dissipate wave and tidal energy as well as providing biodiversity and other ecosystem service benefits. Ideally this should be achieved by re-instating natural sediment supply, but otherwise there may be a need for interventions such as:
    - replacing concrete revetments along river or coastal embankments with carefully designed and managed planting projects that trap sediments to become self-sustaining e.g. using reedbeds, willow, marram grasses or similar (see Case study 6. River Monnow Bank and toe protection in Roca, M. et al., 2017)
    - carefully and environmentally designed beach or foreshore nourishment (Mickovski, S. and Walvin, S., 2015) or
    - where dredging is necessary for navigational safety or flood conveyance, the selection of sensitive, environmentally proven dredging methods that retain sediment in the natural system rather than removing it for disposal.

The scale of application of individual measures will depend on the problem type being addressed (i.e. the cause of the problem and its symptoms (SEPA, 2010)). Several of these measures can be applied at catchment scale (e.g. land-use management). Others may involve a locally implemented measure that benefits the wider catchment (e.g. removing or realigning a structure to facilitate sediment flows). Sometimes a measure may only be applied, and deliver its benefit, locally: for example, a habitat restoration or hydromorphological diversification initiative may be intended to reduce erosion or promote sustainable sedimentation at a specific site). Most river basin management plans will contain a mixture of strategic and local measure as appropriate to the problem type(s) identified in sub-chapters 2.3 to 2.5. Furthermore, it is often the case that measures provide co-benefits in addressing other environmental pressures (e.g. most of the measures to manage sediment run-off will likely have positive effects on nutrient leakages and on biodiversity).

Many of the sediment management measures listed on Table 2.5 involve ‘working with nature’ in some way to restore or enhance natural processes and associated habitats. As highlighted above, such measures are especially useful when multiple objectives need to be met, for example protecting or enhancing biodiversity while also ensuring flood protection, erosion control or navigational safety. Case study 2.4 discusses three international ‘working with nature’ initiatives and signposts to different categories of case study.

Case Study 2.3: Working with nature case study examples

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[25] https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/working-with-natural-processes-to-reduce-flood-risk

[26] Deltares (2021) Economic rationale of NBS in freshwater ecosystems. Bregje van Wesenbeeck, Sien Kok, Camilo Benitez Avila, Robyn Gwee, Ellis Penning. 11206081-002-ZKS-0001, 22 February 2021

[27] https://www.ice.org.uk/knowledge-and-resources/case-studies/managed-realignment-at-medmerry-sussex

[28] https://www.dredgingtoday.com/2021/11/11/medmerry-scheme-leading-the-way-on-new-global-standard-for-nature-based-solutions/

Author: Jan Brooke

Three 'with nature' initiatives are of particular relevance to aquatic sediments: Working with Nature (WwN) promoted by PIANC, the World Association for Waterborne Transport Infrastructure (see https://www.pianc.org/working-with-nature); Building with Nature (BwN) promoted by EcoShape (see https://www.ecoshape.org/en/); and Engineering with Nature (EwN), by the US Army Corps of Engineers (see https://ewn.erdc.dren.mil).

The latter's 'Engineering with Nature' Atlas (Volumes 1 and 2) showcases EwN, WwN and BwN examples in projects from around the world including Europe. Sediments and sediment management feature strongly throughout the publication. The Atlas, which is downloadable from https://ewn.erdc.dren.mil/?page_id=4174, categorises case studies as follows:

- Beaches and Dunes: Protecting Coastlines and Enhancing Recreation
- Wetlands: Creating Natural Defences and Aquatic Habitats
- Islands: Discovering Placement Solutions with Multiple Benefits
- Reefs: Stabilizing Shorelines and Creating Habitat
- Riverine Systems: Strengthening and Restoring Natural Waterways
- Floodplains: Mitigating Flood Risk Through Natural Processes
- Use of Vegetation and Natural Materials: Exploring Alternative Interventions
- Environmental Enhancement of Infrastructure: Engineering Structures to Include Beneficial Habitat

Whilst it is not a comprehensive list, the Mitigation Measures Library associated with CIS Guidance Document 37 'Steps for defining and assessing ecological potential for improving comparability of Heavily Modified Water Bodies' (available on the Commission's website[29]) also describes various potential measures for managing sediment quantity in situations where an existing physical modification has impacted on the hydromorphology and, in turn, on the ecology of the water body. This library of measures is arranged by water body type. For rivers, 'typical impacts on original ecology' might include interruption of sediment continuity or an increase in fine substrates. For transitional and coastal water bodies, these impacts might include removal or changed nature of substrate, relocation or disposal of sediment, modifications to sediment supply or transport, changes in suspended sediment levels and so on. The Library provides examples of mitigation measures that can be implemented to address these and similar sediment-related impacts on WFD status. Some Member States also have their own libraries of potentially relevant measures. Figure 2.5 illustrates how mitigation measures are applicable throughout a river basin.

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[29] https://ec.europa.eu/environment/water/water-framework/facts_figures/guidance_docs_en.htm

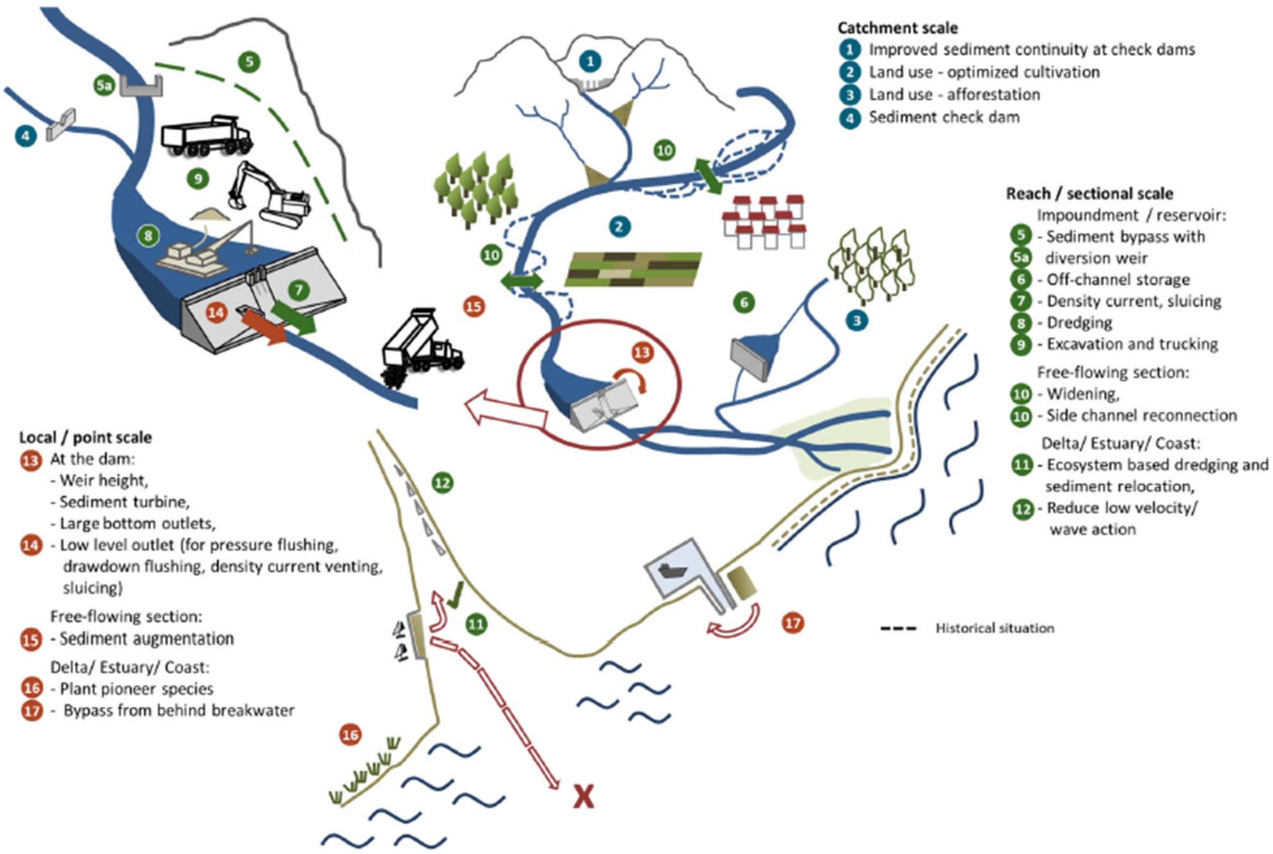

Figure 2.6: Mitigation measures to address excess sediment quantity are applied throughout river basins. Source: Habersack et al. 2019.

Several additional case studies elaborate on the different measures selected to address sediment quantity problems. A number of examples focus on restoring continuity.

Case study 2.4: Restoring sediment continuity in the Po River (Italy).

The Po River SMP from Italy explains how priority is given to measures that facilitate longitudinal, lateral and vertical continuity, in particular restoring sediment transport in degraded reaches that have significant upstream disconnections; reconnecting river channels with their floodplains; and restoring the widest lateral mobility corridors.

For a full description of the case study see Annex A.

Case study 2.5: Improving connectivity in the Talvera river (Province of Bolzano, Italy)

The case of the Talvera river (a tributary of the Isarco river) illustrates how a selection of measures may be adopted to improve longitudinal connectivity for both fish and sediments, and to restore habitats/physical heterogeneity. The main measures implemented included the removal or partial opening of sills in the urban stretch and the removal of two large check dams in the upper reach, replaced by a single selective check dam, intercepting only large wood and boulders.

This case study has been included in the HyMoCARES project (https://www.alpine-space.eu/projects/hymocares). The project developed a conceptual framework and operational tools to integrate the ecosystem services concept in Alpine river basin planning and management, with a special focus on factors affecting river hydromorphology, including sediment continuity and ensuring integration of local and basin scales.

For further information on the case study see https://www.alpine-space.eu/projects/hymocares/en/case-studies/case-studies/talvera

Several examples illustrate cases where sediment augmentation has been used in restoration. A priority should always be given to addressing sediment issues by identifying and tackling the source of the problem at the larger scale. Sediment augmentation is a costly activity addressing the downstream impacts of an upstream problem. However, in some situations it is the only viable solution that is compatible with current uses of the system.

Case study 2.6: The Upper Rhine (Germany) Sediment Nourishment initiative illustrates how the effect of dams blocking sediment transport may be offset.

Authors: Thomas Hoffmann, Stefan Vollmer and Gudrun Hillebrand

To prevent downstream erosion with strong negative impacts on water level, ground water, morphology and ecology of the Rhine and its neighbouring floodplains, 0.4 Mt of gravel are artificially supplied to the Rhine channel downstream of Iffezheim each year. Despite the cost-intensive measure, there are no alternatives to the current practice of sediment supply without constraining navigation, hydropower generation and without degradation of the ecological status of the Rhine river. Monitoring changes in bed level shows that sediment nourishment successfully prevents channel incision and thus helps to maintain a balanced sediment regime downstream of Iffezheim.

The German Waterways and Shipping Administration (Wasserstrassen- und Schifffahrtsverwaltung des Bundes, WSV) is responsible for maintaining the navigation in the Upper Rhine. The German Federal Institute of Hydrology provides the necessary scientific understanding to support effective management (including knowledge on transport mechanics and grain size of transported sediment). To provide a coherent picture on the sediment budget of the Rhine and to evaluate human impacts on the sediment transport, a budget for the whole Rhine has been developed (Quick et al., 2020).

The major challenge to sediment augmentation is the sustained acquisition of suitable material. Material has been purchased from gravel pits in the floodplain and bedrock mines in the Black Forest but cost-effective alternative sources are currently sought.

Fig.2.6: Sediment nourishment Upper Rhine (source: blubb.media GmbH)

Link to Video: https://www.wsa-oberrhein.wsv.de/Webs/WSA/Oberrhein/DE/SharedDocs/Videos/Geschiebezugabe_EN.mp4;jsessionid=523B948AEA0B17A351F3E0E4DC574AC9.live11291?__blob=publicationFile&v=10

For further information see:

Frings, R.M., Gehres, N., Promny, M., Middelkoop, H., Schüttrumpf, H., Vollmer, S., 2014. Today's sediment budget of the Rhine River channel, focusing on the Upper Rhine Graben and Rhenish Massif. Geomorphology, 204(0), 573-587.

Hillebrand, G., Frings, R., 2017. Von der Quelle zur Mündung: Die Sedimentbilanz des Rheins im Zeitraum 1991 - 2010, Bericht KHR/CHR II-22. Internationale Kommission für die Hydrologie des Rheingebietes, Lelystad. ISBN: 978-90-70980-39- 9, DOI: 10.5675/KHR_22.2017.

The restoration of reaches of two alpine rivers draining the Southern Alps in France provide examples of how locally sourced gravel replenishment may be used in restoration.

Case study 2.7: Restoring sediment continuity in the Buëch river (Southern Alps, France).

A pilot gravel replenishment project has been implemented by EDF (French electricity company), in order to ensure sediment continuity downstream the Saint-Sauveur dam. The restoration works involved gravel dredging in the proximal fan of the reservoir and reinjection below the dam as artificial berms. This action is part of a wider revision of the reservoir management, including a lower flow rate threshold for the total opening of the three flood gates, in order to increase sediment transport below the dam during flood events. A dedicated monitoring programme is active to track the geomorphic and biological response of the reach.

For a full description of this case study go to: Buech – Alpine Space (alpine-space.org) https://www.alpine-space.org/projects/hymocares/en/case-studies/case-studies/buech

Case study 2.8: The restoration of the Upper Drac River (Southern Alps, France)

Historic gravel mining resulted in significant channel incision and narrowing in the Upper Drac river; in particular, regressive erosion was threatening the stability of the right-bank dike of the Champsaur reservoir. The restoration project of the degraded reach near St-Bonnet consisted in the creation of a new wide and shallow channel, coupled to sediment reinjection, using more than 450 000 m3 of coarse sediments, from adjacent alluvial terraces and other complementary sources upstream, leaving the river free to self-restore its morphological configuration towards a braided morphology.

A dedicated monitoring programme is active to track the geomorphic and biological response of the reach to the gravel reinjection and assess whether active sediment sources upstream are sufficient to maintain the restored configuration in the long term.

For a full description of this case study go to: https://www.alpine-space.org/projects/hymocares/en/case-studies/case-studies/drac

A case study from Spain illustrates how sediment augmentation may be combined with increasing a rivers lateral mobility in morphological restoration.

A further case study from Spain illustrates the important role of channel forming discharges in addition to sediment augmentation in morphological restoration of rivers below dams

Case study 2.9 The restoration of the Aragon River (Ebro basin Spain)

The Aragon River (Ebro basin, Spain) provides an example of a degraded river (incised in response to dredging and regulation) being restored using a combination of sediment augmentation and floodplain reconnection. Monitoring of the scheme has shown the successful response of the river system, in ecomorphological terms, and this has contributed to a shift in its management strategies.

For a full description of the case study see Annex A.

Case study 2.10 Evaluating the role of channel forming discharges in morphological restoration (Catalan basins, NE Spain)

An evaluation of the experimental flood releases downstream of reservoirs on the Llobregat and Ter rivers illustrates the important role of channel forming discharges in sediment dynamics, particularly when coupled with sediment injections (active and passive techniques were tested). The released flows showed a high capacity to mobilize and transport the injected volumes of sediment, contributing to the morphological restoration of these regulated rivers. Further experiments are being designed to optimize such combined actions, in those and in other nearby river systems

For a full description of the case study see Annex A.

2.6.3 Guiding principles for selection and evaluation of measures

Taking into account the catchment/cell- or site-specific context (i.e. as discussed in the preceding Sections), a list of potentially suitable generic or specific measures can be generated for each catchment or water body where sediment quantity-related status failures have been confirmed.

The rationale used in CIS Guidance Document 37 to support the identification of mitigation measures for Heavily Modified Water Bodies provides an example of how to approach the selection of potentially suitable measures for managing issues related to sediment quantity and dynamics, as follows:

- confirm the nature and scale of the **pressure** [*see Section 2.2 and 2.3*]
- understand the current status of the hydromorphological supporting elements compared to the natural **state** of the catchment or water body; consider whether the current status of any physico-chemical supporting elements is also relevant and if so, how the current status compares to the natural state of the catchment or water body [*see Section 2.4 and 2.5*]
- establish which Biological Quality Eelements have been adversely **impacted** (directly or indirectly) by the sediment supply, continuity or transport capacity issue, and *how* they are impacted; take into account any wider implications for ecological functioning and/or (e.g., where required by other policy instruments) the provision of ecosystem goods or services [*see Section 2.2*]
- identify a range of generic or specific measures that may contribute, alone or in-combination, to improving sediment quantity/dynamics and hence ecological status/potential (**response**) [see Section 2.6]
- use forecasting (numerical or physical modelling, expert judgement, etc. [*see Section 2.4*]) to understand the cumulative extent of the anticipated status improvements and to assess this against the respective WFD ecological objectives (**response**).

These principles can be applied to select a list of measures or ‘management options’ to address pressures on sediment quantity. When planning measures, other considerations need to be taken into account to select the measures which will be implemented on the basis of the management options. These are described in chapter 4.6, as part of the different steps for developing integrated sediment management plans.

Chapter 3: Sediment contamination

Key messages

- Several of the contaminants that enter the surface water have a preference to associate to, and thus accumulate in sediment.
- Sediment associated contamination may adversely impact the WFD status of waterbodies.
- Sediment contamination can be managed by taking prevention, mitigation or remediation measures.
- Priority should always be given to solutions aiming at addressing pollution at the source. Remediation measures may be necessary but are less effective and can be very costly.

3.1 Introduction

3.1.1 Aim and focus of this chapter

Sediment associated contamination may adversely impact the WFD status of waterbodies. This chapter describes how such contamination can be addressed in a WFD context and focuses on how to assess the impact from contaminants and how to manage it. In cases where a problem is suspected due to the sediment associated contamination, this chapter will provide guidance on understanding and confirming the nature of the problem and selecting appropriate mitigation measures. Regarding contaminants, both conventional toxic substances as well as contaminants of emerging concern are addressed. The role of sediment in determining the impact of excessive nutrients is also described. For more details, reference is made to other publications and some aspects are also illustrated by case studies. Furthermore, reference is made to several CIS Guidance documents[30].

3.1.2 Problems caused by sediment contamination

As already explained in section 1.5 sediment associated contaminants may impact either or both the chemical and ecological status of a water body. For member states that have established sediment EQSs for priority substances and/or river basin specific pollutants, an exceedance of such a standard implies that the chemical status should be classified to not good and/or the ecological status to moderate. Ecological status may also be impaired (classified to moderate, poor or bad depending on the severity of the alterations) by the presence of sediment contamination (including excessive nutrients) that exerts quantifiable impacts on one or more of the Biological Quality Elements of the WFD, such as benthic invertebrate fauna.

Directive 2008/105/EC allows Member States to apply sediment EQSs for priority and other substances (Annex 1 of 2008/105/EC as amended by Directive 2013/39/EU), therefore the possibility of including sediment contamination directly within the assessment of good chemical status is possible. This was so far done by some of the member states, including Italy, Norway and Sweden. Sediment EQSs are also established for river basin specific substances by e.g. Germany. However, it is worth noting that at the time of writing no sediment EQSs had been defined yet in the EQS directive, and so it is likely that in several Member States, sediment contamination is not an explicit element of the assessment of chemical status. Nevertheless, contaminated sediments could under certain conditions act as a source of contaminants to other compartments (water column and/or uptake in biota). The sediments then contribute to the risk of water and/or biota concentrations exceeding EQSs set for these compartments but also inhibit the WFD objective to progressively reduce pollution from priority substances and the elimination of priority hazardous substances. It is also

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[30] https://ec.europa.eu/environment/water/water-framework/facts_figures/guidance_docs_en.htm

required (Art. 3.6 of the EQS Directive) to monitor the trend of accumulating priority substances in sediment and/or biota. In case sediment associated contamination is monitored and a significant increasing trend of sediment concentration is observed, measures have to be taken.

Depending on the type of data available, a problem resulting from contaminated sediment might in a WFD context be identified via one or more of the following indicators:

1. Biological Quality Elements (ecological status);
2. Sediment EQS for specific pollutants as set by Member States according to Annex V 1.2.6 and/or for priority pollutants set by Member States according to the EQS Directive;
3. Evidence of certain pressures within the river basin.

Impacts on ecological status

Chapter 1 explains how sediment plays a critical role in supporting many of the Biological Quality Elements used in the ecological status assessment. Failure to achieve good status/potential for fish, invertebrates, macrophytes and/or phytoplankton can be due to, and thus be indicative of the presence of contamination in the sediment. This can apply even if good chemical status is achieved. However, since impaired ecological status may be due to (a combination of) many diverse river basin pressures, evidence for direct links between sediment -associated contamination and ecological impairment needs to be gathered. This chapter sets out a two-stage approach to diagnose the presence of sediment -associated contamination and to establish the risks of ecological impacts due to that contamination:

1. Comparison of measured sediment concentrations of contaminants against sediment Quality Guideline Values (Section 3.5.3, Assessing the risks and potential impact of individual contaminants in sediment). This approach screens sediment contamination measurements against defined thresholds, allowing a first step identification and prioritisation of areas of sediment contamination;
2. A weight-of-evidence approach to assess the actual impacts of contamination (Section 3.5.3, Assessing the actual and combined impact of all contaminants in sediment).

River basin pressure assessment

Another indicator of possible sediment associated contamination issues is the presence within the river basin of certain types of pressure(s) associated with sources of contamination, including historical sources that may have left a legacy of contamination in sediments. These pressures can be summarised as being current or caused by historical activities that are a potential source of contaminant(s) already associated to solid matter that may erode into surface waters, or contaminant(s) that may associate extensively to sediments within the water column. Examples of such activities and their potential consequences are included in Table 3.1.

Table 3.1. Examples of contamination related pressures and consequences for sediment (not meant to be all inclusive)

Contamination related pressure	Consequences for sediment
Contamination resulting from industrial production	Discharge of contaminants into surface waters with potential for association to, and thus contamination of sediment
Contamination resulting from land management (agricultural intensification)	Increased concentrations of particulate nutrients, pesticides and potentially other contaminants, e.g. metals in runoff in to surface water and thus may lead to the contamination of sediment
Contamination released from contaminated floodplains or land, including not properly managed waste facilities (e.g. landfills and	Leaching of contaminants, erosion of contaminated soils/solid waste particles into surface water – directly and/or via groundwater – and thus contaminated soil contaminates sediment

mine tailing ponds) adjacent to surface waters	A severe flood event may remobilize the contamination and bring it back into the surface water where it may contaminate sediment
Contamination resulting from urban activities	Urban contamination, e.g. urban treated wastewater, combined sewer overflows or urban runoff of contaminated dust via rainstorm water may enter surface waters with potential for association to, and thus contamination of sediment
Contamination resulting from harbour and marina activities	Ship maintenance may e.g. result in anti-fouling paints entering surface waters with potential for association to, and thus contamination of sediment

3.1.3 The further structure of this chapter

This chapter from here on follows a simple and straightforward structure. Section 3.2 describes how sediment contamination is relevant to the WFD. Section 3.3 explains how sediment becomes contaminated and how sediment associated contaminants transport down-stream (sections 3.3.1-3.3.3). How sediment associated contaminants may cause impacts that hinder the achievement of WFD goals, is described in section 3.4. Section 3.5 on sediment contamination assessment starts describing what overall approach to take towards assessment (section 3.5.1), followed by an explanation of how to identify and prioritize contamination sources (section 3.5.2) and how to assess if and how contamination in sediment impacts ecological and chemical status (section 3.5.3). Section 3.6 describes the overall approach to take to manage sediment associated contamination (section 3.6.1) i.e. a three-step approach: 1) how to prevent contamination of sediment (section 3.6.2); 2) how to mitigate downstream transport of sediment associated contamination (section 3.6.3); and 3) what mitigation or remediation techniques to apply (section 3.6.4).

3.2 Sediment contamination in a policy context

Key messages

- The WFD includes a few explicit and several implicit links to sediment associated contamination. Thus, the management of sediment associated contamination is inherent part of the WFD.
- Several other EU environmental Directives also address the issue of sediment associated contamination as they directly or indirectly address sediment management: the Floods Directive, the Habitats Directive, the Marine Strategy Framework Directive and also the Waste Framework Directive (see chapter 1 section 1.5.2).

The WFD aims at maintaining and improving the aquatic environment in the EU Member States. The overall objective of the WFD is that all European waters should achieve good status or good potential for HMWB/ AWB. The WFD also aims to achieve no further deterioration in status, and to improve the aquatic environment by progressive reduction or phasing out of discharges, emissions and losses of priority and priority hazardous substances. Furthermore, river basin specific pollutants and nutrients need management as relevant contaminants of concern in order to achieve the WFD goals.

Management by the Member States to achieve the objective of the WFD and its daughter directive on priority substances (2008/105/EC, as amended by 2013/39/EU) is an iterative process: each 6-years the river basin management plan should be updated. Contamination associated to sediment should be considered in this context, giving rise to several questions that will be further described in different sections of this chapter:

1. River basin districts need to be characterized in terms of pressures and impacts (*WFD art 5 and Annex II; CIS guidance no 3*). Significant drivers and pressures should also be reported (*Annex 1a and 1c in CIS guidance no 35, i.e. the WFD Reporting guidance*).
    a. What are the sources and pathways of contaminant input to the aquatic environment? (section 3.3.1)
    b. Which of these contaminants are associated to sediment? (section 3.3.2)
    c. When, where and how are sediment associated contaminants transported to downstream water bodies or the sea? (section 3.3.3)
2. Inventory of discharges, emissions and losses of priority substances to be performed (*art 5 2008/105/EC; CIS guidance no 28*) and reported (*Annex 7 of the reporting guidance*). The inventory can also include emissions data in sediment if available.
    a. What are the sources, pathways and pressure types behind priority substances emissions, contributing to the contamination of sediment? (section 3.3.1-3.3.3)
    b. Is there a significant trend of priority substances in the sediment? (section 3.3.3)
3. Establish and report chemical surveillance and operative monitoring programmes of both priority substances and river basin specific pollutants, as well as trend monitoring of accumulating priority substances in sediment and/or biota (*WFD art 8 and Annex V; 2008/105/EC art 3; CIS guidance no 19 and 25; section 4 and Annex 8 of the reporting guidance*)
    a. When and where is it relevant to monitor substances in sediment? How to monitor? (section 3.5.1 & 3.5.2)
4. EQSs for additional compartments, i.e. other than water or biota (including sediment), may be established both for priority substances, and for river basin specific pollutants (EQSD article 3, *WFD Annex V; section 1; CIS guidance no 27; section 4 and Annex 8 of the reporting guidance*)
    a. How to establish sediment EQS and take bioavailability into account when sediment is used to assess status? (*CIS guidance no. 27*)
    b. How to handle natural background concentrations if interfering with the possibility to achieve objectives (not exceeding EQSs)? (section 3.5.3)
    c. How to check if an EQS failure for biota or water can be related to sediment contaminant dispersal? (section 3.5.3)
5. Establish biological monitoring programmes (*WFD art 2 Annex V, Decision 2018/229/EU*)
    a. How to assess the effects (impact) from contaminants in sediment on benthic flora and fauna, such as macroinvertebrates as well as to organisms higher in the food-chain? (section 3.5.3)
6. Under certain circumstances, the setting of WFD exemptions from the objectives may be necessary (*Art 4; guidance on exemptions*).
    a. When would a time extension and/or less stringent objectives be relevant due to contamination in sediment? (section 3.4)
7. Develop and implement a Program of Measures (PoM) based on monitoring results and the initial river basin characterization (art 11, Annex III).
    a. How to link cause-and-effect, i.e. ascertain that any measures to reduce the sediment contamination will also improve the state (reduce impact)? (section 3.5.3)
    b. How to implement the necessary measures to prevent deterioration of sediment contamination? (section 3.6.2)
    c. What are cost-effective measures to counteract failing the WFD objectives due to sediment associated contamination? (section 3.6.3 and 3.6.4)

3.3 Sources and transport of sediment associated contaminants

Key messages

- Contaminants, including nutrients, can reach surface waters via point and diffuse sources, via airborne deposition, via ground-water and potentially in the form of inadvertent spills.
- Many of these contaminants are on to the priority substances list of the WFD (2000/60/EC). In addition, there are river basin specific pollutants and other potentially relevant contaminants of emerging concern, which must also be addressed.
- Sediment can act as a sink or a source for contaminants and nutrients, depending on the hydrological and chemical conditions.
- Persistent contaminants that are strongly associated to sediments may remain within the river basin for long periods following cessation of active inputs.
- Remobilized, contaminated sediment, especially the fine sediment that contains the majority of the contaminants, may be dispersed, resulting in an uncontrolled downstream transport of the contaminated material. This process may repeat itself over hundreds of kilometers (in the largest river basins), leading to an accumulation of contaminants in sediments when further contamination sources are passed.

3.3.1 Sources and pathways of contaminant inputs to the aquatic environment

River basin districts need to be characterized in terms of pressures and impacts (*WFD art 5 and Annex II; further described in CIS guidance no 3*). Significant drivers and pressures should also be reported (*Annex 1a and 1c in WFD reporting guidance*). Member States also need to perform an inventory of discharges, emissions and losses of priority substances (*art 5 2008/105/EC; further described in CIS guidance no 28*) and report these (*Annex 7 of the reporting guidance*). Furthermore, Member States must identify river basin specific pollutants and generate Environmental Quality Standards, monitoring schemes and regulatory measures for such pollutants.

The role of sediments in controlling the distribution and impacts of contaminants within a river basin needs to be understood as comprehensively as possible, in order to diagnose situations where sediment associated pollutants are likely to hinder the achievement of Good Chemical Status and/or Good Ecological Status, and to design optimal measures to alleviate and/or mitigate the impacts of such contamination. It is therefore key to establish which contaminants enter the water phase and can be expected to associate to particles and then end up in sediment (see next section), and how and from where they are emitted to the aquatic environment, as well as the drivers behind these processes.

Persistent contaminants that are strongly associated to sediments may remain within the river basin for long periods following cessation of active inputs. Therefore, the characterization of drivers and pressures with respect to contamination needs to include analysis of historical as well as present day pressures.

Contaminants, including nutrients, can reach surface waters via point and diffuse sources, via airborne deposition and potentially in the form of inadvertent spills (Fig. 3.1) (Salomons and Brils, 2004; Kowalewska et al., 2011). CIS guidance no 35 (WFD Reporting guidance) lists the main drivers (Annex 1c, CIS guidance no. 35) and related pressures (annex 1a, CIS guidance no. 35) which are differentiated in point and diffuse sources. *Point sources* include: urban waste water, stormwater overflows, industrial emissions (including from plants covered and not covered by the Industrial Emissions Directive), emissions from contaminated sites or abandoned industrial sites, waste disposal sites, mine waters, nnavigation. *Diffuse sources* include: urban and agricultural run-off, forestry, transport, erosion of contaminated land or abandoned industrial sites, discharges not connected to a sewerage network, atmospheric deposition, aquaculture.

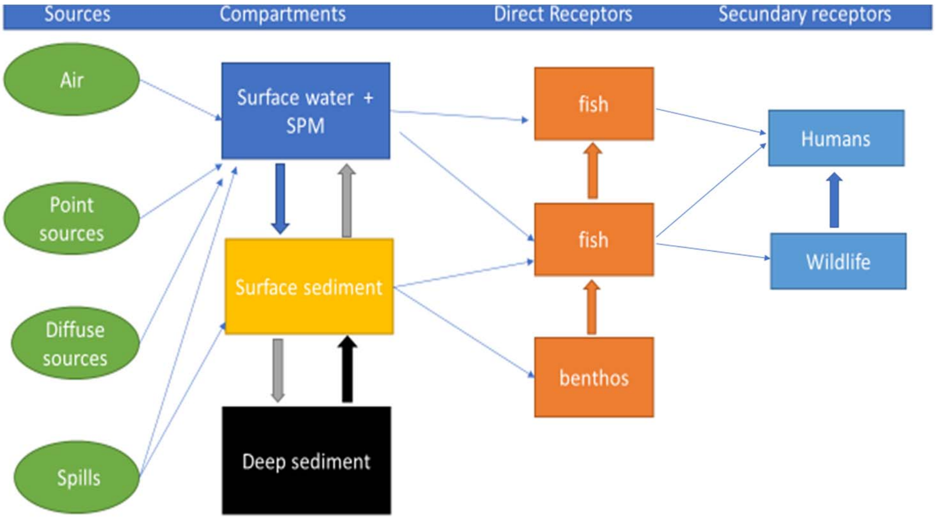

Figure 3.1. Pathways of contaminants from source to receptors (SPM = Suspended Particulate Matter) Note: direct link of spills to Surface sediments in case of dredging spills.

Case study 3.1 - Elbe basin: contaminant sources, provides an overview of the status of a river basin where present day contamination is largely derived from historical sources. Organic pollutants such as DDT, HCB and PCBs, are predominantly derived from the Czech Republic. Metals and the metalloid As, but also PCDD/F and HCH originate in Germany mainly from Elbe important tributaries like Mulde and Saale. Hamburg is still primary source region for TBT and derivates. (see annex A)

Case study 3.2 - Rhine basin: contaminant sources, provides another example of a river basin where present day contamination is largely derived from historical sources. The lower, older and more contaminated sediment layers may partly remobilize by floods or by dredging. Then the sediment associated contamination is transported with the flow of water and will impact downstream river sections. (see annex A)

3.3.2 Contaminant association to sediments

Contaminants and nutrients entering surface waters can associate to particles and thus can be found in suspended and bed sediments (Ch.1, Section 1.4). This association means that sediment can act as a sink or a source for contaminants and nutrients, depending on the hydrological and chemical conditions. The form in which contaminants are or become associated to sediments may be an important influence on their subsequent fate and impact. Contaminants may be reversibly adsorbed to sediment particle surfaces, be occluded within particles, or be present as mineral phases (for example, in the case of metals entering surface waters from historic mining locations). Contaminants that are reversibly adsorbed are more likely to pose a threat to biota in the water column since they are susceptible to re-release into the water phase if hydrological and/or chemical conditions change. Contaminant form may also change within bed sediments. The most studied and pertinent example of this is the formation of sulfide precipitates by many metals, including cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), in anoxic sediments. This change in form has a significant influence on the bioavailability of these metals, but, as is the case for many changes in form, is at least partially reversible if conditions change, for example, by the exposure of anoxic sediments to oxygenated water during dredging.

The contaminants that are known to associate to, and thus are usually found in sediment are: metals such as Cd, Cu, chromium (Cr), mercury (Hg), Pb and Zn as well as organic pollutants including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organochlorine pesticides, dioxins and furans (PCDD/F), and organometallic compound such as tributyltin (TBT). Nutrients, particularly phosphorus, contaminants of emerging concern (e.g. PFAS, Drugs, alkylphenols) and (micro) plastics can also associate to sediment (see e.g. Thiebault et al. 2021, Fenet et al. 2003). In addition, there may be specific regional concerns that lead to contamination of water bodies, such as the accumulation of Hg, dioxins and PCB-containing fibre sediments near paper mills, see the Fiberbanks case study in section 4.6 and in annex A.

Many of these contaminants are on the priority substances list of the WFD (2000/60/EC). In addition, there are river basin specific pollutants and other potentially relevant contaminants of emerging concern, which must also be addressed. For such contaminants, the EU member states and river basin authorities are responsible for their assessment and denomination of relevance, but in most cases the same effect mechanisms and potential measures apply.

CIS guidance no 25 discusses the details of contaminant monitoring in sediment. An important property of many chemicals is their preference for the solid phase. A poorly soluble compound is more likely to adsorb to sediment particles. The (log) octanol-water partition coefficient (K_{ow}) is a good predictor of the partitioning potential of organic contaminants between water and solid phase. Substances with a relatively high log K_{ow} (i.e. $\geq$ 3) are hydrophobic and thus may concentrate in sediment (CIS Guidance no. 27). Consequently, a log K_{oc} (organic carbon-water partition coefficient) or log K_{ow} of ≥ 3 is used as a trigger value for sediment effects assessment. Some substances can occur in sediments even though they do not meet these criteria so, in addition, evidence of high toxicity to aquatic organisms or sediment-dwelling organisms or evidence of accumulation in sediments from monitoring, would also trigger derivation of a sediment EQS. For saltwater environments it should be acknowledged that salinity has been reported to influence the water solubility of organic chemicals entering marine ecosystems. Salinity appears to generally decrease the water solubility and increase the potential for sediment association (Saranjampour et al., 2017). Table 1 of CIS guidance no 25 lists the priority substances listed in the 2008 version of the EQS Directive and gives an indication of the preferred monitoring matrix, differentiating between sediment, biota and water. Also, the 2013 version of the EQS Directive includes a list of sediment/biota relevant substances.

Various types of processes play a role in sediment contamination, from the association to organic matter in suspended particulate matter (SPM) to adsorption by clay minerals, as well as in their redistribution, through biotic and abiotic exchange processes at the interface with the water column (Li et al., 2000; Santschi et al., 2001; Spencer and Macleod, 2002). Contaminants in water enter the sediment compartment by deposition or adsorption, often in association with organic material. They can re-enter the water column by desorption or resuspension. The driving forces for these processes are bioturbation[31], scouring and transport movements. Some solid material remains in the water column as SPM. In general, the finer the particles, the larger the active surface, and thus the higher the concentration of specific contaminants that associate to such a surface, such as metals. These finer particles also stay longer in the water column, deposit less easily and are thus more easily transported by the water flow.

Bed sediments are often considered to be sinks for contaminants. Contaminants are most likely to remain associated to bed sediments over time if the latter remain undisturbed. In zones of net sediment deposition, historically contaminated sediments may become 'buried' by deposition of uncontaminated sediment, reducing the risk of chemical or physical remobilization and of impacts on aquatic organisms. However, changes in hydrological and/or chemical conditions in the water column can induce physical and/or chemical remobilization of contaminants. Examples include resuspension of bed sediments due to dredging or under

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[31] the disturbance of sedimentary deposits by living organisms

high flow conditions such as storm events, or via biotic and abiotic exchange processes at the sediment-water interface in response to a chemical change in the water column (Li et al., 2000; Santschi et al., 2001; Spencer and Macleod, 2002).

In several cases across Europe where the supply of contaminants into surface waters has ceased due to reduction or complete cessation of emissions, contamination in bed sediments may persist as a legacy (Croudace et al., 2015). Hence, in locations with a long record of sedimentation, sediment cores reflect the history of the pollution in a given river basin. This 'legacy of the past' is hidden at the bottom of rivers, behind dams, in lakes, estuaries, seas and on the floodplains of many European river basins (Salomons and Brils, 2004). In other cases, the supply is still active for both the continuation of polluting activities and the presence of waste materials as secondary sources, for example, in disused mining sites where large amounts of mine residues are still subject to weathering.

Many of the considerations already noted apply to the association of contaminants with sediments in transitional and coastal waters. Sediment-associated contaminants in these environments will be transported according to the specific fine sediment dynamics of the environment (Section 1.3.1). For saltwater environments it should be acknowledged that the physico-chemical characteristics of saltwater show important differences compared to freshwater environments. For example, seawater is characterized by a higher ionic strength and the observed gradients in abiotic factors such as chlorine content e.g. have consequences for the speciation and hence bioavailability of metals (MERAG, 2016). For example, adsorbed cadmium may transfer into the dissolved phase due to its strong association with the chloride ion, while many neutral organic compounds are subject to the 'salting out' process, which increases their adsorption to sediments (Turner, 2003).

3.3.3 Downstream transport of sediment associated contaminants

Most of the time the bulk of sediment remains on the river bed or deposited on flood plains. However, the conditions at the very same site can in turn vary over time. The underlying processes are explained in sections 1.2 and 1.3. Bioturbation and diffusion processes can cause release of contaminants into the overlying water. Remobilized, contaminated sediment, especially the fine sediment that contains the majority of the contaminants, may be dispersed, resulting in an uncontrolled downstream transport of the contaminated material. This process may repeat itself over hundreds of kilometers (in the largest river basins), leading to an accumulation of contaminants in sediments when further contamination sources are passed. Over time, a significant proportion of the riverine contaminant burden may enter transitional waters and ultimately, the coastal and marine environments. However, the flux patterns of sediments, and thus of sediment associated contamination, within estuaries are complex and site-specific (Chapter 1, Section 1.3.2), so it is always important to identify site-specific characteristics and use these findings to support local decision making.

Case study 3.3 - Elbe basin: downstream transport of PCBs provides an example of the long-distance transport of sediment-associated contamination within a major EU river basin. PCB concentrations in the suspended sediments reached up to 6.000 µg/kg (sum 6 PCB-congeners) which is the highest ever measured value at the Elbe Czech-German border. Up to 500 km downstream and over long periods of time critical exceedances of the German environmental quality standard (EQS) for PCB occurred. (see Annex A)

3.4 Sediment -associated contaminants affecting WFD objective achievement

Key messages

- Sediment associated contaminants can have adverse effects on aquatic organisms and thus potentially impact the attainment of Good Ecological Status in waterbodies. (Bio)availability plays a key role here and contamination is only one of the many factors affecting these organisms.
- The attribution of impact to sediment contamination needs to be based on analysis / evidences.
- Sediment associated contamination may also affect the attainment of Good Chemical Status or Potential in waterbodies, but the relationship between the waterbody chemical status and sediment contamination is usually complex.

Research on European and global rivers, and sediment-related ecotoxicological studies in general, have demonstrated that sediment associated contaminants can have adverse effects on organisms that live in, or on sediment and thus can impact benthic ecology, as well as organisms higher up in the food-chain. Exposure depends on the magnitude of contaminant concentrations, mixtures of contaminants and their interactions (synergy, antagonism, additivity), species-specific bioavailability as well as toxicity (Figure 3.2) and thus potentially impact the attainment of Good Ecological Status in waterbodies.

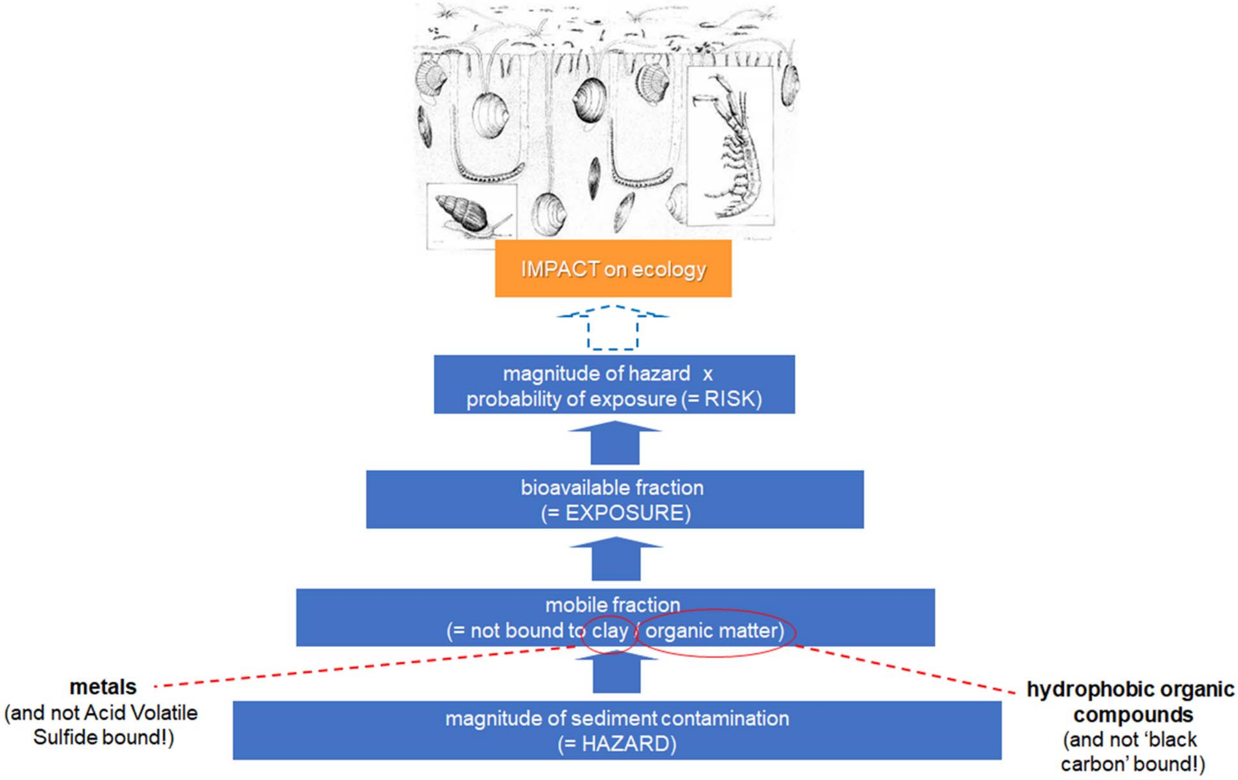
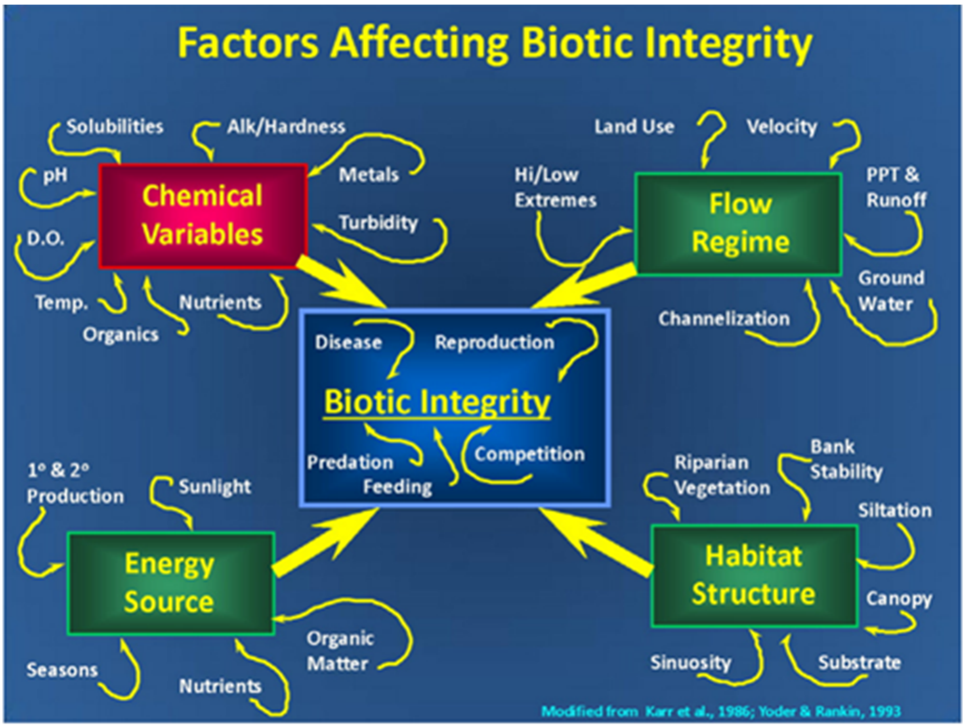


Figure 3.2. From contamination in sediment to actual impact on ecology (Brils 2019).

The potential impact of sediment associated contamination is not the only factor affecting biotic integrity (see Fig. 3.3). That integrity is affected by a variety of environmental variables, both naturally and anthropogenically occurring, or, influenced. Variables defining the existence and functioning of a waterbody itself (e.g. hydromorphology and hydraulics), and hence forming habitats for benthic organisms, are described in Chapter

2, including man-made alterations. Therefore, the attribution of impact to sediment contamination needs to be supported by evidence, as described in this Chapter.



Modified from Karr et al., 1986; Yoder & Rankin, 1993

Figure 3.3. Besides chemical variables (like contaminants) many other factors affect biotic integrity (Posthuma et al., 2016 DOI: 10.1016/j.scitotenv.2016.06.242).

For example, the abundance of certain species may decrease while other, more susceptible species may disappear completely, ultimately resulting in a decreased biodiversity. These changes in populations of species also cause indirect food web effects. Decreased abundances of prey species results in a decrease in food availability for the respective predators, which can be pelagic species living in the water column.

If substances are released from sediment to the water column, they may impact fish and pelagic organisms such as zoo- and phytoplankton. Furthermore, the direct uptake of chemicals via (pore)water or ingestion of contaminated sediment particles may lead to bioaccumulation of the chemicals within the organism, which may lead to toxic impacts. Highly bio-accumulative contaminants may show increased tissue concentrations through food chains, resulting from essentially irreversible tissue uptake of the contaminant through the consumption of ‘contaminated organisms’. This food chain transfer of contaminants (bio-magnification) may ultimately result in effects on reproduction or health of top predators, e.g. fish-eating birds and mammals such as cormorants and otters. Therefore, due to contaminant bioaccumulation in, and effects on sediment-dwelling organisms, sediment -associated contamination may contribute to disruption of the whole aquatic ecosystem because of benthic-pelagic food web coupling. In addition, consumption of severely contaminated fish (e.g. eel) or consumption of meat or milk from livestock raised on flood plains contaminated via sediment deposition during floods, could also have an impact on human health (cf. Section 1.4). There are examples of floodplains where use by livestock has been restricted due to contamination (Salomons and Brils, 2004).

Nutrients are important intrinsic natural variables of ecosystems and occur in the water phase as well as in sediments. However, anthropogenically-induced excess exceeding natural variability, causing eutrophication, is one of the main pressures affecting aquatic ecosystems in the EU. Like hazardous substances, sediments act as sink and source for nutrients. This is particularly relevant for phosphorus which tends to bind to sediment, which has accumulated over time in sediments in several EU coastal waters and lakes in particular, causing major eutrophication problems. This sediment-water coupling is a natural component of nutrient cycles influencing benthic and pelagic food webs and by that the ecological status.

Ecological status

The Biological Quality Elements most likely to be directly impacted by bed sediment contamination are those relating to organism groups that live either on, or within the sediment: the benthic invertebrate community and possibly the phytobenthos and macrophytes as well. As explained previously, impacts on either of these groups may indirectly impact other groups, and hence ecosystem integrity as a whole. Where both the bed sediment and water column are contaminated (leading to a failure of good chemical status, see following section), it is highly challenging to attribute the degree of effect that is due to the sediment associated contamination even if river basin specific pollutants are addressed. Is it key to consider that, where both sediment and water column are contaminated due to upstream inputs, reduction of such inputs is likely to reduce water column contamination more rapidly than bed sediment contamination, as concentrations of sediment-associated contaminants reduce only slowly (e.g. due to burial by fresh sediment, and by gradual release of contaminant back into the water column). Therefore, ecological impacts due to contaminated sediment may only become clear following clean-up of the water column.

Chemical status

Good chemical status for water bodies means that concentrations do not exceed any of the Environmental Quality Standards (EQSs) included in Directive 2008/105/EC (revised by Directive 2013/39/EU). Concentrations also cannot exceed national EQSs set for these substances in additional compartments, if any.

Directive 2013/39/EU prescribes surface water (inland and other waters) and/or biota EQSs for the priority substances and other substances listed (Annex II). No sediment EQSs are prescribed, although Member States may choose to derive and use sediment EQSs for these substances (Art. 3). No EU-wide sediment EQSs currently exist, although some sediment EQSs have been set at national level. Therefore, it is possible for a waterbody to achieve good chemical status solely based on surface water and/or biota EQSs.

The relationship between the waterbody chemical status and sediment contamination is usually complex. Exceedance of surface water or biota EQSs could occur due to the release of contamination from bed sediments or suspended particulate matter into the water column or via food chain transfer. However, release from bed sediments is only one of several possible sources of water column contamination. The link between bed sediment and water column contamination is complex and depends on the physicochemical properties of the contaminants. A water body may have good chemical status but have elevated contaminant concentrations in the bed sediment. Sediment associated contaminants may not be released due to the current environmental conditions (e.g. redox potential, pH, temperature, alkalinity, salinity), or they may be released at a rate that does not result in detectable concentrations in biota or the water column. The reverse may also occur: the water body may contain high levels of dissolved, priority substances that do not associate to sediment. Thus, the water body does not meet chemical quality standards, while the sediment may be relatively clean.

3.5 Sediment contamination assessment

Key messages

- According to the WFD Member States are required to establish an inventory of emissions, discharges and losses of all Priority Substances and Priority Hazardous Substances and shall also arrange for the long-term trend analysis of concentrations for priority substances that tend to accumulate in sediment and/or biota.
- Member States shall take measures aimed at ensuring that such concentrations do not significantly increase in sediment and/or relevant biota. In addition to the list of priority substances, other substances may pose sediment contamination issues, in particular the “River Basin Specific Pollutants”. The WFD requires to assess priority pollutants and river-basin specific pollutants with environmental quality standards (EQS). Exceedance of the EQS indicates a hazard and thus, potential impact on human health and the environment.
- Member States may establish, for priority substances, EQSs for sediment at national level and apply those EQSs instead of the EQSs for water set out in the Directive if it offers at least the same level of protection. It is not an obligation to establish sediment EQSs, but once established and implemented at national level, it is an obligation for sediment contamination levels to comply with these EQSs. For assessment of the actual impact of sediment associated contamination, effect-based methods, such as bioassays and pollution-sensitive (ecological) indices obtained by field inventory, may be used.

3.5.1 Overall approach

The overall, generic assessment approach for understanding the risk of sediment associated contaminants to achieving of the WFD objectives is basically to assess their sources, pathways and receptors throughout the entire river basin (see Fig. 3.1 and 3.4). In any river basin there are numerous sources of contamination (section 3.3.1) and pathways of these contaminants to and from sediment (section 3.3.2 and 3.3.3). Through these pathways the risk of these contaminants can be propagated through the basin towards (potentially) impacted receptors (Brils and Harris, 2009).

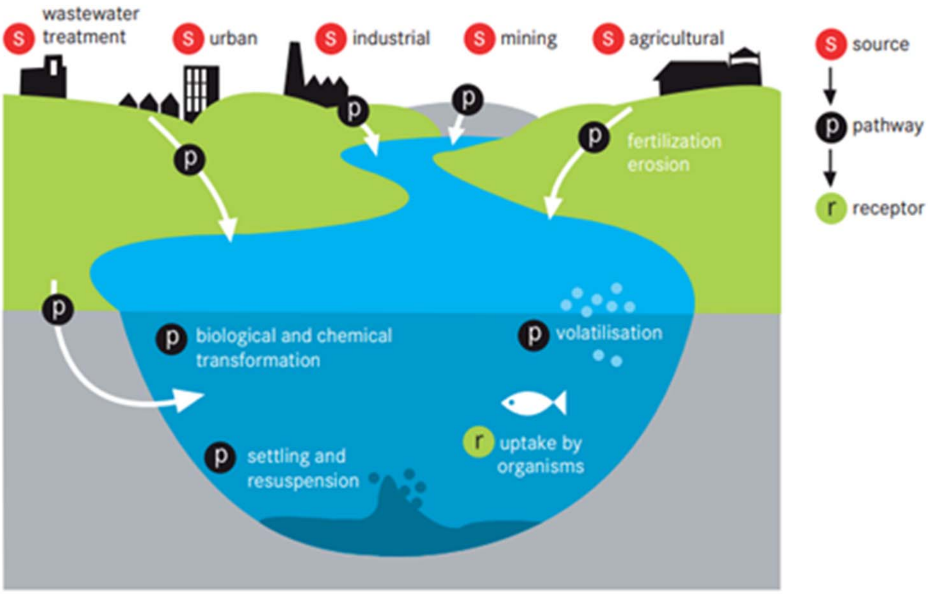


Figure 3.4. Sediment associated contamination sources (s), pathways (p) and receptors (r) (Brils and Harris, 2009).

3.5.2 Identification and prioritization of sources and pathways of contamination

According to Article 5 of the Environmental Quality Standards (EQS) Directive Member States should *establish an inventory* of emissions, discharges and losses of all Priority Substances (PS) and Priority Hazardous Substances (PHS). The 2008 Environmental Quality Standards Directive (EQSD), revised in 2013[32] lists all priority substances used to determine chemical status, as well as their environmental quality standards (EQS). The approach towards the identification and prioritization of sources and pathways of such substances includes an inventory, monitoring (including sampling), analysis and risk assessment, and these aspects are described in CIS guidance no 3, 25 and 28. The inventory may have to be complemented with Contaminants of Emerging Concern (CECs) and river-basin specific pollutants. At the time of writing, WFD CIS WG Chemicals work is currently underway to support the quantification of point sources and diffuse emissions. Documents are being drafted under CIS WG Chemicals activity, sub-group on emissions (Oct 2020).

According to the EQS Directive Article 3(6), Member States shall also arrange for the long-term trend analysis of concentrations of those priority substances listed in Part A of Annex I that tend to accumulate in sediment and/or biota. Furthermore, Member States shall take measures aimed at ensuring, subject to Article 4 of Directive 2000/60/EC, that such concentrations do not significantly increase in sediment and/or relevant biota. Member States shall determine the frequency of monitoring in sediment and/or biota so as to provide sufficient data for a reliable long-term trend analysis. As a guideline, monitoring should take place every three years, unless technical knowledge and expert judgment justify another interval.

In addition to the list of priority substances, other substances may pose sediment contamination issues. These include in particular the “River Basin Specific Pollutants”, which are other pollutants which may cause risk for the achievement of good ecological status in a specific river basin and which should therefore be listed by Member States in the relevant River Basin Management Plans, and made subject to national thresholds. There are also other substances of emerging concern that may need consideration. The instrument that is used to identify additional substances of EU wide concern is the ‘Watch List’ for surface waters. Categories of concern are certain pesticides, widely used pharmaceutical products, other metals and persistent organic pollutants (POPs). Some of these chemicals may already be of concern in specific river basins and should thus already

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[32] I.e. amended by Directive 2013/39/EU

have been identified as river basin specific pollutants by the competent authorities. These topics are under the scope of the work programme of the CIS WG Chemicals.

CIS guidance no 25 discusses the details of contaminant behaviour in sediment and the role of *monitoring* sediment towards meeting the goals of the WFD. It includes guidance for the implementation of chemical monitoring of sediments, including recommendations of general requirements to ensure fitness for purpose, i.e. decision-making (statistical considerations, data analysis, quality control/quality assurance, etc.), general and technical aspects for the preparation of sampling strategies and analytical procedures (chapter 5 of that guidance), and recommendations on spatial and temporal trend monitoring including trend analysis.

CIS guidance no 25 also includes recommendations for the selection of chemical pollutants preferred for sediment or suspended particulate matter (SPM) monitoring. SPM is considered as part of the water body and the WFD requires to analyse ‘total water’, i.e. water plus SPM. For organic contaminants, these are hydrophobic compounds with a log $K_{ow} \geq 5$ (see also section 3.3.2). For organic compounds with a log K_{ow} between 3 and 5, the choice of monitoring in sediment or SPM will depend on the degree of contamination. CIS guidance no 25 clearly distinguishes between operational (aimed at status assessment) and surveillance (aimed at long-term change assessment) monitoring. Regarding *operational monitoring*, sediment is a recommended matrix for the assessment of chemical status for some metals and hydrophobic compounds in marine and still, lentic water bodies, provided a sediment EQS is available. In dynamic, lotic water bodies, however, sediments do not often provide an appropriate matrix for status assessment because of their high variability. For the purpose of *surveillance monitoring*, sediment – or alternatively SPM and biota – are the most suitable method matrices for many substances because : they integrate in time and space the contamination in a specific water body; the changes of contamination in these compartments are not as fast as in the water column; long term comparisons can be made.

Ultimately the identification and prioritization of sources and pathways of contamination should result in an estimate of the total contaminant input, the breakdown into classes of substances and specifically for sediment, identifying those substances that are hydrophobic in nature and tend to concentrate in sediment. For pathway assessment there is also a need for sediment transport models applicable to the entire river basin, that support the investigation and prioritization of sediment contamination hot-spots. This assessment phase should result in:

- The identification in the river basin of the substances of concern i.e. that contaminate sediment;
- The identification of the zones where significant contamination is expected and/or may become a secondary source of contamination if remobilized and transported downstream;
- A listing of contaminated areas of concern with a sediment volume exceeding a certain threshold level, e.g. 1000 m^3, as applied in case of the Rhine (ICPR, 2009) as well as the Elbe (IKSE, 2014). These areas are possibly posing a risk for the ecological and/or chemical status.

3.5.3 Assessment of the impact of contamination on WFD status, including use of EQS

This section deals with sediment contamination assessment methods that are already implemented or can be readily implemented in river basin management plans. In addition, it addresses assessment methods that could be integrated and further developed.

Assessing the risks and potential impact of individual contaminants in sediment

Currently WFD demands to measure priority pollutants and river-basin specific pollutants and assessing them with environmental quality standards (EQS), which are effect-based according to CIS guidance no 27. The WFD defines EQS as “the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment.” This means that exceedance of the EQS indicates a hazard (see also Fig. 3.2) and thus, potential impact on human health and the environment.

The approach to risk assessment of sediment associated contaminants follows the general approach taken for the assessment of other environmental compartments. This is to compare measurements of the concentration of the contaminant in the compartment against one or more 'threshold' concentrations which indicate a change in the status of hazard (see also Fig. 3.2 of the system). Where an environmental concentration exceeds a threshold concentration, this should trigger further action. The degree of risk, expressed as the ratio of the measured concentration to the threshold (the risk characterization ratio, RCR), may be used, for example, to prioritize locations for more detailed analysis. It should be noted here that 'risk' does not equal 'impact' as bioavailability may be reduced in the field compared to the conditions under which the toxicity data used to derive the threshold were generated. Sediment EQSs for organic compounds are according to CIS 27 generally to be expressed for a certain TOC level (5%), but also other factors can influence bioavailability. Further investigations are needed to assess whether exceedance causes actual impacts. Nevertheless, the higher the risk, the higher the probability of impact will be.

Technical Guidance 27 describes how a sediment Quality Standard (QS) can be derived and taken into account when establishing Environmental Quality Standards (EQSs) for a contaminant. CIS guidance 27 also describes common other approaches to derive quality standards for sediment.

Different derivation approaches are available for threshold concentrations (see CIS guidance no 27). The approaches have generally in common that they are effect-based, i.e. the derived values are related to effects on biota. Moreover, many allow derivation of two concentration values for each substance and emphasize that these indicate probabilities of impact:

1. Threshold Effect Concentration (TEC) as a concentration below which adverse effects on benthic invertebrates are unlikely to be observed; and
2. Probable Effect Concentration (PEC) as a concentration above which harmful effects on benthic invertebrates are likely to be observed.

Restrictions and reservations on defining legally binding EQSs may exist due to a lack of, or uncertainty about data for their derivation. Nevertheless, Sediment Quality Guidelines (SQGs) can still be defined, unless there is a complete lack of ecotoxicity data for their derivation. SQGs may be used to identify areas of concern and to prioritize management options in RBMPs. In Europe, for example, de Deckere et al. (2011) and MacDonald et al. (2000) derived sediment TEC and PEC values for several substances (metals, PAH, PCB, DDD, DDE, HCB) as consensus values (geometric means) of two derivation approaches, the Screening Level Concentration Approach (SLCA) and the Effects Level Approach (ELA). The values have been partly incorporated into Flemish legislation and values for a few substances were included in the list of Threshold Values (TVs) of the Elbe sediment management concept (ICPER 2014; list was partially updated in 2018).

Case study 3.4 - Rhine basin: Hot-spot identification, provides an example of Sediment Quality Guidelines (SCG) in the Rhine river basin. Three assessment steps were taken to identify the hot-spots: 1) Verification of contamination by applying SQGs based on ICPR Target Values; 2) Verification of amount; and 3) Assessment of the risk of remobilization. (see Annex A)

Case study 3.5 - Elbe basin: Threshold Values, provides an example of the use of TVs (Elbe) in the Elbe river basin. A risk analysis was done for 29 relevant inorganic, organic and groups of contaminants. Lower and Upper Threshold Values (TVs) were defined and allocated to these contaminants. The risk analysis was performed in two stages: 1) Evaluation at the sub-basin level to identify the main source areas of particle-bound contaminants; and 2) Source-related evaluation within the source areas identified under Stage 1.(see Annex A)

In the MSFD assessment of environmental status of the marine environment, the use of different types of SQGs are common. Threshold values expressed for sediment have been established by e.g. Denmark, Finland, France, Germany, Italy, Malta, Netherlands, Poland, Romania, Spain, Sweden and the UK, see overview by the JRC (Tornero et al, 2019). The threshold values used are based either on the QS from EQS dossiers, US ERL (Effects Range Low) values, BAC (Background Assessment Concentration) values, OSPAR EACs(Environmental Assessment Criteria) or were developed on national level.

In compliance with the EQS Directive, Member States may establish, for priority substances, EQSs for sediment at national level and apply those EQSs instead of the EQSs for water set out in the Directive if it offers at least the same level of protection. It is not an obligation to establish sediment EQSs, but once established and implemented at national level, it is an obligation for sediment contamination levels to comply with these EQSs.

EQSs should be established through a transparent procedure (see art 3.2(d) of EQSD and CIS guidance no 27) involving notifications to the Commission and other Member States through the Committee referred to in Article 21 of the WFD in order to ensure a level of protection at least equivalent to the EQS set up at Community level. For River Basin Specific Pollutants, the WFD, Annex V.1.3.6 allows MS to choose the medium for applying the EQS, i.e. water, sediment or biota. The criteria for triggering an assessment are consistent with those under REACH Regulation. A log K_{oc} or log K_{ow} of ≥ 3 is used as a trigger value for sediment effects assessment for organic compounds (see also section 3.3.2). But some substances can occur in sediments even though they do not meet these criteria. Thus, evidence of high toxicity to aquatic organisms or sediment-dwelling organisms, or evidence of accumulation in sediments, from monitoring can also trigger the requirement to derive a sediment EQS. The procedure for the derivation of sediment EQS is described in chapter 5 of the CIS guidance no 27 and can also be used to derive sediment EQS for river-basin specific pollutants. There are in principal two different procedures, the sediment EQS can be based on data from sediment toxicity tests or, if such data are missing or insufficient, on data from toxicity tests performed using pelagic organisms (assuming equal sensitivity). In the latter case, a recalculation is made from water to sediment (based on equilibrium partitioning theory). It is acknowledged that sediment EQSs developed using the latter methodology generally involves higher uncertainties and should be considered preliminary.

Furthermore, this guidance describes how to use these values. If contaminant concentrations are below the sediment EQS the status is good. If concentrations are above a sediment EQS that is considered uncertain, more information is needed about the actual risk before concluding that the status is not good. Examples given are a Tenax extraction and/or bioassays to take bioavailability into account and the Triad approach (see Fig. 3.5).

In some cases, it should be considered that the concentrations of very hydrophobic organic substances such as PCBs, PCDD/F and mercury may be too low to impact sediment-dwelling organisms but due to biomagnification[33] they may impact predators (see also section 3.4). When sediment is the primary source of exposure for target species (macrophytes, fish or mammals), a quality standard for contaminant in sediment for such substances can be derived from the quality standard for contaminant in biota, if there is evidence for sorption potential or high toxicity for sediment-dwelling organisms (see CIS guidance no. 27 for details of how to assess this). Available exposure models range from very simple ones, based on accumulation factors from sediment to biota, to food-web models.

The chemical status of water bodies needs to be assessed under representative conditions. Clearly under extreme low water flow conditions the concentrations of contaminants may increase due to a lack of dilution. Similarly, extreme high water and flooding may result in surplus deposition of contaminants in bed sediments and/or floodplains. The WFD allows not to consider temporary deterioration to be in breach of the directive if this is the result of accidents or circumstances of natural cause or force majeure which are exceptional or

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[33] Process by which a contaminant increases its concentration in the tissues of organisms with each step in the food chain

could not reasonably have been foreseen, subject to strict criteria set out in its Article 4(6). Neither of these events will be considered to result in a breach of the WFD, even if the contamination were to temporarily cause a lower classification (art. 4(6) of the WFD). In the case of accidental spills, the question is whether the chemicals in the spill are hydrophobic or otherwise particle-reactive (e.g. metals). If such is the case the situation could lead to long-term deterioration of the chemical status due to sediment contamination.

Assessing the actual and combined impact of all contaminants in sediment

For assessment of the actual effect of the bioavailable fraction of all combined contaminants in sediment, effect-based methods, such as bioassays and pollution-sensitive (ecological) indices obtained by field inventory, may be used. The latter is already partly but less explicitly considered in some metrics for assessment of biological quality elements (BQEs) for the ecological status. However, sediment specific impact assessments are not often implemented, while the need for an integrated assessment of contaminated sediments has been recognized since the 1980s, with the development of the Triad approach (Long and Chapman, 1985; Chapman, 1990). However, work is ongoing to address this issue.

The Triad approach consists of three lines-of-evidence: sediment chemistry to determine chemical contamination, sediment bioassays to determine toxicity and ecological surveys (field inventory) to detect alteration of benthic communities (Fig. 3.5). *Sediment chemistry* has already been addressed in section 3.3.2. *Effect-Based Methods* (bioassays *in vitro* and *in vivo*, biomarkers) can be used to evaluate the combined effect of all bioavailable contaminants in sediment, including in many cases most contaminants not analysed. This is also described in the Technical Report on aquatic effect-based tools (EC, 2014). Furthermore, as described in section 5.3 of CIS guidance no 27, this can be relevant in the tiered assessment when there is an uncertainty related to the derivation of an EQS (see above). However, performing effect-based methods has a cost (financial and biological) and should be triggered by a cluster of signals of toxicity (known historical pollution, data of the sediment chemistry etc.). A *field inventory* assesses the taxonomic composition and abundance of benthic invertebrate fauna *in situ* at a certain moment in time. This relates to the WFD ecological status assessment. In that assessment some impacts of contaminated sediments on biota are captured entirely, for example, by some metrics applied on macroinvertebrate data. However, there is a lack of specific pollution-sensitive metrics, and many macroinvertebrates in WFD-data are not exclusively endobenthic and are to a large extent exposed rather to contamination in the water phase. By defining river-basin-specific EQSs for sediment at the national level, which has been done by some EU member states, the probability of impact of specific sediment-bound pollutants has been also integrated in the ecological status assessment.

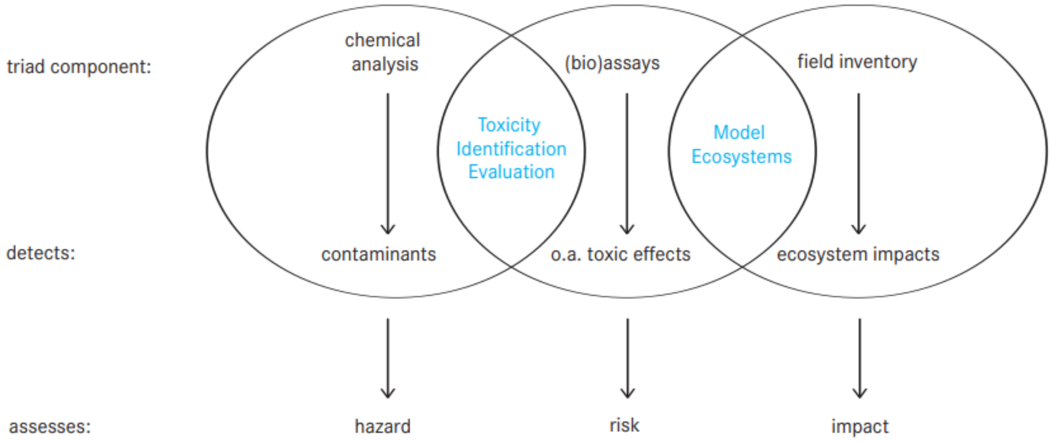

Figure 3.5. The Triad approach (Salomons and Brils, 2004).

3.6 Management of sediment associated contamination

Key messages

Sediment contamination can be managed by taking specific prevention, mitigation and/or remediation measures:

1) **Prevention**: It is easy to contaminate sediment, but once in the sediment, it is often difficult and costly to revert the situation. Thus, it is common sense to strive for no further deterioration of contamination status and where sediments are still of (relatively) pristine status, to aim for Zero-Pollution, as prevention is more effective than remediation.

2) **Mitigation**: Specific measures can be taken focusing on the pathway of exposure to reduce the mobility and thus the bioavailability of sediment associated contamination. Thus, also to mitigate the downstream transport of sediment associated contamination.

3) **Remediation**: Remediation techniques can be applied on site (*in situ*), or the contaminated sediment can be removed and transported to another location (*ex situ*) where remediation techniques are applied. Remediation techniques reduce the concentration of sediment associated contamination or reduce the effectiveness of that contamination in causing impact.

Mitigation and remediation costs depend very much on the site-specific circumstances.

3.6.1 Overall approach

The overall approach for managing sediment associated contamination for achieving WFD objectives is to start with a thorough inventory and assessment of the actual situation as described in section 3.5. If assessment suggests a need for intervention measures to manage contamination, three types of measures can be applied:

1. *Prevention*: taking specific measures at the *source* to prevent the contamination of sediment;
2. *Mitigation*: taking specific measures focusing on the *pathway* of exposure, to reduce the mobility and thus the bioavailability of sediment associated contamination. This will reduce the impact on the risk *receptors*;
3. *Remediation*: taking specific measures to reduce the concentration of sediment associated contamination, or to reduce the effectiveness of that contamination in causing impact. Remediation techniques can be applied on site (*in situ*), or the contaminated sediment can be removed and transported to another location (*ex situ*) where remediation techniques are applied. If applied *in situ* it will reduce there the impact on the risk *receptors*.

3.6.2 Prevention of sediment contamination

It is easy to contaminate sediment, but once in the sediment, it is often difficult and costly to revert the situation through remediation (see section 3.6.4). Consequently, the ‘pollution prevention pays’ principle (Royston, 1979) naturally applies to sediment. Furthermore, by dredging and thus removing the contaminated sediment from the aquatic system, the habitat and food sources for (benthic) organisms are also removed. For these reasons it is common sense to, not only for air, water and soil but also for sediment, strive for no further deterioration of contamination status and where sediments are still of (relatively) pristine status, to aim for Zero-Pollution (EC, 2021), as prevention is more effective than remediation.

Preventing the contamination of sediment requires the reduction or elimination of sources, or the blocking of the pathways of contaminants to the surface water (section 3.3.1). The terminology used by the WFD and other guidance documents for addressing contaminant input is: emissions, discharges and losses. Major point sources of contamination are usually subject to specific permits that set upper emission standards, which are subject to continuous review, and to modification according to the development of knowledge over time. Smaller point sources may have escaped earlier scrutiny. They can be detected by targeted sampling and analysis. Related to preventing contamination of point sources it is also relevant to mention that the Environmental Liability Directive (ELD) may apply (EC, 2004), for instance in case of a mine tailing dam failure (see example in EC, 2013).

Diffuse sources are more difficult to quantify, but the WG Chemicals is supporting work to develop algorithms that will provide more specific estimates. The reduction of diffuse contaminant input to the aquatic environment may involve the need to remediate contaminated soil and groundwater, change land use, the phasing out of the use specific substances such as pesticides and biocides or to identify and manage secondary sources such as products and goods from which (banned) hazardous substances can still enter the aquatic environment while still in use.

Case study 3.6 - Swedish TBT CASE, highlights the challenge but also importance to identify and manage secondary sources to prevent new sediment contamination in spite of a several decade long ban on TBT. Sediments in Swedish marinas being TBT hot spots (concentrations in sediment being several orders of magnitude higher than the sediment EQS), chemical status generally being “not good”, effects being observed and no recovery in sight, would all taken together suggest that remediation measures are needed at these sites. However, so far remediation was performed only at a few sites in Sweden. (see Annex A)

Case study 3.7 - International cooperation led to dramatic contaminant load reduction in the Elbe, illustrates that remediation and environmental protection measures in the industrial sector and the dismantling of industry in central Germany and the Czech Republic decreased contamination loads of many substances to less than one-tenth of its former maximum values. (see Annex A)

Case study 3.8 - Ban on tributyltin, provides an example of the progressive reduction of sediment TBT load in the Port of Hamburg. This reduction is due to the ban on TBT use, combined with treatment of dock wastewater and the removal of high TBT-contaminated old sediments.(see Annex A)

3.6.3 Mitigation of downstream transport of sediment associated contamination

The transport and fate characteristics of sediment-associated contamination are controlled by the transport and fate of the sediment itself (sections 1.2 and 1.3). Much of the sediment bedload and suspended load will be deposited in the lower reaches of river systems (including floodplains) due to the relatively low water velocities. Therefore, the contaminant load also concentrates here, and it is therefore not surprising to find that the contaminant concentrations in sediment are higher here than in upstream sections.

When developing specific strategies to manage the contaminated sediment in the river basin, three criteria can be used for deciding upon the management of deposition areas (areas of concern):

1. The contaminants threaten groundwater or drinking water quality or have ecological impact .
2. The sediment deposit hinders other uses (e.g. flood control, navigation).
3. Disturbances (e.g. navigation or flooding) are likely, which will cause major remobilization and resuspension.

The recommended mitigation strategy depends on which of these criteria apply and is described in Table 3.2. When considering which strategy to apply a distinction should be made between specific hot spots in the upstream river basin and the sediment deposition in or near the mouth of the river. The concerns are different for the two categories: near the river mouth or the estuary one often finds ports that must regularly remove large amounts of sediment (contaminated or not) for navigational reasons.

Table 3.2. Strategies to mitigate downstream transport of sediment associated contamination (for criteria see text, * more details on the mentioned mitigation or remediation techniques are provided in table 3.3 & 3.4).

Number of criteria that apply	Description of the situation	Recommended mitigation strategy*
None of the three	Contaminated sediment does not pose a threat to groundwater or drinking water quality or ecology, neither to human health, forms no hindrance to other uses and disturbances are not likely that remobilize and re-suspend sediment	Sediment can remain in place. Cleaner sediment will eventually settle on top of the contaminated sediment. Monitoring and re-assessment of risks may be needed to ensure the absence of effect or change on the long term.
One	The risk of contaminant release is too high (navigation, flooding, local disturbances), but the other criteria on hindrance and threat to groundwater do not apply	Local capping (see Table 3.3)
Two	There is risk of resuspension and there is a threat to groundwater or it forms a hindrance	Removal of sediment with environmental dredging techniques is an option. Environmental dredging is a form of precision dredging where specific measures are taken to prevent the spread of re-suspended material. Depending on the degree of contamination, the material should be displaced under water, deposited upland or disposed in a confined disposal facility
All three	Heavily contaminated sediment poses a threat to groundwater or drinking water quality or ecology, forms a hindrance to other uses and disturbances are likely that remobilize and re-suspend sediment	The material must be removed, and since it poses a threat to environment and health, confined disposal is necessary. There is then still the choice between providing an underwater confined disposal area or an upland disposal facility.

3.6.4 Choice of mitigation or remediation technique(s)

The mitigation or remediation techniques that can be applied to manage contaminated sediment are listed and characterized in Table 3.3 and 3.4 respectively. Of great importance are the costs of different treatment options. Simple technologies such as sand-separation and land-farming/ripening are generally slightly more expensive than disposal, while costs for stabilisation and thermal immobilisation technologies are substantially higher. But the costs depend very much on the site-specific circumstances such as characteristics of dredged material, amount of sediment, capacity of a disposal site, through-put of treatment facilities, transport and the revenues or costs for beneficial use, type of contract and legislation (see e.g. Netzband et al., 2002). According to these site-specific conditions large variations in costs occur, as illustrated in Fig. 3.6 (Salomons and Brils, 2004).

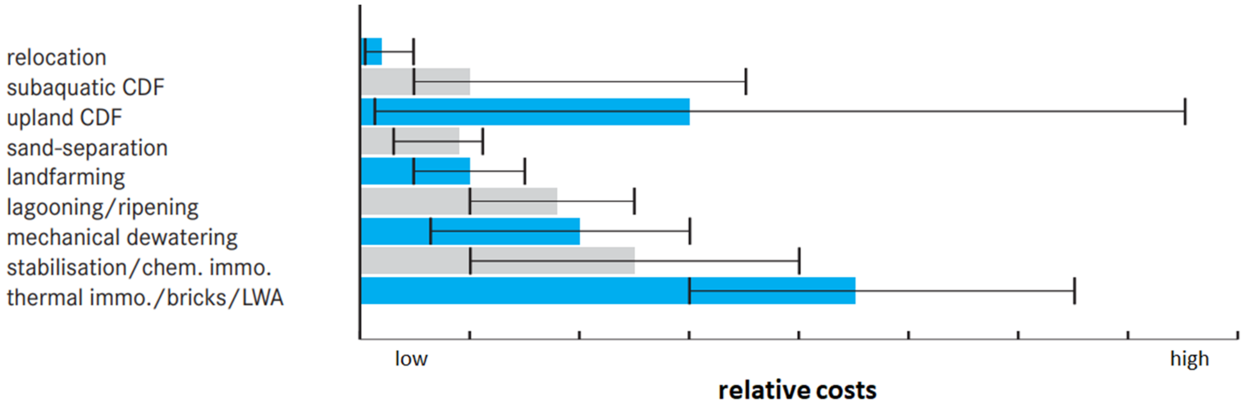

Figure 3.6. Treatment and disposal costs (Salomons and Brils, 2004). The height of the columns represents average and the bar shows the range of costs (Netzband et al., 2002). Disposal options on the left and to the right treatment options vary in wide ranges due to different boundary conditions. (Note: Revenues or costs for application of the products are not included. The costs for sand-separation do not include dewatering and/or disposal; CDF = Confined Disposal Facility; LWA=Light Weight Aggregate; chem = chemical; immo = immobilisation).

Table 3.3. *Mitigation* techniques for contaminated sediment. Indicative estimation of the Costs (see text) and Effectiveness: + = low, ++ = medium, +++ high (* estimates are indicative as Costs and Effectiveness depend very much on the site-specific circumstances: information sources used and recommended for further reading: PIANC, 1998; Netzband et al., 2002; Bortone et al., 2004; Bortone & Palumbo 2007; Spadaro, 2011; CEDA 2019a & 2019b.)

Technique	In-situ	Ex-situ	Effect-iveness	Costs	Brief description
Sediment trapping	x		++	+ / ++	Suspended matter can be brought to a specific stop by technical structures that are especially prepared for this purpose. Or this can also occur as a side effect in existing structures, such as flow control structures, groyne fields, side structures (oxbows). With both options, sediments and thus the transport of contaminants can be controlled to a certain extent.
Capping	x		+++	+	Covering (isolating) contaminated hotspots with a layer of clean sediment. This technique can be combined with physical treatment of the clean sediment (e.g. mixing with activated charcoal, clay or zeolites) thus to make the cap (re)active, i.e. capable to scavenge contaminants that may diffuse from the contaminated sediment to the cap.
Barriers	x		+++	++	Construction of an isolating structure around the hotspot to prevent dispersion.
Environmental dredging & sub-aquatic disposal	x		++	+	Precision dredging in combination with measures to prevent spreading of suspended material (turbidity), such as suspended screens around the dredging site. Dredging followed by underwater placement at a non-dispersive site, e.g. a deep pit or fjord. This technique can be combined with capping.

Technique	In-situ	Ex-situ	Effect-iveness	Costs	Brief description
Environmental dredging & upland disposal	x	x	++	+++	Precision dredging in combination with measures to prevent spreading of suspended material (turbidity), such as suspended screens around the dredging site. Dredging followed by further remediation (treatment) and then disposal upland. Note: disposal upland, especially in the context of agricultural and forestry use, must be carried out in compliance with preventive soil protection.
Environmental dredging & confined disposal	x	x	++	++	Precision dredging in combination with measures to prevent spreading of suspended material (turbidity), such as suspended screens around the dredging site. Dredging followed by disposal in a confined disposal facility (CDF).

Table 3.3. *Remediation* techniques for contaminated sediment. Indicative estimation of the Costs (see text) and Effectiveness: + = low, ++ = medium, +++ high. (The estimates are indicative as Costs and Effectiveness depend very much on the site-specific circumstances; information sources used and recommended for further reading: PIANC, 1998; Netzband et al., 2002; Bortone et al., 2004; Bortone & Palumbo, 2007; Spadaro, 2011; CEDA 2019a & 2019b.)

Technique	In-situ	Ex-situ	Effect-iveness	Costs	Brief description
Natural attenuation	x		+	+	Naturally occurring micro-organisms degrade organic compounds and/or aging of the contamination reduces it bioavailability. The effectiveness of this process may be monitored and thus the technique is called Monitored Natural Attenuation (MNA) or monitored natural/enhanced recovery). This technique may also be combined with biological and/or chemical treatment.
Biological treatment	x	x	++	++	Targeted additives are added to the contaminated sediment to stimulate micro-organisms that contribute to the (bio)degradation of organic compounds. However, if applied *in situ*, it should be assessed whether these additives have no negative effects to biota.
Chemical treatment	x	x	++	++	Specific mixtures are added to the contaminated sediment, targeted to enhance the degradation of well-defined substances of concern. However, if applied *in situ*, it should be assessed whether these mixtures have no negative effects to biota.
Physical treatment	x	x	++	++	*In situ:* The goal of physical treatment may be the binding of contaminants and/or reduce their bio-availability. This may be achieved by mixing in activated charcoal, clay or zeolites. The choice of additive depends on the type of contaminants. The method could be helpful to immobilize a range of contaminants, such as PCB's, PAH's, TBT, Hg, dioxins, chlorinated benzenes and others (*in-situ*). However, it should be assessed whether these additives have no negative effects to biota. *Ex situ:* Binders are added to physically strengthen the sediment to enhance its suitability for structural or non-

Technique	In-situ	Ex-situ	Effect-iveness	Costs	Brief description
					structural engineering use (such as infill for land reclamation) while also reducing the mobility and solubility of the contaminants. Suitable binders include hydraulic cements, GGBS (ground granulated blast furnace slag), fly-ash, lime, bentonite, calcium aluminate, super-sulphated cement, magnesium and iron oxides and activated carbon.
Phytoremediation	x	x	+	+	Plants such as hemp, pigweed and mustard are used to bio-accumulate metals and degrade organic contaminants. It is a relatively low-cost solution and has the added value of potential recovery of valuable metals from the plants. This method requires a commitment to long-term monitoring to ensure that the plants continue to thrive.
Land farming		x	+	++	Contaminated dredged sediment is disposed upland for treatment, i.e. drying and ploughing. This enhances the degradation of organic compounds.
Thermal desorption		x	+++	++	In this specialized *ex-situ* process contaminated sediment is heated indirectly in a rotary kiln to volatilize the contaminants. The off-gas is then treated separately and either discharged, collected or thermally destroyed.
Sediment Washing and Sand Separation		x	+++	+	Sediment washing separates the coarse (sand and gravel), non-contaminated fraction from silts and clays, which have the greatest contaminant absorption capacities. The sand and gravel can be beneficially re-used. The finer fractions may be further treated by organic destruction using strong oxidants, liquid-solid separation and subsequent back-end dewatering to produce a sediment filter cake end-product, which can also be beneficially used.
High Temperature Processing		x	+++	+++	High temperature rotary kilns or plasma systems operating at 1400 ˚C can be used for commercial scale treatment and beneficial use of sediments. When heated at temperatures high enough to melt sediments, the addition of modifiers/minerals creates a pozzolan. The organics are dissociated or destroyed, and the metals are immobilised in a glassy slag and pulverised to produce a construction grade/stabilised cement.

Chapter 4: Integrated sediment management planning

4.1. Introduction

Sediment management in European river basins takes many different forms, from local emergency measures not based on any planning, to regional or basin wide sediment management plans, serving several different objectives. Many of these measures and plans are directly connected with the River Basin Management Plans, but there is also a broad range of measures and sectorial plans which are triggered by uses such as navigation, flood protection, shore protection, reservoir management, drinking water or hydropower. All these measures and plans can affect water body conditions and should generally be integrated within the framework of the WFD (and/or MSFD where relevant).

As an example, a reservoir sediment management plan typically focuses on allowing the safe and efficient functioning of dams and related reservoir. A dredging plan to allow navigation is also a sectorial plan focused on ensuring good conditions for navigation. In both cases, depending on how sediments are managed, such plans can have significant effects on ecological and chemical status of water bodies, which need to be addressed. Therefore, these sectorial plans need to be contextualized in the frame of WFD. A solution to integrate these different uses while achieving the objectives of the WFD is to apply integrated sediment management planning.

In the context of this document, the term 'integrated sediment management planning' is used in the sense of a management process which promotes a holistic approach for setting objectives and measures for sediment management, consistent with WFD, taking into account all different needs, uses or policy-related objectives. It also promotes the involvement of all actors[34] and stakeholders[35] concerned by the sediment management planning processes. This principle is fully in line with the WFD concept of integrated protection and sustainable management of water.

Chapters 1 to 3 described the different concepts and methodologies associated with the management of sediment quantity and contamination at the river basin or coastal cell scale, as well as at the water body scale. This chapter (4) builds on these concepts and focuses on how to implement them in an integrated sediment management planning process, with the aim to reach the WFD's objectives. It provides recommendations and best practices, based on experiences collected from different parts of Europe.

The first sections of this chapter focus on general and transversal aspects which are important for integrated sediment planning:

- Section 4.2 - defines the concept of 'integrated sediment management planning' and describes its main benefits;
- Sections 4.3 and 4.4 - provide guidance on how to integrate sediment management planning in the WFD's legal framework, to take into account other relevant legislation and best practices to ensure consistency of sediment planning among sectoral plans;
- Section 4.5 - focuses on governance, involvement of stakeholders and transboundary cooperation which are crucial aspects of integrated sediment management planning;

The last and main section of this chapter (section 4.6) provides practical indications and recommendations on the development of an 'integrated sediment management plan' (ISMP) which is defined in the context of this document as a 'tool' to apply the concept of integrated sediment management planning. Section 4.6 proposes the ideal approach to build a 'standard' ISMP, but it should not be seen as a rigid framework as it may be

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[34] Actor: institution or organisation that are actively involved in sediment management processes or measures

[35] Stakeholder: actors and others affected by or influencing sediment management measures

adapted to the specific problems and context of concerned river basins. In particular, the logic and concepts presented in section 4.6 are also relevant when sediment is addressed as part of the RBMPs and not as a specific ISMP (see different possible approaches in figure 4.2). As an integrated sediment management plan can only be successful if well designed, implemented, monitored and assessed, these aspects are addressed in this section.

The principle of adaptive management is also covered in this chapter, as it is considered as particularly relevant in the context of sediment management, as a way to address uncertainty and complexity of sediment processes, ensure stakeholder involvement and to evaluate progress in implementing measures and achieving objectives.

The key questions that are addressed in this chapter include:

- What are the benefits of developing an integrated sediment management plan (ISMP) in the context of the River Basin Management Plan?
- What are the key steps for developing an ISMP?
- What are the main challenges met when developing and implementing integrated sediment planning? How to address them?

Key messages:

- Sediment management planning is a fundamental process that needs to be implemented as a long term task, in order to minimize the environmental impacts associated to anthropic pressures on river basins and coasts
- Adaptive sediment management is an effective way of dealing with the uncertainty and complexity associated to sediment processes
- Successful sediment management requires an appropriate governance framework and the support of relevant stakeholders
- Setting a formal framework or legal basis associated to the plan will help secure its implementation, as well as the allocation of sufficient funding and dedicated human resources

4.2. Definition and benefits of integrated sediment management planning

What is integrated sediment management planning?

As mentioned above, integrated sediment management planning is a process that enables to integrate into a consistent 'sediment management plan' the objectives of environmental policies with those stemming from socio-economic activities (e.g., navigation, flood risk mitigation, hydropower production, irrigation) taking place at the river basin or coastal cell scale. An integrated sediment management planning requires the knowledge of the basin and/or coastal-cell specific sediment dynamics, in both quantitative and qualitative terms, to allow planners a prompt understanding of the unbalances to be addressed and fixed in order to reach the environmental objectives of WFD, and/or of the dynamics of contaminated sediment, while integrating them with those of other relevant environmental directives (e.g. Floods, Habitat) and socio-economic activities.

Concretely, it means setting objectives for the main sediment-related issues identified within a river basin and defining the integrated measures necessary to attain such multiple objectives. Remarkably, the very same knowledge basis on sediment transfer at the catchment scale is needed to develop a restoration strategy for the aims of the WFD or of an infrastructure programme, navigation plan or flood risk management (see sections 4.3 and 4.4). In such a way, it is possible to comply with WFD's and the objectives of different sectorial plans (e.g. Flood Risk Management Plans, Navigation) and the measures envisaged on the sediments into a basin scale context. This information is in particular important to understand the impacts of management activities / event at the river basin scale, and to adapt them based on that. Figure 4.1 shows a map illustrating possible outcomes from an integrated sediment management plan.

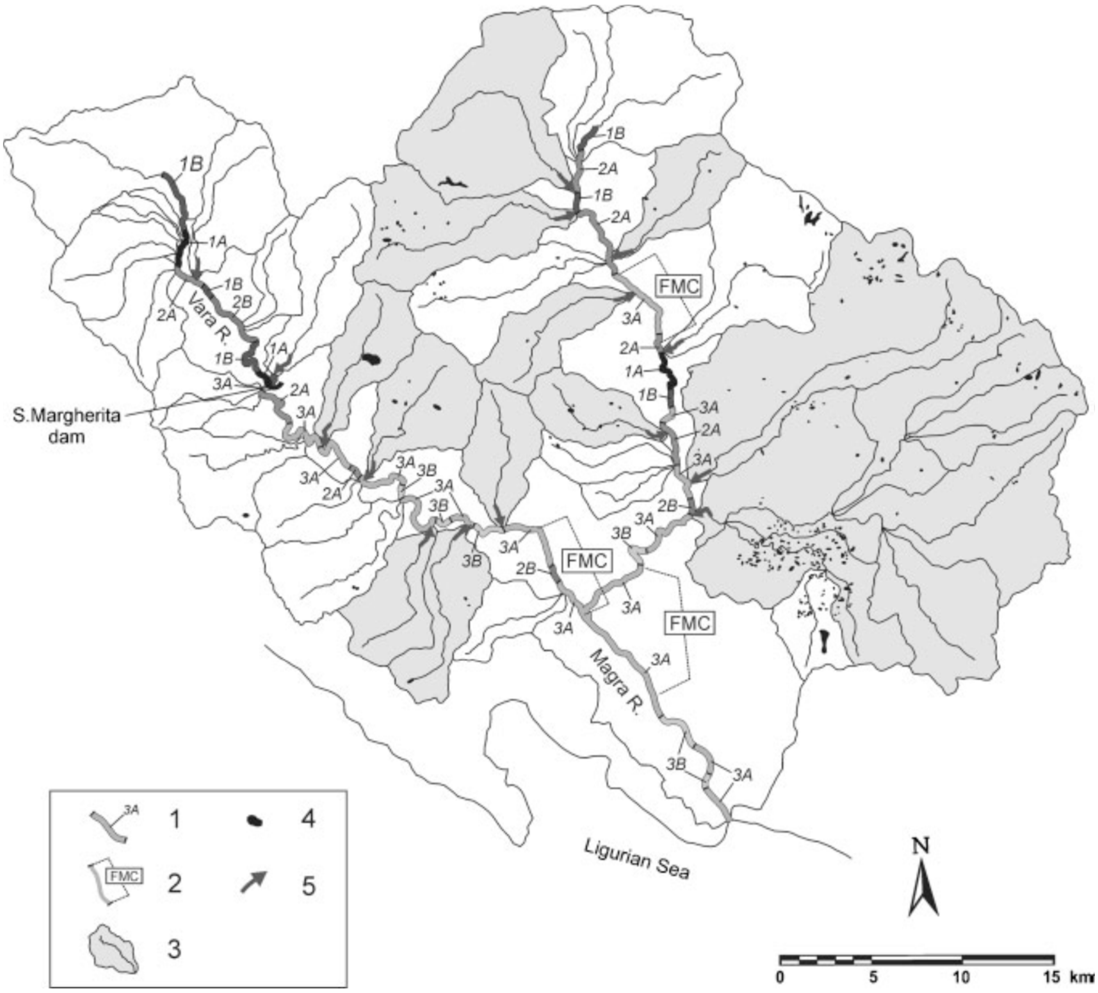

Figure 4.1: Map of strategies for sediment management. (1) Classification of the river segments.(2) Reaches where the Functional Mobility Corridor (FMC) can be promoted. (3) Sub-catchments selected for potential sediment recharge with associated actions). (4) Landslides selected for potential sediment recharge with associated action (5) Main tributaries with high sediment delivery. Source: Rinaldi et al., 2009.

How to apply integrated sediment management planning?

Integrated sediment management planning can take different forms, from a set of integrated sediment-related measures grouped and included in the RBMPs to an individual document, separated but fully consistent with the RBMPs. Whatever form it is given, it is crucial that plans' objectives and measures are consistent and completely aligned with the RBMPs, and that all the measures contained inside them explicitly consider the possible effects on/from upstream and downstream water bodies. Figure 4.2 below provides an overview of different possible approaches to implement integrated sediment management plan in relation with the RBMPs.

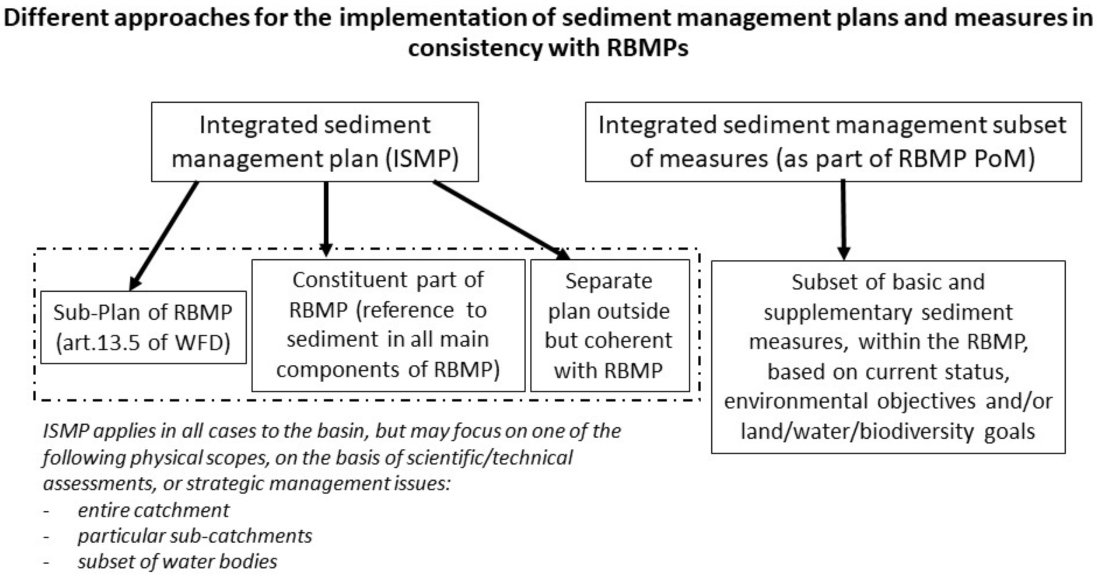

Figure 4.2: Different approaches for the implementation of sediment management plans and measures in consistency with RBMPs

It is worth to highlight that in many European river basins sediment management plans are de facto already implemented as part of international river basin commission protocols (e.g. Rhine, Elbe) in the framework of WFD. In some countries, they are legally envisaged as part of RBMPs. It is for example the case in Italy, where national legislation envisages the development of Sediment Management Plans as means to achieve the objectives of the WFD and FD (see annex A case study 2.4). The different examples and case studies presented in this document illustrate these different situations. Section 4.3 provides more details on the integration of the ISMP in the context of the WFD. It should be noted that some guidelines or guidance documents have been developed in specific Member States or river basins on the development of integrated strategies for the management of sediment (e.g. Danube Sediment Management Guidance (Habersack et al., 2020a.), Guidance on sediment management in the Sava (cf Annex A case study 4.4), LAWA position paper on integrated sediment management in Germany (LAWA, 2019)).

What are the benefits of integrated sediment management planning?

One of the first question that may arise before applying integrated sediment management planning is: what are the benefits of such approach? There are many benefits to be expected: improvement of the environmental status, adaptation to climate change, saving financial resources, integrating different uses in a sustainable way at the river basin scale, etc. One of the key aspects is that it helps planners and managers of waterbodies to share the same knowledge basis and information with all relevant actors and stakeholders, and developing sediment management scenarios whose consistency with WFD objectives can be promptly verified. In the long term (at the multi-decadal scale), such approach will lead to save resources as sediment-related problems will have been anticipated and potential damage will be avoided, also in relation to climate change impacts.

Table 4.1 aims at providing, without being exhaustive, some examples of typical sediment-related anthropic pressures, the benefits of addressing them in an integrated way, as well as the consequences of not acting to manage issues properly. The table also lists the challenges associated to an integrated tackling of each pressure. It is important to highlight once again how the lack of such integrated approach raises the risks of: i) planning measures not able to lead to the expected effects (especially if impacts at large scales are not investigated/understood), ii) not reaching agreement on the measures, and iii) consequently a lack of implementation and inefficiencies in the use of financial resources.

Table 4.1: Examples of need for holistic approach to identifying strategic level benefits of sediment management measures

Example of issues related to sediment	Consequences of not acting	Benefits of addressing the problem in an integrated way	Associated challenges	Examples of possible measure(s) as part of an ISMP (cf chapters 2 and 3 for more comprehensive lists of measures)
Sediment quantity examples				
Bed erosion due to deficit in available sediment (e.g., upstream structures trapping sediments; groynes and lateral training infrastructures facilitating rapid transport of sediment through system)	Downstream (or downdrift) erosion/incision and water level drop Loss of connectivity (e.g., dry out of floodplain, disconnection of groundwater table). Deterioration of ecological status and ground water quality) Loss of ecosystem services (e.g. reducing carbon storage) Economic impacts (e.g. reduced scope for waterway transport)	Improvement in or maintenance of ecological status, and floodplain conditions Avoid damage or disruption of water uses and associated costs (e.g by maintaining or enhancing inland waterway transport) Avoid damages (and associated costs) by protecting floodplain and/or aquifer.	Social and/or economic acceptability of removing or modifying structures to improve continuity upstream and in tributaries (especially when benefits occur in another RBD or Member State). Securing cost-effective sources / transport of material from gravel pits. applying win-win solutions	At source: remove or modify structures to restore sediment continuity upstream and in tributaries. Mitigate: sediment bypassing; adapt groynes or other structures to help stabilise river bed. Offset: sediment supplementation
Presence of structures intended to control coastal erosion which reduce sediment supply into the wider system	Downdrift intertidal areas become sediment-starved leading to ecological deterioration. Need for new structural intervention to protect downdrift assets.	Improvement in ecological status downdrift. Damage costs avoided i.e., related to otherwise necessary expenditure on habitat restoration or flood defence structures.	Social and/or economic acceptability of removing or realigning erosion control structures (especially if the benefits occur in another RBD or Member State).	At source: remove or re-align erosion control structures. Mitigate: introduce sediment bypassing measures.
Past and/or current over-extraction of sediments (for construction industry use, flood risk mitigation, navigation)	Local to catchment wide ecological deterioration. Downstream (or downdrift) erosion/incision and water level drop with associated environmental and economic impacts.	Ecological status improvement including in downstream (or downdrift) areas Damage costs avoided (e.g. cost saving related to	Securing alternative aggregate source to sustain construction. Including damage costs avoided (i.e., costs of implementing downstream erosion control measures) in the benefit-cost assessment	At source: constrain extraction. Mitigate: reduce extraction to a sustainable level.

		expenditure on downstream erosion control measures).	Social and/or economic acceptability if the benefits accrue in another RBD or Member State.	
Sediment contamination examples				
Current or potential future sediment contamination	Transport of contaminant downstream with ecological and economic consequences in areas where they are deposited. Impact on the ecology (e.g. reduced abundance and composition of benthic invertebrates; reduced breeding success of certain species) Increased costs in the treatment of drinking water Constraints on dredging and disposal of sediment (e.g. to ensure safe navigation) Restrictions on fish consumption Reduced income from tourism and recreation.	Improvement in ecological status, including in areas downstream. Costs avoided (e.g. related to otherwise necessary expenditure on dredging and disposal or treatment of contaminated sediments; on drinking water treatment) Improved options to use dredged material beneficially (e.g. for ecological enhancement) Reduced business losses or disruption (e.g., tourism and recreation, angling/fisheries) in affected area.	Applying the polluter pays principle Including damage costs avoided (e.g., costs of water treatment works or of upstream dredging and land disposal or treatment of contaminated sediments) or other cost savings in the benefit-cost assessment if the benefits accrue in another RBD or Member State.	At source: constrain the polluting activity (e.g., require counter-pollution measures; revoke permit) or in-situ capping or removal disposal/remediation of contaminated sediments.
Sediment contaminated by historical sources (mines, landfills, etc)	Chemical status deterioration. Transport of contaminated sediment downstream with ecological and economic consequences in areas where they are deposited.	Improvement in chemical status; also in downstream ecological status. Damage costs avoided (e.g. related to otherwise necessary expenditure on dredging and treatment of contaminated sediments; on soil remediation following flooding, etc.)	Identifying polluter to apply polluter pays principle Dealing with costs if a legacy issue. Including damage costs avoided (e.g., costs of physical works or water treatment) in the benefit-cost assessment if the benefits accrue in another RBD or Member State.	At source: physical works to prevent leakage. Mitigate: install water treatment.

4.3 Requirements of the WFD linked to integrated sediment management

Key messages

- Integrated sediment management plans (ISMP) and / or sediment measures are to be included in RBMP
- Objectives of ISMP should be to reach and maintain the WFD's good status / potential while providing a sustainable use of water bodies
- Apply the concept described in CIS guidance 37 in case of conflicts between reaching good status and maintaining specific water uses regarding sediment management issues
- Secure funding and apply the cost recovery principle to finance sediment-related measures

The previous chapters described the requirements of the WFD regarding sediment quantity and contamination. This section complements these by providing an overview of the requirements of the WFD which are relevant in the context of sediment management processes.

Appropriate sediment dynamics are important for achieving the management targets of RBMP. Hence, although different approaches can be followed (see figure 4.2), it is crucial to integrate sediment management measures and planning as part of the River Basin Management Plan (RBMP) (art. 13 WFD, Annex VII). Objectives and measures for sediment management must be integrated in the relevant RBMPs and programs of measures, and conversely all measures and objectives of the RBMPs should be taken into account when planning sediment related measures. In case impacts on sediment contamination or quantity are identified as significant pressures hindering the achievement of the WFD's objectives, this should be included and addressed as such in the RBMPs (Annex VII, A.2 of WFD). Recognising impacts on sediments as a significant pressure for ecosystems is crucial to trigger implementation of appropriate measures and the allocation of funding. Chapter 2 and 3 provide information and methods relevant to assess pressures on sediment quantity and contamination.

Case study 4.1: Sediment Balance Alterations proposed as a significant water management issue in the Danube 3rd River Basin Management Plan

River Basin : Danube

Author: Helmut Habersack

For the first time Sediment Balance Alterations became a Significant Water Management Issue in the 3rd Danube River Basin Management (DRBMP) (covering the period 2022-2027).

Sediment quantity in the Danube River Basin was already mentioned in the 1st DRBM Plan in 2009 and was considered as a potential Significant Water Management Issue in 2013. In the year 2019 the Danube Sediment project (http://www.interreg-danube.eu/approved-projects/danubesediment) produced two outputs as basis for the development of the 3rd Danube RBMP (Habersack et al., 2020a,b): (i) The Danube Sediment Management Guidance which provides recommendations towards an improved sediment balance in the Danube River Basin, (ii) The Manual for Stakeholders which offers assistance for sediment related actions in the Danube River Basin and future programmes of measures. Based on key findings of this project, the sediment balance alteration has been identified as a new sub-item of the Significant Water Management Issue "Hydromorphological alterations" in the 3rd Danube RBMP.

The ICPDR's basin-wide vision aims at reaching a balanced sediment regime and an undisturbed sediment continuity and to provide type-specific natural bed forms and bed material as well as a dynamic equilibrium between sedimentation and erosion. The balanced sediment regime should also enable the long-term provision of appropriate habitats for the type-specific aquatic communities and groundwater dependent terrestrial ecosystems.

An important suggestion will be the discussion of the establishment of a harmonized sediment quantity monitoring network in order to gain deeper understanding of sediment quantity related problems.

Links to relevant documents :

http://www.icpdr.org/main/sites/default/files/nodes/documents/ic231_drbmp_update_2021_draft_v10.pdf

https://www.interreg-danube.eu/approved-projects/danubesediment/outputs

In terms of governance, the WFD requires Member States to involve the public and all interested parties in its implementation (art. 14 WFD). This principle should be followed in the context of sediment planning as described in section 4.6. The WFD also requires Member States to establish transboundary cooperation (art. 13, 2. WFD), which is particularly relevant for sediment management, and should be addressed in sediment planning (cf section 4.5.3). It is recommended to integrate the ISMP in the existing governance framework of the WFD as much as possible and in transboundary bodies where relevant.

In general, it is crucial to ensure that the ISMP's objectives and measures aim at achieving the WFD objectives of good status/potential (art. 4 WFD), while integrating the objectives of other policies (e.g. MSFD, Floods Directive, Habitats Directive). Section 4.4 provides guidance to set objectives for the ISMP in line with relevant policies. This requires a good monitoring system, as described in previous chapters, which is aligned with the monitoring framework established for the WFD (art. 8 WFD, Annex V) and other policies where relevant and able to underpin updated evaluations on sediment dynamics in the catchment.

One of the main challenges in defining objectives and measures for integrated sediment planning is to integrate all socio-economic uses which interact with natural sediment dynamics, and finding solutions to reduce their impacts, in order to guarantee the sustainability of the different uses of waterbodies. Such concept aims at ensuring sustainable use of all water bodies, natural or HMWB, while protecting natural resources in the long term (art.1(b)). Sediment management planning should be undertaken in accordance with this principle.

This concept is also at the centre of the definition of Good Ecological Potential (GEP), which is the objective to be set in (heavily) physically modified water bodies where good status cannot be reached without significantly impacting existing uses or wider environment, referred to as heavily modified water bodies (art 4.3 WFD). This means that the different uses impacting sediment should be first identified and assessed. The objectives set should follow the requirements of art 4(3), and the principles set in CIS guidance n°37 which provides a methodology and guidance to define good ecological potential[36]. When developing the objectives of an ISMP, if criteria / methods have already been developed at national / local scale to define GEP, these can be the basis for the development of sediment objectives. Those criteria / methods can be adapted or improved on the basis of the knowledge gained during the ISMP process. If such criteria or methods do not exist yet and are developed in the context of the ISMP, they can be the basis to develop methodology / criteria for GEP, and subsequently applied to other water bodies. When defining such objectives, it is crucial to ensure that they do

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[36] https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/d1d6c347-b528-4819-aa10-6819e6b80876/details

not compromise the achievement of the WFD's or other environmental legislation's objectives in upstream or downstream water bodies, as required by the WFD (art.4(8)).

Planning of measures should also follow WFD's principles and requirements. In particular, it is important to assess both the process-based functionality and the cost-effectiveness of measures, as a way to select the most appropriate measures in the ISMP (cf section 4.6).

Funding of measures of the ISMP should be secured and, where appropriate, follow the principles of cost-recovery and the polluter pays principle, as required by the WFD (art. 9 WFD).

It is worth mentioning that ISMPs can contribute to improve the fulfilment of the WFD's requirements in case of new projects (e.g., related to water abstraction, flood risk mitigation) which might deteriorate the status of water bodies (art. 4(7)) of the WFD). Specifically, ISMPs can improve the integration of sediment-related considerations in other planning instruments in order to minimise the impacts of such projects. CIS guidance n°36 provides guidance on how to implement art. 4(7)[37].

4.4 Other relevant legislation: how to integrate different policies in sediment management planning

As already stated in chapter 1, sediment management is a cross-cutting issue and needs to be addressed in a harmonized way across policies. Several other EU environmental policies address the issue of sediment management directly or indirectly, including the Floods Directive, the Habitats and Bird Directive, the Marine Strategy Framework Directive (MSFD), as well as the Waste Framework Directive (see chapter 1, section 1.5.2). Several sectoral policies, either at EU, national or local level, also address different uses associated to sediment management, including navigation, water supply, power generation, irrigation, water level operation, flood protection, land drainage, urban planning, forestry, and other equally important sustainable human development activities. The WFD explicitly requires the integration of water uses which may influence sediment processes and consequently water status (cf. previous section).

Due to the central role that sediments play in shaping water bodies and sustaining aquatic ecosystems, ISMP is the appropriate tool where conflicting goals of different policies are explicitly addressed, and the best approaches to solve such conflicts are proposed. Integration of those policies in the planning process requires integrating the value of functioning aquatic ecosystems with the technical requirements associated with specific uses of the relevant water bodies, and selecting cost effective measures while considering socio-economic impacts. Sound sediment management planning is likely to bring significant co-benefits, by improving sediment conditions for aquatic ecosystems whilst also reducing maintenance costs associated with the different activities in the basin.

Some general key principles for a successful integration are listed below:

- During the early stages of the planning process, identify all policies and legislation that interact with, or are otherwise relevant to, sediment management
- Integrate all relevant policies as soon as possible in the planning process, first at strategic level, and then at the different scales
- Engage public authorities and ensure all relevant sectors and interested parties are involved from the earliest steps and throughout the planning process
- Consider the requirements, objectives and constraints of the different policies and legislations when developing objectives and measures in the sediment management plans

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[37] https://circabc.europa.eu/sd/a/e0352ec3-9f3b-4d91-bdbb-939185be3e89/CIS_Guidance_Article_4_7_FINAL.PDF

- Implement as much as possible “win-win” solutions that allow to reach multiple objectives and, in particular, Nature Based Solutions (e.g. restoration of floodplains as a way to reduce flood risks while restoring the lateral transport of sediments)
- Align all relevant policies’ instruments with the objectives and measures set out in the sediment management plan, to avoid incoherence
- Set as a pre-requisite that individual project authorisations, or funding decisions, related to uses that may impact sediment, should be in line with the objectives and measures set out in the sediment management plan.
- Communicate well on the objectives and measures of the ISMP and in particular on their benefits, both with the public and with stakeholders.
- Take into account the timescales of other policies when setting measures.

One of the key steps is to identify other planning instruments that may already exist in the river basin and to ensure that these are consistent with the ISMP, or, if not, to align them with the ISMP. Some examples of good practices in terms of integration of planning instruments are listed below:

- In cities, urban planning should adequately consider the hydromorphological effects of the expansion of urban plots (e.g. increased areas contributing sediment-starved runoff, leading to river erosion in urban and peri-urban channels), and the benefits derived from the adoption of new approaches to urban design and maintenance (Sustainable Drainage Systems (SuDS), urban Natural Water Retention Measures (NWRMs), sponge cities, among many others). Conversely, if an ISMP defines, e.g. an erodible corridor, this needs to be reflected in the urban planning (i.e. updating the urban development plans/mapping should be mandatory).
- Infrastructure plans may also have relevant effects in sediment dynamics, by creating specific conditions and disconnections which may modify water and sediment-related processes by inducing land fragmentation, changes in runoff direction and accumulation or modifications in soil infiltration. Design of infrastructure networks should consider land vulnerability and synergic effects, by adopting approaches which are less invasive and consider land and water.
- Forest planning should address the direct and indirect effects on sediment associated with different planning strategies. Different types of land mosaics in agro-forestry landscapes induce distinct spatial-temporal runoff patterns, and processes of sediment genesis. As such, EU-wide and national forest and agricultural plans and programmes should give priority to those land schemes which harmonize agro-forestry production with the occurrence of optimal objective-based scenarios for sediment production and transport.
- Nutrient and plant protection schemes should consider the risks associated with sediment pollution and include appropriate measures to minimise them (e.g. catch crops, wetlands, organic farming or agroecology)
- National and regional strategies and measures for the implementation of the Common Agricultural Policy should consider sediment related pressures and address them. In particular, sufficient dedicated support should be allocated to measures aiming at reducing pressures on sediment due to agricultural activities (both from a quantitative and qualitative perspective) and on the other side, support should not be given to practices which may increase such pressures. It is particularly important for this purpose to align these strategies and measures with the RBMPs and / or ISMPs, and to involve properly environmental authorities.
- Navigation plans in large river systems require a balanced sediment regime, without substantial degradation or aggradation of the channel bed. Both effects may threaten the navigability of waterways through changes of the water levels or decreasing water depths, which generally triggers

maintenance work or water structures to regulate it. However, such regulation can be detrimental to the achievement of good ecological status by disrupting natural sediment processes. It is therefore important, when planning navigation projects or maintenance, to take into account natural sediment dynamics and minimise as much as possible impacts on these. To address such conflicting goals in an integrated way, a 'Joint statement on Inland Navigation and Environmental Sustainability' was adopted in the Danube river basin to develop guiding principles and good practices to make inland navigation more sustainable[38].

- Renewable energy plans should also consider sediment transport patterns both in relation with new and existing hydropower plants, and provide appropriate solutions and measures to ensure sediment continuity, as required by the WFD. This will benefit not only the ecosystems but also to the hydropower plant itself, as accumulation of sediment upstream dams can have negative impacts on energy generation.
- Integration of the WFD goals in flood risk management plans (FRMP for Flood Directive) is already foreseen. However, a specific care should be dedicated in these latter to the evaluation of sediment dynamics and to the establishment of erodible corridors, as these are vital to develop effective FRMP and integrated measures based on natural processes. Reconnecting rivers allows natural dissipation of floods and sediment loads, with recovery of habitats and ecology.

Case study 4.2: Integration of multiple uses in the Po Sediment Management Plan

Country: Italy

Author : Martina Bussettini

The Po River is the largest river in Italy, draining the widest floodplain of southern Europe (almost 48.000 km^2) thus affected by severe modifications due to the significant anthropic pressures exacerbated since the 1950', and in particular sediment mining, channelization and urbanization in river corridors. Their impact, mainly a profound incision of river bed, is still causing problems in stability of bridges and flood protection structures, in the efficiency of intakes, (i.e low flow level decreased, followed by groundwater table), habitat loss, morphological simplification and lack of sediments supplied to the Adriatic Sea coast.

Consequently, an ISMP was drafted, aiming to a sustainable management of sediment and river channel, in order to address river channel evolution towards morphological configurations of higher dynamic equilibrium and ecological value, compatibly with the sustainable uses of the water bodies (e.g. navigation) and the need to manage flood risk.

Such general objectives are to be achieved through measures that have to also account for several local criticalities, but inside the general framework of the ISMP, where the consistency with WFD is verified.

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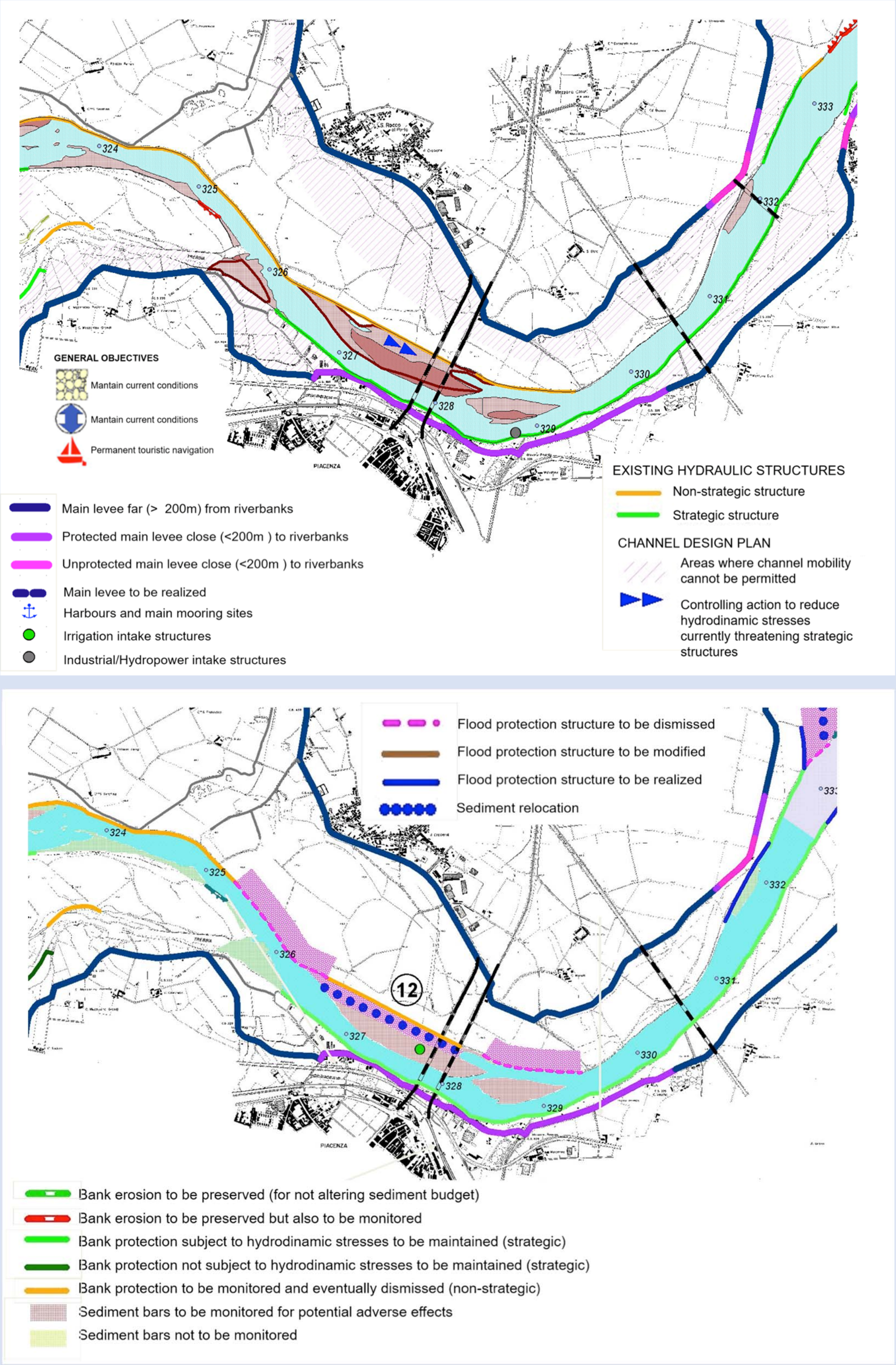
[38] https://www.icpdr.org/main/activities-projects/joint-statement-navigation-environment#:~:text=The%20Joint%20Statement%20summarises%20principles%20and%20criteria%20for,infrastructure.%20The%20%60Joint%20Statement%C2%B4%20is%20a%20guiding%20document



Example of River Basin ISMP sub-map of general objectives and related types of measures. Modified from Autorità di Bacino del Fiume Po (2005) .

For more detail on sediment management planning in the Po basin see Annex A detailed case study 2.4.

4.5 Governance: responsibilities and involvement of actors and stakeholders

Key messages:

- Involve all stakeholders as early as possible in the process, both during the development of the management plan and during its implementation
- Ensure that all relevant stakeholders are involved and active
- Ensure good communication, dialogue between stakeholders
- Identify responsibilities and interests of the different stakeholders

4.5.1 Roles and responsibilities of the different actors involved

One of the first steps in developing an ISMP is to identify the roles and responsibilities of the different actors that are directly or indirectly actively involved in sediment management in the river basin. The development of River Basin Management Plans (RBMPs) is primarily under the responsibility of water managers and river basin authorities, which includes in particular planning all measures to reach good status and ensuring that legal requirements are enforced. They will generally be the 'drivers' of the ISMP process. However, the responsibilities associated to sediment management within a river basin have to be integrated within the implementation of the WFD, whereby several actors are to be involved. The main responsibilities associated with the most common sediment issues can be listed as follows (this is not an exhaustive list):

- Regarding **sediment transport and integrity**: maintenance of sediment transport can be shared by water authorities, water and shipping administrations (in relation with maintenance work to maintain water depth), or possibly other water users.
- **Management of weirs and dams** including the bypassing of sediments is under the responsibility of the owner or operator of the structures – e. g. water authorities, water and shipping administration, hydropower companies.
- In relation with **human-derived lack or excess of sediment supply to rivers**: different types of land use activities are relevant, thereby, stakeholders can include urban planning authorities, civil protection agencies, agriculture and forestry authorities, farmer's organisations.
- Regarding **sediment contamination**: relevant organisations to be involved include the industry (including mining), farmers' organisations, water companies (wastewater discharges), urban authorities (surface water discharges), highway authorities (discharges from roads).

4.5.2 Involvement of stakeholders

Sediment management is associated to many different uses. Ensuring involvement of key stakeholders, good dialogue and interactions between them is therefore crucial. The engagement and involvement of stakeholders in the ISMP process can bring benefits such as the enrichment of the process with different perspectives and objectives, with information and data, as well as support and commitment for the proposed sediment management measures. Ensuring a good dialogue and communication with all stakeholders is therefore important. This can help in particular finding solutions in case of diverging objectives. Stakeholders have to be involved early enough to contribute to the development of the ISMP in a meaningful way. Stakeholder involvement can also be seen as instrumental in opening up the policy-making process, making it more transparent and understandable for everyone (more ideas, more solutions, using a common language, communication, endorsing local considerations, etc.), or in helping developing ownership on the outcomes of the process.

It is therefore important to identify all stakeholders and their role / responsibility in relation with the ISMP. These stakeholders can be classified into 3 main categories, depending on the spatial scale:

1. **Policy makers and public authorities**, including: politicians (national, local), public water authorities and agencies, other relevant regulators.
2. **Economic actors** in different **water user sectors**: hydropower, other energy sources, dredging, sand and gravel extraction, navigation, agriculture, drinking water, tourism/leisure activities, fisheries, industries.
3. **Citizens** (community members, etc.), & **NGOs** (e.g. environmental, social, cultural).

After being identified, relevant stakeholders have to be involved. There is no 'one-size-fits-all' solution for such involvement: it should be addressed on a case-by-case basis considering the context and local constraints. Involving all stakeholders might not be practicable in some cases, in particular for strategic or large scale planning as there may be too many, and not all stakeholders necessarily need to be involved to the same degree at this step. Stakeholder involvement can be done with different degrees of participation, depending of the spatial scale: informed, consulted, role as adviser or even co-producers of the plan. To support the process, it is recommended to identify and build on existing consultation structures or committees if such organisation exist at the appropriate scale – in particular, existing governance structures for the WFD.

Stakeholders' involvement can be more challenging in transboundary river basins. International river basin commissions should be involved in this case, or established if they do not already exist (cf section 4.5.3). Stakeholders should be involved in all steps of the ISMP: from its development to its implementation. The aim ultimately is to agree on the diagnosis, and to develop integrated, sometimes multi-organisational, solutions to solve them, taking into account different stakes. This involvement should be adaptive according to evolving conditions and changing stakeholders (e.g. new activities). Clear roles and responsibilities should be set for all stakeholders during all phases.

Case study 4.3: Stakeholder involvement in the Elbe (Germany) in the context of the 'Overall concept Elbe' and 'Forum Tideelbe'

In the Elbe, specific structures have been put in place to involve stakeholders in the river management of the Elbe:

- The Overall concept Elbe[39] is a project which involved public authorities and stakeholders, to set the principles and objectives for the integrated management of the Elbe river, upstream of the Geesthacht weir, focussing on sediment management to mitigate erosion and integrate different uses with the need to protect natural areas, in line with the WFD and Habitats and Bird's Directives. Rules of procedure and binding bodies for cooperation have been developed at executive and working level.
- The Forum Tideelbe[40] which is a structure of cooperation between relevant states, the federal government and relevant public authorities and organisation, to organise a structured and technically oriented dialogue and promote the sustainable development of the Tidal Elbe, taking into account navigation and nature protection.

For more detail, the detailed case study is presented in annex A.

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[39] https://www.gesamtkonzept-elbe.bund.de/Webs/GkElbe/DE/Home/home_node.html; https://www.ikse-mkol.org/fileadmin/media/user_upload/D/05_EU-Richtlinien/IEF/2019/WFD/IEF_20190409_04_Gabriel.pdf

[40] https://www.forum-tideelbe.de/

4.5.3 Transboundary cooperation

Transboundary cooperation as defined in the WFD (art. 13) is generally well established within the framework of international river basin commissions. Transboundary cooperation is important for international basins as sediment transport and contaminants should be addressed at the scale of the entire catchment. Regarding sediment management, there are several examples of transboundary cooperation already in place in several river basins in the EU (see summary box below). In the context of these cooperation frameworks, agreements on management objectives and/or measures for sediment management have been adopted in several river basins (e.g. Danube, Rhine, Elbe). This has led to increased cooperation on this topic, and to the implementation of a range of measures.

There are still some challenging issues that need to be addressed at transboundary scale to reach the objectives of integrated sediment management, both related to inputs of contaminants and transboundary sediment contamination, and to sediment quantity issues, as well as emerging concerns. Such challenges include in particular addressing pressures originating from other countries (e.g. upstream in the river basin). This can in particular be made more difficult by the fact that identifying the source of a pressure can be sometimes challenging. Transboundary agreements and cooperation can help in this context (see box 4.1), as well as International River Basin Management Plans (art. 13 of the WFD).

Box 4.1: Sediment management planning in the context of international river basin commissions (see Case studies 4.3 and 4.4; Annex A)

Danube: Within the last years a lot of research and planning has been performed on sediment quantity (Interreg DTP project "DanubeSediment") and contamination (Interreg DTP project "SIMONA") at the Danube river basin scale. The results are implemented for further activities into the ICPDR Danube river basin management plan update in 2021[41], which includes sediment balance alteration as a significant water management issue.

Elbe: The Sediment Management Concept of the ICPER (2014)[42] underlines that contaminated sediments and unbalanced sediment conditions are among the main reasons for the failure to meet the WFD management objectives. For the first time, an integrated sediment management concept was developed in support of management planning in a large international river basin (see Annex A; case study 4.3). Work is now ongoing to put the concepts of this plan into practice[43].

Rhine: The International Commission for the Protection of the Rhine (ICPR) published in 2020 a report on the implementation of the 2009 adopted sediment management plan[44] and new relevant sedimentation areas. In addition the 16th Conference of Rhine Ministers in Amsterdam on 13 February 2020 adopted a new, forward-looking 'Rhine 2040' programme[45] with specific goals for sediment contamination and quantity:

1. Implementation of the measures identified in the ICPR Sediment Management Plan by 2025 and transparent communication in the event of implementation problems;

2. Examination of the updating of the Sediment Management Plan in close coordination with the planned work on the water type-specific sediment balance.

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[41] http://www.icpdr.org/main/sites/default/files/nodes/documents/ic231_drbmp_update_2021_draft_v10.pdf

[42] mkol.org/fileadmin/media/user_upload/E/06_Publikationen/01_Wasserrahmenrichtlinie/2015_ICPER-Infomation-Sheet_Sediment.pdf

[43] https://www.ikse-mkol.org/extranet/arbeitsgruppen/wasserrahmenrichtlinie-wfd/sedimentmanagement/workshop-2021

[44] https://www.iksr.org/en/public-relations/documents/archive/technical-reports/reports-and-brochures-individual-presentation?tx_news_pi1%5Baction%5D=detail&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Bnews%5D=637&cHash=a5e69425f182761caf76e17e7c0c9f3d

[45] https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Sonstiges/EN/ot_En_Rhine_2040.pdf

Sava: A program for the development of a sediment management plan in the Sava river basin was accepted at the 55th Session of the ISRBC (29-30th September 2020)[46]. The adopted protocol emphasizes the importance of sustainable sediment management to maintain the water regime. It promotes active international cooperation to enhance appropriate policies and to coordinate and reinforce action at all appropriate levels. The aim is to promote sustainable sediment management related to quality and quantity, and to promote solutions which carefully balance the socio-economic and environmental objectives within the whole Sava river basin (see Annex A; Case study 4.4).

Case study 4.5: The sediment management strategy in the Scheldt estuary, an example of international cooperation

Author: Volker Steege and Frederik Roose

The long term sediment strategy in the Scheldt estuary, which is under development by the Flemish-Dutch Schelde Comission (VNSC)[47] is an example of transboundary cooperation in coastal and transitional areas. This strategy focuses on the maintenance of reference coastline and coastal foundation (nourishments) and the maintenance of navigation channel (dredging and depositing), in the framework of adaptation to climate change (sea level rise) and improvement of habitats (Habitats Directive), in line with the requirements of the WFD and MSFD. The programme includes pilot projects, monitoring and research.

4.6 Integrated sediment management plan development and implementation

Key messages:

- Overall objectives related to sediment quantity and sediment contamination at the river basin scale are to be defined first; objectives at smaller scales follow by implementing a scaling approach, to reflect the hierarchical dependency of smaller on larger scales (including individual water bodies)
- Consider both sediment quantity and contamination goals together in a consistent way
- Characterisation and analysis of the system form the foundations of an ISMP. Objectives and measures should be based on a good understanding of processes at river basin scale, as well as an analysis of the problems and cause / effect relationships
- Measures identified to manage sediments must comply and explicitly refer to the objectives defined for the river basin and each single water body
- When designing and selecting measures, follow the principle of addressing problems at the source and of the mitigation hierarchy (avoid, mitigate, compensate)

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[46] http://www.savacommission.org/dms/docs/dokumenti/documents_publications/basic_documents/protocols/program_sava_sediment_management_plan_final.pdf

[47] https://www.vnsc.eu/agenda-voor-de-toekomst/sediment/

- An ISMP can only be successful if well implemented, monitored and evaluated. Allocate and secure sufficient human and financial resources over a long term to the ISMP, a formal framework or 'legal basis' to secure its implementation, and ensure its objectives / measures are fully integrated and aligned with all relevant legislations and planning instruments (including environmental and sectorial).
- Align the ISMP with the WFD legal timeframe and set management objectives and processes on the long term
- Identify responsibilities, and involve stakeholders and the public early in the process
- Apply the principles of 'adaptive management'

This section introduces and describes a conceptual framework to help river basin managers develop and implement 'Integrated sediment management plans' (ISMP) in the context of the WFD (cf section 4.2 for the definition of ISMP).

The proposed framework, described in figure 4.3, was elaborated on the basis on previous experiences of sediment management plans development. It lists the main steps that are generally followed when developing such plan. This chapter describes each of these steps and provides references to best practices and guidance to implement them. It should be noted that depending on the context and scale of the problem, steps can be applied in a different way /order. This should not be seen as a rigid framework but more as a 'tool-box' which can be adapted to the specific contexts.

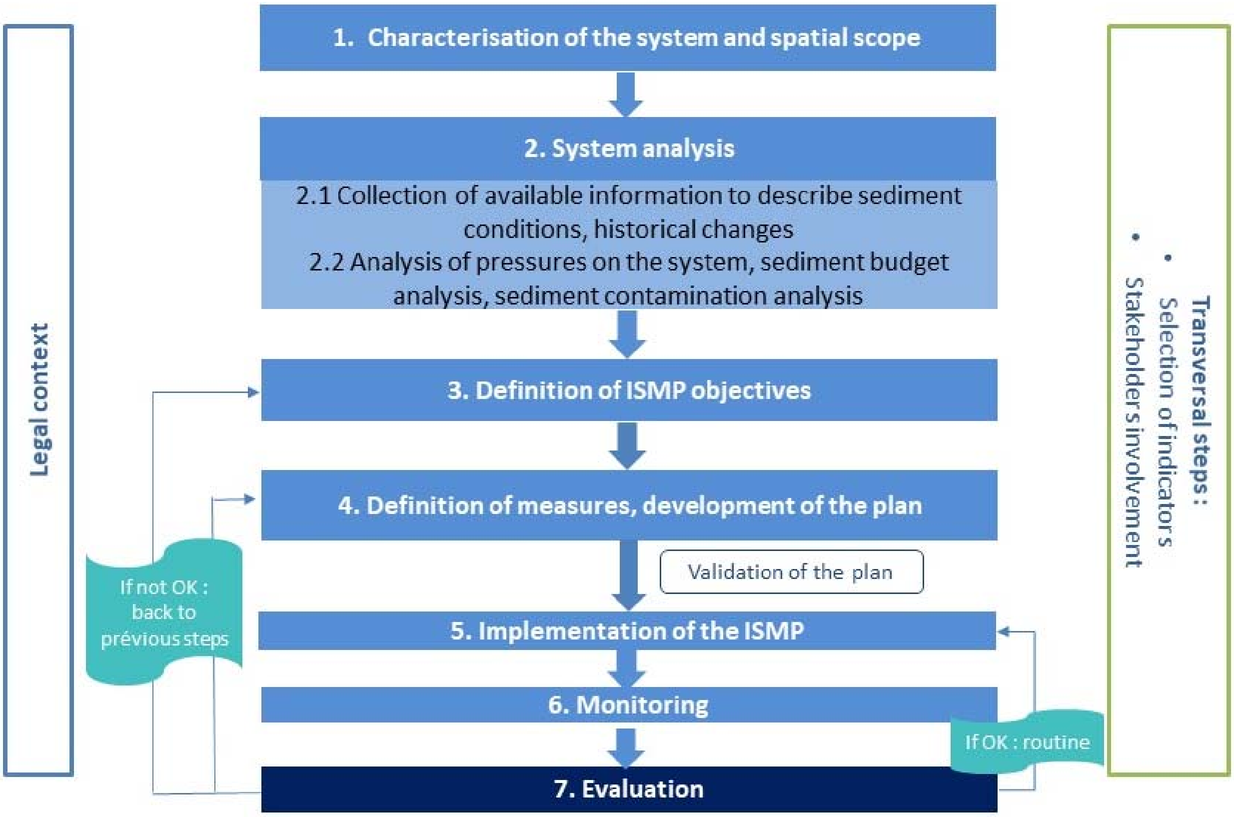

Figure 4.3: process for the elaboration and implementation of an ISMP – please note that this can be adapted based on the specific context of each planning process (Informed by Loire et al., 2020)

In order to address the complexity and uncertainty inherent to sediment processes, this framework builds on the concept of 'adaptive management', which provides tools and methods to take decisions in this context, while offering the possibility to adapt objectives and measures, if necessary, in later stages of the process. It is important to note that, as explained in chapter 1, sediment processes depend on many parameters and conditions, including on the geological setting, present geomorphological characteristics, as well as on past and current human pressures present in the river basin/coastal water bodies. All these aspects make actual sediment characteristics and transport regimes highly specific. Therefore, the aim of this section is to help river managers address these specificities by providing the general approach and examples of methods and tools, but it does not provide 'one size fits all' solutions.

Box 4.2: The legal context

The legal context is defined here as the different legislations that trigger, influence or may impact the ISMP. This includes both environmental and sectorial policies. Understanding and describing the legal context is crucial before starting to develop an ISMP, as it will determine the goals and relevant sediment management measures as well as the legal context in which ISMP stands. The legal context also determines what general sectorial information is needed to develop the plan and the competent authorities and stakeholders which will be involved, each in their own role, all along the planning cycle. Sections 4.3 and 4.4 provide more specific information respectively on the requirements of the WFD with regards the ISMP, and on interaction between sediment planning and sectoral policies.

Transversal steps

Selection of indicators

The selection of indicators is an important aspect of the different steps of an ISMP. The term ‘indicators’ is used in its broad sense and thus includes not only the indicators used for the WFD monitoring / assessment, but also more broadly other types of indicators that can be useful in this context. It in particular includes:

- Indicators focusing on sediment quantity, transport and contamination and their impacts: hydromorphological parameters, deficit / surplus, sediment and water contamination, biological responses (for ex: spawning success on gravel banks), etc.
- Indicators focusing on uses and management activities (for ex: flushing of reservoirs, agricultural practices, dredging activities, amount of bed load addition, pollutant inputs, etc).

Indicators can serve the following purposes:

- Characterise the system / water body: sediment deficit / surplus, composition, contamination, impacts on the biology, water quality (steps 1 and 2);
- Set objectives and goals for measures, which need to be associated to a timeline and intermediate objectives (step 3);
- Monitor progress in implementing measures and in achieving the objectives of the ISMP (steps 5 and 6);
- Evaluate the effectiveness of measures and adapt the plan if needed (step 7).

Specific recommendations and examples of indicators are provided in the relevant steps of this framework, as well as in chapter 2 and 3. In addition, some general principles for selecting and setting indicators are listed below:

- Start by listing indicators already used in the concerned river basin, coastal cell or water body, in the context of the WFD and other relevant legislation or plans. It is recommended to use in priority these as far as they are relevant in this context, and in case additional types of indicators are needed, to align them with existing indicators.
- For practical reasons, indicators need be measurable with reasonable effort and during the entire duration of the ISMP, including during monitoring and evaluation phases.
- Methodologies and databases may be developed as part of the ISMP. Responsibilities for the monitoring and for the management of databases need to be clearly defined. This implies that sufficient resources are allocated in the ISMP.

Stakeholder’s involvement

Clarifying responsibilities and associating relevant stakeholders is an important aspect of the ISMP. All relevant stakeholders have to be involved when defining objectives and measures as a minimum, but it is highly recommended to involve them already in diagnosis phases, as they can provide valuable information and data. Engaging stakeholders in early phases of the plan development can also help in addressing potential conflicts at very early stages of the process, in developing ownership of the ISMP, and agreeing on appropriate measures. Establishing a formal governance for the ISMP can be beneficial.

Detailed information and recommendations on responsibilities and involvement of stakeholders are provided in section 4.5.

Step 1 : characterisation of the system and spatial scope(s)

Key questions for this step

- What are the main characteristics of the river basin system / coastal cell?
- What is / are the most appropriate spatial scope(s) for the ISMP?
- What is / are the most appropriate scale(s) / management units to address sediment quantity and contamination problems

Key messages

- Information from different sources (e.g. maps, data records, monitoring and research) is crucial to characterize the system, define the spatial units and the sediment conditions
- Using the scaling approach, starting from the river basin scale down to local scales or coastal cell areas, is essential. This is particularly relevant for sediment planning in transboundary basins
- Ideally, a basin wide sediment management plan should be developed first, before addressing specific water bodies.

Characterising the system is a first important step of the development of an ISMP as it allows to understand the main issues that will have to be addressed, and based on that define the scope and scale of the plan. It will also be the basis for the more in deep and detailed system analysis (step 2). A pre-requisite for characterising the system is the availability of sufficient solid information, such as e.g. geographical, geological, topographic and aerial data, hydrography, morphological characteristics of river channels and characteristics of its sediments (see Fig. 4.2).

As explained in chapter 1 of this guidance, sediment transport and processes occur at the scale of the river catchment or river basin, and are dependent on natural conditions, on the historical context, and on pressures associated to anthropogenic or climate changes. These processes and conditions occurring at river basin scale determine the hydromorphological conditions and quality of sediments locally. This is the reason why the WFD clearly requires that sediment continuity is addressed as part of the hydromorphological elements, which implies to understand the influence from upstream reaches and tributaries on downstream reaches, and to address these interactions. It is therefore important, when managing sediments, to start understanding and addressing the problem (i.e. analysis of processes, pressures, setting of objectives) at the river basin scale (when relevant at transboundary scale), and then from this basis define operational objectives and measures at smaller scales (main river of a basin, smaller sub-catchments, smaller tributaries, hydromorphological unit, reservoir and its catchment). Lack of addressing the problem at the right spatial (and temporal) scale and addressing sediment related issues only locally risks being counterproductive as measures may not be effective or they may unwillingly affect other water bodies. In many cases sediment issues cannot be solved with individual measures at the water body scale, and measures need to be planned at the scale of the river basin.

This is a key principle that needs to be taken into account when defining the spatial scope(s) and scale of the plan. ISMP may in particular cover different scales. For example, for large river basins we may have a main basin plan defining the objectives/constraints to be fulfilled by the main tributaries (e.g. provide more bedload to the main river course, increase flood retention capacity) which would then be translated into specific objectives and measures in the related tributaries (to be included in the RBMPs, sectorial plans and / or specific ISMP where relevant).

It should be noted that this is a general principle, but that in specific cases there may be local sediment issues that can be addressed locally. This approach should be taken only if such local solutions prove not to depend on wider scale causes and/or do not have a negative impact at a wider scale.

Working at river basin scale may require to address the specificities and differences between different types of ecosystems, in particular freshwaters, transitional waters and coastal areas, while taking into account interactions between them and continuity (in particular upstream / downstream exchanges). Note that some coastal cells that are included in the delineated river basins may not exchange sediments with the river itself or adjacent coastal cells.

Defining the spatial scope of an ISMP should be done in close connection with the system analysis (cf step 2) and can be adapted during the process on the basis of the results of this analysis. Measures and monitoring of ISMP need to be taken at the most appropriate scale and adapted to the management units, defined under the WFD (river basin districts and water bodies) and MSFD (Marine Reporting Units). The following figure (Fig. 4.4) illustrates an example of a delineation of spatial units for a river basin in Italy.

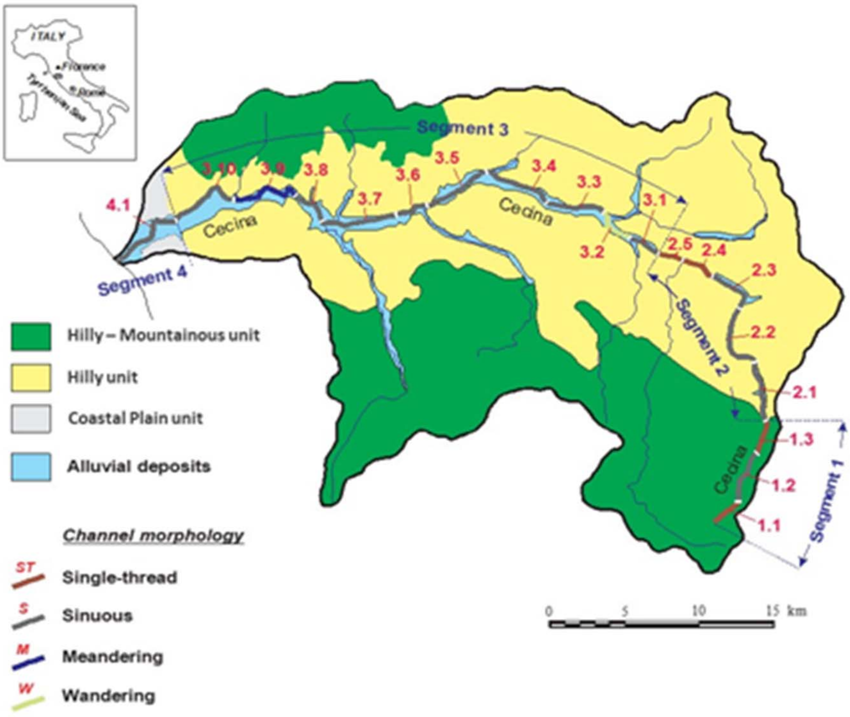

Figure 4.4 Landscape units (Physiographic units, segments, reaches) and morphological classification of river reaches for the Cecina River. Modified from Rinaldi et al., 2011.

Step 2: System analysis

Step 2.1 Collection of available information to describe sediment conditions, historical changes

Step 2.2 Deficit / surplus analysis, Analysis of sediment contamination and composition, pressures and impacts, need for action?

Key questions that are addressed:

- Which representative elements of the river or coastal system need to be analysed?
- How to identify the pressures and their drivers, and evaluate the need for action?

Key message:

- Preparatory studies form the basis for an ISMP. Planning of measures should be based on an analysis of the problems and cause / effect relationships

The system analysis is a crucial step in the development of an ISMP, as it provides the necessary information to set the objectives and measures of the plan. Specific guidance and methodologies for the system analysis and for defining indicators are provided in the previous chapters (chapter 2 for quantity and 3 for contamination), and more details can be found in the references thereby provided. This sub-chapter summarises the main aspects to be addressed for this step, and provides some guidance on relevant parameters and indicators that can be used.

The prior actions for a system analysis include:

- **Setting up a workflow:** starting with history, identification of sediment sources sinks and pathways along the catchment, boundary conditions, data needs, evaluation of the data, pressures assessment, measures and scenarios (start simple and go into more detail on this basis).
- **Setting up a check-list for information gaps**: Which data are already available? What are the knowledge gaps to be filled (e.g. sediment quantity, hydromorphology, sediment contamination, nutrients)?
- **Gathering data and information** to describe the current situation and pressures (e.g. historical, data, sources, land use, boundary situation, sediment budget)

Step 2.1 :Collection of available information to describe sediment conditions, historical changes

Key questions:

- Which information are available to assess sediment-related characteristics and dynamics?
- What is the current situation and trajectory in the river basin regarding sediment quantity and contamination? Is it reflected in the WFD status (hydromorphological, chemical, ecological quality elements) and how?

The collection of information to describe the current situation and of historic changes regarding river channel morphology, including sediments, is the starting point to define clearly what the problem is, in order to address it properly in the ISMP.

Sediment dynamics and sediment management measures act at various time scales, leading to rapid changes on the one hand and long-term evolution of aquatic systems on the other. Thus, the description of the river history, and particularly of the changes that have had an influence on qualitative and quantitative sediment state as well as hydromorphological and ecological status of the water body, can provide crucial information to assess the level of disturbance of the system, compared to 'undisturbed' conditions. It also informs on the causes of disturbance. Historical analysis allows to establish the current state of sediment dynamics and their causes, identify pressures and set management objectives. Chapter 1 - Section 1.2 and 1.3 – describe the importance of long-term developments for i) river basins and ii) costal and transitional systems, respectively. The example in Figure 4.5 illustrates the results of an analysis of historic information to assess channel evolution in the Po River (Italy).

In order to define what the current situation is for sediment processes, it is necessary to first identify and map the portions of the river basin to be considered (e.g. river stretches and their corridors, floodplains or adjacent hillslopes) and to characterize them in relation with sediment processes (e.g. aggraded, incised, in balance;)

and whether their morphological pattern has changed in the recent past (e.g. meandering to straight; multichannel to single-channel) – see figure 4.5. The situation of sediment of sources (e.g. tributaries; active landslides), sinks and pathways as well as the major pressures on sediments (e.g. weirs, major infrastructures) has to be mapped in order to understand how the system works and to provide information to calculate sediment budget (see chapter 2 - section 2.4.1). The relevant tributaries or coastal sub-cells can be differentiated according to their quantitative impacts on the overall system, based on sediment volume, and/or significant pollutant loads.

Also it is necessary to identify possible sources of current and past contamination, to define which contaminants need to be considered, in line with the WFD (based on the list of priority substances and river basin specific pollutants, in particular) and MSFD requirements. Chapter 3 provides specific guidance on the identification of sediment contaminants that may pose risk (See sections : 3.4 Sediment-associated contaminants affecting WFD objective achievement and 3.5 Sediment contamination assessment).

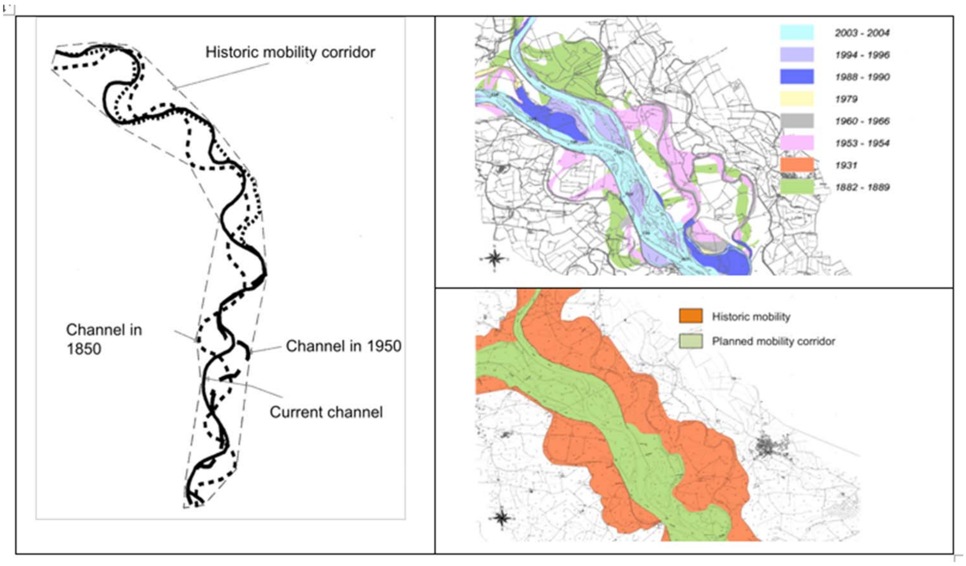

Fig. 4.5: Channel evolution (a) modified from Malavoi et al. 1998; (b) Po River channel evolutionPo River channel historic and planned mobility corridor. Modified from Po River Basin Authority, 2008.

Once the river or coastal system is mapped, the **current state of sediment** should be assessed, both from a quantitative and a qualitative perspective, and always in relation with the WFD good status/potential. If the analysis prove that, e.g. a water body is undergoing a severe sediment unbalance, the consistency with WFD status assessment should be promptly verified. The first source of data to consider for assessing the current state is to collect and analyse the information and data from the WFD's status assessment.

For quantitative and habitat aspects, the hydromorphological quality elements of the WFD are the parameters which primarily inform on potential disruption in sediment transport dynamics (e. g. aggradation or degradation), as they react more directly to such pressure, provided that appropriate hydromorphological assessment methods, i.e. considering the spatial and temporal dimensions of processes, are used. Chapter 2 describes in particular the links between hydromorphological quality elements and sediment related pressures/impacts (reference: 2.2.1 Sediment quantity in the context of the WFD), including sediment balance as well.

This assessment has to be seen in the context of the effects of river regulations and control (e.g. for navigation, flood control, energy generation), (see also chapter 1). Monitored data are very important for a proper assessment (e.g. sediment transport, river bed, floodplains; see chapter 2 – section 2.5), as well as methods that assess hydromorphological state in relation with sediment dynamics, (e.g. Morphological Quality Index, Rinaldi et al, 2013; MiMAS, SEPA 2012; Valmorph, BfG, 2017).

Regarding **sediment contamination**, data collected on the monitoring of water or sediment contamination (for priority substances, River Basin Specific Pollutants or nutrients) can also inform on potential issues as well as information of emissions of pollutants in water as data on sediment contamination may not always be available for all pollutants. Chapter 3 provides the different sources of information, which can be used (section 3.5.2 Identification and prioritization of sources and pathways of contamination).

Biological parameters are also important to consider, to detect whether aquatic species are affected by disturbances in the sediment conditions. Biological parameters sensitive to sediment-related pressures can in particular inform on such impact. For more detail on the biological responses to sediment related pressures please refer to the following sections pf this document: for sediment quantity section 2.2.1 and for sediment contamination section 3.1.2.

At this stage, an analysis of gaps in data is necessary, in order to assess whether existing data is sufficient or not for the ISMP system analysis. If gaps are identified, additional monitoring may be necessary and planned in this context, and the collected information can subsequently supplement the WFD dataset. Table 4.2 below summarises the main information that may be relevant to describe the current state of sediment. Please note that this includes parameters or information that are required by the legislation, as well as not required but that may be collected in the context of the ISMP, when relevant.

Table. 4.2: Overview of main information, parameters or indicators that can be collected to assess the current status of sediment. For more detailed information refer to relevant sections of chapters 2 and 3.

	Sediment quantity	Sediment contamination
Drivers/ Pressures	**Current and past activities having impact on sediment quantity in the water body / river basin**: water related uses (navigation, recreation, energy generation, flood or erosion control, mining, sediment extraction, nature conservation, urbanization, dredging, etc.), activities in the catchment area (land use, land cover, etc, …) **Historic changes of the river morphology**: past maps, photographs, documents, etc. Changes in processes due to **climate change**, demographic and economic developments **Hydraulic structures** (dams, weirs, levees, dykes, etc.)	**Pollutants discharged in the environment**: WFD list of emission of pollutants, other pollution inventories, identification of pollution hotspots, contamination local or widespread **Source of pollution in the water body / river basin**: agriculture, sewage treatment plants, industry, navigation, etc., information on historic pollution, contamination current or historic source
State: sediment conditions	**State of water bodies:** WFD hydromorphological quality elements (morphology, hydrology, river continuity, sediment balance alteration), if relevant MSFD descriptors. **Additional informations if not already included in hydromorphological quality elements:** bedload and suspension loads, grain size distributions of the bed and the transported material, river bed level and width changes (erosion, sedimentation),	**State at water body level**: list of relevant pollutants, WFD chemical status (monitored in water, sediment or biota), state regarding River Basin Specific Pollutants, general physicochemical elements (nutrient concentrations, oxygen, etc)

	river channel, sedimentation in floodplain, …	
Impact on the biology	**WFD and MSFD biological quality elements** sensitive to changes in sediment conditions - flora: phytoplankton, phytobenthos and macrophytes - fauna: benthic invertebrates, fish and marine mammals	**WFD and MSFD biological quality elements** sensitive to sediment contamination and eutrophication: - flora: phytoplankton and macrophytes - fauna: benthic invertebrates, fish and marine mammals
Measures already in place	Existing policies in place, action plans or measures to manage sediment quantity and/or contamination	

Case study 4.6: Assessing the level of bed incision in the Lower Rhine, example of methodology

In the lower Rhine, a standardised hydromorphological classification approach called "Valmorph" was used to assess bed level changes and assess changes in erosion rates since beginning of the 20th century. These results were used to assess the effects of management measures and to better understand responses of ecosystems.

For more detail, the detailed case study is presented in annex A.

Step 2.2 : Deficit / surplus analysis, Analysis of sediment contamination and composition, pressures and impacts, need for action?

Key questions

- What is/are the problems related to sediment quantity and contamination (sediment unbalance, river bed erosion or sedimentation)? What are the causes of these changes and do they hinder the achievement of WFD objectives?
- Is there sufficient knowledge from previous studies (cf information collected for previous steps)?
- How to assess pressures and impacts on the river system and on the ecology?
- Are measures needed to address those pressures?

Based on the information collected in the previous step, a more detailed assessment of pressures and impacts may be required in order to characterise the deficits or surplus of sediments and/or contamination of sediment and associated pathways, which hinder the achievement of the WFD and MSFD objectives. If such significant pressures are confirmed, it is necessary to investigate what are the drivers of those pressures, in order to define the management actions and types of measures required to address them.

With regards to assessing pressures on sediment quantity, chapter 2 describes the main types of sediment quantity-related problems (reference: section 2.3.1 - Types of sediment quantity related problems). This can in particular help characterising the problems encountered to better address them.

In order to answer the question "is there a deficit or surplus of sediment?", a sediment budget analysis is necessary. This should lead to a better understanding of whether there is a deficit or surplus of the expected sediments for that specific context (taking into account grain size), but should also inform on the temporal scale of the sediment processes (e.g. temporary versus continuative trend). On the last aspect, it should be noted that a deficit may be local even though there is a sufficient supply in the river basin as a whole and a deficit may be ongoing even if its causes stopped decades ago. The principles and methodologies to develop sediment budget are described in detail in chapter 2 (reference: section 2.4 - The sediment budget approach: a tool for understanding sediment in the context of the WFD).

With regards to sediment contamination, chapter 3 provides an overview on how to identify a sediment contamination problem which can be the basis for the analysis of the ISMP (reference: 3.5 Sediment contamination assessment).

The following table (Table 4.3) provides a non-exhaustive list of examples of possible parameters or indicators associated that can be used for the deficit / surplus analysis and the analysis of sediment contamination and composition. More detailed information on methodologies and approaches is available in chapters 2 and 3.

Table 4.3: Examples of parameters or associated indicators for deficit/surplus analysis and analysis of sediment contamination and composition. For more detail see chapters 2 and 3.

Indicator	Possible use to assess pressures	Example of methodology, data basis
Sediment quantity		
Suspended sediment regime and budget (ideally calculated for different size fractions)	Determination of suspended sediment transport regime Identification of major sources of fine sediment Identification of major sinks of fine (contaminated) sediments	Suspended sediment monitoring at the channel reach/water body boundaries, in case integrated with numerical modelling of soil erosion and suspended transport
Bedload transport regime and budgets (ideally calculated for different size fractions)	Determination of bedload transport regime Identification of the main coarse sediment sources and sinks)	Bed load monitoring at the channel reach/water body boundaries, in case integrated with numerical modelling of bedload transport
Hydromorphology		
Riverbed elevation and channel width changes	Geomorphological response to changes in sediment supply vs transport capacity conditions	Bathymetric monitoring, integrated if needed by numerical/physical modelling; Monitoring of channel width variations based on repeated aerial photographs
Planform and cross-section characteristics (structure of bed, banks and floodplains, morphological units)	Identification of hydromorphological alterations with respect to “undisturbed” conditions	Field-mapping, mapping based on aerial photographs and satellite images, online available geodata:
Sediment continuity	Identification of alterations regarding longitudinal and lateral sediment connectivity with regard to “undisturbed” conditions	Mapping of transversal and longitudinal structures which prevent sediment transport processes

Riverbed and floodplain substrate (ideally for both surface and sub-surface layers)	Quantification of substrate metrics; Identification of armouring and/or colmation problems	Surface and volumetric sediment sampling; use of ground or UAV-based photographic methods; remote sensing methods (aerial photographs or satellite images)
Hydrology		
Hydrological regime	Extent, magnitude, timing and frequency of floods to assess lateral channel-floodplain connectivity and associated sediment/contaminant transport	Monitoring based on gauging stations; hydrodynamic modelling; existing documentation of past flood events
	Establishing water budget	Monitoring using gauging stations, and modelling of water budget
Flow velocity	Evaluation of flow velocity (magnitude) as a control for abiotic habitat Spatial variability of flow velocity, also as a visual indicator of morphological diversity	Flow meters; radar sensors; large Scale particle image velocimetry
Surface water – ground water exchange	Evaluate channel bed conditions (e.g. colmation)	Monitoring and modelling ground water
Sediment contamination		
Known and potential sediment-associated pollutants	Identification and prioritization of management options / sites (see also section 3.6)	Monitoring of sites being potential sinks (e.g. floodplains, zones with water from mines, groyne fields, weirs and locks, areas with known legacy pollution) Risk assessment using sediment quality guidelines (e.g. EQS, TSV, TEC/PEC) Application of effect-based methods
	Identification of diffuse and point sources (see also section 3.6)	Assessment of potential sources such as sediment and old sediments, legacy pollution at the water body, wastewater treatment plants, agriculture see also pressures table 3.1

Once pressures on the quantity or contamination of sediment are characterised, it is necessary to analyse whether **impacts** on water status are to be expected or not, in order to decide if actions are needed. This impact analysis should be based primarily on the information described in step 2.2, but it may be necessary to collect additional data, if those are not sufficient. As described previously sediment dynamics are long term processes, therefore it is important to consider potential impact on a long term scale. It might also be useful to establish a baseline monitoring in the context of the ISMP, in order to have long term data available when needed.

For each significant pressure identified and in case there are potential impacts, it is then important to assess what are the drivers of the pressure (e.g. activity, historical change, natural processes). To identify these the following questions can help:

- Are pressures associated to natural or anthropogenic drivers (or combination of both)?
- Are pressures related to ongoing or past activities?
- In case of multiple pressures, is it possible to characterise the significance or relative contribution of each of them and how do they interact?

Chapters 2 and 3 provide more detailed guidance on the assessment of pressures and drivers, to characterise respectively sediment quantity related pressures (2.1.2 Does the water body of interest have a sediment quantity problem? & 2.3 Sediment quantity imbalance) and sediment contamination related pressures (references: 3.1.2 Problems caused by sediment contamination & 3.3.1 Sources and pathways of contaminant inputs to the aquatic environment).

The following cases studies illustrate examples of approaches to understand pressures on sediment, respectively related to sediment imbalance and sediment contamination.

Case study 4.7: Diagnosis of sediment imbalance in a coastal cell to understand sediment deficits (Portugal)

The analysis of the recent evolution of the coastline of mainland Portugal reveals the existence of significant beach sediment deficits. Based on the results from the European project Conscience (www.conscience-eu.net), and following damages produced in winter 2014 by the Hercules storm, sediment imbalances were assessed at the Portuguese coast with the aim of defining a set of measures to address sediment risks related to climate change and to ensure a sustainable management of sediment. The analysis led to quantify sediment balance based on the inventory and characterization of sediment supply and distribution process, both natural and of anthropogenic nature were carried out. The current situation was considered to be representative of the last two decades, while the reference situation characterises the situation prior to the existence of a relevant, anthropic induced negative disturbance in the sedimentary balance which would prevail in the 19th century

For more detail, the detailed case study is presented in annex A.

Case study 4.8: The Fiberbank projects (Sweden) – identifying and assessing the risks from highly contaminated fiber sediment hot spots near pulp and paper factories

Since the end of the 19th century, about 30 pulp and paper factories have operated in the Swedish province of Västernorrland. Waste water, which contained wood or cellulose fibers, was for several decades discharged directly into the adjacent coastal marine environment. The impact on the seafloor community in these otherwise productive areas is severe, with no higher life forms than bacteria being able to survive. In 2010 a project was launched to develop a method, using hydro-acoustic surveying techniques, to identify fibrous sediments, and to use the methodology to map their spatial distribution. Another objective was to estimate the contamination levels of hazardous substances in these sediments. The results of this projects allowed to identify and map impacted areas, and to assess risks associated with fiber sediments. The next step on this basis will be to complete the surveys in other areas and to develop remediation approaches (R&D projects ongoing).

For more detail, the detailed case study is presented in annex A.

Step 3 : Definition of ISMP objectives

Key points :

- Objectives of ISMP should aim at reaching the WFD good status/potential objectives and be realistic in the timeframe (including both short and long term objectives)

- Define overall large-scale objectives, and cascade down into specific objectives at smaller scale
- Define suitable indicators of success associated to these objectives
- Describe risks of not achieving the objectives and identify measures to avoid such risks (adaptive management)
- Take into account risks associated to climate change

The system analysis (step 2) is the basis for defining the objectives of the ISMP and associated indicators. These should primarily be based on the objectives of the WFD/MSFD (good status/potential according to the WFD and good environmental status according to the MSFD). Objectives of other relevant policies also have to be addressed in an integrated way (e. g. Habitats Directive, Floods Directive, sectoral policies).

The key aspects for **determining objectives** are the following:

1. **Identify the different issues that need to be addressed** on the basis of the previous diagnosis of river basin or cell-specific pressures and impacts (contamination, nutrients, fine sediment, deficit or surplus, etc.). It is important to address them in a consistent way, which requires to identify interlinkages between them (e. g. overlaps of measures for diffuse retention of flood volume with sediment management or sediment deficits in lower river stretches because of retention upstream).

2. **Set specific objectives at the relevant scales:** large-scale objectives at the river basin scale first, then translate them into objectives at a regional and local scale (cf step 1 on definition of scale of the plan). As explained previously sediment management within a water body is closely linked to bodies of water downstream and upstream, and objective and associated measure have to be analysed with regard to their regional and supra-regional effects, as required by the WFD.

Box 4.3. Example of methodology : the river scaling approach

The River Scaling Concept RSC (Habersack, 2000) proposes a two scale approach:

(i) downscaling from the basin to the local/point scale. It is important to analyse the sediment related changes at the basin scale (e.g. sediment production, erosion, transport and transfer (including sediment balance and continuity), sedimentation and remobilisation at the system level. Via sectional and local scales detailed analyses have to be done at the local / point scale, including grain size analysis, process investigations.

(ii) in the upscaling phase an aggregation of the information derived at the smaller scales is done in order to come up with deficits and finally measures e.g. by applying models at the various scales, eventually concluding that it is important to implement measures also in the catchment to improve the overall sediment budget and thus improve the boundary conditions for the smaller scales.

The following map in Figure 4.6 reports general objectives set at basin scale for the Magra river basin, which can subsequently be translated into more local objectives.

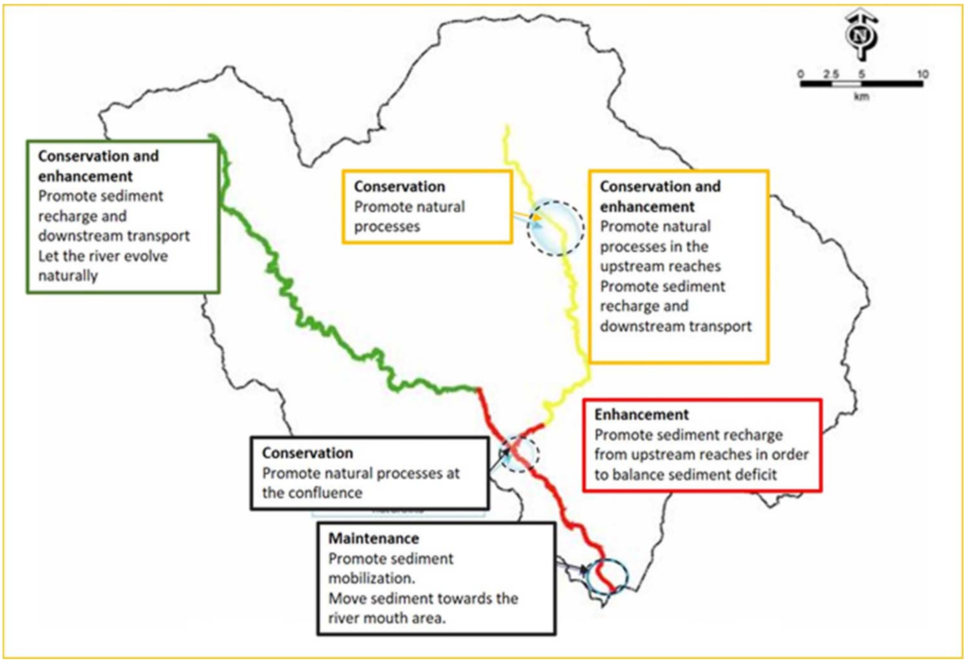

Figure 4.6: Map of general objectives (Magra river, Italy). Source: Rinaldi 2009

3. **Consider and address in a consistent way all current uses and historic changes which have affected and will continue to affect sediment processes**. This information should be provided by the previous step, the "system analysis". The presence of important uses, and consequently of heavily modified water bodies and landscapes in a river basin, can affect sediment and can create disturbance. For instance, agriculture and forestry can lead to surplus of fine sediments in some bodies of water and input of contaminants, while dams or weirs can affect the sediment balance. It is often not possible to restore a completely natural state of sediment chemical status (i.e. a complete lack of contamination) and undisturbed sediment transport at the scale of the river basin, and in most cases there will always be a need to manage sediment to some extent. Therefore, the objectives need to be set with the aim to restore sediment processes and conditions as close as possible to their natural state, in order to reach the WFD objectives, while maintaining necessary uses in the river basin in a sustainable way. In order to define objectives while taking into account these uses, it is recommended to apply the principles developed in CIS guidance 37 on setting Good Ecological Potential objectives in HMWBs[48]. The long-term dimension of sediment processes also needs to be well reflected in the ISMP, which implies that management objectives also need to be set on the long term.

4. I**nvolve all relevant stakeholders in the definition of objectives, and clearly identify responsibilities** (cf step 2). This will help in particular in defining what are the needs and constraints in relation with the important uses affecting sediment, and help selecting the most appropriate solution.

5. **Set appropriate indicators associated to the objectives**. A temporal framework for regular evaluations of the ISMP is also important to be able to readjust, if needed, the objectives and measures of the plan, in line with the principles of adaptive management. One critical issue when defining indicators and the temporal framework is the time gap between the implementation of measures and reaction of the system. As there is still scientific uncertainty on this issue, it is recommended to select indicators which are expected to react more directly to the measures, such as hydromorphological indicators integrated with the most relevant biological indicators.

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[48] https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/d1d6c347-b528-4819-aa10-6819e6b80876/details

Step 4 : Definition of measures, development of the plan

Step 4.1: definition of measures

Step 4.2: development and endorsement of the plan

Step 4.1 : Definition of measures

Key messages

- Establish management options based on the system analysis
- Prioritise measures taking into account socio-economic considerations

Once the objectives are set, a key step in the development of the ISMP is the definition and prioritisation of measures, and on this basis the development and endorsement of the plan itself. The latest should in particular set a timeframe for the implementation and allocate roles and responsibilities for the implementation.

The development of the actual ISMP requires to define the set of actions that will be selected for the plan, on the basis of the diagnosis and the objectives elaborated in previous steps. The plan can include in particular actions at different scales (bodies of water, river basin area). It lists the measures to be implemented in a timeframe and describes the governance framework and actors involved.

In order to select the most appropriate measures it is recommended to first develop management options. These include a set of the most cost-effective combination of measures to reach the objectives. It can also include measures that are already in place or already planned to be implemented. The selection of measures should be primarily based on the environmental outcome expected in relation with the objectives. Some important additional aspects also to be considered include the costs of measures, their technical feasibility (e.g. framework conditions for relocation of sediments within the water body, landfill sites for contaminated material), potential impacts on other components of the environment and on uses in the catchment, human resources required for the implementation and monitoring, etc. These different management options need to be compared to select the most appropriate set of measures based on these different aspects.

Case study 4.9: Example of a tool for the socioeconomic evaluation of measures (Germany)

A method for testing the socioeconomic evaluation of measures has been developed as part of the national implementation of Marine Strategy Framework Directive (MSFD) in Germany and is published as background document within the MSFD reporting. This method is not specific to sediment, but it can be applied for sediment related measures. https://www.meeresschutz.info/berichte-art13.html?file=files/meeresschutz/berichte/art13-massnahmen/MSFD_Art13_PoM_annex_2_socio-economic_assessment.pdf.

As sediment quantity and sediment contamination are closely linked, it is very important at this stage to address both issues in a consistent way when defining management options. In particular, it is necessary to always consider the potential impacts (positive or negative) of these management options, and to adapt them in case of conflicting outcomes. A typical situation would be the remobilization of contaminated sediments when restoring sediment continuity. In some situations it might be necessary to evaluate different alternatives, and to assess their balance between benefits and impacts on the environment. When taking such decision it is crucial to evaluate the benefits of impacts in the long term and at large scale, and not only locally.

The following box summarises the main categories of measures, as defined in chapter 2 and 3, in relation with sediment quantity and contamination. In order to select the most appropriate measures for the management options, chapter 2 and 3 provide lists and examples of measures to address the main pressures on sediment quantity and contamination, including tables of generic measures associated with the most common pressures (references: 2.6 Good practice measures to manage sediment quantity & 3.6 Management of sediment associated contamination).

Box 4.4: Main categories of measures to be considered when developing management options (for more detail refer to chapter 2 and 3)

- Main categories of measures to address a quantitative and hydromorphological pressures
    - Sediment supply issues
    - Continuity issues
    - Local hydromorphological modifications / transport capacity issues

- Main categories of measures to address sediment contamination
    - Prevention or reduction of the transfer of pollutants into bodies of water from point sources and diffuse sources
    - Management options for polluted sediments in order to minimise the remobilisation of pollutants
    - Remediation measures

Once the most appropriate set of measures is selected, in case prioritisation of measures is needed, it should be based on technical / scientific and socio-economic consideration, and should address the following:

- Analysis of the impacts of different options on the achievement of the WFD objectives, for parameters relevant in that context.
- Efficiency of measures. In particular measures which require no or little management actions and based on natural processes can be very efficient (nature based solution, restoration measures, etc.).
- Application of the mitigation hierarchy principle and prioritise measures addressing the problem at the source
- Assessment of the cost and benefits of the potential measures, and of potential disproportionate costs when relevant (in line with art. 4-5 WFD).

It should be noted that the WFD requires to implement all measures necessary to achieve good status / potential objectives by 2027 at the latest, and that exemption to this principle can only be allowed under specific conditions and should be duly justified in the RBMPs (art. 4.4 – 4.5 of the WFD).

For heavily modified water bodies, the selection of measures is closely linked to the definition of the objective of Good Ecological Potential (GEP). It is therefore important to ensure that the ISMP is well aligned with the process of GEP definition for the relevant water bodies (cf section 4.3).

Once the measures are selected, it is recommended to perform a risk analysis, to assess the different types of risks that may affect the implementation and success of measures, including those associated to climate change, and unfavourable future developments taking place within the basin, which may undermine the effect of restoration measures. Proper coordination at the river basin scale is needed when developing and implementing measures. To address such risk, and the complexity and uncertainty inherent to sediment management, adaptive management is an appropriate tool, and it is recommended to apply its concepts.

Finally, involving stakeholders is crucial for this step, as measures will generally have impacts on different uses in the river basin. They should therefore be involved and participate in the decision making process to ensure that all relevant uses are well integrated.

The following box summarises some key principles that can be followed when defining measures. Case study 4.10 described in annex A provides an example of recommendations elaborated in the Danube river basin in the context of the Interreg Danube sediment project.

Box 4.5: Key principles for setting and planning measures

- A river basin/catchment or coastal sediment cell scale approach is often preferable to an approach based only at the scale of the water body because of the hierarchical dependency of smaller on larger scales. Start from defining measures at larger scale and break them down on to site-specific ones
- Set operational planning for all measures, define milestones and final goal
- Define solutions which are also effective when considering the effects of climate change (a climate proofing approach is recommended)
- Prioritise measures with multiple benefits, win-win situations
- Apply the mitigation hierarchy, meaning that preference should be given to measures that avoid the adverse impact. If avoidance of the impact is not possible, mitigation measures should be taken – at source or as close as possible to the source of the effect. If neither avoidance nor minimisation is possible, measures to offset the adverse effect can be considered.
- Anticipate potential conflicts and find solutions in the planning phase, involving stakeholders
- Define strategies based on the principle of “Working with Nature”[49] and “Beneficial Use of Sediments”[50]
- Use the principles of adaptive management as a way to open possibilities for flexible reactions on changing environmental conditions or undesired side-effects which may occur during the implementation of the plan
- Include ecosystem services and costs of non-action into the cost-benefit analysis
- Look for information on similar experience, case studies, guidance on good practices, know-how's, recommendations available on internet
- In case measures to improve sediment transport may negatively affect the sediment contamination downstream (e.g. in case sediments are contaminated), possible alternatives can be investigated and it might be useful to conduct a risk / benefit analysis.
- There is no “one-size-fits-all" solution to problems related to sediment quantity and dynamics; rather a wide range of possible measures should be reviewed and assessed for effectiveness, both alone and in-combination

Step 4.2: Development and endorsement of the plan

Key messages :

- Establish a time schedule for implementation, monitoring and evaluation of measures
- Allocate clear tasks and responsibilities for the implementation
- Summarise key components of the plan in a clear structured document
- Ensure participation of all relevant groups, stakeholders, actors with clear tasks and responsibilities

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[49] “Working with Nature” is a philosophy of an integrated process which involves working to identify and exploit win-win solutions which respect nature within management projects at waters. https://www.pianc.org/uploads/files/EnviCom/WwN/WwN-Position-Paper-English.pdf

[50] “Beneficial Use of Sediment” is herein defined as “the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development”. https://dredging.org/news/381/the-latest-ceda-publications-on-the-beneficial-use-of-sediments

Once the measures are selected, the ISMP document(s) can be drafted. It should include in particular a description of the results of the previous steps (system analysis, objectives, etc).

Operational planning for the implementation of measures needs to be included, in line with the timeframe of the objectives defined in step 3. It generally includes for all measures: a time schedule, clear description of responsibilities, clear financial plan, a monitoring plan with appropriate resources. This operational plan should be secured on the long term.

The **evaluation phase** should also be planned in the ISMP, as it is a crucial component of adaptive management. Sufficient resources should also be allocated to this and indicators and monitoring should be adapted.

The following box describes the content of a 'typical' ISMP document, based on examples collected from existing plans. Annex A also includes some examples of ISMP which can be consulted (see Case Studies 2.5, 4.3 and 4.4 in particular).

Box 4.6 : Example for content of a typical ISM Plan

Legal context and competent authorities

Characterization of the river system

- General setting (e.g. topographic and aerial data, channel planform, geo-lithological and chemical characterization of sediments)
- Analysis and map of sediment transport (connectivity and budget)
- Assessment of sediment connectivity, including main obstacles and active sediment sources
- Assessment of sediment contamination sources and pathways

Historic analysis and current conditions

- Reconstruction of the evolutionary trajectory of channel morphology and of main factors affecting it
- Assessment of hydromorphological status
- Forecast of future trajectory based on current constraints and factors at catchment scale
- Definition of river mobility corridor

Objectives of the plan (general and specific)

- Ecological status + nature conservation objectives linked to morphology/sediment dynamics
- Flood risk mitigation objectives linked to morphology/sediment dynamics
- Indications for reservoir management plans
- Links with management of riparian vegetation and wood

Programme of sediment management measures

- Possible measures (categories)
- Multi-criteria comparison analysis and selection of management alternatives

Monitoring Programme

Timetable and evaluation process

Step 5 : Implementation of the management plan

Key messages

- Define a formal framework for implementation of measures associated with clearly defined responsibilities (a binding framework may be appropriate)
- Identify and secure funding sources for the whole duration of the ISMP
- Set a timetable for the implementation of measures, aligned with the RBMPs cycles, and regularly monitor it
- Allocate clear responsibilities and ensure commitment for implementation, monitoring and evaluation
- Establish technical and administrative support
- Ensure public participation at every step, when possible
- Communicate well on the plan and on its benefits

The implementation of the ISMP may be challenging. Some good practices and recommendations are listed to overcome some of the issues that may hinder its proper implementation.

Formally agree on the allocation of tasks and responsibilities

An ISMP can only be effective if there is a clear allocation of responsibilities with associated commitments to its implementation, and one possible limit might be insufficient involvement of the relevant actors. It was recommended in the previous step to clearly allocate responsibilities for the ISMP especially regarding implementation of measures. This can in addition be formalised in the form of binding agreements with the relevant actors involved, in order to secure the implementation.

Align the implementation of the ISMP with existing projects and/or planning processes

As mentioned previously, the ISMP should of course be well integrated and aligned with the RBMPs. In addition, existing projects or planning processes related to sediment might be already in place and included or aligned with the ISMP:

- international projects (on large rivers that intensify monitoring activities, develop data management practices, build capacity, and intensify stakeholder participation),
- small scale good practices (e.g. dredging practices and use of dredged material on lowland)

It is recommended to create appropriate links with these and as much as possible to align their respective objectives with the objectives of ISMP. More specific guidance on integration of planning processes is provided in section 4.4.

Ensure sufficient technical and administrative support for the implantation for the whole duration for the plan

The success of a plan depends on the allocation of sufficient resources to ensure technical and administrative support. This need to be well planned and supported during the whole duration of the ISMP.

Secure funding for the ISMP

For a successful implementation of the ISMP, appropriate funding should be secured for the whole duration of the plan, for all measures as well as for the management, monitoring and evaluation. Where appropriate, the polluter pays principle should be applied, as required by art.9 of the WFD. Thereby it is important to ensure that costs of non-action are not externalized to downstream users and regions through the use of exemptions or non-compliance with EU quality objectives. For a fair distribution of burdens in case of non-action due to disproportionate costs (Art. 4 WFD), an example of solutions could be to put in place funding mechanisms in the river basins such as a solidarity fund at national or international level.

In that respect, it should be noted that the Directive on environmental liability with regard to the prevention and remedying of environmental damage (Directive 2004/35/EC) can be relevant in this context, in particular where damage results from one of the activities listed in Annex III of that directive or where, in addition to water damage, there is also evidence of damage to protected species or natural habitats and where there is faulty or negligent behaviour involved. The Commission has published guidelines in 2021 providing a common understanding of the term 'environmental damage' as defined in this Directive (EC, 2021)[51]. It clarified in particular the notion of water damage which links to the WFD and to the MSFD.

Communicate on the ISMP

A factor of success for the good implementation of the ISMP is communication and transparency on the process. It is recommended to ensure public participation and to regularly inform about the implementation process and the benefits of the plan, in order to gain public acceptance throughout the process. The use of social media can help to support this part of the implementation.

Step 6 : Monitoring

Key messages:

- Monitoring and feedback loops as a key intrinsic component of ISMP
- Monitoring should be planned and described in a dedicated chapter of the ISMP
- Data should be made available to the public

General principles regarding monitoring in the context of the ISMP

Monitoring in the context of ISMP has a twofold objective:

1. Following the state of implementation of measures, on the basis of the operational planning of measures elaborated in step 4,
2. Assessing the impacts of measures and their contribution to the achievement of the objectives of the ISMP, and of the WFD. In particular the aim is to monitor changes in: sediment processes (transport and contamination), hydromorphology and qualitative indicators (based on WFD chemical and physicochemical status) and biological indicators (based on WFD or MSFD biological indicators). This should be done at representative monitoring sites.

Monitoring of measures and of their impacts is part of the ISMP, and should provide information for regular update of the indicators of the plan (cf step 3). The interpretation of data and impact indicators should be done ideally with sufficient time series and take into account the natural variability associated to natural processes (e.g variation in flow) which may hide the effect of measures.

The monitoring requirements of the WFD, Floods Directive and the MSFD have to be met and all information collected should be used and reported as much as possible in the context of the WFD monitoring and reporting exercise (and similarly for other relevant policies).

Regular monitoring will be critical in evaluating whether measures show expected results, and whether they need to be adjusted. This should be done during the evaluation phase described in the next step.

Chapter 2 and 3 provide more detailed guidance and describe appropriate methodologies to monitor sediment quantity and contamination respectively, which can be used as a basis to elaborate the monitoring framework

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[51] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021XC0407%2801%29&qid=1617956961808

of the ISMP (references: 2.5 Sediment quantity data: monitoring and assessment in the context of the WFD & 3.5 Sediment contamination assessment).

Who does the monitoring and reporting?

It is important to clearly define who is responsible for monitoring and reporting and to provide adequate institutional support. In addition to the public authorities responsible for the implementation of the WFD, river basin communities / international river commissions with their working groups / expert groups can be involved. It is recommended to involve other relevant authorities or institutions and stakeholders which can contribute within the scope of their field of expertise and remit.

Public access to the monitoring results

For the benefit of stakeholders and the general public, it is important to make all data collected publicly available, and to publish monitoring results on a regular base. It can in particular contribute to support the implementation of the plan as described in the previous step.

Case study 4.11: Supporting the establishment of the sediment monitoring programme of hazardous substances according to WFD requirements (Hungary)

A 5 year long (2018-2022) national programme was launched in Hungary, financed by the KEHOP (environmental and energy efficiency operative programme), to develop a methodology and perform additional monitoring to improve the monitoring programs for hazardous substance in sediments in Hungarian river and lake water bodies. The methodology is based on modelling of large scale sediment deposition. The developed methods were based on the general requirements of the WFD and followed the advices from CIS Guidance document No. 25. This lead to the location of 103 sites for the long term national sediment monitoring programme A National Guidance document on sediment monitoring has also been created within the project.

For more detail, the detailed case study is presented in annex A

Step 7 : Evaluation

Key messages:

- Evaluation as intrinsic component of ISMP, allows to adapt measures and actions
- It is recommended to define the evaluation process when developing the ISMP and to include it clearly in the ISMP documents

Evaluation is an important step of the ISMP. It aims at regularly assessing the state of implementation of the plan and progress in achieving the objectives set. It can also be the basis for adjustments to the plan. Due to the complexity of sediment process, and in the context of a changing environment, ISMPs should be considered as "living" documents which foresee adaptive management (Box 4.7).

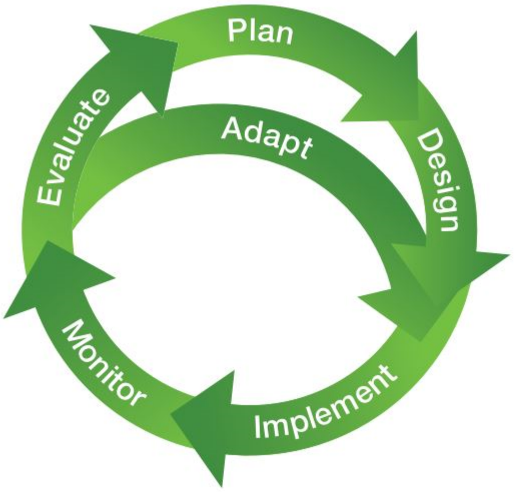
Evaluation should be done on a regular basis and aligned with the management cycles of WFD (every 3 to 6 years) and involve all relevant stakeholders. The evaluation should in particular evaluate whether implemented measures have led to expected results, and if there are undesired or unexpected side effects. The results of such analysis should be used to decide whether the ISMP needs to be adapted (e.g. changes in certain measures, in the monitoring process, in the timeline).

Box 4.7: Definition ‘Adaptive management’

Source: CEDA (2015)[52]:

Adaptive management is a decision framework that facilitates flexible decision-making that can be refined in response to future uncertainties, as outcomes from current and future management actions become better understood. Adaptive management typically involves developing and implementing a management plan that defines the project goals, reviewing progress towards those goals periodically, and, in response to the outcomes of (environmental) monitoring, implementing corrective actions (and refining the plan), as needed, in future.

Adaptive management is a formal process, with specifically agreed upon steps to deal with uncertainties. Its basic steps, included in Fischenich and Vogt (2012)[53], are illustrated in the following figure.



1. **Plan**: Defining the desired goals and objectives, evaluating alternative actions and selecting a preferred strategy with recognition of sources of uncertainty;
2. **Design**: Identifying or designing a flexible management action to address the challenge;
3. **Implement**: Implementing the selected action according to its design;
4. **Monitor**: Monitoring the results or outcomes of the management action;
5. **Evaluate**: Evaluating the system response in relation to specified goals and objectives; and
6. **Adapt**: Adapting (adjusting upward or downward) the action if necessary to achieve the stated goals and objectives.

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[52] https://dredging.org/media/ceda/org/documents/resources/cedaonline/2015-01-ceda_positionpaper-integrating_adaptive_environmental_management_into_dredging_projects.pdf

[53] Fischenich, C. & Vogt, C. (2012) The Application of Adaptive Management to Ecosystem Restoration Project. US Army Corps of Engineers. Technical note: ERDC TN-EMRRP-EBA-10. [Online] Available from: http://el.erdc.usace.army.mil/elpubs/pdf/eba10. pdf [Accessed November 2014].

References Chapter 1

Aigner, J., Kreisler, A., Rindler, R., Hauer, C., Habersack, H. 2017. Bedload pulses in a hydropower affected alpine gravel bed river. Geomorphology 291, 116–127.

Allan, J.D. 1995) Stream Ecology: Structure and Function of Running Waters. Chapman & Hall, 388 pp.

Ancey, C. (2020). Bedload transport: a walk between randomness and determinism. Part 1. The state of the art. Journal of Hydraulic Research, 58, 1–17.

ASCE - American Society of Civil Engineers Task Committee. 1992. Sediment and aquatic habitat in river systems. Journal of Hydraulic Engineering. 118, 669–687.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P. 2017. Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. Geomorphology, 283, 143–157.

Bierman, P.R., Montgomery, D.R. 2013) Key Concepts in Geomorphology. W.H. Freeman, 464 pp..

Bosworth, W.S., Thibodeaux, L.J. 1990. Bioturbation: A Facilitator of Contamination Transport in Bed Sediment. Environmental Progress, 9, 211–217.

Brookes, A., Shields, F.D. 1996. River Channel Restoration: Guiding Principles for Sustainable Projects. J. Wiley & Sons, Chichester, UK, 458 pp..

Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan, eds. 2021. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://issuu.com/poweroferdc/docs/nnbf-guidelines-2021

Manning, W.D., Scott, C.R and Leegwater. E. (eds) (2021). Restoring Estuarine and Coastal Habitats with Dredged Sediment: A Handbook. Environment Agency, Bristol, UK. https://catchmentbasedapproach.org/learn/restoring-estuarine-and-coastal-habitats-with-dredged-sediment/

Burt, T., Allison, R.J. 2010. Sediment Cascades: An Integrated Approach. J. Wiley & Sons, Chichester, UK, 482 pp.

Bussettini, M., Kling, J., van de Bund, W. Eds: Kampa E & Bussettini M, 2018. Working Group ECOSTAT report on common understanding of using mitigation measures for reaching Good Ecological Potential for heavily modified water bodies - Part 2: Impacted by flood protection structures, EUR 29131 EN; Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80290-4,

Boyd, R., Dalrymple, R., Zaitlin, B.A. 1992. Classification of clastic coastal depositional environments. Sedimentary Geology, 80, 139–150.

Carter, R.W.G., 1988. Coastal Environments: An Introduction to the Physical, Ecological, and Cultural Systems of Coastlines. Academic Press, San Diego, 634 pp.

Coelho C., Silva Afonso A., Bernardes C., Silva P., Baptista P., Roebeling P., Fernández-Fernández S., Abreu T., Oliveira T., Ferreira M., Santos F., Monteiro N., Lima M., Nolasco A., Cardoso A., Rocha B., Narra P., Carvalho R., Afonso C., Figueira P., Pound M. 2021. Estudo de Viabilidade da Transposição Aluvionar das Barras de Aveiro e da Figueira da Foz. Sumário Executivo.

Church, M. 1999. Sediment sorting in gravel-bed rivers. Journal of Sedimentary Research, 69, 20–20.

Church, M. 2006. Bed material transport and the morphology of alluvial river channels. Annual Review of Earth and Planetary Sciences, 34, 325-354.

Comiti, F., Mao, L. 2012. Recent advances in the dynamics of steep channels. In: Church M., Biron P.M., Roy A.G. (eds) Gravel-Bed Rivers: Processes, Tools, Environments, Wiley-Blackwell, Chichester, UK , pp351–377.

Comiti, F., Scorpio, V. 2019. Historical Changes in European Rivers. Oxford Bibliographies. Oxford University Press USA (online).

Compeau, G.C., Bartha, R. 1985. Sulfate-Reducing Bacteria: Principal Methylators of Mercury in Anoxic Estuarine Sediment. Applied and Environmental Microbiology, 50, 498–502. doi:10.1128/AEM.50.2.498-502.1985.

Cowell, P.J., Stive, M., Niedoroda, A., de Vriend, H., Swift, D.J.P., Kaminsky, G., Capobianco, M. 2003. The Coastal-Tract (Part 1): A Conceptual Approach to Aggregated Modeling of Low-Order Coastal Change. Journal of Coastal Research, 19, 812–827.

Day, J.W., Kemp W.M., Yáñez-Arancibia, A., Crump, B.C. 2012. Estuarine Ecology, 2nd Edition, Wiley–Blackwell, 568pp..

Dronkers J. 2005. Dynamics of Coastal Systems. Singapore:World Sci.

Espa P, Batalla RJ, Brignoli ML, Crosa G, Gentili G, Quadroni S. 2019. Tackling reservoir siltation by controlled sediment flushing: Impact on downstream fauna and related management issues. PLoS ONE 14(6): e0218822.

European Environment Agency. 2011. Hazardous substances in Europe's fresh and marine waters: An overview. Publications Office of the European Union, Luxembourg, 61 pp..

Eurosion. Living with Coastal Erosion in Europe: Sediment and Space for Sustainability. 2004. Part-1 Major Findings and Policy Recommendations of the EUROSION Project. Guidelines for implementing local information systems dedicated to coastal erosion management. Service contract B4-3301/2001/329175/MAR/B3 "Coastal erosion – Evaluation of the need for action". Directorate General Environment, European Commission, 54 pp

Folegot S, Bruno MC., Larsen S, Kaffas K, Pisaturo GR, Andreoli A, Comiti F, Righetti M. 2021. The effects of a sediment flushing on Alpine macroinvertebrate communities. Hydrobiologia (in press)

Fryirs, K. 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38, 30–46.

Garcia, M. (Ed.) (2008) Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. ASCE library.

Grabowski, R. C., Gurnell, A. M. 2016. Diagnosing problems of fine sediment delivery and transfer in a lowland catchment. Aquat Sci 78, 95–106.

Guidance document No. 25 on chemical monitoring of sediment and biota under the Water Framework Directive. DOI 10.2779/43586

Gurnell AM., Piégay H., Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. Freshwater Biology 47, 601-619.

Gurnell, A. M. 2014. Plants as river system engineers. Earth Surf. Proc. Landform, 39, 4-25.

Gurnell, A. M., Rinaldi M, Belletti B et al. 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat Sci 78, 1–16.

Habersack, H.M., Laronne, J.B. 2002. Evaluation and improvement of bed load discharge formulas based on Helley-Smith sampling in an alpine gravel bed river. Journal of Hydraulic Engineering-ASCE, 128, 484-499.

Habersack, H., Liébault, F., Comiti, F. 2017. Sediment dynamics in Alpine basins. Geomorphology, 291, 1-3.

Habersack, H., Hein, T., Stanica, A., Liska, I., Mair, R., Jäger, E., Hauer, C., Bradley, C. 2016. Challenges of river basin management: Current status of, and prospects for, the River Danube from a river engineering perspective. Sci Total Environ., 543(Pt A), 828-845.

Haidvogl, G. 2018. Historic Milestones of Human River Uses and Ecological Impacts. In: Schmutz, S., Sendzimir, J. (eds.). Riverine Ecosystem Management. Aquatic Ecology Series, vol 8. Springer, Cham.

Hoffmann, T.O., Baulig, Y., Fischer, H., Blöthe, J., 2020. Scale breaks of suspended sediment rating in large rivers in Germany induced by organic matter. Earth Surface Dynamics, 8, 661-678.

Krapesch, G., Hauer, C., Habersack, H. 2011. Scale orientated analysis of river width changes due to extreme flood hazards. Natural Hazards and Earth System Sciences, 11, 2137-2147.

Kondolf, G.M., Podolak, K. 2014. Space and Time Scales in Human-Landscape Systems. Environmental Management 53, 76–87.

Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C. T. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents, Earth's Future, 2, 256-280.

Langston, W.J., Pope, N.D., Jonas, P.J.C., Nikitic, C., Field, M.D.R., Dowell, B., Shillabeer, N., Swarbrick, R.H., Brown, A.R. 2010. Contaminants in fine sediments and their consequences for biota of the Severn Estuary. Marine Pollution Bulletin, 61, 68-82.

Lerat-Hardy, A., Coynel, A., Schäfer, J., Marache, A., Pereto, C., Bossy, C., Capdeville, M.-J., Granger, D. 2021. Impacts of Highway Runoff on Metal Contamination Including Rare Earth Elements in a Small Urban Watershed: Case Study of Bordeaux Metropole (SW France). Archives of Environmental Contamination & Toxicology.

Mao L, Dell'Agnese A, Huincache C, Penna D, Engel M, Niedrist G, Comiti F. 2014. Bedload hysteresis in a glacier-fed mountain river. Earth Surface Processes and Landforms, 39(7), 964-976.

Mao L, Dell'Agnese A, Comiti F. 2017. Sediment motion and velocity in a glacier-fed stream. Geomorphology, 291, 69-79.

Mao L, Comiti F, Carrillo R, Penna D. 2019. Sediment transport in proglacial rivers. In: Heckmann T., Morche. D (eds) Geomorphology of Proglacial Systems. Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes, Springer Internationa. Publishing, Cham, 199-217.

Marchi L, Comiti F, Crema S, Cavalli M. 2019. Channel control works and sediment connectivity in the European Alps. Science of the Total Environment 668, 389-399

Martin J. Baptist, T. Gerkema, B.C. van Prooijen, D.S. van Maren, M. van Regteren, K. Schulz, I. Colosimo, J. Vroom, T. van Kessel, B. Grasmeijer, P. Willemsen, K. Elschot, A.V. de Groot, J. Cleveringa, E.M.M. van Eekelen, F. Schuurman, H.J. de Lange, M.E.B. van Puijenbroek. 2019. Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor', Ecological Engineering, Volume 127, Pages 312-323.

Mazzorana B, Comiti F, Fuchs S. 2013. A structured approach to enhance flood hazard assessment in mountain streams. Nat Hazards 67, 991–1009.

Milner A, Robertson A, McDermott M. et al. 2013. Major flood disturbance alters river ecosystem evolution. Nature Clim Change 3, 137–141.

Nichols, M.M., 1989. Sediment accumulation rates and relative sea-level rise in lagoons. Marine Geology Volume 88, Issues 3–4, August 1989, Pages 201-219.

Petts GE, Möller H, Roux AL (Eds.) 1989. Historical Change of Large Alluvial Rivers: Western Europe. 355 pp. John Wiley and Sons

Quadroni S, Brignoli ML, Crosa G, Gentili G, Salmaso F, Zaccara S, Espa P. 2016. Effects of sediment flushing from a small Alpine reservoir on downstream aquatic fauna. Ecohydrol., 9: 1276– 1288

Rainato R, Mao L, García-Rama A, Picco L, Cesca M, Vianello A, Preciso E, Scussel GR, Lenzi MA. 2017. Three decades of monitoring in the Rio Cordon instrumented basin: Sediment budget and temporal trend of sediment yield, Geomorphology 291, 45-56.

Rapaglia, J., Zaggia, L., Parnell, K., Lorenzetti, G., Vafeidis, A.T. 2015. Ship-wake induced sediment remobilization: Effects and proposed management strategies for the Venice Lagoon. Ocean & Coastal Management, 110, 1-11.

Rinaldi M., Simoncini C., Piégay H, 2009. Scientific design strategy for promoting sustainable sediment management: the case of the Magra River (Central-Northern Italy). River Research and Applications, 25, 607–625.

Rickenmann, D. 2001. Comparison of bed load transport in torrents and gravel bed streams. Water Resources Research 37(12), 3295-3305.

Rinklebe, J.,Antoniadis, V., Shaheen, S.M., Rosche, O., Altermann, M. 2019. Health risk assessment of potentially toxic elements in soils along the Central Elbe River, Germany. Environmental International 126, 76-88.

Ruiz-Villanueva, V., Mazzorana, B., Bladé, E., Bürkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo, D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., and Wohl, E. 2019. Characterization of wood-laden flows in rivers. *Earth Surf. Process. Landforms*, 44: 1694– 1709.

Salomons W, Brils J. (Eds.) 2004. Contaminated Sediments in European River Basins. Published by Sed-Net Organization (available online).

Schleiss AJ, De Cesare G, Franca MJ, Pfister M (eds). 2014. Reservoir sedimentation. CRC Press.

Schobesberger, J; Lichtneger, P; Hauer, C; Habersack, H; Sindelar, C. 2020. Three-Dimensional Coherent Flow Structures during Incipient Particle Motion. J HYDRAUL ENG. 146(5), 04020027

Steel, R. & Milliken, K. 2013. Major Advances in siliciclastic sedimentary geology 1960-2012 Geological Society of America Special Paper 500 2013. Special Paper of the Geological Society of America. 500..

Swart, Huib & Zimmerman, J.T.F. 2009. Morphodynamics of Tidal Inlet Systems. Annual Review of Fluid Mechanics. 41. 10.1146/annurev.fluid.010908.165159.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience, 2(10), 681-686.

Tang, Y., Zhang, M., Sun, G., Pan, G. 2019. Impact of eutrophication on arsenic cycling in freshwaters. Water Research, 150, 191-199

Tockner K., Zarfl C., Robinson C.T. (Eds.). 2022. Rivers of Europe (2nd edition),Elsevier, 922 pages.

Tsai CW, Huang S-H. 2019. Modeling suspended sediment transport under influence of turbulence ejection and sweep events. Water Resources Research 55, 5379– 5393.

Turowski JM, Rickenmann D, Dadson SJ. 2010. The partitioning of the total sediment load of a river into suspended load and bedload: a review of empirical data. Sedimentology 57, 1126-1146.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. The journal of Geology, 30(5), 377-392.

Winterwerp, J.C., Wang, Z.B. 2013. Man-induced regime shifts in small estuaries—I: theory. Ocean Dynamics 63, 1279–1292.

Wohl E, Bledsoe BP, Jacobson RB, LeRoy Poff N, Rathburn SL, Walters DM, Wilcox AC. 2015. The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management. BioScience, 65 (4), 358–371.

Wohl, E. 2018. Sustaining River Ecosystems and Water Resources. Springer.

Wohl, E. 2019. Rivers in the Landscape, 2nd Edition. Wiley, 512 pp.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D., Comiti, F., Gurnell, A., Piégay, H., Lininger, K., Jaeger, K., Walters, D., Fausch, K. 2019. The natural wood regime in rivers. Bioscience, 69, 259-273.

Woodroffe, C. D. 2003. Coasts, Form, Process and Evolution. Cambridge: Cambridge Univ. Press

References Chapter 2

Alewell, C., Meusburger, K., Brodbeck, M., & Bänninger, D. 2008. Methods to describe and predict soil erosion in mountain regions. *Landscape and Urban Planning 88*(2-4): 46-53.

Asselman, N.E., & Middelkoop, H. 1995. Floodplain sedimentation: quantities, patterns and processes. *Earth Surface Processes and Landforms 20*(6): 481-499.

BMVI 2016. Sedimentdurchgängigkeit der Bundeswasserstraßen im Binnenbereich. Metastudie. Bundesanstalt für Wasserbau (BAW), Karsruhe und Bundesanstalt für Gewässerkunde (BfG), Koblenz.

Bogen, J. 1992. Monitoring grain size of suspended sediments in rivers. Erosion and Sediment Transport Monitoring Programmes in River Basins. In: *Proceedings of the Oslo Symposium, August 1992*. IAHS Publ. no. 210, 1992.

Brown, A. G., et al. 2009. From sedimentary records to sediment budgets: multiple approaches to catchment sediment flux. *Geomorphology 108*(1-2): 35-47.

Bunte, K. & Abt, S.R. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 428 p.

Bussettini M, Vezza P. (2019). Guidance on Environmental Flows. Integrating e-flow science with fluvial geomorphology to maintain ecosystem services. World Meteorological Organization-No. 1235. ISBN 978-92-63-11235-4.

Chalov, S., Golosov, V., Tsyplenkov, A., Theuring, P., Zakerinejad, R., Märker, M., & Samokhin, M. 2017. A toolbox for sediment budget research in small catchments. *Geography, Environment, Sustainability* 10(4): 43-68.

Church, M. A., D. G. McLean, and J. F. Wolcott, River bed gravels: sampling and analysis, in *Sediment Transport in Gravel-bed Rivers*, edited by C. R. Thorne, J. C. Bathurst, and R. D. Hey, pp. 43-88, John Wiley & Sons Ltd. Chichester, England, 1987.

Comiti, F., Scorpio, V. 2019. Historical Changes in European Rivers. Oxford Bibliographies. Oxford University Press USA (online).

Comiti, F., Scorpio, V., Andreoli, A., Coviello, V. 2021. Management of coarse sediment fluxes and morphological dynamics of Alpine rivers: lessons learned from South Tyrol (Eastern Italian Alps). Proc. International Symposium on Bedload Management, November 8 – 10 2021, Interlaken, Switzerland

Chalov, S., Golosov, V., Tsyplenkov, A., Theuring, P., Zakerinejad, R., Märker, M., & Samokhin, M. 2017. A toolbox for sediment budget research in small catchments. *Geography, Environment, Sustainability*, *10*(4), 43-68.

Collins, S. E., Thoms, M. C., & Flotemersch, J. E. 2015. Hydrogeomorphic zones characterize riverbed sediment patterns within a river network. *River Systems*, *21*(4), 203-213.

Cox, J. R., Huismans, Y., Knaake, S. M., Leuven, J. R. F. W., Vellinga, N. E., van der Vegt, M., & Kleinhans, M. G. 2021. Anthropogenic effects on the contemporary sediment budget of the lower Rhine-Meuse Delta channel network. *Earth's Future*, e2020EF001869.

De Jalon D., Bussettini M., Rinaldi M., Grant G.E., Friberg N., Cowx I.C., Magdaleno F., Bujise A.D. (2016). Linking Environmental Flows to Sediment Dynamics. Water Policy 19(2) DOI: 10.2166/wp.2016.106.

De Jonge, V. N., Schuttelaars, H. M., Van Beusekom, J. E. E., Talke, S. A., & De Swart, H. E. 2014. The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Ems estuary. *Estuarine, Coastal and Shelf Science*, 139, 46–59.

Dépret, T., Riquier, J., Piegay, H. 2017. Evolution of abandoned channels: Insights on controlling factors in a multi-pressure river system. *Geomorphology*, 294, 99-118

Dietrich, W. & Dunne, T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie N.F. Supplement Band* 29: 191-206.

Folk, R.L. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *The Journal of Geology* 62(4): 344–359.

Gellis, A.C., & Walling, D.E. 2011. Sediment source fingerprinting (tracing) and sediment budgets as tools in targeting river and watershed restoration programs. *Stream restoration in dynamic fluvial systems: scientific approaches, analyses, and tools 194*: 263-291.

González-Correa, J.M., Fernández-Torquemada, Y., Sánchez-Lizaso, J.L. 2008. Long-term effect of beach replenishment on natural recovery of shallow Posidonia oceanica meadows. Estuarine, Coastal and Shelf Science 76.4: 834-844.

Habersack, H., Aigner, J., Haimann, M., Klösch, M., Liedermann, M., Hauer, C., Piégay, H. 2019. The Sediment Balance of Alpine Rivers - Dynamics of Erosion and Sedimentation. In: Muhar, S; Muhar, A; Egger, G; Siegrist, D (Eds.), Rivers of the Alps - Diversity in Nature and Culture, 11; Haupt Verlag, Bern

Habersack, H; Kreisler, A; Rindler, R; Aigner, J; Seitz, H; Liedermann, M; Laronne, JB. 2017 Integrated automatic and continuous bedload monitoring in gravel bed rivers. GEOMORPHOLOGY.; 291: 80-93.

Habersack H., Baranya S., Holubova K., Vartolomei F., Skiba H., Babic-Mladenovic M., Cibilic A., Schwarz U., Krapesch M., Gmeiner Ph., Haimann M. 2019. Danube Sediment Management Guidance. Output 6.1 of the Interreg Danube Transnational Project Danube Sediment co-funded by the European Commission, Vienna. https://www.interreg-danube.eu/uploads/media/approved_project_output/0001/39/ee566924f1764d4798dc7bb9b59537ce84d98101.pdf

Hajigholizadeh, M., Melesse, A. M., & Fuentes, H.R. 2018. Erosion and sediment transport modelling in shallow waters: A review on approaches, models and applications. *International journal of environmental research and public health 15*(3): 518.

Halleraker J., Van De Bund W., Bussettini M., Gosling R., Döbbelt-Grüne S., Hensmann J., Köller-Kreimer V., Kling J., Kampa E. (2016). WG ECOSTAT report on common understanding of using mitigation measures for reaching Good Ecological Potential for Heavily Modified Water Bodies. Part 1: impacted by water storage. Luxembourg: Office for Official Publications of the European Communities, 2016, JRC103830, EUR 28413; doi:10.2760/649695.

Heininger, P., Keller, I., Quick, I., Schwartz, R., Vollmer, S. 2015. Sediment Management on River-Basinscale: The River Elbe. In: Cullmann/Heininger, Sediment Matters pp. 201-247

Hillebrand, G., & Frings, R. 2017. Von der Quelle zur Mündung: Die Sedimentbilanz des Rheins im Zeitraum 1991 – 2010. Lelystad: Internationale Kommission für die Hydrologie des Rheingebietes. KHR-Bericht I-22. KHR/CHR II-22.

Hoffmann, T. 2015. Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems. *Earth-Science Reviews* 150: 609-627.

Hoffmann, T., Hillebrand, G., Schmegg, J., and Vollmer, S. 2017. Monitoring long-term suspended sediment yields in Germany: Quality controls on changing sediment sampling strategies. *Proceedings of the IAHR:*

HydroSenSoft, International Symposium and Exhibition on Hydro-Environment Sensors and Software. Madrid, 1-3 March 2017, 1-7.

Horowitz, A.J. 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrol. Process.* 17: 3387–3409.

Jäckli, H. 1957. Gegenwartsgeologie des Bündnerischen Rheingebietes. Ein Beitrag zur exogenen Dynamik alpiner Gebirgslandschaften.- Beiträge zur Geologie der Schweiz - Geotechnische Serie 36: 136 S.

Kampa, E. & Bussettini, M. 2018. River Hydromorphological Assessment and Monitoring Methodologies – FINAL REPORT. Part 1 – Summary of European country questionnaires.

Keesstra, S., Nunes, J.P., Saco, P., Parsons, T., Poeppl, R., Masselink, R., Cerdà, A. 2018. The way forward: can connectivity be useful to design better measuring and modelling schemes for water and sediment dynamics? *Science of the Total Environment* 644: 1557-1572.

Kondolf, G.M., Mathews, W.V.G. 1991. Unmeasured residuals in sediment budgets: a cautionary note. *Water Resources Research* 27: 2483–2486.

LAWA 2017. Bewertung der Durchgängigkeit von Fließgewässern für Sedimente. LAWA, Jena.

Llena, M., Vericat, D., Cavalli, M., Crema, S., & Smith, M. W. 2019. The effects of land use and topographic changes on sediment connectivity in mountain catchments. *Science of the Total Environment, 660,* 899-912.

Marta Roca, Manuela Escarameia, Olalla Gimeno, Lucas de Vilder, Jonathan Simm, Bruce Horton and Colin Thorne. 2017. Green approaches in river engineering Supporting implementation of Green Infrastructure. HR Wallingford Ltd.

Merz, J.E., Pasternack, G. B., & Wheaton, J. M. 2006. Sediment budget for salmonid spawning habitat rehabilitation in a regulated river. *Geomorphology* 76(1-2): 207-228.

Mickovski, S & Walvin, S 2015, A comparative study of beach nourishment methods in selected areas of the coasts of the United Kingdom and The Netherlands. in Coastal Cities 2015: International Conference on Coastal Cities and Their Sustainable Future. vol. 148, WIT Transactions on The Built Environment, WIT Press, pp. 85-96.

Naden, P.S.; Murphy, J.F.; Old, G.H., Newman, J., Scarlett, P., Harman, M., Duerdoth, C.P., Hawczak, A., Pretty, J.L., Arnold, A., Laizé, C., Hornby, D.D., Collins, A.L., Sear, D.A. & Jones, J.I. 2016. Understanding the controls on deposited fine sediment in the streams of agricultural catchments. *Sci. Tot. Environ.*, 547: 366-381.

Notebaert, B., Verstraeten, G., Govers, G., Poesen, J. 2009. Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology. *Earth Surface Processes and Landforms* 34(2): 217-231.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D. M., Horowitz, A. J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., Trustrum, N.A. 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications 21*(7): 693-717.

Parsons, A.J. 2011. How useful are catchment sediment budgets? *Progress in Physical Geography: Earth and Environment* 36: 60-71.

Perks, M.T. 2014. *Suspended sediment sampling*. Geomorphological Techniques, Chap. 3, Sec. 3.6. British Society for Geomorphology.

Piqué, G., Batalla, R. J., López, R., & Sabater, S. 2017. The fluvial sediment budget of a dammed river (upper Muga, southern Pyrenees). *Geomorphology*, *293*, 211-226.

Quick, I. & Langhammer, J. 2015. Sediment continuity – survey, assessment and derivation of recommendations for restoring the hydromorphological indicator. 9th Intern. SedNet conference, Solving societal challenges: working with sediments, 23-26 Sept. 2015, Kraków

Quick, I.; König, F.; Baulig, Y.; Borgsmüller, C.; Schriever, S. 2017. The hydromorphological classification tool Valmorph 2 for large and navigable surface waters. BfG-Report No. 1910. Federal Institute of Hydrology. Koblenz

Quick, I., König, F., Baulig, Y., Schriever, S., & Vollmer, S. 2020. Evaluation of depth erosion as a major issue along regulated rivers using the classification tool Valmorph for the case study of the Lower Rhine. In Habersack, H., Liedermann, M., Tritthart, M., Eder, M. (editors): International Journal of River Basin Management, Volume 18, 2020, Issue 2: Major Issues in Large River Basin Management, pp. 191-206.

Rapp, A., 1960. Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. *Geog. Annal.* 42A: 71–200.

Reid, I. and Dunne, T. 2016. Sediment budgets as an organizing framework in fluvial geomorphology. In: Tools in Fluvial Geomorphology, Kondolf, G. M. and Piegay, H. (Eds.), 2016.

Rode, M. & Suhr, U. 2006. Uncertainties in selected surface water quality data. *Hydrol. Earth Syst. Sci. Discuss.* 3: 2991–3021.

Rollet A.J., Piégay H., Dufour, S., Bornette G., Persat, H. 2013. Assessment of consequences of sediment deficit on a gravel river bed downstream of dams in restoration perspectives: application of a multicriteria, hierarchical and spatially explicit diagnosis. *River Research and* Applications*,* 30, 939–953.

Rosati, J.D. 2005. Concepts in sediment budgets. *Journal of Coastal Research* 21(2 (212)): 307-322.

Rovira, A., Batalla, R. J., & Sala, M. 2005. Response of a river sediment budget after historical gravel mining (the lower Tordera, NE Spain). *River Research and Applications* 21(7): 829-847.

Sarretta, A., Pillon, S., Molinaroli, E., Guerzoni, S., & Fontolan, G. 2010. Sediment budget in the Lagoon of Venice, Italy. *Continental Shelf Research 30*(8): 934-949.

SEPA, 2010. Engineering in the water environment: good practice guide. Sediment management. First edition, June 2010.

Slaymaker, O. 2003. The sediment budget as conceptual framework and management tool. *Hydrobiologia* 494: 71-82.

Sousa, J.J., Bastos, L. 2013. Multi-temporal SAR interferometry reveals acceleration of bridge sinking before collapse. *Natural Hazards and Earth System Sciences*, 13, 659–667.

Standing Conference on Problems Associated with the Coastline (2004). SCOPAC Sediment Transport Study. https://www.scopac.org.uk/scopac_sedimentdb/pbay/index.htm

Udden, J.A. 1914. Mechanical composition of clastic sediments. *Geological Society of America Bulletin* 25(1): 655–744.

Valentine, P.C. 2019. Sediment classification and the characterization, identification, and mapping of geologic substrates for the glaciated Gulf of Maine seabed and other terrains, providing a physical framework for ecological research and seabed management. U.S. Geological Survey Scientific Investigations Report 2019–5073, 37 p.

Vázquez-Tarrío, D., Tal, M., Camenen, B., Piegay, H. 2019. Effects of continuous embankments and successive run-of-the-river dams on bedload transport capacities along the Rhone River, France. *Science of the Total Environment*, 658, 1375–1389.

Von Züllig, H. Sedimente als Ausdruck des Zustandes eines Gewässers. *Schweiz. Z. Hydrologie* 18**,** 5–143 (1956).

Walling, D.E., Collins, A.L., Jones, P.A., Leeks, G.J.L., Old, G. 2006. Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR catchments, UK. *Journal of Hydrology*, 330(1-2), 126-141.

Walling, D.E., He, Q., & Appleby, P.G. 2002. Conversion models for use in soil-erosion, soil-redistribution and sedimentation investigations. In *Handbook for the assessment of soil erosion and sedimentation using environmental radionuclides* (pp. 111-164). Springer, Dordrecht.

Walling, D.E., Owens, P.N., Waterfall, B.D., Leeks, G.J.L., and Wass, P.D. 2000. The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. *Science of the Total Environment* 251: 205-222.

Walling, D.E., Webb, B.W., Woodward, J.C. 1992. Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport. Eros. Sediment Monit. Program. River Basins. *Proc. Int. Symp. Oslo 1992*, 279–288.

Warrick, J.A. 2015. Trend analyses with river sediment rating curves, *Hydrological Processes* 29: 936-949.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *The Journal of Geology* 30(5): 377–392.

Wilkinson, S.N., Dougall, C., Kinsey-Henderson, A.E., Searle, R.D., Ellis, R.J., & Bartley, R. 2014. Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. *Science of the Total Environment* 468: 1210-1224.

Wilkinson, S.N., Prosser, I.P., Rustomji, P., Read, A.M. 2009. Modelling and testing spatially distributed sediment budgets to relate erosion processes to sediment yields. *Environmental Modelling & Software* 24(4): 489-501.

Wischmeier, W.H. & Smith, D.D. 1962. *Soil loss estimation as a tool in soil and water management planning*. Int. Assoc. Scient. Hydrol. Pub. 59: 148-159.

Wischmeier, W.H. & Smith, D.D. 1978. *Predicting rainfall erosion losses*. USDA Agr. Res. Serv. Handbook, 537.

Zwiers, M., Dales, D. and Hunt, H. 1996. Mablethorpe to Skegness Beach Nourishment: is it working? In Partnership in Coastal Zone Management, edited by J. A. Taussik and J. Mitchell, Samara Publishing, Cardiganshire, pp. 631-637

References Chapter 3

Bortone G., Arevalo E., Deibel I., Detzner H.D., de Propris L., Elskens F., Giordano A., Hakstege P., Hamer K., Harmsen J., Hauge A., Palumbo L., van Veen J., 2004. Synthesis of the SedNet work package 4 outcomes. J Soils & Sediments 4: 225.

Bortone G., Palumbo L. (Eds.), 2007. Sediment and Dredged Material Treatment. Elsevier. 209 pp.

Brils J, Harris B (Eds), 2009. Towards Risk-Based Management of European River Basins – Key-findings and recommendations of the RISKBASE project. Final deliverable of the European Commission funded project under reference GOCE 036938, December 2009, Utrecht, The Netherlands. Available via: https://www.researchgate.net/publication/236332901_Towards_Risk-Based_Management_of_European_River_Basins_-_Key-findings_and_recommendations_of_the_RISKBASE_project

Brils J., Barcelo D., Blum W., Brack W., Harris B., Müller D., Négrel P., Ragnarsdottir V., Salomons W., Slob A., Track T., Vegter J., Vermaat J., 2014. Synthesis and Recommendations towards Risk-Informed River Basin Management. In: Brils J., Brack W., Müller D., Negrel P., Vermaat J. (Eds) Risk-Informed Management of European River Basins. Springer, p367-391

Brils J., 2019. (Re)mobilization and downstream transport of sediment-associated contaminants: an overview. WFD CIS ECOSTAT Sediment Management workshop, 1-2 April 2019, Dubrovnik.

CEDA. 2019a. Sustainable Management of the Beneficial use of Sediments (info paper). Central Dredging Association, www.dredging.org

CEDA. 2019b. Assessing the Benefits of using Contaminated Sediment (position paper). Central Dredging Association, www.dredging.org

Chapman P.M., 1990. The sediment quality triad approach to determining pollution-induced degradation. Sci Total Environ 97-98, 815-825.

CIS guidance no 3, 2003. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Analysis of Pressures and Impacts. Technical report, 157 pp.

CIS guidance no 13, 2005. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Overall approach to the classification of ecological status and ecological potential. Technical report, 48 pp.

CIS guidance no 19, 2009. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance on surface water chemical monitoring under the Water Framework Directive. Technical report, 132 pp.

CIS guidance no 25, 2010. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance on chemical monitoring of sediment and biota under the Water Framework Directive. Technical report, 82 pp.

CIS guidance no 27, 2018. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Technical Guidance for deriving Environmental Quality Standards - version 2018. Technical report, 210 pp.

CIS guidance no 28, 2012. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Technical Guidance on the Preparation of an Inventory of Emissions, Discharges and Losses of Priority and Priority Hazardous Substances. Technical report, 69 pp.

Croudace I.W., Romano E., Ausili A., Bergamin L., Rothwell G., 2015. X-ray core scanners as an environmental forensic tool: a case study of polluted harbor sediment (Augusta Bay, Sicily). In Micro-XRF Studies of Sediment Core, eds I. W. Croudace and R. G. Rothwell (Berlin: Springer), 393–421.

de Deckere, E., W. de Cooman, V. Leloup, P. Meire, C. Schmitt and P. von der Ohe (2011). Development of sediment quality guidelines for freshwater ecosystems. Journal of Soils and Sediments 11(3): 504-517

EC, 2004. Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage.

EC, 2013. Environmental Liability Directive Protecting Europe's Natural Resources. European Union 2013. ISBN 978-92-79-29753-3.

EC, 2014. Technical report on aquatic effect-based monitoring tools, 83 pp. doi: 10.2779/7260

EC, 2020. EU Action Plan "Towards a Zero Pollution Ambition for air, water and soil – building a Healthier Planet for Healthier People. European Commission (EC) Directorate General ENV.C - Quality of Life, Ref. Ares (2020)5152184 - 01/10/2020

EC, 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil, Ref. SWD(2021) 140 final.

Fenet, H., Gomez, E., Pillon, A., Rosain, D., Nicolas, J. C., Casellas, C., & Balaguer, P. 2003. Estrogenic activity in water and sediments of a French river: contribution of alkylphenols. Archives of environmental contamination and toxicology, 44(1), 0001-0006.

ICPR, International Commission for the Protection of the Rhine River, 2009, Sediment management plan Rhine, ICPR-report 175, Koblenz. 18 p.

IKSE, Internationale Kommission zum Schutz der Elbe, 2014. Sedimentmanagementkonzept der IKSE - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. 200 p.

Kowalewska G., Belzunce-Segarra M. J., Schubert B., Heininger P., Heise, S., 2011. The role of sediments in coastal monitoring. In Chemical marine monitoring: Policy framework and analytical trends, eds P. Quevauviller, P. Roose, and G. Verreet (Hoboken, NJ: John Wiley & Sons), 377–395. doi: 10.1002/9781119990826.ch12

Li X., Wai O. W. H., Li Y. S., Coles B. J., Ramsey M. H., Thornton I., 2000. Heavy metal distribution in sediment profiles of the pearl-river estuary, South China. Appl. Geochem. 15, 567–581. doi: 10.1016/S0883-2927(99)00072-4

Long E.R., Chapman P.M., 1985. A sediment quality triad: measures of sediment contamination, toxicity and infaunal community composition in Puget Sound. Mar Pollut Bull 16:405Royston MG (1979) Pollution Prevention Pays. Pergamon Press. eBook ISBN: 9781483147109, 214 pages.

MacDonald, D. D., Ingersoll, C. G., & Berger, T. A. 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Archives of environmental contamination and toxicology, 39(1), 20-31

MERAG (2106) Marine risk assessment. Fact Sheet 04, May 2016. Metals Environmental Risk Assessment Guidance (MERAG)

Netzband A., Hakstege A.L., Hamer K., 2002. Treatment and confined disposal of dredged material. Report, part two, of Dutch-German exchange on dredged material (DGE). 36 pages, Bonn, Den Haag, https://sednet.org/download/DGE-Part-II-Treatment.pdf

PIANC, 1998. InCom WG 17: Handling and Treatment of Contaminated Dredged Material (CDM) from Ports and Inland Waterways - Volumes 1 and 2 on CD-ROM

Posthuma L., Dyer S.D., de Zwart D., Kapo K, Holme C.M, Burton Jr GA., 2016. Eco-epidemiology of aquatic ecosystems: Separating chemicals from multiple stressors. Sci Total Environ, 573:1303-1319. doi: 10.1016/j.scitotenv.2016.06.242.

Salomons W, Brils J (eds), 2004. Contaminated Sediments in European River Basins. Final deliverable of the European Commission (EC) funded project SedNet (2002-2004), EC contract No. EVK-CT-2001-20002, 69 pp. Available via: https://sednet.org/wp-content/uploads/2016/03/Sednet_booklet_final_2.pdf

Santschi P.H., Presley B.J., Wade T.L., Garcia-Romero B., Baskaran M., 2001. Historical contamination of PAHs, PCBs, DDTs, and heavy metals in Mississippi River Delta, Galveston Bay and Tampa Bay sediment cores. Mar. Environ. Res. 52, 51-79.

Saranjampour, P., Vebrosky, E. N., Armbrust, K. L. 2017., 2017 Salinity impacts on water solubility and n-octanol/water partition coefficients of selected pesticides and oil constituents. Environ Toxicol Chem. 36(9):2274-2280.

Spadaro, P. A. 2011., Remediation of Contaminated Sediment: A Worldwide Status Survey of Regulation and Technology. Terra et Aqua, 123: 14-23

Spencer K.L., and Macleod C.L., 2002. Distribution and partitioning of heavy metals in estuarine sediment cores and implications for the use of sediment quality standards. Hydrol. Earth Syst. Sci. 6, 989–998.

Thiebault, T., Alliot, F., Berthe, T., Blanchoud, H., Petit, F., & Guigon, E. 2021. Record of trace organic contaminants in a river sediment core: from historical wastewater management to historical use. Science of the Total Environment, 773, 145694.

Tornero, V., Hanke, G., and the MSFD Expert Network on Contaminants. 2019. Marine chemical contaminants – support to the harmonization of MSFD D8 methodological standards. Matrices and threshold values/reference levels for relevant substances. JRC technical reports. EUR 29570 EN, Publications office of the European Union, Luxembourg.

Turner, A., 2003. Salting out of chemicals in estuaries: implications for contaminant partitioning and modelling. Science of the Total Environment 314–316, 599–612.

References Chapter 4

EC, 2004. Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage.

EC, 2021. Commission Notice Guidelines providing a common understanding of the term 'environmental damage' as defined in Article 2 of Directive 2004/35/EC of the European Parliament and of the Council on environmental liability with regard to the prevention and remedying of environmental damage 2021/C 118/01

Habersack H., Baranya S., Holubova K., Vartolomei F., Skiba H., Babic-Mladenovic M., Cibilic A., Schwarz U., Krapesch M., Gmeiner Ph., Haimann M. 2020a. Danube Sediment Management Guidance. Output 6.1 of the Interreg Danube Transnational Project Danube Sediment co-funded by the European Commission, Vienna. https://www.interreg-danube.eu/uploads/media/approved_project_output/0001/39/ee566924f1764d4798dc7bb9b59537ce84d98101.pdf

Habersack H., Baranya S., Holubova K., Vartolomei F., Skiba H., Schwarz U., Krapesch M., Gmeiner Ph., Haimann M. 2020b. Sediment Manual for Stakeholders. Output 6.2 of the Interreg Danube Transnational Project DanubeSediment co-funded by the European Commission, Vienna.

ICPDR. 2021. Danube River basin Management Plan. Part A – Basin-wide overview. Updates 2021. http://www.icpdr.org/main/sites/default/files/nodes/documents/ic231_drbmp_update_2021_draft_v10.pdf

LAWA. 2019. The need for sediment management plans in river basin management, Position paper and General concept for the preparation and contents of an integrating sediment management plan, Jena. https://www.lawa.de/documents/lawa-sedimentmanagment-teil-a-positionspapier_1575971825.pdf https://www.lawa.de/documents/lawa-sedimentmanagment-teil-b-grobkonzept_1575971866.pdf

Loire R., Piégay H., Malavoi J.-R., Kondolf G.M., Melun G. 2020. Les lâchers morphogènes depuis un barrage justification opérationnelle et protocole d'intervention. La Houille Blanche, pp. 66–75

Malavoi J.R., Bravard J.P., Piegay H., Heroin E., Ramez P., Determination de l'espace de liberte des cours d'eau, Bas-sin Rhone Mediterranee Corse, Guide Technique N°2, 1998, 39 pp..

Quick, I. 2012. Sediment management concept with special regard to hydromorphological aspects. In: Die Elbe und ihre Sedimente. Magdeburger Gewässerschutzseminar 2012, Tagungsband. S. 167-168. Hamburg

Quick I., König F., Baulig Y., Borgsmüller C.; Schriever S. 2017. The hydromorphological classification tool Valmorph 2 for large and navigable surface waters. BfG-Report No. 1910. Federal Institute of Hydrology. Koblenz.

Quick I., König F., Baulig Y., Schriever S., Vollmer S. 2020. Evaluation of depth erosion as a major issue along regulated rivers using the classification tool Valmorph for the case study of the Lower Rhine. International Journal of River Basin Management,18(2): 191-20

Rinaldi M., 2009. Approfondimenti dello studio geomorfologico dei principali alvei fluviali nel bacino del Fiume Magra finalizzato alla definizione di linee guida di gestione dei sedimenti e della fascia di mobilità funzionale. Relazione Finale Convenzione di Ricerca tra Autorità di Bacino del Fiume Magra e Dipartimento di Ingegneria Civile e Ambientale, Università di Firenze, 152 pp..

Rinaldi M., Surian N., Comiti F., Bussettini M. 2011, MANUALE TECNICO – OPERATIVO PER LA VALUTAZIONE ED IL MONITORAGGIO DELLO STATO MORFOLOGICO DEI CORSI D'ACQUA – Versione 1, Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, 232 pp..

Rinaldi M., Simoncini C., Piégay H, 2009. Scientific design strategy for promoting sustainable sediment management: the case of the Magra River (Central-Northern Italy). River Research and Applications, 25, 607–625

Rinaldi M., Surian N., Comiti F., Bussettini M. 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI) . Geomorphology, Volumes 180–181, 2013, Pages 96-108,ISSN 0169-555X

Annex A: Case studies

Case study 2.1: Beneficial relocation of dredged sediment for port maintenance in the Mersey Estuary - Working with Nature

This case study provides an example of the use of stakeholder consultation to provide a beneficial use option for dredged sediment relocation within a commercially-used estuary.

Author: Jan Brooke

Country: United Kingdom

River basin: North West

This example illustrates a case of integration of environmental considerations in the sediment management planning process for navigation. The results of such integrated approach led to applying win-win solutions both for navigation and the environment.

Suspended fine sediment from the Mersey Estuary enters the Liverpool and Birkenhead Dock system via the pumps and lock entrances. The accumulated sediment requires regular dredging to maintain safe depths for navigation. Until recently, Peel Ports, operator of the Port of Liverpool, disposed of this dredged sediment 20km offshore in Liverpool Bay (Fig. A2.1.1).

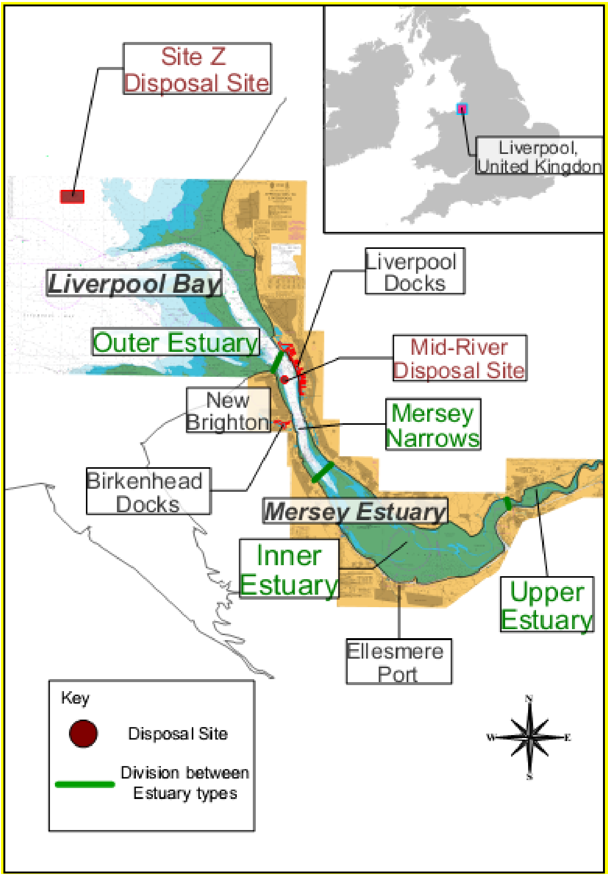

Fig A2.1.1. Map of the Mersey Estuary showing offshore (Site Z) and mid-River sediment disposal locations (Illustration from Brooke and Bird, 2013).

While sediment disposal offshore was not causing any adverse environmental impacts, the following considerations prompted the port's Marine Team to instigate a stakeholder engagement initiative to identify whether options might exist to use the maintenance dredged material beneficially:

- The Environment Agency's 2006-2008 classification of WFD ecological potential had identified that the 'sediment management' mitigation measure was not yet in place for the Mersey Estuary HMWB[54];

- Natural England's consultation response to the port's draft Maintenance Dredge Protocol baseline document (prepared to demonstrate compliance with the EU Habitats Directive) expressed support for an initiative to ensure the continued supply of sediment to the intertidal habitats of the Mersey Estuary designated Special Protection Area;

- The port itself was aware that both transport costs and carbon emissions could be reduced if a beneficial use could be identified closer to the point of dredging.

The stakeholder engagement exercise highlighted that flood-tide placement at the existing Mid River 'bad weather' disposal site, only 1km from the Docks, would facilitate the natural up-estuary transport of fine

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[54]

sediments. Subsequent hydrodynamic modelling and tracer studies, followed monitored trials using adaptive management principles, confirmed the viability and beneficial nature of this option.

From the outset, the Mersey Estuary beneficial use initiative followed PIANC's[55] Working with Nature philosophy. This aims to change the way port and waterway operators think about construction and maintenance activities by working through the following four steps prior to deciding on a project design or delivery mechanism:

- Establish the project need and objectives
- Understand the characteristics of the natural environment in which the activity is to take place
- Engage with relevant stakeholders; listen to their ideas and aspirations
- Identify the potential for a win-win solution based on the above.

In 2018, the 'Beneficial Placement of Dredged Sediment – Mersey Estuary' project received PIANC's Working with Nature Certificate of Recognition, confirming the success of this Peel Ports' initiative.

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[55]

Case study 2.2: Sediment augmentation and floodplain reconnection in the Aragon River

This case study describes measures taken to restore the sediment characteristics and floodplain connectivity of the Aragon River, Spain, to a more natural state.

Author: Fernando Magdaleno

Country: Spain

River basin: Ebro

Summary

In recent years, the territory associated with the middle and lower reaches of the Aragón and Arga rivers (in Navarre, Northern Spain, before their confluence with the Ebro River), has suffered numerous problems as a result of recurrent floods and river incision. The river system is characterized by large and fertile floodplains, in which intensive agricultural activities are carried out presently, and where several municipalities (12) and numerous linear infrastructures are located. At the same time, it constitutes an area that supports various natural sites protected by regional regulations and by the European network Natura2000 (Fig. A2.2.1). In particular, most of these sites sustain riparian and alluvial forests protected by the Habitats Directive (92/43/EEC), and host critically endangered faunal species such as the European mink (*Mustela lutreola*).

Since the beginning of the 21th century, the Government of Navarre and the public company Gestión Ambiental de Navarra (GAN) - with support from the Ebro Basin Agency and the Spanish Ministry for the Ecological Transition and the Demographic Challenge - have dedicated large efforts to the restoration of the Aragón and Arga rivers. Their historical degradation originated from their progressive flow regulation, the occupation of the rivers´ floodplains and the ecomorphological effects of the rectification of specific reaches, carried out in an attempt to reduce flood risks and to gain new areas for agriculture. The restoration initiatives in the area have been conducted from a perspective of integration of European obligations in terms of water, flood risks and biodiversity, and have been partly developed by means of different EU-funded projects.

Geographical context

The case study is located in the Ebro basin, in NE Spain. The Aragón River is a left tributary to the Ebro mainstem, and drains a wide portion of the Pyrenees area. The Arga River is a tributary of the Aragón channel, which flows, among other municipalities, through the city of Pamplona.

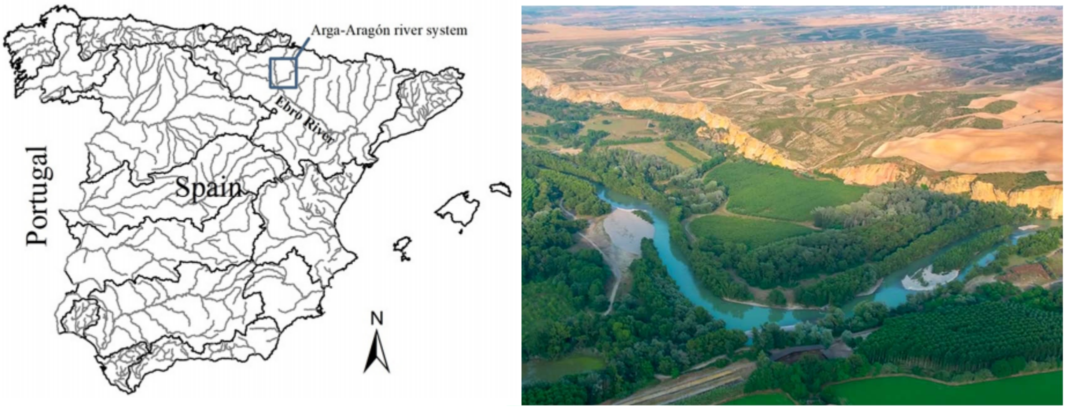

Fig. A2.2.1 (a) Location of the Aragón River within the Ebro Basin; (b) Photograph of a reach in the lower course of the river, characterized by large cultivated floodplains which surrounds riparian and alluvial forests, and dryland areas in the nearby environments (Source: Government of Navarre & MN Consultors).

The Aragón River is regulated by the Yesa reservoir (447 hm^3, built in 1959) and the Itoiz reservoir (417 hm^3, built in 2004 on one of its main tributaries), which largely modify its flow and sediment patterns. But also by other smaller dams (e.g. several hydropower plants located along its course). Sediment genesis has also been modified, during the last decades, due to changes in land use in the headwaters (rural abandonment and natural afforestation of the upper basin). The average flow of the Aragon River in one of the gauging stations of its lower course (Caparroso) reaches ca. 65 m^3/s (along the time series 1912-2018). The water body where the sediment augmentation was developed (ES091MSPF421) has Good ecological and Good chemical status, and is entirely part of an Area with Potential Significant Flood Risk (ES091_ARPS_BAR).

Description of the issue

The river had been dredged in the 80s and 90s of the past century to increase water conveyance during flood events. The sediments dredged (with a dominance of gravels) were used to construct bank levees with the objective of protecting arable lands from flooding. The embankments and the deficit of sediments (as a result of dredging, trapping in the upstream reservoirs and reduced genesis due to changes in land use in the headwaters) had contributed to ongoing incision, progressive loss of ecohydrological connectivity between the riverbed and the floodplain, and decay of aquatic and riparian habitats.

Some municipalities and specific water users were still requesting further dredging and new defence works in the first decade of the new century. Nonetheless, regional and state-wide administrations, with the support of different Universities and Research Centres carried out a thorough assessment of potential alternatives for the management of the river system and the sediment dynamics. Those studies involved 2D hydraulic modelling, hydromorphological detailed analyses, and ecological/water quality studies. Against a falsely-based social feeling of river sections raising due to sediment accretion, the afore-mentioned assessments showed that the Aragon River was facing accelerated incision and morphological degradation. Also that continued dredging could not, by any means, offer further protection to the nearby towns, while it constituted an expensive and ecologically disturbing activity. As part of the finally prioritized alternatives, sediment augmentation in the Aragon River was selected, along with floodplain reconnection by removal or relocation of former defence works. In parallel, habitat restoration for vulnerable or endangered communities and species was conducted, in an attempt to harmonize WFD, Flood Risk Directive and Birds and Habitats Directive objectives.

Management of the issue

The functional restoration of the river system involved: i. removal of 7,5 km of levees and rip-raps[56] (and the relocation of many others), ii. increase of 80 ha in the river dynamic territory, iii. habitat improvement of 128 ha (over 25 different areas), iv. creation of 13,6 ha of wetlands (in 14 different areas), v. removal of 116 ha of cultivated poplars, and vi. reforestation of patches in degraded sites, with vegetative and non-vegetative propagules, including bio-engineering techniques in the constructed wetlands. But more particularly, and with the objective of restoring the hydromorphological pattern of the river and rebalancing sediment transport, 105.000 m^3 of sediments in the Aragon River were reintroduced, which were originally part of the (removed) embankments (Fig. A2.2.2).

Fig. A2.2.2. (a) Removal of embankments to reconnect riverbed and floodplains in Natura2000 sites; (b) embankment removal and reintroduction of sediments - in some cases, performed by the same operators which decades ago had dredged the river and constructed the berms (Source: Gov. Navarre & MN Consultors).

Sediment reintroduction was conducted following a pre-designed planning. Sediment materials were reincorporated into the river in sections whose depth and width allowed an easier downstream transport, and temporally executed when the affection to aquatic habitats and species (due to potentially increased turbidity or clogging could be smaller/non-critical for vulnerable populations). A vast majority of the reintroduced sediment volumes was formed by gravels of different size. A campaign of sediment sampling was initially developed, in order to understand the distribution of grain sizes along the project site and optimize the operations; this involved field sampling for the coarser clasts, and laboratory determination of the finer fractions of sediment. As formerly indicated, reintroduced materials originated in the existing embankments, but also came from excavated nearby floodplains.

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[56] Human-placed rock or other material used to protect shoreline structures against scour and water, wave, or ice erosion

Outcomes

So far, and in accordance with the extensive monitoring conducted (March 2014-July 2019), the restoration measures developed have shown their effectiveness in terms of sediment dynamics amelioration and ecological restoration, under the conditions imposed by the many anthropogenic pressures and impacts studied during the initial stages of this large process of functional restoration.

Sediment monitoring consisted of coupled topographic and bathymetric analyses in a wide river area (6.3 km) which included the project site and river reaches upstream and downstream of it (river sections and longitudinal profiles/local slopes), and sediment budgets in the entire area monitored. The main results of the monitoring are (Fig. A2.2.3): i. river incision has stopped and even reversed in most of the project area, and even in upstream areas, following a complex mosaic of geomorphic patches; ii. annual flooding and the reintroduced sediments have contributed to a geomorphic reorganization of the river reach, in which more natural forms and processes are now dominating the river dynamics; iii. newly organized riparian habitats are contributing to a rich biogeomorphic readjustment which may mitigate the ongoing ecological decay which had been found prior to the works (Pérez-Martín *et al.*, 2015)..

Also thanks to the successful implementation of the restoration projects and their didactic role on authorities and people, no new extensive dredging or new defence works have been approved or implemented since the early application of the restoration actions in the study area, despite the many floods during that time. The project has enjoyed a wide national and international acknowledgement, which has also contributed to its positive social reception, and to its conversion into a paradigmatic intervention in the Ebro and in other Spanish basins. The functional restoration of the Aragon River was finalist in the 2016 European River prizes. Prior to that, the river was rehabilitated in different sites as part of the Life GERVE Project (2006-09), which was selected as one of the 26 Best LIFE Nature Projects in 2007-08.

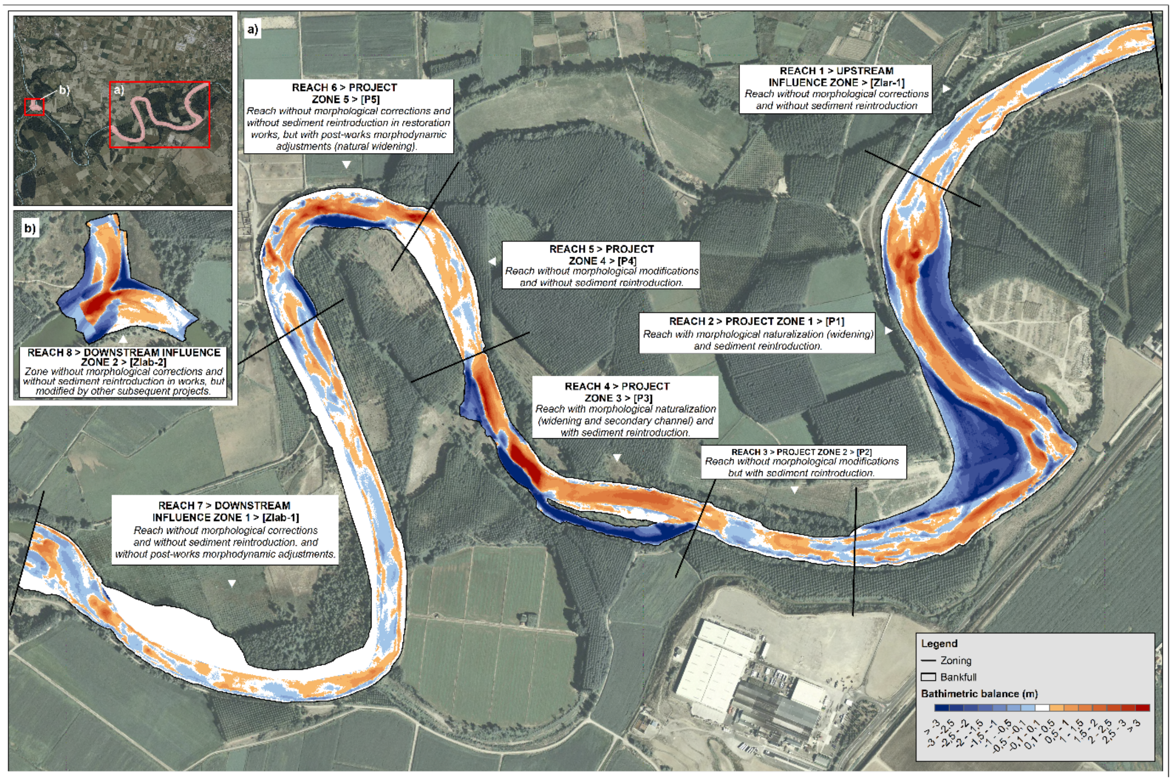

Fig. A2.2.3.- Inter-annual bathymetric balance (2014-2019) in the project area, which shows the areas which have lowered during that period (cold colours) - mostly as result of floodplain excavation/reconnection, but also due to the post-work geomorphic reorganization – and the areas which have raised (in warm colours), reverting the previously ongoing incision. Source: Government of Navarre & MN Consultors.

Contextual information

The documented case study was carried out by the Regional Government of Navarre. After this initiative, the Ebro Basin Agency has developed other projects aimed at improving flow-sediment-ecology interactions in the study area. Most recently, a broader initiative which upscales and shares much of the vision of the former case has started for an improved management of the central sector of the Ebro River (ca. 325 km in length): the Ebro Resilience Project (https://ebroresilience.com/). This project is based on the interadministrative cooperation between the basin agency, 3 regional governments and 62 municipalities.

References

Magdaleno, F. 2020. Multi-functional restoration of the Arga-Aragón River System (Navarre, Spain). In book: Best Practices in Evaluation and Restoration of Degraded Mediterranean Environments. Monografías do IBADER - Serie Territorio. Ibader. Universidade de Santiago de Compostela. Lugo

http://www.ibader.gal/ficha/547/924/Best-Practices-in-Evaluation-and-Restoration-of-Degraded-Mediterranean-Environments-2019-.html

Pérez-Martín, C., Manzano, M., Cadiach, O., Pascual, R., Jaso, C., García, G., Martín-Vide, J.P. 2015. Basis and preliminary results of the experimental project of restoration and Habitat creation for the European mink (Mustela lutreola) in the river Aragón (Navarre). In: Proceedings of the final seminar of the Life + Mink Territory project LIFE09 NAT/ES/531 9-10-11 June 2015 Pamplona/Iruñea. Chapter: 3. The European Project LIFE MINK TERRITORY (LIFE09/NAT/ES/531) and the Government of Navarre].

Serra-Llobet, A., Kondolf, G. M., Magdaleno, F., & Keenan-Jones, D. (2022). Flood diversions and bypasses: Benefits and challenges. Wiley Interdisciplinary Reviews: Water, 9(1), e1562.

Case study 2.4: Sediment management plans in Italy and river Po sediment management plan

This case study describes the structure of the sediment management plan for a major EU catchment, the Po river basin in Italy.

Author: Martina Bussettini

Country: Italy

River basin: Po

Sediment Management Plans in Italy

According to the Italian legislation[57], Sediment management plans (SMP) are an obligatory and integral part of RBMPs, aimed to integrate the objectives of WFD and FD. Indeed, SMPs aim to enhance river hydromorphological and ecological status and to reduce flood risk through a specific programme of measures targeting sediment transport, river channel and fluvial corridor morphology, position and operational scheme of hydraulic infrastructures or any other infrastructure in the fluvial corridors or on the hillslopes that may interfere with sediment dynamics and morphological processes in the river networks.

Italian legislation also recognizes SMPs as essential instrument and knowledge basis to identify those "integrated measures" in FRMP aimed to reduce flood risk while protecting and restoring ecosystems and biodiversity.

SMPs consists of three components:

1. Characterization and analysis of the fluvial systems, with a particular focus on reach morphology and sediment transfer processes.

Catchment-wide general setting (geology, topography, climate, hydrology, land cover, land use); multi-scale delineation of spatial units (e.g. sub-catchments, reaches) and their characterization. Analysis of factors and processes controlling the spatial pattern of channel morphologies: sediment sources and delivery, sediment budget, controlling factors (e.g. bed slope and stream power).

2. SMPs' objectives in terms of target river corridor and channel morphology, achieving hydromorphological and ecological enhancement and reducing hydraulic risk. Measures to achieve such objectives shall reduce sediment unbalance and the disconnection of river channels with their floodplain, wherever feasible.

3. Identification of further measures to reach SMP objectives, including an adequate monitoring programme to follow the effects of measures and update the river system characterization. The selection of the most appropriate measures among possible alternatives shall derive from a compared evaluation of the expected effects in a sufficient spatial and temporal horizon. Measures allowing longitudinal, lateral and vertical continuity are considered as a priority, in particular restoring sediment transport of sediments in degraded reaches due to significant upstream disconnections, reconnecting river channels with their floodplains and restoring the widest lateral mobility corridors; hydromorphological restoration.

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[57] Legislative Decree 152/06, article 117, 2-quater (National Environmental Act)

Removal of sediment or vegetation at the local scale, or any other artificiality in the river corridor, have to be solidly justified through evaluations, related to the river evolutionary trajectory, of the expected outcomes in the long term and compared to alternative measures. If sediments are removed in aggraded reaches of a river, priority shall be given for their reintroduction in sediment-starved reaches on the basis of the characterization of stage 1 and consistently with the objectives in stage 2.

SMPs are designed and implemented by RBD Authorities, in coordination with other competent authorities (e.g Regional Administrations).

The Po River Sediment Management Plan

The current SMP was shaped in 2006, through a Po River Basin Authority Act (Deliberazione 9/2006) stating the need to implement a SMP to regulate sediment management, river channel morphology and infrastructure maintenance. Successively, the SMP has been legally recognised as a substantial part of the RBMP and as a sub-plan inside theRBMP and as a priority measure in the FRMP. The plan is currently undergoing an update in order to support the implementation of a catchment wide restoration plan.

The Po SMP consists of three parts:

1. updating river system characterization
2. *identification of target* river corridor and channel morphology and *definition of the* objectives of flood risk mitigation and hydromorphological status protection or enhancement
3. definition of measures to reach the objectives.

The SMP has different degrees of maturity in the different sub-basins composing Po River Basin.

For the Po river channel, subdivided into three segments (upstream, intermediate, downstream), the plan and its measures are already under implementation, consistently with the available funding. Its Programme of Measures (PoM) envisages the protection of fluvial forms and processes, the restoration of sediment dynamics (erosion, sedimentation, transport), through removal of non-strategic structures (or their adaptation) and the reactivation of lateral river branches and fluvial forms recovery. Implementation of the SMP is considered as win-win measure inside both Po RBMP and FRMP.

The SMP is founded on a detailed analysis of river channel morphology and sediment transport dynamics, carried out quantifying the modifications occurred on river banks, river channels forms and river bed in the last decades, based on geomorphic maps of historic trends, DTM (Digital Terrain Model) and accurate topographic surveys

In the downstream part of the Po river, about 650 km lateral flood defence (levees and embankments) constrain Po river main stem (490 km), from Turin to the Po delta. The SMP PoM envisages there that:

- 105 km non-strategic structure shall not be maintained anymore
- 20 km lateral structures shall be removed
- 34 km groynes built to allow navigation will be lowered.

The following table describes the different components of the Po SMP and their contents.

Table A2.4.1. Contents of the Po SMP Technical report[58].

1.LEGAL CONTEXT AND AGREEMENT AMONG RBD COMPETENT AUTHORITIES
2.ANALYSIS AND CHARACTERIZATION
Morphological characteristics of river channel Topographic and aerial data Granulometry and lithological characterization of channel sediments Sediment transport • Models and methods used • Analysis of occurred planform/vertical modifications of river banks and emerged features (bars, islands) • Evaluation of sediment volumes • External sediment inflows • Sediment budget
3. SEDIMENT MANAGEMENT PROGRAMME
Current context and critical conditions • Map of current morphology and pressures • Ongoing hymo processes in the incised channel • Flood defences • Anthropic pressures • Sediment transport indicators • Comprehensive picture of the Current context SMP Objectives • General and local objectives and their map • General objectives • Local objectives • Comprehensive view of SM objectives in the river SMP Measures • Measures types and map • Extraordinary strategic structural measures • Ordinary strategic structural measures • Ordinary strategic non-structural measures • Criteria and bans for local interventions • Relevant measures at the river segment • Priorities in relevant measures • Monitoring activities

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[58] https://adbpo.gov.it/archiviodelibere/delibera-1-2008-24-gennaio-2008-adozione-del-programma-generale-di-gestione-dei-sedimenti-alluvionali-dellalveo-del-fiume-po/

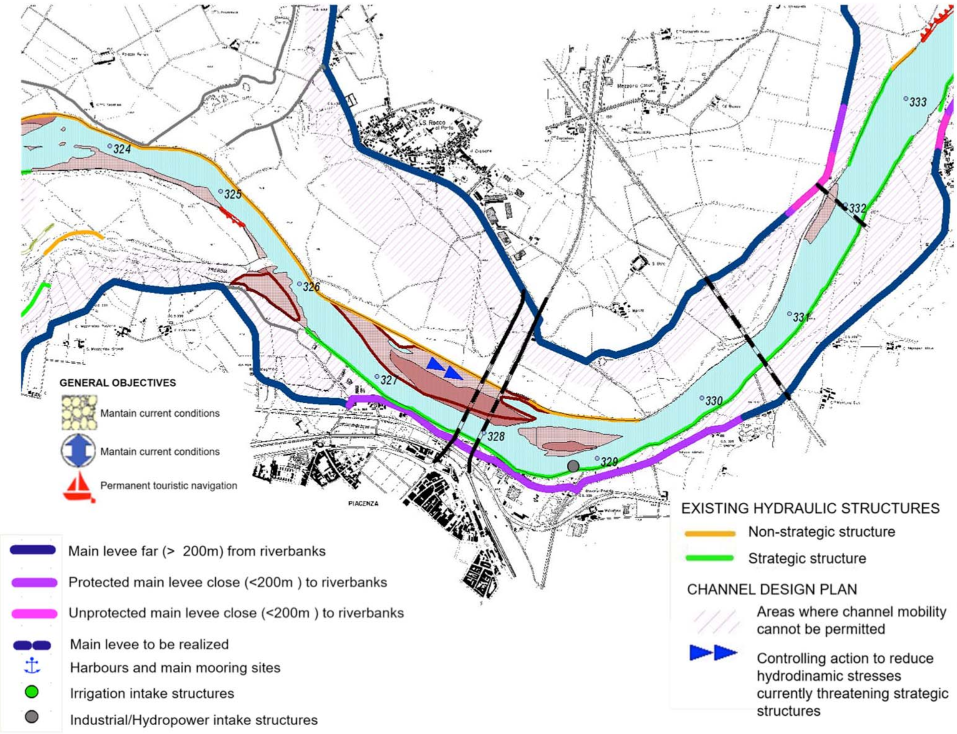


Figure A2.4.1. Map of the SMP Objectives (modified from *Autorità di Bacino del Fiume Po (2005))*

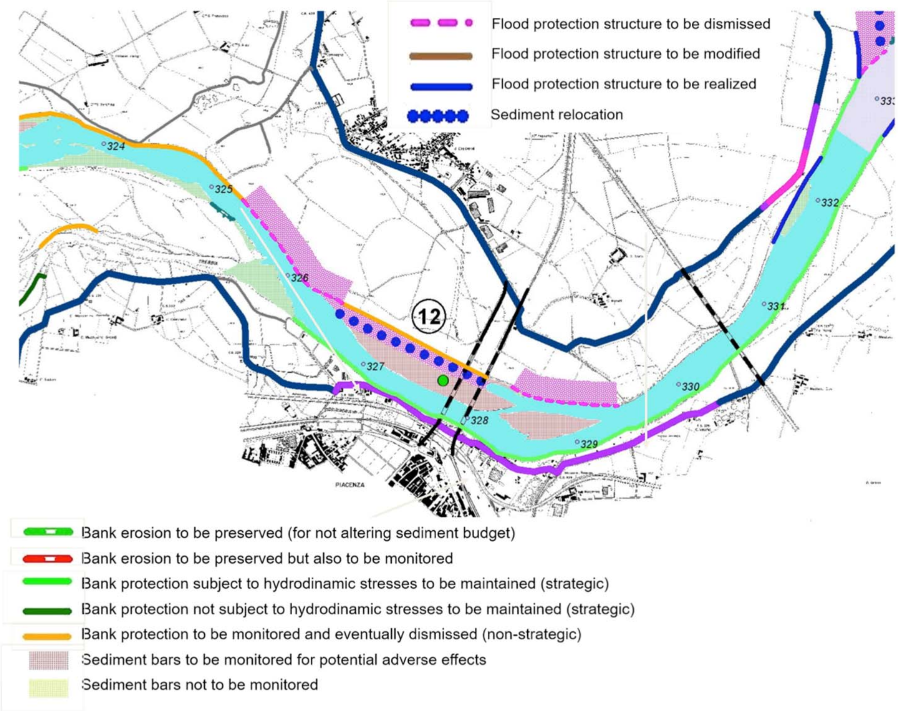


Fig. A2.4.2. Map of the SMP measures. (modified from *Autorità di Bacino del Fiume Po (2005))*

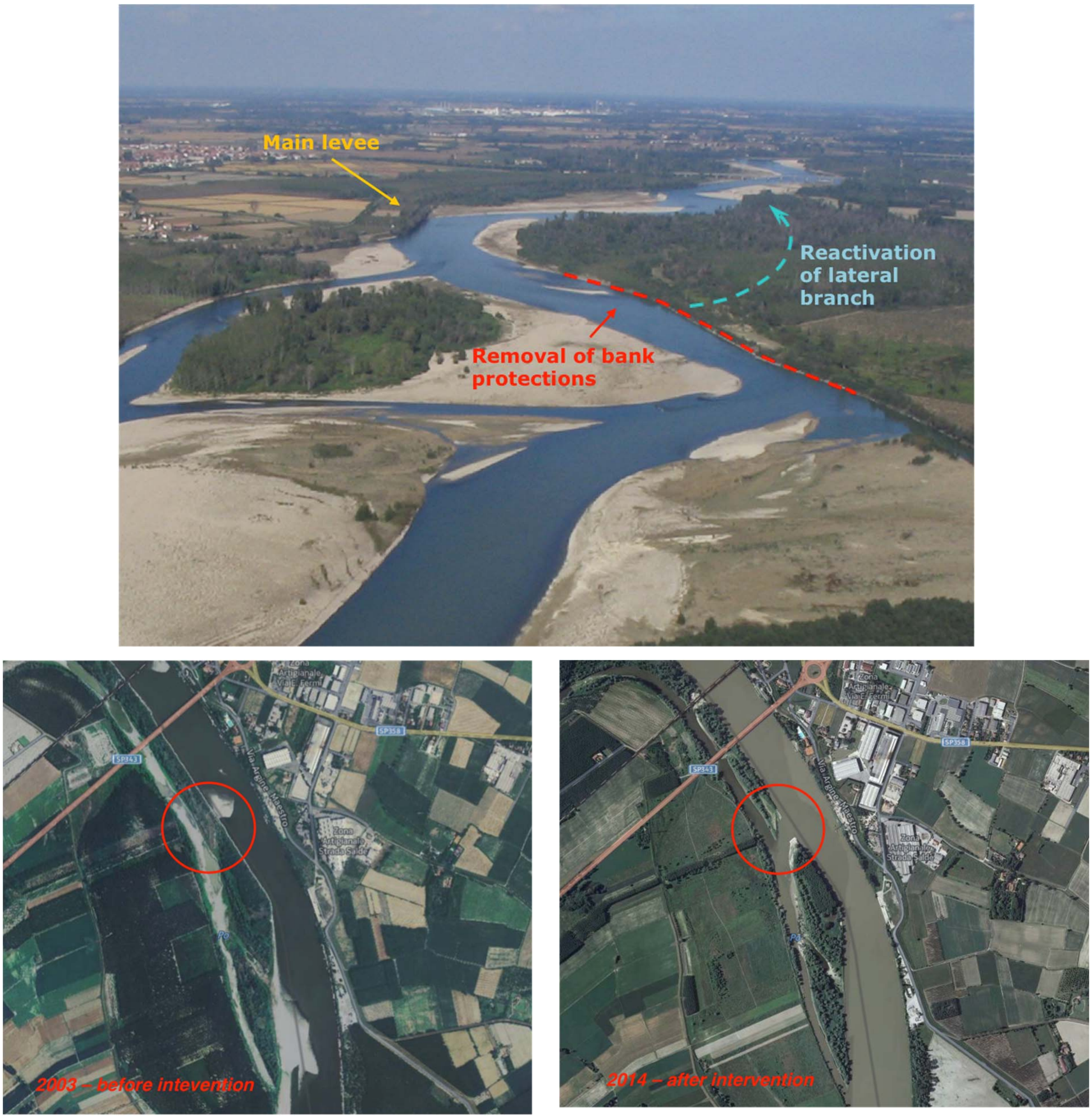


Fig. A2.4.3. SMP measures. Reactivation of a lateral branch of Po River.

References

Decreto Legislativo 152/2006. Norme in materia Ambientale.

Autorità di Bacino del Fiume Po. Delibera n. 9/2006 del 5/4/2006 Direttiva tecnica per la programmazione degli interventi di gestione dei sedimenti degli alvei dei corsi d'acqua. (Articoli 6, 14, 34 e 42 delle Norme di Attuazione del PAI) e ss.mm.ii.

Segreteria Tecnica del Bacino del fiume Po (2008). Il recupero morfologico ed ambientale del fiume Po. Il contributo del Programma generale di gestione dei sedimenti del fiume Po.

https://adbpo.gov.it/i-programmi-di-gestione-dei-sedimenti-del-fiume-po/

Case study 2.10 Experimental flood releases: a potential tool to (partially) restore riverine sediment dynamics downstream of dams

This case study provides examples of pilot testing of experimental flood releases downstream of reservoirs, as a tool to partially restore riverine sediment dynamics downstream of dams

Authors: Mònica Bardina , Antoni Munné , and Albert Rovira

Country: Spain

River basin: Catalan

Summary of content

In 2005, the Catalan Water Agency (ACA) defined the channel forming discharge (Qg) that had to be released, at least, once per year, downstream of the reservoirs located in the Catalan basin District (North-East Spain). However, the effects of the Qg on the morphology of the river system were not fully evaluated. Accordingly, three pilot tests were set up downstream of two reservoirs to assess the effects on the river morphology. The pilot tests involved the artificial generation of the Qg flood from the reservoir, the monitoring of the suspended sediment transport and the analysis of the changes in channel morphology and riverbed texture. In addition, artificial sediment injections were also carried out during the pilot test using two different methods (active and passive) with the aim to evaluate its viability as a potential tool to partially restore the flow of the finest sediment fractions downstream of dams.

Geographical context

The Llobregat River (with a catchment area of 4,948 km^2) and the Ter River (3010 km^2) are in the North-East of Spain, being the two main fluvial arteries of the Catalan Basin District (Fig. 1).

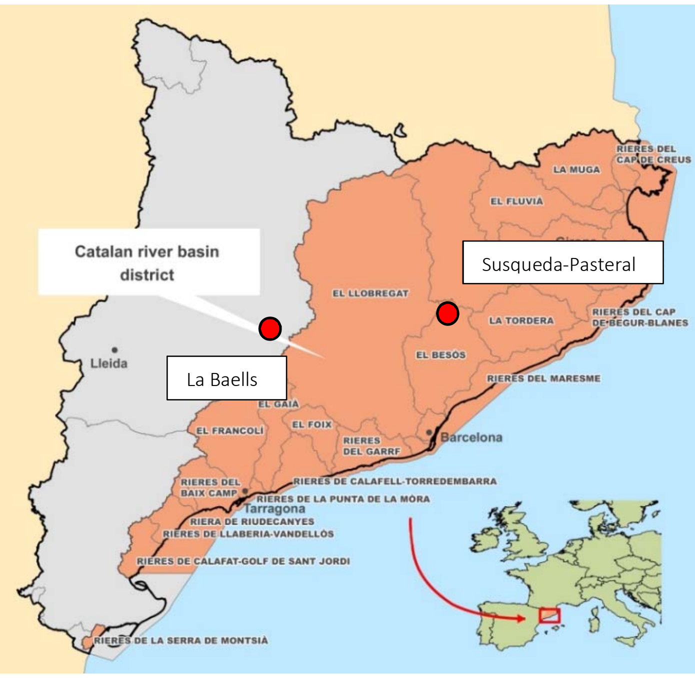


Fig. A.2.10.1. Scheme of the Catalan Basin District and location of the La Baells and Susqueda-Pasteral dams (figure provided by ACA-Catalan Water Agency).

La Baells reservoir, constructed in 1976 for water supply and hydropower generation, is located in the upper parts of the Llobregat basin and it regulates the Llobregat flow regime, since no significant tributaries exist for several kilometres downstream of the reservoir. Below the dam, the river shows two well differentiated hydro-morphological segments: in the first one, that covers the first 2 km, the river has a rock-confined valley, with an average longitudinal slope of 0.0089 and a mean channel width of 9 m (Fig 2A). In the second segment (last 5.8 km), the river valley presents a narrow and discontinuous floodplain, an average longitudinal slope of 0.0085 and a mean active river channel width of 17 m.

Fig. A2.10.2. Views of the Llobregat River (left), and the Ter River (right) (Images provided by ACA-Catalan Water Agency)

The Susqueda-Pasteral reservoir is in the middle part of the Ter river basin (3010 km^2), close to the city of Girona. The reservoir was constructed in 1855 for hydropower generation, water supply and irrigation purposes. Below the dam, the river also shows two differentiated hydro-morphological segments: in the first segment, with a total length of 16 km, the active channel has an average width of 28 m. There, the river valley sustains a narrow floodplain and an average longitudinal slope of 0.00419, in average. In the second segment, the Ter River has a wide floodplain and an average longitudinal slope of 0.00347 (Fig. 2B). The total length is 10 km, and the active channel width, 70 m. Downstream of the reservoir, the Ter River is partially regulated due to the existence of significant tributaries.

The area of interest comprises the first 8 km of the Llobregat river below la Baells reservoir and, the first 26 km of the Ter river below the Susqueda-Pasteral dam.

The underlying issue

In 2005, the Catalan Water Agency (ACA) approved the Environmental Flow Plan (PSCM) that, for the first time, defined the regime of minimum environmental flows and the channel forming discharge (Qg) to achieve and protect the composition and structure of river ecosystems in acceptable quality following the Water Framework Directive (Bardina *et al.* 2016). The Qg was calculated with hydrological methods and defined as the most probable maximum annual flood in natural regime (in the period 1940-2000). According to the PSCM plan, the Qg has to be released from large hydraulic infrastructures (i.e. those with a storage capacity> 5 hm^3 or with a regulation rate> 0.5) of the Catalan Basin District, with the aim of improving the morphological dynamics of the river and thus, minimize the effects of hydrological regulation and sediment trapping exerted by the reservoirs. Since then, the Qg is released, at least, once a year for a period of 24 hours and in the most frequently occurring month. Nevertheless, the effects on channel morphology and riverbed (as well as the sediment transport capacity) had never been evaluated from a hydro-morphological dynamical perspective. Only, some preliminary studies were carried out in the basin of the Cardener River (Pallares 2015, Magdaleno 2017). The positive effects of the Qg has been found in some temporary river basins regulated by reservoirs, such as the Gaià River. Although no specific studies have been carried out, the Qg flows have allowed reaching the environmental flows regime in the river and reactivated the sediment transport downstream of the reservoir (Garcia Burgos *et al.* 2020, Magand *et al.* 2020).

Management of the issue

Three pilot tests (two downstream of the la Baells reservoir, and one below Susqueda-Pasteral dam) were conducted. The first pilot test was performed on May 9, 2019, downstream of La Baells dam, where a sediment injection was carried out by using a backhoe (active method). Sediments were located parallel to the riverbank and injected mechanically to the flow when the peak discharge was achieved. Water was released from the reservoir upper gates by discharging clean water, i.e. without sediment, in order to observe the sediment transport dynamics of the injected sediments (i.e. sediment wave time, suspended sediment concentrations, volume mobilized, etc.) at two monitoring points.

On November 26, 2020, a second pilot test was carried out, also downstream of La Baells reservoir, by reproducing the first pilot test flood hydrograph. In this test, a non-artificial sediment injection was performed, and water was released from the bottom gates of the reservoir. This allowed the analysis of the hydro-sedimentary dynamics of the channel forming flood under normal operational conditions as well as the comparison of both pilot tests.

On November 23, 2020, the pilot test in the Ter River was conducted, downstream of Susqueda-Pasteral reservoir, where a sediment injection was also carried out. In that case, sediments were placed parallel to the riverbank and arranged forming trapezoidal cords using the flow hydraulics (i.e. drag force) to erode and mobilize them (passive method).

Monitoring works mainly consisted of grain size analyses of the riverbed surface, elevation of topographic channel cross-sections, collection of suspended sediment samples and water level recording at the entrance and exit of the monitoring river reach. In addition, sediment tracers (marked sediment particles) on active river bars were used.

Outcomes

Below La Baells reservoir, the Qg released was large enough to partially mobilize and transfer the fine and medium riverbed particles of the active areas located at the medium and lower parts of the monitoring site. In contrast, at the upper part of the study site, sediment transport was almost marginal because the riverbed is extremely armoured there, and few deposition areas are available. In that context, an increase of the magnitude of the channel forming discharge peak (as restoration measure) could become counterproductive because the sediment deficit could be accentuated and the riverbed armouring extended to areas further away from the dam. Accordingly, the morphological (and sediment transport continuous) restoration in this area could only be achieved by means of artificial sediment injections (or by-passing sediments from the reservoir) because of the strong sediment deficit created by the dam. Despite the low generalized riverbed mobility, the designed Qg was validated.

In the Ter River, discharges released from the Susqueda-Pasteral reservoir mobilized riverbed particles (from silt to coarse gravels) along all the study area, validating the Qg. Overall, the riverbed shows a low armouring degree given the lateral input of sediment from the tributaries that mitigate the sediment deficit generated by the reservoir. However, existing weirs located in this area interfere with the natural suspended sediment dynamics by delaying the suspended sediment wave from the water wave. In that case, sediment injection (by means of the passive method) was partially successful because the flood was not able to completely mobilize them. Nevertheless, sediment injections, jointly with the opening of bottom gates of the reservoir, are appearing as a potential tool to partially restore the flow of the finest sediment fractions (i.e. clay, sand, and gravels).

Contextual information

This study was funded and supervised by the ACA and implemented by Labaqua-Suez and Serbaikal Engineers S.L. enterprises in collaboration with the University of Girona and the Institute of Research and Agri-food Technology (IRTA).

Pilot tests were conducted in coordination and agreement of all the social stakeholders in the study areas (i.e. fishers associations, town halls, water consortiums, etc.). Furthermore, informative leaflets were distributed to the public through multimedia channels. After pilot tests, press releases were sent to the various media and two dissemination videos were made and uploaded to the Catalan Water Agency web site:
http://aca.gencat.cat/ca/laigua/proteccio-i-conservacio/cabals-de-manteniment/cabals-generadors-i-sediments/index.html

This study represents a first step in understanding the response of the morphological system of the river reaches located immediately below reservoirs to improve their management. The morphological assessment of the moderate and small-scale flood events (released from the reservoirs at least once a year) allows determining its impact on river morphology and define the need (and degree) to restore its hydro-morphological dynamics. This study has special relevance in that it is the first time that channel forming discharges downstream reservoirs has been evaluated (from a morphological point of view) in Spain. In addition, the potential viability of two sediment injection methods (one active and another passive) has been assessed as restoring tools.

References

Bardina M, Honey-Rosés J, Munné A (2016) Implementation strategies and a cost/benefit comparison for compliance with an environmental flow regime in a Mediterranean river affected by hydropower. Water Policy 18 (2016) 197–216. https://doi.org/10.2166/wp.2015.169

Garcia Burgos, E., Bardina, M.; Munné, A., Solà, C. (2020). Aproximación multifocal para la recuperación hidromorfológica de la cuenca del río Gaià. RestauraRios 2020.03: 10p. https://doi.org/10.51443/RestauraRios.2020.03

Magand, C., Alves, M. H., Calleja, E., Datry, T., Dörflinger, G., England, J., Gallart, F., Gómez, R., Jorda-Capdevila, D., Marti, E., Munne, A., Pastor, V. A., Stubbington, R., Tziortzis, I. and Von Schiller, D. , 2020. Implementing e-flows in the lower Gaià River (NE Spain) affected by a big dam built for industrial water supply purposes in Intermittent rivers and ephemeral streams: what water managers need to know. Technical report – Cost ACTION CA 15113.10.5281/zenodo.3888474. https://digital.csic.es/bitstream/10261/214789/3/2020_SMIRES_management_handbook_optimitzat.pdf

Magdaleno F (2017) Experimental floods: A new era for Spanish and Mediterranean rivers? Environmental Science & Policy 75:10-18. https://doi.org/10.1016/j.envsci.2017.05.011

Pallares A, 2015 Efectes de l'alliberament de cabal generador a preses de Catalunya. UPC. https://upcommons.upc.edu/bitstream/handle/2117/83798/PallaresGiralAlba_Memoria.pdf?sequence=1&isAllowed=y

Videos of the pilot tests in the Llobregat and Ter River (available in a few weeks)

Analysis and proposals for sediment management in dams. Monitoring in the Llobregat river - YouTube. https://www.youtube.com/watch?v=arGBpXEehVY&list=PL2O8tMC5EiTrjA8Vu5uy7E-YZFpfd2n53&index=10

Análisis y propuestas de gestión de los sedimentos en los embalses. Monitorización en el río Ter – YouTube. https://www.youtube.com/watch?v=u4qf_MYxOdo

Case study 3.1: Elbe basin: Identification of source of sediment contamination

This case study provides an overview of the status of a river basin where present day contamination is largely derived from historical sources.

Author: Ilka Carls and Rene Schwartz

Country: Germany

River basin: Elbe

Full description

The Elbe basin comprises a highly developed transboundary European region with a strong economy and very old and intensive industrial and mining traditions (FGG Elbe, 2013; IKSE, 2014). Human activities during decades and centuries caused a long-term contamination of the river basin. The Elbe's current problem – an array of "classical" pollutants – is, to a great extent, not caused by current (recent) inputs. Of considerably higher importance are multiple-persistent bio-accumulative and geo-accumulative substances from a long industrial legacy (FGG Elbe, 2009; Heininger et al., 2014; Schwartz et al., 2015). The historical and recent pollution sources (primary and secondary point sources, diffuse sources) are found throughout the whole Elbe river basin. Organic pollutants such as Dichlorodiphenyl-trichloroethane (DDT), hexachlorobenzene (HCB) and polychlorinated biphenyls (PCBs) are predominantly coming from the Czech Republic. Metals such as cadmium (Cd), zinc (Zn), mercury (Hg), copper (Cu), lead (Pb) and the metalloid arsenic (As), but also the dioxins / furans (PCDD/F) and the hexachlorocyclohexane (HCH), originate from Germany, mainly from Elbe important tributaries such as Mulde and Saale. Hamburg is still the primary source region for organotin compounds (TBT and derivates) (see Fig. A3.1.1) (IKSE, 2014, Heise et al., 2005, 2007). The first Elbe management plan prepared under the WFD (2010-2015) highlights contamination as one of the most important supra-regional issues in water resources management (FGG Elbe, 2009). The plan underlines that contaminated sediments are among the main reasons for the failure to meet the WFD management objectives. As a consequence, the member states in the International Commission for the Protection of the Elbe River decided to develop a sediment management concept including recommendations for managing sediment. It was published in 2014 (IKSE, 2014) and is available at the following link : https://www.ikse-mkol.org/fileadmin/media/user_upload/E/06_Publikationen/01_Wasserrahmenrichtlinie/2015_ICPER-Infomation-Sheet_Sediment.pdf

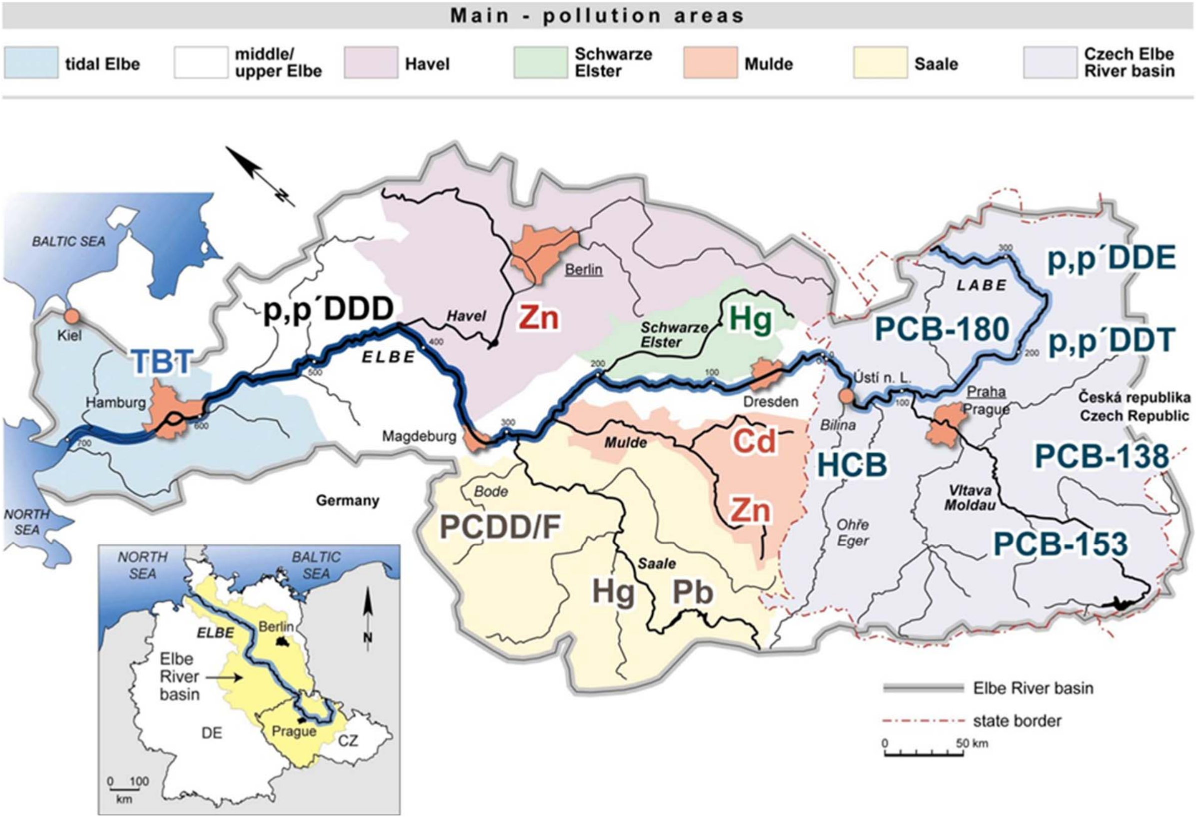


Fig. A3.1.1. The international Elbe catchment and its main contaminant sources (BUE, 2018).

References

BUE, Behörde für Umwelt und Energie, Hamburg, 2018. Ministry of Environment and Energy of the City of Hamburg, Homepage of ELSA: www.elsa-elbe.de.

FGG Elbe, Flussgebietsgemeinschaft Elbe - (Ed.), 2009. Hintergrunddokument zur wichtigen Bewirtschaftungsfrage Reduktion der signifikanten stofflichen Belastungen aus Nähr- und Schadstoffen - Teilaspekt Schadstoffe. Magdeburg. 27 p.

FGG Elbe - Flussgebietsgemeinschaft Elbe - (Ed.), 2013. Sedimentmanagementkonzept der FGG Elbe - Vorschläge für eine gute Sedimentmanagamentpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. 383 p.

Heininger, P., Keller, I., Quick, I., Schwartz, R. and Vollmer, S. 2014. Sediment management on river-basinscale: the River Elbe. In Cullmann, J. & Heininger, P. (Ed.) Sediment matters. Springer Berlin Heidelberg. pp. 201-247.

Heise S., Claus E., Heininger P., Krämer T., Krüger F., Schwartz R. Förstner U., 2005. Studie zur Schadstoffbelastung der Sedimente im Elbeeinzugsgebiet – Ursachen und Trends. Hamburg. 217 p.

Heise S., Krüger F., Baborowski M., Stachel B., Götz R. Förstner U., 2007. Bewertung der Risiken durch feststoffgebundene Schadstoffe im Elbeeinzugsgebiet. Hamburg. 349 p.

IKSE, Internationale Kommission zum Schutz der Elbe, 2014. Sedimentmanagementkonzept der IKSE - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. 200 p.

Schwartz R., Eichweber G., Entelmann I., Keller I., Rickert-Niebuhr K., Röper H. Wenzel C., 2015. Aspekte des Schadstoff-Sediments im Bereich der Tideelbe. In: Hydrologie und Wasserbewirtschaftung, 59, H.6, pp. 414-426

Case study 3.2: Sources of sediment contamination in the Rhine river basin

This case study describes the issue of sediment contamination in the Rhine river basin, which is to a large extent related to historical pollution

Author: Ronald van Dokkum

Country: Germany

River basin: Rhine

Full description

Human interferences with the river bed and the alluvial areas (construction of impoundments and dikes) have structurally changed the fluvial sediment processes in the Rhine basin. During the past decennia, not only quantitative aspects of sediment processes changed, but in addition contaminants accumulated in sediments. The sediment contamination peak was reached in the beginning of the 1970s. Very high direct discharges of contaminants into waters, and diffuse discharges from the catchment since then have continued their negative impact on sediment quality. In the Rhine and its tributaries the lower, older and more contaminated sediment layers may partly be remobilized by floods or by dredging. Then the sediment associated contamination is transported with the flow of water and impacts downstream river sections.

In 2009 the International Commission for the Protection of the Rhine River (ICPR) developed a sediment management plan for the Rhine. The following priority substances of the ICPR action programme 'Rhine 2000' are relevant as they adsorb to sediment and accumulate in suspended matter or bed sediments: the metals lead (Pb), cadmium (Cd), copper (Cu) nickel (Ni), mercury (Hg) and zinc (Zn) as well as the organic micro-pollutants hexachlorobenzene (HCB) and Benzo (a) pyrene (representing the polycyclic aromatic hydrocarbons (PAH)). Also relevant is the polychlorinated biphenyl (PCB) PCB 153 and the sum of 7 indicator PCBs (ICPR, 2009).

References

ICPR, International Commission for the Protection of the Rhine River, 2009, Sediment management plan Rhine, ICPR-report 175, Koblenz. 18 p.

https://www.iksr.org/en/topics/pollution/sediments?Fsize=4&cHash=90ef8c0e444a9413eba9f01888035cf8

Case study 3.3: Elbe basin: downstream transport of PCBs

This case study provides an example of the long-distance transport of sediment-associated contamination within a major EU catchment.

Author: Ilka Carls and Rene Schwartz

Country: Germany

River basin: Elbe

Full description

Historically high PCB concentrations have been detected in the Elbe in spring 2015. Concentrations in the monthly composite samples in the suspended sediments reached up to 6.000 µg/kg (sum 6 PCB-congeners) which is the highest ever measured value at the Elbe Czech-German border profile monitoring site Hřensko/Schmilka. In large areas and over long periods of time critical exceedances of the German environmental quality standard for PCB occurred. In the German Surface Water Ordinance, i.e. the transposition of the WFD into German law, the EQS for one PCB-congener is set to 20 µg/kg (OGewV 2016, Annex 6). The exceedance of the EQS was recorded for another 500 km downstream. Recent studies of PCB in bream underlined the relevance of the incident for the food chain (ELSA, 2016). According to the state water management of the Elbe (Povodí Labe) the extremely elevated concentrations resulted from the improper removal of PCB-containing paint of a railway bridge crossing the Elbe in the city of Ústí nad Labem. Due to the distinct low water levels in the middle and upper Elbe in 2015 and 2016, PCB-loaded suspended solids have deposited preferentially in the adjacent still water areas. Remediation works were accomplished in areas that are loaded with PCB material in the area of the railway bridge. With greater headwater discharges increased levels of PCB would enter the Elbe estuary. This would further complicate dredged material management in the Port of Hamburg, which is located at the tidal lower Elbe with a distance of about 100 km towards the North Sea. As in many other North Sea estuaries, regular maintenance dredging is necessary to keep safe water depths for navigation to the Port. In the tidal Elbe, 15 to 25 million m3 of sediment needs to be dredged annually. There are several options for handling dredged material on the Tidal Elbe, including disposal in the river system, North Sea disposal and – if dredged material is too contaminated – landfilling. Approximately 1 million m3 per year cannot be relocated in the estuary and must be deposited on land, resulting in additional costs that sum up to about 30 million Euros per year (Schwartz et al., 2015; ELSA, 2016; Hamburg Port Authority, 2020). The contamination of PCB sediments at the estuary of the Elbe near Hamburg is caused by the transport of contaminated sediments from the entire extensive Elbe basin.

References

ELSA, 2016. PCB in der Elbe – Eigenschaften, Vorkommen und Trends sowie Ursachen und Folgen der erhöhten Freisetzung im Jahr 2015. Behörde für Umwelt und Energie, Projekt Schadstoffsanierung Elbsedimente, Hamburg, S. 78

Hamburg Port Authority, 2020: Oral presentation by Hamburg Port Authority: http://www.hamburg-port-authority.de

IKSE, 2016. Vorsorge und Schutz vor PCB- und anderen Schadstoffeinträgen aus Altanstrichen in Gewässer des internationalen Flussgebiets der Elbe, S. 2. https://www.ikse-mkol.org/fileadmin/media/user_upload/D/04_Themen/02_Gewasserguete/PCB/IKSE-2016_Vorsorge_PCB_080916.pdf

OGewV, 2016. Verordnung zum Schutz der Oberflächengewässer (Oberflächengewässerverordnung - OGewV) vom 20. Juni 2016 (BGBl. I S. 1373), die durch Artikel 255 der Verordnung vom 19. Juni 2020 (BGBl. I S. 1328) geändert worden ist. Bonn. IN G. F. Government (Ed.) Bonn.

Schwartz R., Eichweber G., Entelmann I., Keller I., Rickert-Niebuhr K., Röper H. Wenzel C., 2015. Aspekte des Schadstoff-Sediments im Bereich der Tideelbe. In: Hydrologie und Wasserbewirtschaftung, 59, H.6, pp. 414-426

Case study 3.4: Contamination of sediments in the Rhine basin: identification and prioritisation of hotspots

This case study provides examples of the use of Sediment Quality Guidelines (SQGs) within a major EU catchment.

Author: Ronald van Dokkum

Country: Germany

River basin: Rhine

Full description

The conceptual approach of the Sediment management plan Rhine (ICPR, 2009) is based on further developed recommendations of the European Sediment Network SedNet and two studies on sediment contamination of the rivers Rhine and Elbe. The approach consists of three assessment steps which were taken within a comprehensive process (Fig. A3.4.1):

1. Verification of contamination
2. Verification of amount
3. Assessment of the risk of remobilization

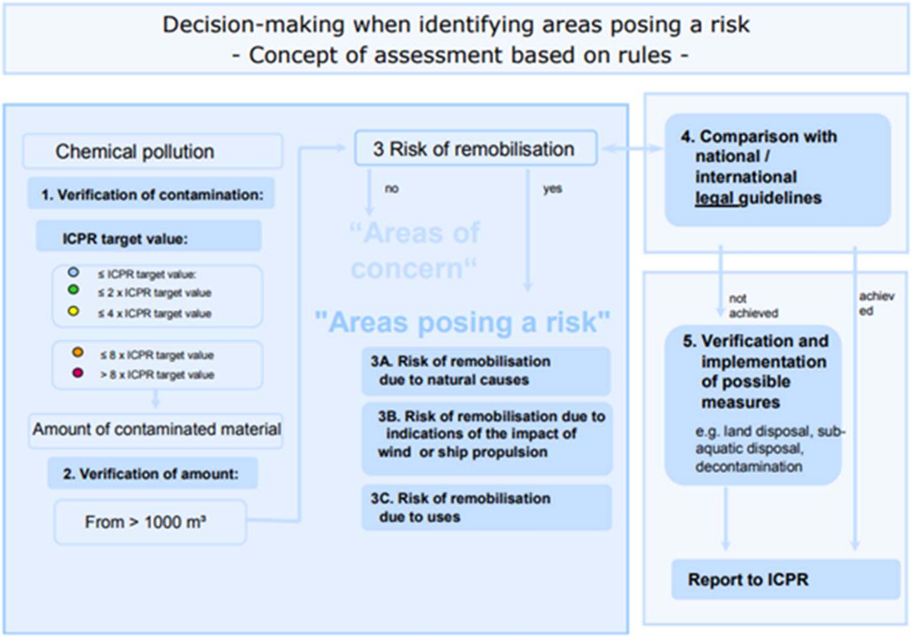
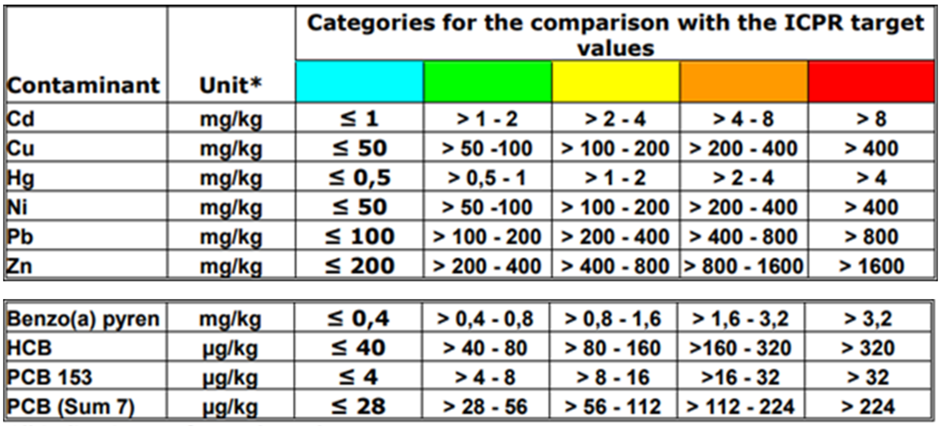


Fig. A3.4.1 Assessment scheme.

1. Verification of contamination

From the International Commission for the Protection of the Rhine (ICPR) action programme Rhine 2000, contaminants which adsorb and accumulate in suspended matter or bed sediment were selected. Areas were identified which were contaminated by one or more of these contaminants. Then the level of contamination of these areas was assessed using the Sediment Quality Guideline (SQG) values as indicated in Table A3.4.1. The ICPR Target Values (blue column Table A3.4.1) were used as a point of reference. Concerning the six metals from the list, use was made of existing Target Values for suspended matter/sediments. For organic pollutants, the value was deducted from the Target Value for the water phase. The relevant level of sediment contamination was selected based on expert discussions, including a detailed analysis of the contamination of sediments and suspended matter along the Rhine. The level of contamination was considered as relevant if it was considerably higher than that detected in the suspended matter of the river today. Thus, a level more than four times higher (i.e. the orange and red columns in Table A3.4.1) than the ICPR Target Value (i.e. the blue column on Table A3.4.1) was selected as a relevant level of sediment contamination. The (pragmatic) definition of this level partly also considers national criteria of assessment.

Table A3.4.1 Assessment of the level of sediment contamination in the Rhine basin. More than four times the ICPR Target Value (blue column) is considered as relevant (orange and red columns)



Contaminant	Unit*	Categories for the comparison with the ICPR target values				
		🟦	🟩	🟨	🟧	🟥
Cd	mg/kg	≤ 1	> 1 - 2	> 2 - 4	> 4 - 8	> 8
Cu	mg/kg	≤ 50	> 50 -100	> 100 - 200	> 200 - 400	> 400
Hg	mg/kg	≤ 0,5	> 0,5 - 1	> 1 - 2	> 2 - 4	> 4
Ni	mg/kg	≤ 50	> 50 -100	> 100 - 200	> 200 - 400	> 400
Pb	mg/kg	≤ 100	> 100 - 200	> 200 - 400	> 400 - 800	> 800
Zn	mg/kg	≤ 200	> 200 - 400	> 400 - 800	> 800 - 1600	> 1600
Benzo(a) pyren	mg/kg	≤ 0,4	> 0,4 - 0,8	> 0,8 - 1,6	> 1,6 - 3,2	> 3,2
HCB	µg/kg	≤ 40	> 40 - 80	> 80 - 160	>160 - 320	> 320
PCB 153	µg/kg	≤ 4	> 4 - 8	> 8 - 16	>16 - 32	> 32
PCB (Sum 7)	µg/kg	≤ 28	> 28 - 56	> 56 - 112	> 112 - 224	> 224

All indications refer to dry substance

2. Verification of amount

For the sedimentation areas with a relevant level of contamination, the amount of contaminated sediment was determined. It was agreed upon that areas with an amount of more than 1000 m³ of contaminated sediment, were the sedimentation areas to pass to the third assessment step.

3. Assessment of the risk of remobilization

For the areas with more than 1000 m^3 contaminated sediment the risk of remobilization was assessed. In case there *was no risk of remobilization*, these areas were assigned as '*Areas of concern*'. In general, these areas do not represent any risk for downstream river sections. Nonetheless, attention must be paid to these sediments and during periodic maintenance dredging or individual construction measures they should be treated in accordance with the rules for national re-deposition of dredged material, or they should be subject to controlled disposal. In case there *was a risk of remobilization* due to flood (Type A), wind or ship propulsion (Type B), or dredging, re-deposition or navigation (Type C) it was assessed if these sediments could detrimentally impact the good water status of downstream areas. Such areas were classified as '*Areas posing a risk*' with a further classification of the specific type of remobilization risk (A, B or C).

Outcome

Out of the more than 90 assessed areas, 22 areas were classified as ‘Areas posing a risk’ (Fig. A3.4.2) and 18 areas were classified as ‘Areas of concern’. By the end of 2018, rehabilitation measures at 10 of the ‘Areas posing a risk’ (all in the Netherlands) were carried out successfully. After further research it was concluded that rehabilitation of five ‘Areas posing a risk’ was not necessary. Rehabilitation measures at the remaining ‘Areas posing a risk’ are still not decided upon (ICBR, 2020).

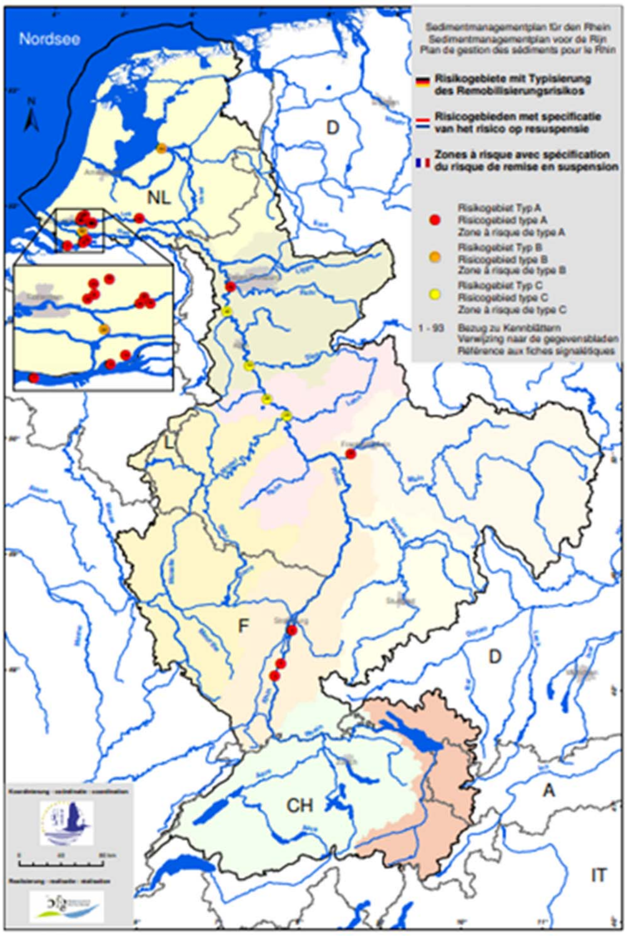


Fig. A3.4.2: Areas in the Rhine basin that pose a risk due to remobilization of contaminated sediment by flood (Type A), wind or ship propulsion (Type B), or dredging, re-deposition or navigation (Type C).

References

ICPR, International Commission for the Protection of the Rhine River, 2009, Sediment management plan Rhine, ICPR-report 175, Koblenz. 18 p.

ICPR, International Commission for the Protection of the Rhine River, 2020, Implementation of the Sediment management plan, ICPR-report 267 (only available in German, French and Dutch), Koblenz. 30 p.

https://www.iksr.org/en/topics/pollution/sediments?Fsize=4&cHash=90ef8c0e444a9413eba9f01888035cf8

Case study 3.5: Elbe basin: risk analysis and threshold Values

This case study provides examples of the use of Threshold Values (TVs) within a major EU catchment.

Author: Ilka Carls and Rene Schwartz

Country: Germany

River basin: Elbe

Risk analysis and prioritisation of actions

The member states in the International Commission for the Protection of the Elbe River (ICPER) decided to develop a sediment management concept in preparation for the WFD management cycle 2016-2021. For the first time, an integrated sediment management concept was developed in support of management planning in a large international river basin. The sediment management concept of the ICPER (Fig. A3.5.1) focuses on sediment quality, sediment budget, hydromorphology, and navigation related sediment aspects from a supra-regional perspective (IKSE, 2014, Heininger et al., 2014).

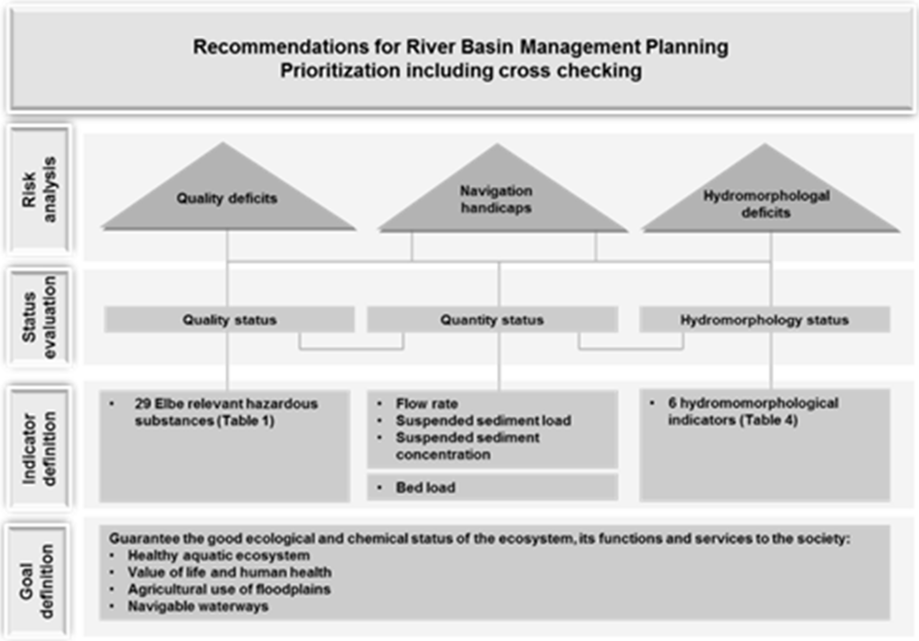
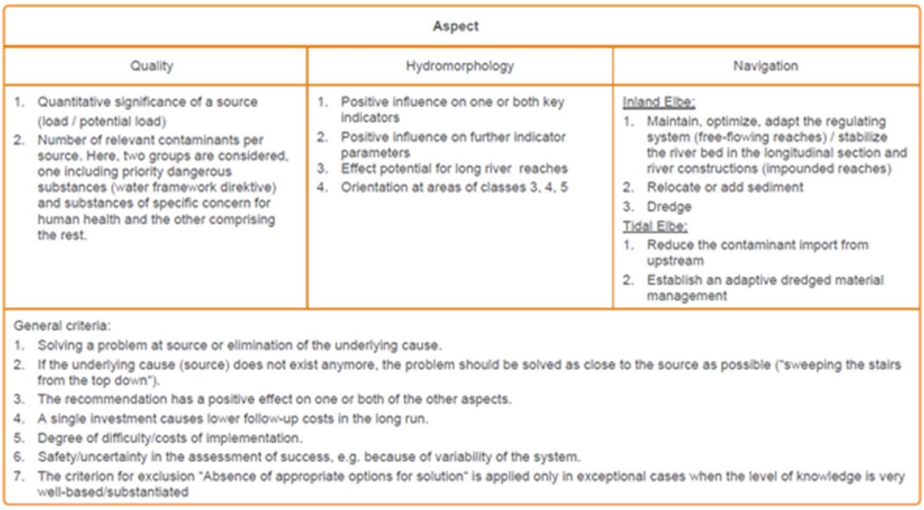


Fig. A3.5.1. General conceptual set up of ICPER sediment management concept (IKSE, 2014).

After defining management goals, significant indicators were defined in order to evaluate the status of the system in terms of quality, quantity and hydromorphology.

Then the risks that arise from the insufficient sediment status for the attainment of the targeted objectives were analysed. Finally, the significance of these risks weighted based on specific aspects and general criteria for prioritization (see Table A3.5.1), and recommendations for river basin management planning are derived.

Table A3.5.1: Criteria for prioritization of management actions (IKSE, 2014).



Aspect		
Quality	Hydromorphology	Navigation
1. Quantitative significance of a source (load / potential load) 2. Number of relevant contaminants per source. Here, two groups are considered, one including priority dangerous substances (water framework direktive) and substances of specific concern for human health and the other comprising the rest.	1. Positive influence on one or both key indicators 2. Positive influence on further indicator parameters 3. Effect potential for long river reaches 4. Orientation at areas of classes 3, 4, 5	Inland Elbe: 1. Maintain, optimize, adapt the regulating system (free-flowing reaches) / stabilize the river bed in the longitudinal section and river constructions (impounded reaches) 2. Relocate or add sediment 3. Dredge Tidal Elbe: 1. Reduce the contaminant import from upstream 2. Establish an adaptive dredged material management
General criteria: 1. Solving a problem at source or elimination of the underlying cause. 2. If the underlying cause (source) does not exist anymore, the problem should be solved as close to the source as possible ("sweeping the stairs from the top down"). 3. The recommendation has a positive effect on one or both of the other aspects. 4. A single investment causes lower follow-up costs in the long run. 5. Degree of difficulty/costs of implementation. 6. Safety/uncertainty in the assessment of success, e.g. because of variability of the system. 7. The criterion for exclusion "Absence of appropriate options for solution" is applied only in exceptional cases when the level of knowledge is very well-based/substantiated		

The risk analysis for the the "quality aspect" was done for 29 relevant inorganic, organic and groups of contaminants with respect to each of the identified management goals. Lower and Upper Threshold Values were defined and allocated to these contaminants (see part 2 of this case study). The risk analysis was performed in two stages:

1. Evaluation at the sub-basin level to identify the main source areas of particle-bound contaminants; and
2. Source-related evaluation within the areas identified under Stage 1.

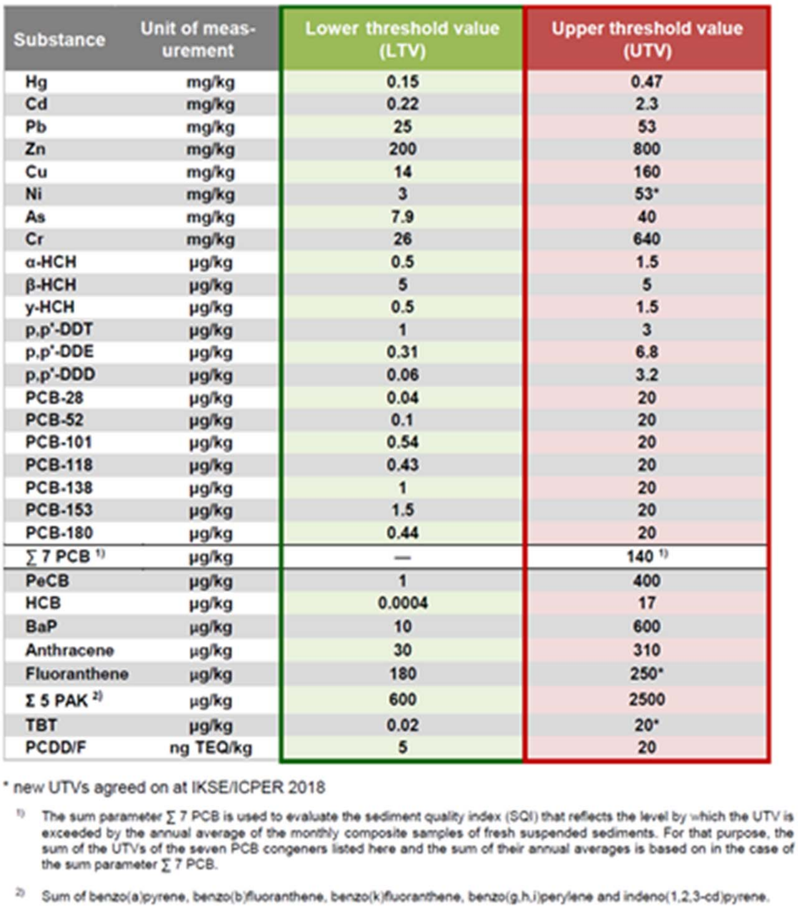
The types of pollution sources considered included: a) point sources; b) contaminated sediments/historical sediments, c) historical contaminations such as brownfields or old mining sites in an adjacent zone to the river, and d) other sources (e.g. emissions from urban systems). Depending on hydraulic conditions, sediments may be sources or sinks of contaminants. Therefore, besides the source function (mainly induced by floods), the sink function was also included in the analysis. This refers primarily to floodplains' role, but also to examples of other types of sinks such as natural and artificial river lakes, storage reservoirs, and harbour basins. Consequently, recommendations in the concept refer also to the potential sink functions.

As a result, all the relevant sources in the basin districts were described and ranked. Altogether, 38 source-related recommendations for river basin management planning were derived and prioritized~~,~~ which includes a collection of proven management practices and technical examples from the Elbe and other rivers. From the qualitative perspective, source-related recommendations were given in the fields of: reduction/restoration of point sources; reduction/restoration of historical contaminations; removal of historical sediment deposits sensitive to remobilization; management of fine sediments in the river combined with the optimization of maintenance strategies; reduction of imports of contaminated fine sediment from urban areas, and utilization and management of contamination sinks.

Threshold values

Table A3.5.2 lists the 29 Elbe relevant inorganic and organic contaminants and groups of contaminants as well as the specific Lower and Upper Threshold Values (LTV and UTV) allocated to them. The LTV is a contaminant-specific limit below which – in accordance with current knowledge and regulation status – all water management objectives that depend on good sediment status can be achieved independent of time and location. These water management objectives include good chemical and ecological status of the water bodies, integrity of the aquatic communities, soil protection (meadows/marshland) and human health. The UTV was mostly established based on values obtained through commonly accepted derivation methods for EQS. When not available, eco-toxicologically derived values (state of knowledge) or the strictest values of other national regulations available (good professional practice) apply. Pursuant to the sediment management concept exceeding the UTV requires a source-related risk analysis combined with the development of recommendations for action (IKSE, 2014; FGG Elbe, 2013). Based on the LTV, the sediment quality index (SQI) is calculated by Elbe river basin managers to describe and document temporal and spatial changes (trends) as well as the intensity of pollutant levels in suspended matter and sediments.

Table A3.5.2: Lower and Upper Threshold Values for Elbe-relevant sediment contaminants (FGG Elbe, 2013; IKSE, 2014).



Substance	Unit of measurement	Lower threshold value (LTV)	Upper threshold value (UTV)
Hg	mg/kg	0.15	0.47
Cd	mg/kg	0.22	2.3
Pb	mg/kg	25	53
Zn	mg/kg	200	800
Cu	mg/kg	14	160
Ni	mg/kg	3	53*
As	mg/kg	7.9	40
Cr	mg/kg	26	640
α-HCH	µg/kg	0.5	1.5
β-HCH	µg/kg	5	5
y-HCH	µg/kg	0.5	1.5
p,p'-DDT	µg/kg	1	3
p,p'-DDE	µg/kg	0.31	6.8
p,p'-DDD	µg/kg	0.06	3.2
PCB-28	µg/kg	0.04	20
PCB-52	µg/kg	0.1	20
PCB-101	µg/kg	0.54	20
PCB-118	µg/kg	0.43	20
PCB-138	µg/kg	1	20
PCB-153	µg/kg	1.5	20
PCB-180	µg/kg	0.44	20
∑ 7 PCB 1)	µg/kg	—	140 1)
PeCB	µg/kg	1	400
HCB	µg/kg	0.0004	17
BaP	µg/kg	10	600
Anthracene	µg/kg	30	310
Fluoranthene	µg/kg	180	250*
Σ 5 PAK 2)	µg/kg	600	2500
TBT	µg/kg	0.02	20*
PCDD/F	ng TEQ/kg	5	20

* new UTVs agreed on at IKSE/ICPER 2018

1) The sum parameter ∑ 7 PCB is used to evaluate the sediment quality index (SQI) that reflects the level by which the UTV is exceeded by the annual average of the monthly composite samples of fresh suspended sediments. For that purpose, the sum of the UTVs of the seven PCB congeners listed here and the sum of their annual averages is based on in the case of the sum parameter ∑ 7 PCB.

2) Sum of benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(g,h,i)perylene and indeno(1,2,3-cd)pyrene.

References

FGG Elbe, Flussgebietsgemeinschaft Elbe - (Ed.), 2013. Sedimentmanagementkonzept der FGG Elbe - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. 383 p.

Heininger, P., Keller, I., Quick, I., Schwartz, R. and Vollmer, S. 2014. Sediment management on riverbasinscale:

the River Elbe. In Cullmann, J. & Heininger, P. (Ed.) Sediment matters. Springer Berlin

Heidelberg. pp. 201-247.

IKSE, Internationale Kommission zum Schutz der Elbe, 2014. Sedimentmanagementkonzept der IKSE - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. 200 p.

IKSE, Internationale Kommission zum Schutz der Elbe, 2014. Information-Sheet about the Sediment management concept of the ICPER. https://www.ikse-mkol.org/fileadmin/media/user_upload/E/06_Publikationen/01_Wasserrahmenrichtlinie/2015_ICPER-Infomation-Sheet_Sediment.pdf

Case study 3.6: On the case of tributyltin (TBT) within Swedish coastal waters

This case study provides an example of the need to consider the possibility of continuing emissions of a substance into the environment, even if its use is banned, prior to considering contaminated sediment management options

Authors: Ann-Sofie Wernersson and Henrik Bengtsson

Country: Sweden

River basin: all waters including TraC

Context

The anti-fouling substance tributyltin (TBT) has been banned for several decades in Sweden but still remains a problem in the Swedish aquatic environment, a conclusion that can be made from both chemical and effects data (imposex studies).

TBT is still among the top five priority substances leading to chemical status of a water body being “not good”. The national sediment EQS (1.6 µg/kg dw 5% TOC) is frequently exceeded, and at about a quarter of all coastal water bodies (N=162), the TBT status is not good. The extent of the problem is probably even worse, as additionally 213 coastal water bodies “at risk”, monitoring data are missing, thus the status regarding TBT is there “unknown”. In marine off shore sediments, downward concentration trends are suggested by data from 2003, 2008 and 2014. The recovery observed is most likely attributed to the international ban of TBT (see also Case study 3.8). However, in the Baltic the concentrations are still above the national sediment EQS for TBT at all monitoring stations, even though they are all located off shore and far from local sources (Apler & Josefsson, 2016).

The MSFD initial assessment from 2018, taking both chemical concentrations and imposex observations into account, confirms that the marine environmental status is still not good. On the west coast some downward trend in effects (imposex) monitored at reference sites (far from marinas) can be observed but no decreasing trend in effects is observed on the East Coast (Baltic Sea).

Identifying continuous emissions of TBT

TBT being banned, the sediments in marinas being TBT hot spots (concentrations in sediment being several orders of magnitude higher than the sediment EQS), chemical status generally being “not good”, effects being observed and no recovery in sight, would all taken together suggest that remediation measures are needed at these sites. However, so far remediation has been performed only at a few sites in Sweden. There are numerous reasons for this but one important aspect to consider before remediation is the risk of sediment re-contamination.

The sediments at a large number of west coast marinas have been investigated in both upper layers and at 10 cm depth, surprisingly often showing that the TBT concentrations are frequently higher in the surface layers (Bengtsson & Cato, 2011). In addition, the ratio between TBT and its degradation products (MBT and DBT) is frequently above one. Taken together this suggests that TBT is still, decades after the ban, being emitted to the aquatic environment at a faster rate than the degradation rate in sediment.

In follow up studies, extreme TBT concentrations were encountered in the topsoil as well as in storm water (both sludge and water) collected from marinas (Bengtsson & Wernersson, 2012). Concentrations are several magnitudes above the generic quality criteria for remediation of soil and the EQS for TBT in surface water, respectively. However, before considering soil remediation at marinas to prevent sediment contamination, it is necessary to take into account that almost all of the marinas are still active and the TBT paint is still present beneath the modern paints on older vessels. There are strong indications that old paint containing TBT is being released during handling of the boat (boat uptake from the waters in the autumn and preparations in the spring).

Current emission reduction measures

Several efforts have been so far to reduce the emissions of TBT and other antifouling paints into the aquatic environment. SwAM (Swedish Agency for Marine and Water Management) has developed technical guidance and guidance values for different types of treatment methods that can be used to minimise antifouling paint leakage into the water during boat uptake. Several marinas on the west coast have also installed such equipment. On the east coast, another type of equipment has been installed, that reduces the need to use paints.

Stockholm University further developed and calibrated a hand held tool (Energy Dispersive X-Ray) that could be used to measure if an individual ship hull contains tin, interpreted as TBT when >100 ug/cm^2 (Ytreberg et al., 2016). In the Stockholm area several marinas have had campaigns that aimed at removing all the old paint from such ship hulls.

Nevertheless, additional efforts might be needed to reduce the emissions further and to make conclusions about the need for large scale soil and sediment remediation. The importance of groundwater dispersal from soil at these sites are largely unknown. There is some evidence of air dispersal of contaminated soil particles. Whether these are spread from the already contaminated soil or rather from above ground handling of the ship hulls, or both, remains to be investigated.

References

Apler, A., Josefsson, S. 2016, Chemical contamination in offshore sediments 2003–2014. SGU-rapport 2016:04, Geological Survey of Sweden, Uppsala, Sweden, 188pp.

Bengtsson, H, & Cato, I., 2011: TBT i småbåtshamnar i Västra Götalands län 2010 – en studie av belastning och trender. Länsstyrelsen i Västra Götaland, rapport 2011:30

https://www.diva-portal.org/smash/get/diva2:1345312/FULLTEXT01.pdf

Bengtsson, H, & Wernersson A., 2012: TBT, koppar, zink och irgarol i dagvatten, slam och mark i småbåtshamnar, Västra Götalands län 2011. Länsstyrelsen i Västra Götaland, rapport 2012:16.

https://www.lansstyrelsen.se/download/18.4e0415ee166afb593243f11/1540884863441/2012-16.pdf

Ytreberg, E., Bighiu, M. A., Lundgren, L, Eklund, B. 2016. XRF measurements of tin, copper and zinc in antifouling paints coated on leisure boats. Environmental Pollution, Vol 213, 594-599.

Case study 3.7 : Contaminant load reduction in the Elbe via international cooperation

This case study provides an example of the progressive reduction of contaminant loading in the Elbe river basin due to international cooperation in load reduction.

Author: Ilka Carls

Country: Germany, Czech Republic

River basin: Elbe

From the mid-1980s to the mid-1990s the Elbe river represented Western Europe´s most contaminated river with high contamination loads, namely metals and chlorinated hydrocarbon compounds. The International Commission of the Elbe River (ICPER/IKSE) was founded in October 1990. It was the first international contract signed by a reunited Germany. This marked a turnaround regarding activities directed towards remediation of the environment and water protection. The IKSE submitted several proposals and recommendations that have been successfully implemented (IKSE, 1996). Comprehensive remediation and environmental protection measures in the industrial sector and the massive dismantling of industry in central Germany and the Czech Republic decreased contamination loads of many substances to less than one-tenth of its former maximum values. An outstanding example of this is the reduction of the mercury (Hg) load in the Elbe (Fig. A3.7.1). From 1989 to 1995 the renewal of infrastructure (e.g. construction of sewage treatment plants) and the closure of unprofitable businesses led to a Hg load reduction in the Elbe by around 80%.

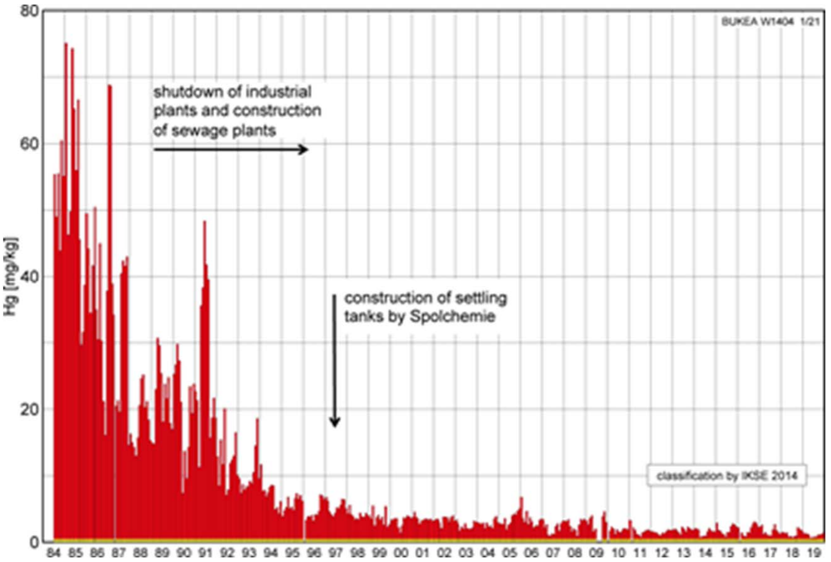


Figure A3.7.1: Mercury levels in suspended Elbe sediments at measurement station Schnackenburg (BUKEA, 2021; Data from FGG Elbe - FIS).

References

BUKEA, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft, 2021. Ministry of Environment, Climate, Energy and Agriculture - Department of Water Protection, Free and Hanseatic City of Hamburg.

FGG Elbe - FIS, Fachinformationssystem der Flussgebietsgemeinschaft Elbe, specialized information system, https://www.fgg-elbe.de/fachinformationssystem.html

IKSE, Internationale Kommission zum Schutz der Elbe, 1996. Abschlussbericht über die Durchführung der im „Ersten Aktionsprogramm (Sofortprogramm) zur Reduzierung der Schadstofffrachten in der Elbe und ihrem Einzugsgebiete“ enthaltenen Maßnahmen. Magdeburg

Case study 3.8: The effect of substance use bans on contaminant sediment loadings in the Elbe : tributyltin

This case study provides an example of the progressive reduction of sediment contamination loading due to the implementation of a ban on the use of a specific substance, tributyltin (TBT)

Author: Ilka Carls

Country: Germany, Czech Republic (but relevant to all countries)

River basin: Elbe (but relevant to all waters including TraC)

Tributyltin (TBT) is a persistent and highly effective biocide that was used globally as an antifouling agent in paint to prevent fouling on ship hulls. TBT from the hulls also enters the aquatic environment where it due to its physicochemical characteristics especially concentrates in sediment. In the environment it causes hormonal disorders leading to imposex and thus infertility in sea snails (UBA, 2007). Therefore, the use of TBT in antifouling coatings on ships was banned in 2003 (Anti-fouling Convention of the International Maritime Organization, 2001). Because of its effective biocidal properties, TBT has also been used in e.g. wood protection, hygiene or textile impregnation. Since 2010 triorganotin compounds may no longer be used in products across the EU if the concentration of tin in the product, or in parts thereof, exceeds 0.1% by weight (BUE, 2015). The ban on use, combined with treatment of dock wastewater and the removal of high TBT-contaminated old sediments, shows its effect e.g. in the Port of Hamburg (Fig. A3.8.1).

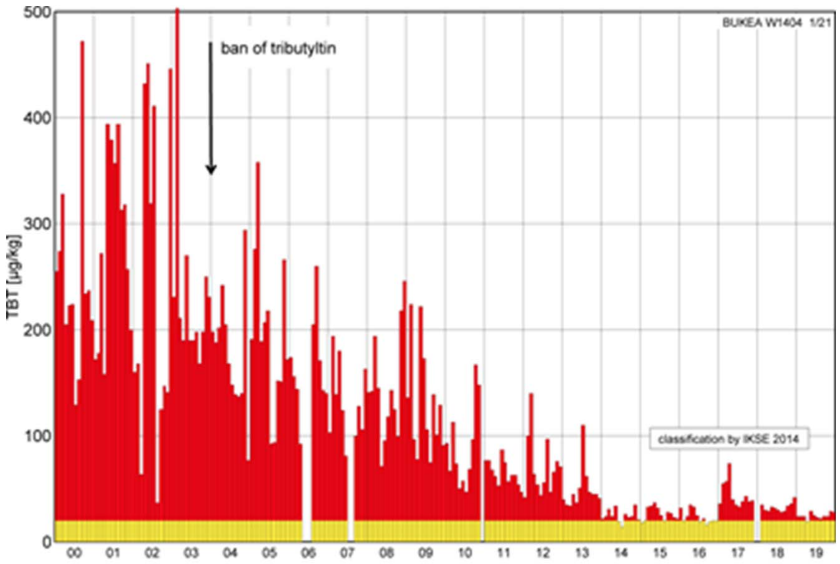


Fig. A3.8.1. TBT levels in suspended sediments at Seemannshöft (Port of Hamburg) (BUKEA, 2021; Data from FGG Elbe - FIS).

References

BUE, Behörde für Umwelt und Energie, Hamburg, 2015. Bestandsaufnahme relevanter prioritärer Schadstoffe in Hamburger Oberflächengewässern. Hamburg

BUKEA, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft, 2021. Ministry of Environment, Climate, Energy and Agriculture - Department of Water Protection, Free and Hanseatic City of Hamburg.

FGG Elbe - FIS, Fachinformationssystem der Flussgebietsgemeinschaft Elbe, specialized information system, https://www.fgg-elbe.de/fachinformationssystem.html

UBA, Umweltbundesamt, 2007. Emissionsminderung für prioritäre und prioritäre gefährliche Stoffe der Wasserrahmenrichtlinie – Stoffdatenblätter. http://www.umweltdaten.de/publikationen/fpdf-l/3312.pdf

Case study 4.3: Sediment management concepts, governance and cooperation structures in the Elbe River Basin

This case study provides a short insight into some examples of sediment management plans, cooperations and measures in the Elbe river basin

Author: Volker Steege

Country: Germany

River basin: Elbe (relevant to all waters including TraC)

Context

For decades, there have been numerous activities along the River Elbe to establish sediment management plans, to reduce contamination of sediments and support balanced sediment transport conditions. This case study provides a brief insight of different examples of sediment management activities (e.g. measures projects, strategies) at the German part of the Elbe River Basin (Fig. A4.4.1) – inside and outside of River Basin Management Commissions.

Fig. A4.3.1. Overview of the German River Basin Community Elbe (source: https://www.fgg-elbe.de/fgg_elbe.html)

The main drivers for the sediment management activities are the International Commission for the Protection of the Elbe River (ICPER), the River Basin Community Elbe (RBC Elbe; in German "Flussgebietsgemeinschaft (FGG) Elbe"), the German Federal Waterways and Shipping Administration (WSV) and Hamburg Port Authority (HPA).

With regard to their different responsibilities, various formats of sediment management concepts and forms of cooperation have been established on different issues (contamination, erosion, management of dredged material). Extensive knowledge on sediment contamination, sources, inputs, flows and sediment balance has been developed. Contamination of waters and sediments has been reduced significantly compared to the situation in the 1970s (see previous case studies on the Elbe). Despite this outstanding expertise and activities, good conditions for sediment quantity, transport and contamination in the River Elbe, its tributaries and floodplains are not achieved yet. here are still gaps remaining in terms of knowledge related to pollutant sources, and there are still ongoing emissions of pollutant inputs from industries, old mines, landfills, and contaminated sites. The concepts and plans developed for remediation actions have so far led to the implementation of only few measures due to high costs and unclear responsibilities. For these reasons, it can be expected that restoring good sediment conditions will take several decades.

Examples of implemented activities

The international Elbe –flagship plan is the Sediment Management Concept of the ICPER (IKSE, 2014). The concept underlines that contaminated sediments and unbalanced sediment conditions are among the main reasons for the failure to meet the WFD management objectives. For the first time, an integrated sediment management concept has been developed in support of management planning in a large international river basin that combines spatial, quantity, hydromorphology and quality as well as environmental and use-oriented sediment aspects in one concept (Heininger et al., 2015). This work was preceded by conceptual work in the FGG Elbe (FGG Elbe, 2013). Work is ongoing to put the concept into practice, but progress is still modest (IKSE, 2021).

An important component of the sediment management concepts is the treatment of contaminated dredged material on land. Silty, silty-sandy sediments are processed in the METHA plant (HPA online, 2021) (Mechanical Treatment of Harbour Sediments). METHA has an annual throughput of approximately 233.000 tons of dry substance corresponding to a profile volume of 521.000 m³ for a silt/sand ratio of minimum 28 %. A beneficial use of the treated material is one of the main goals of the concept. While the clean sand can be used as construction material, the material processed by METHA is partly used as surface compaction. The rest is disposed of at a specific landfill, which provides the possibility for environmentally safe disposal that meets all legal and technical requirements. Land treatment and disposal incur costs of around 30 million euros annually for the city of Hamburg.

FigA.4.3.2: Dredging sediment (Elbe fairway, Hamburg) and treatment of sediments from contaminated sites at METHA (source: Boris Hochfeld, Hamburg Port Authority)

Governance and cooperation structures

One example of a well-functioning cooperation between all relevant authorities and stakeholders within the framework of integrated sediment management is the “Overall concept Elbe” (Gesamtkonzept Elbe - GKE) (BMVI, BMUB, 2017). The GKE is a long-term programme agreed upon the German Federal Government, the Federal States and relevant stakeholders (environmental NGOs, navigation NGOs). An important goal is the minimisation of riverbed erosion in connection with the preservation of navigability. It is a project that integrates WFD, nature conservation and navigation. The special feature is the institutionalised cooperation with a large number of authorities and stakeholders. The GKE is mainly funded and staffed by the Federal Government to get more involved in practical work to minimize riverbed erosion. Since a new law came into force in June 2021, the WSV now has the sovereign task of implementing water management upgrading measures to achieve the hydromorphological objectives of the WFD. This is an important step towards achieving the GKE and WFD objectives. Accompanying measures for nature conservation are the responsibility of the federal states.

Another relevant activity on the Elbe, which is not directly part of the WFD river basin management, but is strongly connected to it and related to the integrated sediment management planning, is the “Forum Tideelbe” (Forum Tideelbe, 2020). For the goal of sustainable development of the Tidal Elbe, cooperation between the three states Hamburg, Lower Saxony, Schleswig-Holstein and the WSV as well as exchange with the districts, municipalities, associations and organizations from the region was institutionalized in a new cooperation structure under the title “Forum Tideelbe”, a follow up of “Dialogforum Tideelbe” (https://www.dialogforum-tideelbe.de/). On this basis, a structured and technically oriented dialogue was conducted on issues of estuary management, including sediment management, which recognizes the justified claims of the various Elbe users and takes the Tidal Elbe as a whole into account. The primary objective is to identify and prioritize river engineering measures that promote the sustainable development of the Tidal Elbe. In particular, hydromorphology, water protection (WFD, MSFD), flood protection (FD), nature conservation aspects (HD), ensuring navigable water depths and climate change as well as regional impacts are taken into account.

FigA.4.3.3 : Sediment sampling at the River Elbe, Hamburg (source: Judith Sprenger, Hamburg Port Authority)

Conclusion and perspectives

The examples presented are only a selection of the various sediment management plans/projects/strategies at the Elbe River Basin. It is shown that different actors and institutions are the drivers for sediment management actions in the river basin, depending on their responsibilities. Sediment management at the Elbe River Basin is a mosaic of many types of measures. The common umbrella is to achieve the goals of the WFD, which is a long-term process.

References

BMVI, BMUB (2017). Gesamtkonzept Elbe - Strategisches Konzept für die Entwicklung der deutschen Binnenelbe und ihrer Auen. Ed.: Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) & Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), Bonn. 241 pp.. https://www.gesamtkonzept-elbe.bund.de/Webs/GkElbe/DE/Home/home_node.html

FGG Elbe (2013). Sedimentmanagementkonzept der FGG Elbe - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. Ed.: Flussgebietsgemeinsschaft Elbe. https://www.fgg-elbe.de/files/Download-Archive/Fachberichte/Sedimentmanagement/sedimentmanagementkonzept_fgg_final.pdf

Forum Tideelbe (2020). Die Zukunft der Tideelbe gemeinsam gestalten – Ergebnisbericht 2020. Ed.: Forum Tideelbe. Hamburg. 75pp.. https://www.forum-tideelbe.de/

Heininger, P., Keller, I., Quick, I., Schwartz, R., Vollmer, S. (2015). Sediment Management on River-Basinscale: The River Elbe. In: J. Cullmann and P. Heininger (eds.), Sediment Matters, 201-247. Springer.

HPA-online, 2021: How METHA works - A look at the washing machine of the port of Hamburg. https://www.hamburg-port-authority.de/en/themenseiten/metha

IKSE (2014). Sedimentmanagementkonzept der IKSE. Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. Magdeburg. https://www.ikse-mkol.org/fileadmin/media/user_upload/E/06_Publikationen/01_Wasserrahmenrichtlinie/2015_ICPER-Infomation-Sheet_Sediment.pdf

IKSE (2021). Deutsch-tschechischer Workshop zur Umsetzung des Sedimentmanagementkonzepts der IKSE am 13.04.2021, Results and presentations. Online. https://www.ikse-mkol.org/extranet/arbeitsgruppen/wasserrahmenrichtlinie-wfd/sedimentmanagement/workshop-2021

Case study 4.4: Towards the sustainable management of sediment in the Sava River Basin

This case study describes the steps and activities taken towards setting up a Sediment Management Plan for an international river basin, the Sava.

Author: Samo Groselji

Country: Bosnia and Herzegovina, Croatia, Serbia, Slovenia

River basin: Sava

Introduction

Parties to the Framework Agreement on the Sava River Basin (FASRB), have noted the need to deepen the cooperation and to implement jointly agreed activities aimed at ensuring preconditions for sustainable sediment management in the basin. They have ratified a Protocol on Sediment Management to the FASRB (Protocol). The Protocol has defined a legal basis for the implementation of the activities agreed by the Sava countries, via their joint platform – the International Sava River Basin Commission (ISRBC) emphasizes the importance of the sustainable sediment management to maintain water regime, it promotes active international cooperation, describes sustainable sediment management solutions, and carefully balances the socio-economic and environmental objectives in the Sava river basin.

Context

The Sava River Basin (Sava RB) is a major river basin of Southeastern Europe with a total area of 97,272.2 km^2, comprising the 12% of the Danube River Basin area represents its most significant sub-basins.

The Sava River Basin contributes to the characteristics of the Danube River Basin with its outstanding biological and landscape diversity. It hosts the largest complex of alluvial wetlands in the Danube Basin (Posavina - Central Sava Basin) and large lowland forest complexes. The Sava River is a unique example of river with some of its floodplains still intact, thus supporting flood protection and biodiversity.

The Sava River Basin area is shared among six countries: Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, and small part of Albania. Except for Serbia and Albania, its watershed covers from 45 to 70% of the surface area constituting nearly 80% of the total freshwater resources in those four countries.

The population of the five countries (Albania is not included since only negligible part of the basin area belongs to its territory) of the region is approximately 18 million and half of this number resides in the Sava river basin.

Legal background

Recognizing the vital importance of trans-boundary co-operation towards sustainable development of the Sava River Basin, Bosnia and Herzegovina, Croatia, Serbia, and Slovenia (Parties) signed and ratified the FASRB aiming to achieve the following goals:

a. Establishment of an international regime of navigation on the Sava River and its navigable tributaries;
b. Establishment of sustainable water management; and

c. Undertaking of measures to prevent or limit hazards, and reduce and eliminate adverse consequences, including those from floods, ice hazards, droughts and incidents involving substances hazardous to water.

The FASRB entered into force on December 29, 2004 and the ISRBC as its implementing body was established in June 27, 2005.

Taking into account the provision of the FASRB, the Parties regulate specific issues with separate Protocol. The Protocol was signed in Brčko in July 6, 2015.

The main purpose of the Protocol is the achievement of sustainable sediment management by respecting natural processes, water regime and quality and quantity conditions (i.e. biological, hydro- morphological and physic-chemical elements). According to its provisions the Sediment Management Plan should be developed in the six years cycles covering evaluation of sediment balance, quality and quantity, monitoring, measures to prevent impacts and pollution, control erosion processes, measures to ensure integrity of water regime, protect wetlands, floodplains and retention areas, control reservoir sedimentation and provide conditions for safe navigation. Furthermore, in accordance to the Protocol only maintenance and environmental remedial dredging shall be performed while the capital dredging will be allowed in the designated areas, while. Parties on a yearly basis should exchange the information on planned dredging and provide information on locations, types of dredging, methods for sediment disposal and treatment, as well as quantities of dredged sediment.

Main activities

Before the formal entry into force of the Protocol, several steps and measures of this Protocol had already been implemented. Within the framework of a cooperative effort associating the UNESCO Venice Office, the ISRBC, the European Sediment Network, the UNESCO Intergovernmental Hydrological Programme-(IHP), and International Sediment Initiative, the ISRBC had initiated a project Towards Practical Guidance for Sustainable Sediment Management, using Sava River as a Showcase, resulting in:

- In 2012 the organization of a training course on basic sediment issues where experts from Europe, USA and national experts from the Parties exchanged the information on a) sediment balance throughout the river system; b) sediment monitoring; and c) evaluation of sediment quality and quantity. The participants were asked to transfer their learning experiences into draft practical guidance which would be a basis for the development of Sustainable Sediment Management Plan;
- In 2013 the drafting of a Guidance on Sustainable Sediment Management– Part I as a policy-level (strategic) document and an input in national/entity-level strategic planning on sustainable sediment management, providing expert contribution to unified approach to sustainable sediment management in the Sava River Basin. It also outlines the scope of work/terms of reference for the preparation of Sediment Management Plan;

- Implementing of the projects:
- In 2013: estimation of the Sediment Balance of the Sava River (ISRBC, 2013) implemented by the core expert group, established by the ISRBC, who analysed the sediment balance for the main Sava River course, considering the input from the main tributaries, and forming a basis for sustainable transboundary sediment and water management; and In 2015 : Proposal for the Establishment of the sediment monitoring system for the Sava River Basin (ISRBC, 2015) which outlines strategic

goals and specific objectives of the sediment monitoring and establishes a data exchange system. the existing sediment monitoring data, technical international standards and technics of monitoring has been reviewed and their application in the Sava River Basin assessed and the establishment of online sediment database taking into account the initial functionalities of Sava Geoportal proposed.

- In 2017- : establishment of a pilot sediment monitoring stations in Sremska Mitrovica (RS) and Slavonski Brod (HR);
- In 2020 : development of a program for the development of a Sediment Management Plan (ISRBC, 2020) which provides the list of activities and actions required for the development of the Sava Sediment Management Plan in line with the Protocol (ISRBC, 2020), taking into account the activities already finished or ongoing in the Parties and at the basin-wide level.

As Protocol stipulates Parties continuously exchange data on planned dredging on yearly basis and provide information on locations, types of dredging, methods for sediment disposal and treatment for the Sava River and its main tributaries as well as summarized quantities of dredged sediment for the sub-basins of other tributaries.

With the support of the UNESCO Office in Venice, the ISRBC coordinate the development of the Outline of the Sediment Management Plan for the Sava Basin (planned to be finalised by end of 2021) (Outline) aiming to :

- provide an overview on the existing sediment data on quantity and quality, to analyze and upgrade the existing sediment monitoring system,
- analyze and provide the overview of the improvements for the exiting sediment management measures
- propose institutional arrangements for further development of the Sediment Management Plan.

Further steps

The Sediment Management Plan shall be adopted by the ISRBC not later than six years after the Protocol enters into force and shall be revised at least every six years. The Outline represents the final step towards the development of the full-fledged Sediment Management Plan for the Sava river basin as stipulated by the Article 4 of the Protocol. The Sediment Management Plan shall cover the following issues, inter alia:

a. sediment balance throughout the river system;
b. sediment monitoring;
c. evaluation of sediment quality and quantity;
d. measures to prevent impacts and pollution of water or sediment resulting from dredging;
e. measures to control erosion, torrents and other sediment processes;
f. measures to ensure and maintain integrity of water regime;
g. measures to provide, ensure and maintain conditions for safe navigation;
h. measures to protect wetlands areas and retention spaces;
i. measures to control reservoir sedimentation;
j. designated areas for capital dredging;
k. guidance for the sediment disposal, treatment and use;
l. institutional arrangements for implementation of the Sediment Management Plan

It is in the interest of the Sava riparian countries to establish a coordinated sediment monitoring system in the Sava river basin, as stipulated in Art. 6 of the Protocol on Sediment Management which will be used for preparation and implementation of the Sava river basin Sediment Management Plan. Future sediment monitoring network should cover the whole Sava river basin, although monitoring of sediment on the Sava River main course is a priority. Sediment monitoring in the Sava river basin should be based on coordinated national monitoring programs, have a common or comparable methodology, instruments, and techniques. The data on sediment monitoring shall be uploaded into the already established Hydrological Information System of the ISRBC (https://savahis.org/) which is already used for collecting, storing, analysing, and reporting consolidated hydrological and meteorological data, and should include the sediment data sets in the future.

References

ISBRC, 2013. Towards Practical Guidance for Sustainable Sediment Management using the Sava River Basin as a Showcase: Estimation of Sediment Balance for the Sava River. International Sava River Basin Commission, Zagreb, Croatia. 98p. http://www.savacommission.org/dms/docs/dokumenti/documents_publications/publications/other_publications/balses_final.pdf

ISBRC, 2015. Towards Practical Guidance for Sustainable Sediment Management using the Sava River Basin as a Showcase: Establishment of the Sediment Monitoring System for the Sava River Basin. International Sava River Basin Commission, Zagreb, Croatia. 49p. http://www.savacommission.org/dms/docs/dokumenti/public/projects/establishment_of_sediment_monitoring_in_srb__final.pdf

ISRBC, 2020. Program for development of Sediment Management Plan in the Sava River basin. International Sava River Basin Commission, Zagreb, Croatia. 21p. http://www.savacommission.org/dms/docs/dokumenti/documents_publications/basic_documents/protocols/program_sava_sediment_management_plan_final.pdf

Case study 4.6: Assessing the level of bed incision in the Lower Rhine

This case study describes a methodology for hydromorphological assessment in the lower Rhine in Germany, which has contributed to better understand and manage erosion.

Authors: Ina Quick, Frauke König, Yannik Baulig, Sönke Schriever, Stefan Vollmer (German Federal Institute of Hydrology)

Country: Germany

River basin: Rhine

The 'German Lower Rhine' between Rhine-km 640 to 865.5 provides an example of hydromorphological evaluations of river bed level changes as well as the detection and documentation of the effects of implemented sediment management measures to mitigate channel incision. In order to carry this out, the standardised hydromorphological classification approach 'Valmorph' of the German Federal Institute of Hydrology (Quick et al. 2017) to assess the indicator 'mean bed level changes' was used. This indicator as well as further hydromorphological indicators such as 'sediment continuity' etc. were applied in the context of the sediment management concept of the Elbe River (IKSE 2014; FGG Elbe 2013; Quick & Langhammer 2015; Heininger et al. 2015). The indicator is expressed as change rate in bed heights over time and characterises a river as balanced, excessive or deficient. The classifying of mean bed level changes has been carried out by calculating erosion rates in cm/a, based on measuring data for various time periods between 1896 and 2010. A significant reduction of the previously extremely high bed erosion is detectable since 1985, the beginning of the implementation of sediment management measures by the German Waterways and Shipping Administration to mitigate channel erosion. Currently, the improved situation with its reduced, partly stopped or even reversed incision rates for most river sections of the 225 kilometres investigated, illustrates that management actions effectively support and enhance hydromorphological river conditions. As a result, causal relations become clearly recognisable, the findings allow to evaluate various measures with respect to short- to long-term responses of the ecosystem. These quantitative and hydromorphological sediment aspects are essential to support the achievement of the objectives of the WFD and have to be more deeply factored into river basin management (Quick et al. 2020).

References:

FGG Elbe (2013). Sedimentmanagementkonzept der FGG Elbe - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. Ed.: Flussgebietsgemeinsschaft Elbe.

(Online access: https://www.fgg-elbe.de/files/Download-Archive/Fachberichte/Sedimentmanagement/sedimentmanagementkonzept_fgg_final.pdf)

IKSE (2014). Sedimentmanagementkonzept der IKSE. Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele. Magdeburg.

(Online access: https://www.iksemkol.org/fileadmin/media/user_upload/E/06_Publikationen/01_Wasserrahmenrichtlinie/2015_ICPERInfomation-Sheet_Sediment.pdf)

Quick, I.; König, F.; Baulig, Y.; Schriever, S.; Vollmer, S. (2020): Evaluation of depth erosion as a major issue along regulated rivers using the classification tool Valmorph for the case study of the Lower Rhine. In: Habersack/Liedermann/Tritthart/Eder: Intern. Journal of River Basin Management, Vol. 18/2020, I.2: Major Issues in Large River Basin Managem. 191-206

Quick, I.; König, F.; Baulig, Y.; Borgsmüller, C.; Schriever, S. (2017): The hydromorphological classification tool Valmorph 2 for large and navigable surface waters. BfG-Report No. 1910. Federal Institute of Hydrology. Koblenz

Quick, I. & Langhammer, J. (2015): Sediment continuity - survey, assessment and derivation of recommenda-tions for restoring the hydromorphological indicator. 9th Intern. SedNet conference, Solving societal challenges: working with sediments, 23-26 Sept. 2015, Kraków

Heininger, P., Keller, I., Quick, I., Schwartz, R., Vollmer, S. (2015): Sediment Management on River-Basinscale: The River Elbe. In: Cullmann/Heininger, Sediment Matters pp. 201-247

Case study 4.7: Diagnosis of sediment imbalance in a coastal cell to understand sediment deficits

This case study demonstrates the diagnosis of sediment sources, sinks and imbalances along an entire national coastline. More information can be obtained from https://ce3c.ciencias.ulisboa.pt//file/Livro_GTL_2018.pdf

Author: Fernando Mendes Magalhães

Country: Portugal

River basin: all

Context

The coastline of mainland Portugal extends from the Minho River mouth to the Guadiana river mouth over 987 km (variable depending on the scale) presentsing a great diversity of morpho-sedimentary environments, which include beaches, cliffs, estuaries, lagoons and barrier islands.

The systematic assessment of sediment budget in the Portuguese coast was developed by the “Coastal Working Group”, which was established in the sequence offollowing the damages produced in winter 2014 by the Hercules storm and aimed at identifying a set of measures geared to the medium term, to change the characteristics of risk exposure, whilst incorporating sustainable development in the context of climate change scenarios.

Methodology

In this work, the Portuguese mainland coastal zone was divided into eight sedimentary cells according to the geomorphological characteristics and sedimentary dynamics (Fig. A4.6.1). Sediment budgets for reference and current situations were calculated for each cell. The current situation was considered to be representative of the last two decades, while the reference situation characterises the situation prior to the existence of a relevant, anthropic induced disturbance in the sedimentary balance (e.g. dams, coastal engineering works, port dredging and construction of breakwaters, and sand removal and extractions from rivers and coastal areas), representing conditions observed in the late 19th century. Sediment budget assessment was carried out based on a comprehensive inventory and characterization of sediment sources and sinks, both natural (river solid discharge, coastal accretion/erosion, coastal drift and retention in estuaries) and of anthropogenic nature (dredging, sediment removal, beach nourishment and retention in dam reservoirs) were carried out. Sediment sinks (namely the sediment lost to submarine canyons or dunes) were also considered.

Results

Comparison between reference and present situations has shown that most imbalances are due to human activity, and are mostly related to the reduction of river sediment yield or sediment retention in coastal structures. The largest sediment deficits are found in sediment cells 1 (Minho river – Nazaré) and 4b (Tagus river outer estuary), whereas no significant imbalances were detected in the remainder cells, exception made to localised changes in relation to harbours (Santos et al., 2014). The identification of these imbalances point to the need of to restoring the sediment sources or perform artificial nourishment operations using borrow areas from the continental shelf or from dredging operations related to port / fishing / recreational activities, in order to mitigate coastal erosion and to improve the recreational use and value of the coastline. Sediment management should therefore play a key role in erosion mitigation and intervention strategies, in accordance with the strategic guidelines on coastal erosion proposed in the European projects Eurosion (European Commission, 2004) and Conscience (Marchand, 2010). The present approach will also contribute to the implementation of EU policies related to river basin management (WFD) and to the sea-floor integrity descriptor of good environmental status (of the marine environment (MSFD).

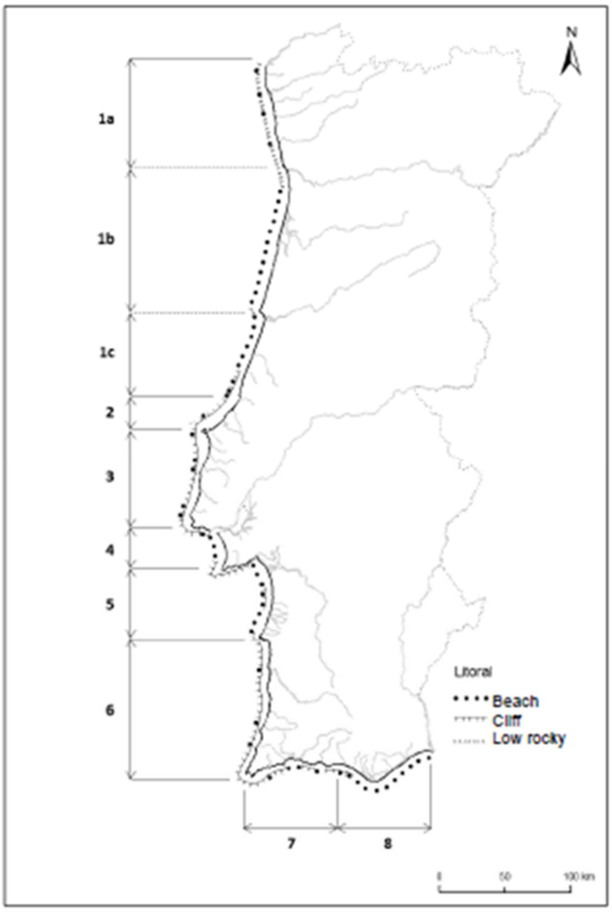


Fig. A4.7.1. Simplified geomorphology of the Portuguese coast and division into sedimentary cells (adapted from Santos *et al.*, 2014).

Reference

European Commission (2004) – *Living with coastal erosion in Europe – Sediment and space for sustainability*, Luxembourg office for official publications of the European Commission, 28p.

Lira, C., Silva, A., Taborda, R. & Andrade, C. (2016) - Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach. *Earth Syst. Sci. Data, 8, 265–278.*Marchand, M., ed.

(2010) – *Concepts and science for coastal erosion management. Concise report for policy makers*. Deltares, Delft, The Netherlands, 32p.

Santos, F., Lopes, A., Moniz, G., Ramos, L. & Taborda, R. (2014) – *Gestão da Zona Costeira. O desafio da mudança*. Lisbon, 237 p

Case study 4.8: The Fiberbank projects – identifying and assessing the risks from highly contaminated fiber sediment hot spots near pulp and paper factories

This case study provides an example of the identification, quantification, risk characterization and ongoing efforts to remediate a specific case of legacy coastal sediment contamination.

Author: Ann-Sofie Wernersson

Country: Sweden

River basin: Bothnian Sea RBD

Introduction

Since the end of the 19th century, about 30 pulp and paper factories have operated in the Swedish province of Västernorrland. Waste water, which contained wood or cellulose fibers, was for several decades discharged directly into the adjacent coastal marine environment. The impact on the seafloor community in these otherwise productive areas is severe, with no higher life forms than bacteria being able to survive.

In 2010 the Geological Survey of Sweden (SGU) and the County Administrative Board of Västernorrland initiated a project where the primary objective was to develop a method, using hydro-acoustic surveying techniques, to identify fibrous sediments, and to use the methodology to map their spatial distribution. Another objective was to estimate the contamination levels of hazardous substances in these sediments. It was found that a combination of hydro-acoustic surveying and sediment sampling can effectively identify and map impacted areas.

Fiberbanks (consisting of almost 100% fiber material) cover more than 1.5 km^2 of the sea floor along the Västernorrland coast. They contain PCBs, DDT and other substances at very high concentrations. About a dozen of the contaminated fiberbanks are deposited in water depths shallower than 15 m (see fig A.4.7.1). These are prone to erosion and dispersal and a number of landslide scars were identified. Underwater landslides can cause large amounts of fibers to rapidly disperse to deeper areas. Contamination levels and the geological and hydrological conditions along the coast suggested that the fibrous sediments are a significant potential threat to the health of the Bothnian Sea's marine ecosystem (SGU, 2014).

This triggered another survey, covering also other provinces and inland waters. Eleven fiberbanks, covering 1,0 km^2 and fiber-rich sediments, covering 12,3 km^2 were identified. Thus 44 fiberbanks with a total area of 2,5 km^2 and fiber-rich sediments covering 26 km^2 have so far been located. Almost 150 samples were analysed for a range of compounds, and it was found that different areas had different contamination patterns.

Sweden had already a national methodology in place for the inventory and prioritisation of contaminated sites based on risks to the environment and human health (Naturvårdsverket, 1999). Aspects considered include hazardous properties of contaminants, their mobility, contaminated volumes/amounts and sensitivity/protection need. However, the method and assessment criteria are primarily applicable to contaminated soil. A methodology for initial risk characterisation of fibersediments was therefore developed (Länsstyrelsen & Golder, 2016). By using this methodology it was found that the classifications were mostly either "large risks" or "very large risks" (SGU, 2016; Länsstyrelsen, 2019). It was recently also found that the fiberbanks release large amounts of greenhouse gas, from decomposition processes of the fibers (Lehoux et al., 2021) (see fig A 4.7.2).

There is thus a need for additional surveys, in other parts of Sweden but also other countries with historic paper mill activities. There is also an urgent need for action. However, the remediation of fiberbanks, having high content of organic material and water and producing large amounts of gas possibly also releasing contaminants upon disturbance, is a major challenge. So far only two Swedish sites have been remediated;

one through dredging and subsequent deposition, the other by capping. Several R&D projects, involving universities, authorities and entrepreneurs, are now running or have recently been undertaken to develop and test novel remediation approaches as well as new tools to address the specific risks identified at these sites (see e.g. Snowball et al 2020).

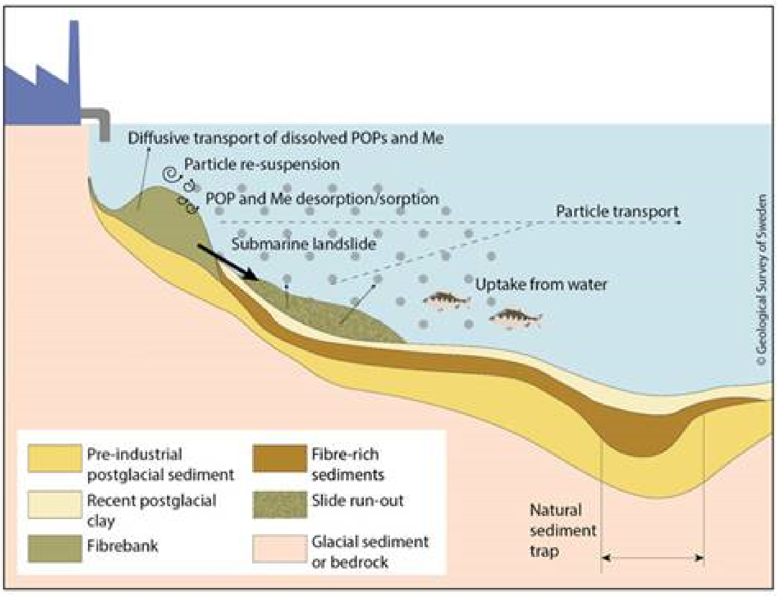


Fig. A4.8.1. Fiberbanks are frequently found near the water surface but can due to landslides or other physical disturbance disperse to deeper areas and cause large scale contamination (fibre-rich sediments). The fibers are often heavily contaminated by metals such as mercury and persistent organic pollutants that pose a potential threat to the ecosystem. Source: Geological Survey of Sweden.

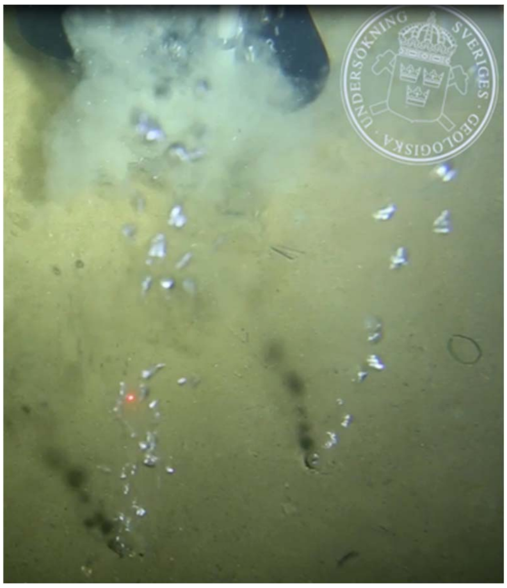


Fig. A4.8.2. Gas (methane and other GHG) coming from the cellulose rich material being degraded. Source: Geological Survey of Sweden.

References

Länsstyrelsen Västernorrland & Golder Associates. 2016. Metodik för riskklassning av fiberhaltiga sediment. https://www.lansstyrelsen.se/vasternorrland/tjanster/publikationer/metodik-for-riskklassning-fiberhaltiga-sediment.html

Länsstyrelsen Västernorrland. 2019. Anna Stjärne, Kristina Rydja, Emelie Haglund. Riskklassning av fiberhaltiga sediment i Västernorrlands län. Publikation nr 2019:11. https://www.lansstyrelsen.se/download/18.4a4eb7416faedec1257a94/1579695568612/Riskklassning%20av%20fiberhaltiga%20sediment%202019.pdf

Lehoux, A.P., Isidorova, A., Collin, F., Koestel, J., Snowball, I., Dahlberg, A.-K., 2021. Extreme gas production in anthropogenic fibrous sediments: An overlooked biogenic source of greenhouse gas emissions. Science of the Total Environment, 781, 146772. https://doi.org/10.1016/j.scitotenv.2021.146772

Snowball, I., Apler, A., Dahlberg, A.K., Frogner-Kockum, P., Göransson, G., Hedfors, J., Holmén. M., Josefsson, S., Kiilsgaard, R., Kopf, A., Löfroth, H., Nylander, P., O'Regan, M., Paul, C., Wiberg, K., Zillén, L. 2020, TREASURE – Targeting Emerging Contaminated Sediments Along the Uplifting Northern Baltic Coast of Sweden for Remediation, En sammanfattning av ett fyraårigt forskningsprojekt om fiberbankar inom forskningsprogrammet TUFFO, Statens geotekniska institut, SGI, Linköping, 2020-07-07. http://www.diva-portal.org/smash/get/diva2:1467943/FULLTEXT03.pdf

Naturvårdsverket, 1999. Metodik för inventering av förorenade områden. Naturvårdsverket rapport 4918.. https://www.naturvardsverket.se/om-oss/publikationer/4900/metodik-for-inventering-av-fororenade-omraden/

Sveriges Geologiska Undersökning. 2014. Fiberbanksprojektet - Kartläggning av fiberhaltiga sediment längs Västernorrlands kust. Anna Apler, Johan Nyberg, Karin Jönsson, Irene Hedlund, Sven-Åke Heinemo & Bernt Kjellin. SGU-rapport 2014:16. http://resource.sgu.se/produkter/sgurapp/s1416-1-rapport.pdf

Annex to SGU 2014:16, with Geological information: http://resource.sgu.se/produkter/sgurapp/s1416-2-rapport.pdf

Sveriges Geologiska Undersökning. 2016. Kartläggning och riskklassning av fiberbankar i Norrland. Johan Norrlin, Sarah Josefsson, Olof Larsson, Lijana Gottby. SGU-rapport: 2016:21. http://resource.sgu.se/produkter/sgurapp/s1621-rapport.pdf

Case study 4.10 Recommendations provided by Interreg Danube Sediment Project in the frame of Danube Sediment Management Guidance

This case study describes the recommendation provided for sediment management in the Danube in the context of the development of the Danube sediment management guidance (Interreg project)

Author: Helmut Habersack

River basin: Danube

The following recommendations apply to the Danube River and its tributaries.

- Development of a basin-wide sediment management concept

We recommend the development of an integrated Danube River Basin sediment management concept and ISMP.

- Improvement of legal regulations and governance

The topic of sediment quantity in the Danube River Basin was already mentioned in the 1st DRBM Plan 2009 and considered as potential Significant Water Management Issue in 2013. Based on key findings of the project, the sediment balance alteration has been identified as a new sub-item of the Significant Water Management Issue “Hydromorphological alterations”.

- Preservation of the sediment continuity and the morphology

In the Danube River Basin, the protection and preservation of the (nearly) undisturbed sediment regime that still exists within the remaining natural free-flowing river sections and tributaries, should be of utmost priority, reflecting the no-deterioration-principle of the WFD. Strategies should be developed to preserve the sediment continuity and morphology in these few remaining, functioning river stretches, respectively rivers.

- Restoration / improvement of the sediment continuity and river morphology

There is a need to restore / improve the sediment continuity of the Danube River and its tributaries where it is interrupted, and / or impacted. Restoration of the sediment continuity means to increase the sediment transport through structures with the aim to reduce the problems associated with a sediment surplus and deficit and to adapt the sediment budget to achieve the best possible morphological conditions in the water bodies and further downstream.

- Reduction of surplus and deficit reaches

The number of river reaches with a clear trend in sedimentation and erosion shall be reduced with the aim of establishing a dynamic equilibrium and morphodynamics. This should be done by restoring sediment continuity on the one hand and by river restoration on the other hand.

- Development and implementation of sediment-related measures addressing navigation, hydropower and flood risk management

Water and sediment are the fundamental elements of a fluvial system, therefore water and sediment need to be managed together. Neglecting sediments in the planning process can result in undesired outcomes of the planned “solution”. An integrated planning process needs to consider how the sediment regime is affected and which problems can occur.

- Defined refeeding of the dredged material

In general, it is recommended to keep the sediments in the river system and, if possible, to stop or minimize the extraction of sand or gravel. If dredging cannot be avoided due to safety reasons, like flood protection or fairway maintenance, the sediments should be reinserted into the river at sections with a significant lack of sediments. Most preferably, the reinsertion of dredged material should take place upstream in free-flowing sections and downstream of the barrier in impoundments. In cases of dredging in impounded reaches, the sediments can be fed back downstream of the barrier to compensate sediment deficit.

- Catchment-related measures

Since sediment related problems should rather be treated at the source of the problem, measures implemented in the catchment area might be the right choice in some cases. If an increase of fine sediment fractions is the problem, land use management and optimized cultivation to reduce the sediment output from e. g. agriculture need to be considered as relevant measures.

- Establishment of harmonized sediment monitoring network and data management

On a basin-wide scale, there are still several sediment data-related issues that need to be addressed. This requires a harmonized sediment monitoring using the same methodology on a transboundary level.

- Sediment quality needs to be included

The project DanubeSediment only dealt with sediment quantity but not with sediment quality. Thus, no detailed recommendations concerning the monitoring of sediment quality can be provided. However, information regarding the topic is available from the Joint Danube Surveys and the SIMONA project.

- Sediment-related risk analysis

Another important aspect for a follow-up project should be to analyse the risk of failing the good ecological status or potential due to sediment-related problems along the Danube River and the tributaries.

- Stakeholder involvement and interdisciplinary planning

To gain an overall acceptance of any sediment management measure, be it maintenance of existing or implementation of new measures, all relevant stakeholders should be included in the process as early as possible. This provides the option to integrate all relevant perspectives into river management and to raise synergies and avoid conflicts between different aims.

- Adaptive implementation of measures and accompanying monitoring

When realising any measure it has to be ensured that an adaptive and holistic planning process is implemented to confirm that the most practically efficient, environmentally friendly and cost effective option is selected, considering the socio-economic needs and constraints. It is necessary to implement an accompanying sediment monitoring during the realisation of sediment management measures in order to monitor and assess the effects of these measures and – if relevant – to be able to adapt them.

Reference

Habersack H., Baranya S., Holubova K., Vartolomei F., Skiba H., Babic-Mladenovic M., Cibilic A., Schwarz U., Krapesch M., Gmeiner Ph., Haimann M. 2019a. Danube Sediment Management Guidance. Output 6.1 of the Interreg Danube Transnational Project Danube Sediment co-funded by the European Commission, Vienna. https://www.interreg-danube.eu/uploads/media/approved_project_output/0001/39/ee566924f1764d4798dc7bb9b59537ce84d98101.pdf

Case study 4.11 Supporting the establishment of the sediment monitoring programme of hazardous substances according to WFD requirements

This case study demonstrates the steps taken to establish a national scale sediment monitoring programme for hazardous substances, in Hungary.

Authors: **Zsolt Jolankai; Mate Kardos; Adrienne Clement; Laszlo Koncsos**

Country: Hungary

River basin: all

Introduction

A 5 year long (2018-2022) project is taking place in Hungary, financed by the KEHOP (environmental and energy efficiency operative programme) national programme, to support the implementation of the WFD monitoring programmes In the context of this project a methodology has been developed and additional monitoring has been performed – among others - to improve the monitoring of hazardous substances in sediments in Hungarian river and lake water bodies. The developed methods were based on the general requirements of the WFD and followed the advices from CIS Guidance document No. 25. A National Guidance document on sediment monitoring has also been created within the project.

The project involved in particular the following tasks:

- Development of a large scale sediment deposition modelling methodology able to locate river segments with elevated sediment deposition;
- Location of 40 points for sediment sampling based on modelling results, field survey and basic sediment analysis;
- Carry out analysis of hazardous substances in the samples collected at the 40 spots;
- Measure concentration distribution between different matrixes (water-sediment-biota);
- Locate 103 points for the long term national sediment monitoring programme.

The following methods have been used:

- <u>Modelling</u>: Several monitoring concepts has been examined within the project on pilot catchments. The catchment erosion processes have been described with the SWAT (Soil & Water Assessment Tool) model and an aggregated hydrological and transport model, which consists of a linear cascade type hydrological framework and a simplified but physical erosion process model. The channel transport processes are described by a 1D sediment transport model based on the van Rijn concept;
- <u>Sampling and analysis to support locating the sampling spots</u>: Trial samples were taken at 81 spots. Samples were taken at each spots in the top 8-10 cm using 1-5 subsamples using an Ekman sampler (applicable for disturbed and loose sediments). Samples were homogenized (larger fractions have been removed) and mixed on site. In the lab samples were filtered on a 4 mm sieve. The sampling aimed to sample deposition zones, therefore at each sampling site the inactive flow zones (eddies) were looked for. The samples were analysed for total dry matter content, total organic matter content (loss on ignition method) and particle size distribution curves. The latter was needed to find spots where the fraction of sediment with less than 63 µm is over 5% of the total volume. Several criteria have been taken into consideration for the selection of the sampling points, including: deposition zones by model results, anthropogenic effects (known point sources, diffuse sources of contaminants), strategic positions (mouth of larger rivers, points above larger reservoirs), representativity of each water body type, results of chemical status based on water quality data, especially where unknown causes of Environmental Quality Standard exceedance are present, sections with possibly background contamination levels;

- Sampling and analysis of hazardous substances in sediments: Core samples from the upper 10 cm were taken from multiple points of multiple cross sections at the previously located sampling spots to generate mixed samples. Altogether 20-30 l of loose sediment have been collected at each location. Fractions less than 63 µm have been used for analysis.

Results

The results of the predictive sediment erosion/deposition modelling are shown in Fig. A4.9.1. Fig. A4.9.2 shows the locations of sampling points for the national long term sediment monitoring programme.

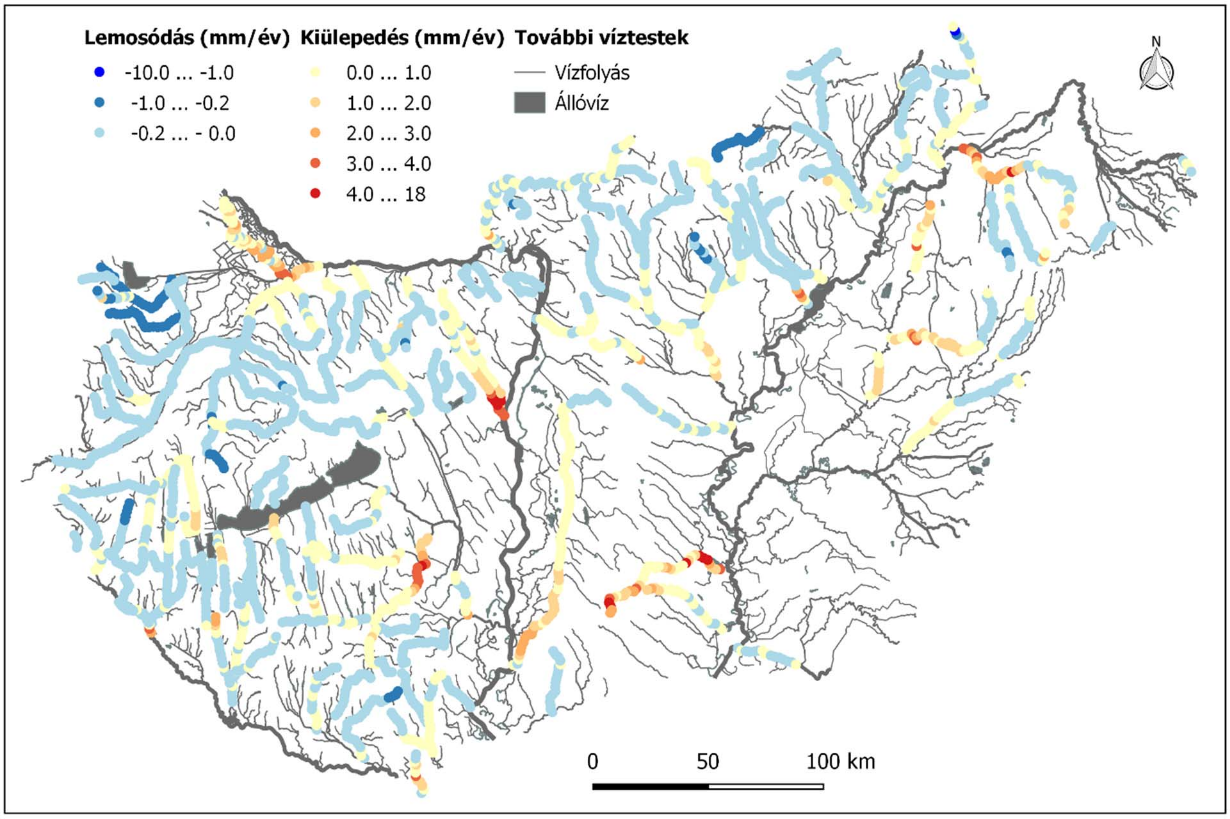


Fig.A4.11.1. Results of sediment dynamics modelling: predicted net erosion (blue points) and net sedimentation (yellow/red points).

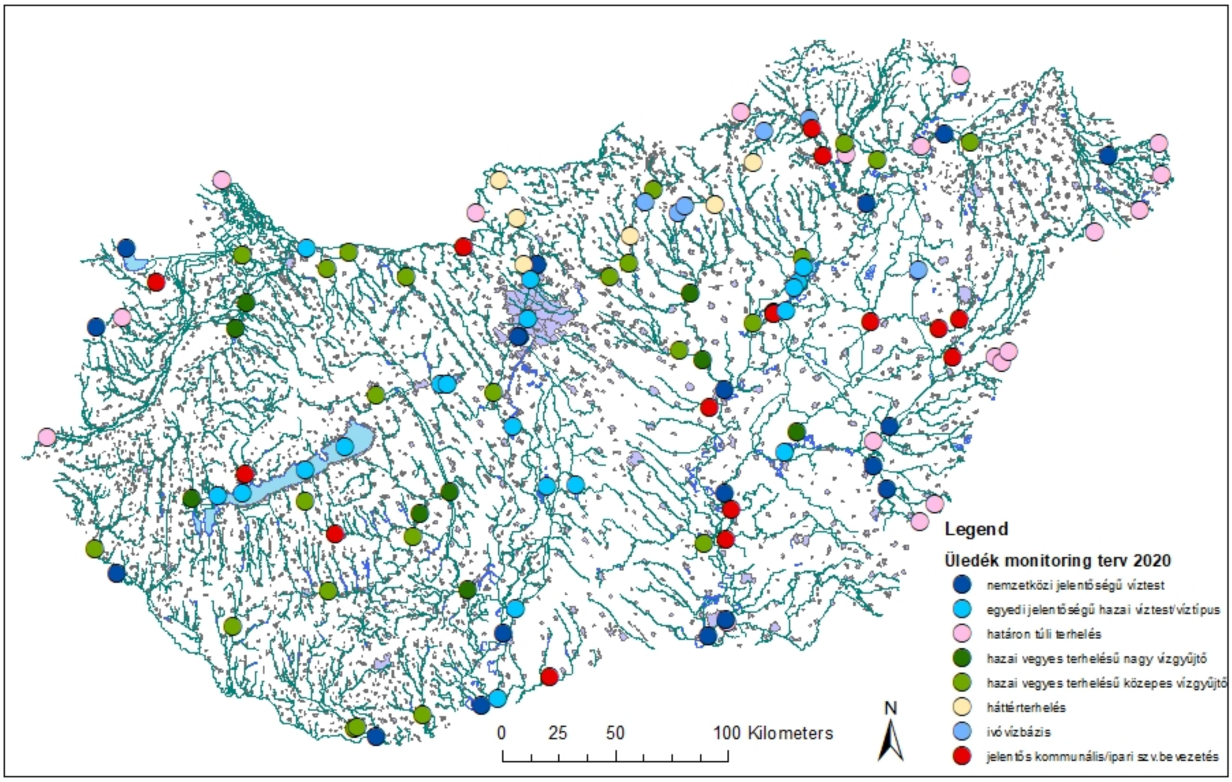


Fig.A4.11.2. Locations of sampling points for the national long term sediment monitoring programme. Differently-coloured points represent different types of waterbody.

Annex B: Methods for the collection and assessment of suspended sediment and bed load

For an overview of methods frequently used for the collection and assessment of suspended sediment, channel bed sediments and determining channel form see Table B1.

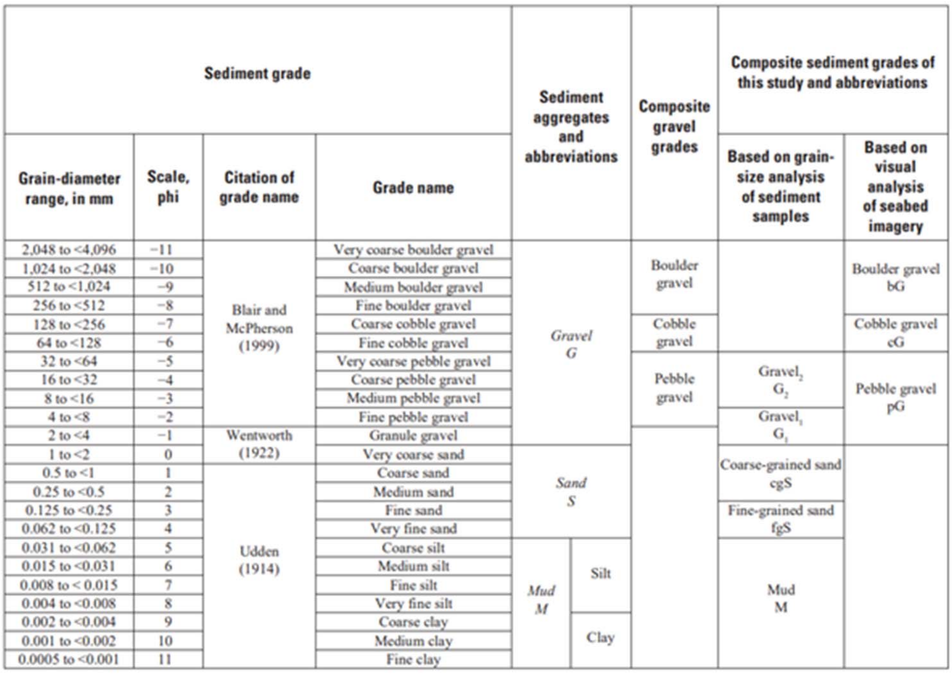
Assessing particle size

The most significant and studied feature of bed material is its particle size. Its determination requires the analysis of three axes which together define the three-dimensional shape of the particles. Although, in some studies, particle size may be defined by just one variable (for instance, the length of the intermediate particle axes). Particle size is frequently described by means of the intermediate-axis length (typically known as the b-axis), the nominal diameter (cubic root of the product of the value of the three axes), and the particle-sieve diameter (sieve size which the particle can pass or not).

Sediment grains have been classified for decades into grain size grades. Classification is based on the range of grain diameters doubling for each coarser grade (19 grades, from 0.0005 to 256 millimeters (mm)), following procedures developed by Udden (1914), and after by Blair and McPherson (1999) who included four more grades (uplifting the upper interval until 4,096 mm), leaving a total number of 23 grades - from clay particles to boulders. Original names of the sediment grades were also modified afterwards by different authors, currently including names proposed by Udden (1914), Wentworth (1922), and Blair and McPherson (1999). Wentworth's classification is one very much used internationally, and considers 10 sediment classes defined by the weight percent content of the aggregates (clay, silt, sand, gravel) they contain and are named using a maximum of two terms. The weight percent content of each aggregate is treated equally by Wentworth in defining class boundaries. The lower limit for an aggregate for inclusion in a sediment class would be >10 weight percent (Valentine, 2019). Other classifications or procedures were proposed by Folk (1954), or by Krumbein (1936) and (Bunte & Abt, 2001) who converted grades expressed in millimetres to more operational scales.

Normally, sediment classifications have an intermediate level of complexity, to avoid a lack of detail (which would limit its usefulness) or an excessive number of classes (which would render the interpretation of the results more complex). The analysis should be relevant to the hydromorphological and ecological traits of the river system.

Classifications are used worldwide, providing a common standard for the comparison of grain-size analyses. Nonetheless, different authors and studies have proposed new approaches to sediment classification, although usually constructed on the basis of the above-mentioned methods. For instance, approaches which take into account the influence of sediments on the quantity and quality of river habitats, or the way in which sediments are transported.



Sediment grade				Sediment aggregates and abbreviations		Composite gravel grades	Composite sediment grades of this study and abbreviations	
Grain-diameter range, in mm	Scale, phi	Citation of grade name	Grade name				Based on grain-size analysis of sediment samples	Based on visual analysis of seabed imagery
2,048 to <4,096	−11	Blair and McPherson (1999)	Very coarse boulder gravel	*Gravel* *G*		Boulder gravel		Boulder gravel bG
1,024 to <2,048	−10		Coarse boulder gravel					
512 to <1,024	−9		Medium boulder gravel					
256 to <512	−8		Fine boulder gravel					
128 to <256	−7		Coarse cobble gravel			Cobble gravel		Cobble gravel cG
64 to <128	−6		Fine cobble gravel					
32 to <64	−5		Very coarse pebble gravel			Pebble gravel	Gravel$_2$ G$_2$	Pebble gravel pG
16 to <32	−4		Coarse pebble gravel					
8 to <16	−3		Medium pebble gravel					
4 to <8	−2		Fine pebble gravel				Gravel$_1$ G$_1$	
2 to <4	−1	Wentworth (1922)	Granule gravel					
1 to <2	0		Very coarse sand	*Sand* *S*			Coarse-grained sand cgS	
0.5 to <1	1	Udden (1914)	Coarse sand					
0.25 to <0.5	2		Medium sand					
0.125 to <0.25	3		Fine sand				Fine-grained sand fgS	
0.062 to <0.125	4		Very fine sand					
0.031 to <0.062	5		Coarse silt	*Mud* *M*	Silt		Mud M	
0.015 to <0.031	6		Medium silt					
0.008 to < 0.015	7		Fine silt					
0.004 to <0.008	8		Very fine silt					
0.002 to <0.004	9		Coarse clay		Clay			
0.001 to <0.002	10		Medium clay					
0.0005 to <0.001	11		Fine clay					

Figure B1 - Classifications of sediment grains, sediment grades, composite sediment grades, and sediment aggregates. Grain diameter range is based on the scheme of Udden (1914) converted to decimal values from fractions; the phi scale is based on the scheme of Krumbein (1936); the composite gravel grades and the gravel, sand, silt, and clay sediment aggregates are from Wentworth (1922); and the mud sediment aggregate is from Folk (1954). Extracted from Valentine (2019).

Statistical analysis of collected data to understand sediment dynamics

Following the collection and size determination of sediment particles, and prior to its incorporation in a budget, statistical analyses are often performed to understand how the sediment may behave in the water body. Not all attributes of sediment data are relevant for all budgets and cases. This means that data must be prepared to meet the requirements for their incorporation into a budget. Statistical analyses of samples initially requires studying the particle-size frequency and percentage frequency-distribution. After that, a cumulative frequency distribution is extracted, which allow defining specific percentiles which are informative of the data distribution (for instance D_5, D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, D_{95}), and particular statistical parameters, although those parameters can also be directly derived from a frequency distribution.

For the sake of complementarity, some studies do not only focus on assessing particle size, but also on other attributes of the materials, such as shape or angularity. Particle form may affect sediment transport, habitat suitability for certain species, and the structure of river forms. Normally, shape will refer to the ratio of the three axes lengths, while angularity will be indicating whether a particle has angular edges or a rounded surface.

In the case of suspended sediments, it is also important to assess particle size. This knowledge is relevant because variations in size are of importance to hydropower installations and other man-made devices in the river, and also to some species/habitats requirements. Different authors have shown complex patterns of spatial and temporal variation, also considering that grain size composition is subject to hysteresis effects (Bogen, 1992). The smallest particles of the suspended load (those below 63 μm) have a relevant role in biogeochemical fluxes, and is on many occasions cohesive and transported as flocculated or aggregated particles (Owens *et al.*, 2005).

Table B1: Overview of methods to assess (i) suspended sediment load, (ii) channel bed form and bedload, (iii) bed sediments (based on a combination of technical and scientific sources, including Liedermann et al. (2018, 2013), Habersack et al. (2017), Haimann et al. (2014), Gray et al. (2009) , Wren et al. (2000))

Technique	Parameter	Application	Limitations
Methods to asses suspended sediment load			
Point-integrated sampling	Suspended sediment concentration (SSC), organic carbon (OC) content and particle size distribution (PSD)	• Direct estimation of SSC at sampling point • Estimation of suspended sediment load (if sampling location represents cross-sectional average) • If sampling is repeated with sufficient frequency, changes of SSC and suspended load can be detected (e.g. by automatized sampling) • OC and PSD allow to evaluate characteristics and hydraulic conditions for transport of suspended matter	• Point measurement → sample point may not represent channel cross section • Rapid changes in SSC (especially in small catchments) difficult to detect with non-automated sampling • Estimation of PSD (using laser analyzer) requires minimum amount of sediment (typically > 30 FNU are required for direct analyzing water samples in laser analyzer) • Estimated PSD might not resemble floc./aggregate size of suspended matter in channel
Depth-integrated sampling	Similar to point-integrated sampling but integrates over water column	• Estimation of depth integrated characteristics • Estimation of suspended sediment load (if sampling location represents cross-sectional average or sampling is repeated several times in a cross-section)	• Similar limitations to point (integrated) sampling • depth integration: no vertical variability of SSC, OC, PSD • for larger rivers: ship or bridge required
Multiple point integrated sampling in river cross-section	Spatial and temporal variation of SSC, OC and PSD	• Evaluation of cross-sectional suspended sediment characteristics • Estimation of cross-sectional integrated fluxes	• Very time consuming and cost intensive • Additional velocity measurements required to calculate sediment flux. • For larger river: ship or bridge required
Optical back scatter (OBS)	Turbidity as surrogate for SSC	• High-resolution time-series, esp. for detection of fine suspended sediment (very sensitive for clay and silt fractions)	• Point measurement → sample point may not represent channel cross section • Surrogate: turbidity also controlled by other parameters than SSC (e.g. grain size, color of sediment) • Requires site specific calibration (based on water sampled SSC)

Acoustic back scatter (ABS)	ABS as surrogate for SSC	• High-resolution time-series, esp. for detection of suspended sand	• Point measurement → sample point may not represent channel cross section • Surrogate: ABS also controlled by other parameters than SSC (e.g. grain size) • Requires site specific calibration (based on water sampled SSC)
Acoustic doppler current profiler (ADCP)	Acoustic back scatter as surrogate for SSC	• Vertical and horizontal variation of SSC • Estimation of cross-section integrated fluxes	• Surrogate: ABS also controlled by other parameters than SSC (e.g. grain size) • Requires site specific calibration (based on water sampled SSC) • Problems of inversion of ADCP back scatter signal
In-situ laser analyzer	Equivalent grains size of suspended sediment grain, aggregate or floc size, volume sediment concentration	• Estimation of in-situ aggregate or floc size as a function of material properties and turbulent flow characteristics • High-resolution time-series of grain, aggregate or floc size distribution of suspended, e.g. for detection of discharge dependent changes of sediment dynamics	• Point measurement → sample point may not represent channel cross section • Limited range of detectable grain sizes and SSC • Aggregate or floc size not identical to mineral grain size
• Methods to assess channel bed (form) and bed load			
High-resolution bathymetric survey using multibeam echo sounder	Channel bed elevation, roughness and structures	• Estimation of water depth (for various discharges) to support navigation • Identification of bedforms (dunes, ripples) • Evaluation of channel bed habitat	• Application limited to the acquisition of the status quo, not accounting for dynamic processes
Repeated high-resolution bathymetric surveys	Changes of bed elevation and structure	• Estimation of bed degradation and aggradation (sediment deficit or surplus) • Estimation of bed form migration and inference of bed load transport rates (only feasible with very high temporal resolution)	• Estimation of bed level changes not necessarily linked to total bed load transport. Bed level changes capture the volume difference between two events • Difficulties to infer bed load below the moving structures used for the surveys
(Bed load) Basket samplers (e.g. Helley-Smith, Bunte trap, BfG sampler)	• Bedload flux • Grain size distribution of transported bed material	• Direct sampling of bedload → standard sampling method • Grain size fractionated estimation of bed load	• Limited comparability of different basket sampler types • High spatio-temporal variability of bed load requires an application at

		transport at given water discharge •	various verticals along a cross-section and repeated measurements at every vertical • Very time and cost intensive
Geophones	Detection of vibrations induced by passing bedload material at metal plates integrated into the riverbed	• Estimation of bedload from seismic signal intensity • Continuous bedload measurement • High temporal and spatial resolution • Estimation of initiation of bed load motion	• (In-channel) infrastructure needed • Extensive calibration by bedload sampling • No data for small grain sizes • No or inaccurate grain size information • Many disturbances in urbanized areas
Bedload Trap	Weight increase per time unit after opening the trap	• Installation of a bed load trap at the same level as the river bed which can be opened before and during an event • High temporal resolution	• Poor spatial resolution • Trap must be emptied ant maintained • Installing the trap is difficult and time and cost intensive • Normally can only be maintained during low water season
Hydrophones	Indirect measurement method via noise intensity	• Hydrophone is installed at a single point of a rivers cross-section; noise is detected and calibrated by direct measurements	• Must be well calibrated by direct measurements • No spatial resolution of transport over the cross-section • High potential disturbances by other sound impacts
ADCP-bottom tracking	Movement of channel bed surface	• Continuous measurement of channel bed movement • Spatially integrated bed load estimates if used on boat	• Experimental state: many uncertainties how to translate bottom track signal to bed load transport
Pebble tracer stones	travel distance (pathways)	• Estimation of virtual velocity of single particles • Distribution of periods of rest and movement • Pathways (process understanding)	• Time intensive • Expensive • Low recovery rate of tracer stones, possible
• Methods to assess bed sediments			
Visual classification	Rough estimation of the sediment size and distribution	• Observation of the range and the maximum size of sediments which covers the stream bed, in pre-determined locations	• Can only be feasible in small to middle-sized rivers with low turbidity and low organic coverage for low to moderate discharges • May be suitable for emerged deposits (lateral or point bars, for example) and some inaccessible areas
Grid count	Grain size distribution of surface layer, roughness	• Selection of particles at a pre-determined number of even-spaced grid points in a small sampling area (1-10 m^2); then particles would	• Limited detection of particular grain sizes • Only applicable in wadeable streams

		be picked by field operators (comparable to a pebble count), or measured on photographs (particle sizes measured on a grid superimposed on the photograph)	
Pebble count	Grain size distribution of surface layer, roughness	• Selection, picking and measurement of a pre-determined number of surface particles at constant distances along transects (parallel, or zig-zag schemes) and include a relatively large sampling area (100 m^2) • Pebble counts and their constant distances can be taken by two different procedures: a heel-to-toe walk, or marks along a measuring tape. The most common heel-to-toe method was devised by Wolman (1954), by blindly picking random particles (typically 100) as the operator walks along transects, until covering the entire sampling site • Subsequent grain size analysis (sieving or by measuring b-axis)	• No detection of grain sizes below surface layer • No detection of small grains • Large number of pebbles/clasts need to be measured to give statistically robust results • Only applicable in wadeable streams
Areal samples	Grain size distribution of surface layer, roughness	• Measurement of all particles contained within a small pre-determined area (0.1-1 m^2) of the riverbed • Surface and subsurface can be distinguished • Sampling would be done by picking the particles and measuring their size (or sieving) • Adhesives may also be used to ensure that small particles are adequately included in the sample • Alternatively, there are also non-destructive methods, such as photo sieving or visual estimate	• Samples must be carried to the laboratory • Only applicable in dried areas of a river
Bulk sampling	Considers all sediment sizes present in a given sample site.	• Data collection may involve two samples per site: a surface sample and a subsurface sample, unless no substantial difference between the two.	• If the sample area is submerged, different alternatives may be used, such as a shovel and sampler, a cramshell (grab) sampler, or even a small backhoe shovel

		• The entire sample may be taken to the laboratory for measurement and classification, or particles larger than a specific threshold (e.g., 32 mm) are classified in situ by size using a Wolman approach, while the material passing the field sieve for that specific threshold is put in a sample bag and labeled, in order to be sent to a laboratory.	• To ensure that the sediment sample is statistically representative of the material where it is obtained from, the weight of the sample should be at least 100 times the weight of the largest particle in the sample (Church et al., 1987). This condition my lead, especially in gravel-bed rivers, to collect large samples weighting some hundreds of kilograms. Another criteria for the sample size would be $V[m^3] = 2{,}5 \cdot d_{max}[m]$ for $d_{max}>0{,}06$ m (Huber, 1966; in Fehr, 1984) • Bulk samples (i.e. frequency-by-volume) are directly comparable with Wolman samples (frequency-by-number) (Church et al., 1987)). However, correction factors need to be applied when comparing aerial samples (frequency-by-area) with either bulk or Wolman samples
Freeze Core / Freeze Panel	Almost undisturbed layer-wise grain size distribution of surface and subsurface layers	• Steele pipe is driven into the river bed and cooled down by using liquid nitrogen. Hence the bed material freezes to the pipe and can be lifted out almost undisturbed • The material is divided into different layers, dried and sieved	• Time and cost intensive especially if applied in non-wadeable rivers • Small sample volume compared to grab samples • Hardly applicable during summer seasons (warm water)
Fine sediment sampling using disturbance technique	Fine sediment (<1mm) in surface and subsurface	• Samples may be taken from erosional and depositional areas. Samples collected as a suspension and taken to the laboratory for analysis.	• Only suitable in shallow water • Sample locations must be carefully selected • Only samples fine sediment

References

Haimann, M; Liedermann, M; Lalk, P; Habersack, H (2014) An integrated suspended sediment transport monitoring and analysis concept. INT J SEDIMENT RES. 2014; 29(2): 135-148.

Wren, D.G., Barkdoll, B.D., Kuhnle, R.A., Derrow, R.W. (2000). Field techniques for suspended-sediment measurement, J. Hydraul. Eng. 126 (2) (2000) 97–104, http://dx.doi.org/10.1061/(asce)0733-9429(2000) 126:2(97).

Gray J. R., Gartner J. W. (2009). Technological advances in suspended-sediment surrogate monitoring. Water resources research, Vol. 45, W00D29, doi:10.1029/2008WR007063

Rai, A.K., Kumar, A. (2015). Continuous measurement of suspended sediment concentration: technological advancement and future outlook. Measurement 76: 209-27.

Habersack, H; Kreisler, A; Rindler, R; Aigner, J; Seitz, H; Liedermann, M; Laronne, JB. (2017): Integrated automatic and continuous bedload monitoring in gravel bed rivers GEOMORPHOLOGY. 2017; 291: 80-93. FullText

Liedermann, M; Gmeiner, P; Kreisler, A; Tritthart, M; Habersack, H. (2018): Insights into bedload transport processes of a large regulated gravel-bed river EARTH SURF PROC LAND. 2018; 43(2): 514-523

Liedermann, M; Tritthart, M; Habersack, H. (2013): Particle path characteristics at the large gravel-bed river Danube: results from a tracer study and numerical modelling EARTH SURF PROC LAND. 2013; 38(5): 512-522.

1 # Annex C: Glossary of terms

Term	Definition	Source
Acid volatile sulphide	Defined operationally as the sulphide fraction evolved from sediment when treated with acid, typically 1M hydrochloric acid (HCl). This comprises the pool of sulphide for which potentially toxic trace metals (e.g. nickel, copper, zinc, cadmium, lead, silver, mercury) have a particularly high affinity and thus represents sulphide with which these metals can combine to reduce their bioavailability to and impacts on sediment organisms.	Rickard, D., Morse, J.W., 2005. Acid volatile sulfide (AVS). Marine Chemistry, 97, 141–197. Hammerschmidt, C., Burton, G.A., 2010. Measurements of acid volatile sulfide and simultaneously extracted metals are irreproducible among laboratories. Environmental Toxicology & Chemistry, 29, 1453–1456.
aggradation	The build up of the level of any land surface by the deposition of sediment	https://www.collinsdictionary.com/dictionary/english/aggrade
agitation dredging	The removal of bottom material from a selected area by using equipment to raise it temporarily in the water column and currents to carry it away.	Richardson, T.W., 1984. Agitation dredging: lessons and guidelines from past projects. US Army Corps of Engineers, Washington, DC, U.S.A., 145pp.
angularity	The degree of smoothness or roughness of sediment particle surfaces.	
anoxic	The characteristic of being absent of oxygen.	Oxford Languages: https://languages.oup.com
bed incision	The process of downcutting into a stream channel leading to a decrease in the channel bed elevation. Incision is often caused by a decrease in sediment supply and/or an increase in sediment transport capacity.	https://solareis.anl.gov/
bedload	The sediment transported by a river in the form of particles too heavy to be in suspension	Oxford Languages: https://languages.oup.com
bioavailability	The extent to which a material is taken up into a living organism exposed to that substance (absorbed dose)	Willhite, C., Karyakina, N.A, Walies, A., Yenugadhati, N., Momoli, F., Wisniewski, T., Krewski, D., 2019. Overview of Potential Aluminum Health Risks. In: Encyclopedia of Environmental Health (2nd edition), ed. Nriagu, J.. Elsevier B.V., Amsterdam, NL.

Term	Definition	Source
biological quality elements	A group of freshwater organism types: phytoplankton, macrophytes and phytobenthos, benthic invertebrate fauna, fish fauna, for each of which states that must be achieved to achieve high, good and moderate ecological status are provided in Annex V 1.2.1 of the Water Framework Directive.	
biomagnification	The process by which a compound (such as a pollutant or pesticide) increases its concentration in the tissues of organisms as it travels up the food chain.	https://www.merriam-webster.com/dictionary/biomagnification
bioturbation	the disturbance of sedimentary deposits by living organisms	Oxford Languages: https://languages.oup.com
black carbon	A particulate form of nearly pure elemental carbon with some oxygen and hydrogen bound into a layered, hexagonal structure.	Andreae, M.O., 1995. Chapter 10 – Climatic effects of changing atmospheric aerosol levels. In: World Survey of Climatology. Future climates of the world: a modelling perspective. Henderson-Sellers, A. (ed.). Elsevier B.V., Amsterdam, NL, 608 pp.
braided channel	A river channel characterized by multiple, low flow channels and mid-channel bars subject to frequent changes. Braided channels indicate a relatively high supply of bed-material sediments.	Modified from Ashmore, P., 2014. Morphology and Dynamics of Braided Rivers. Treatise on Geomorphology, 8, 289-312. https://doi.org/10.1016/B978-0-12-374739-6.00242-6
coastal cell	A coastal cell contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries (often corresponding to headlands or jetties) delineate the geographical area within which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion.	www.coastalwiki.org/wiki/Coastal_cell
cohesive-bed channel	A fluvial channel where the bed comprises particles with a mean size <4µm (microns)	Wolanski, E., 2007. Estuarine Sediment Dynamics. In: Estuarine Ecohydrology, Wolanski, E.. Elsevier B.V., Amsterdam, The Netherlands. https://doi.org/10.1016/B978-0-444-53066-0.X5001-6

Term	Definition	Source
colloid	A particle with one dimension within the size range 1nm to 1µm.	Lead, J.R., Wilkinson, K.J., 2006. Aquatic Colloids and Nanoparticles: Current Knowledge and Future Trends. Environmental Chemistry, 3, 159–171. https://doi.org/10.1071/EN06025
colloidal dynamics	The behaviour of suspensions of colloids over time.	
colluvial	Refers to material which accumulates at the foot of a steep slope.	Oxford Languages: https://languages.oup.com
competent flow	In the context of stream hydrology, refers to a threshold flow rate above which sediment of a particular size class may be transported downstream.	
contour farming	The practice of tilling sloped land along lines of consistent elevation in order to conserve rainwater and to reduce soil losses from surface erosion.	Britannica www.britannica.com/topic/contour-farming
downdrift	In the direction of the net longshore transport.	www.coastalwiki.org/wiki/Downdrift
duration curve	In the context of stream hydrology, a cumulative frequency curve that shows the percent of time that a specific discharge at a specific location in a river network was equalled or exceeded in a given time period.	Searcy, J.K., 1959. Flow-Duration Curves. In: Manual of Hydrology: part 2. Low-Flow Techniques. Geological Survey Water-Supply Paper 1542-A. United States Governemnt Printing Office, Washington, DC, U.S.A.
erosion pit	a bed morphology feature – a zone of channel deepening – caused by river channel incisement into underlying substrata of varying erodibility.	Sloof, K.C.J., van Spijk, A., Stouthamer, E., Sieben, A., 2011. Understanding and managing the morphology of Rhine Delta branches incising into sand-clay deposits. River, Coastal and Estuarine Morphodynamics: RCEM 2011. Tsinghua University Press, Beijing. https://repository.tudelft.nl/islandora/object/uuid:b601f35d-9aa0-4e15-a47e-2ca64cc56388/datastream/OBJ/download
fairway	A navigable channel in a river or harbour.	Oxford Languages: https://languages.oup.com
floatation load	The load of sediment within a waterbody that has a density close to or less than that of water.	

Term	Definition	Source
flood conveyance	The transport of floodwaters downstream, with little if any damage.	Oxford Reference: https://oxfordreference.com
functional process zone	A concept within riverine ecosystem study defined as a patch within a river network of distinct hydrogeomorphology and physicochemical characteristics, resulting in distinct ecological characteristics e.g. trophic dynamics.	Thorp, J.H., Thoms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Research and Applications, 22, 123–147.
geomorphology	The study of the creation of landforms by river processes through the removal and transfer of material on the Earth's surface.	Lewin, J., Brewer, P.A., 2005. Fluvial Geomorphology. In: Encyclopedia of Geology, Selley, R.C., Cocks, R.M., Plimer, I.R. (eds.). Elsevier B.V., Amsterdam, The Netherlands.
green-blue infrastructure	A strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services.	European Commission, 2019. Guidance on a strategic framework for further supporting the deployment of EU-level green and blue infrastructure. Commission Staff Working Document SQD(2019) 193 final. European Commission, Brussels.
hydromorphological quality elements	A set of aspects of hydromorphology: hydrological regime, river continuity, and morphological conditions, for each of which states that must be achieved to achieve high, good and moderate ecological status are provided in Annex V 1.2.1 of the Water Framework Directive.	
hyporheic	Pertaining to the volume of subsurface sediments where groundwaters and surface waters are actively exchanged.	Schlesinger, W.H., Bernhardt, E.S., 2020. Inland Waters. In: Biogeochemistry: an Analysis of Global Change (4th edn.), Schlesinger, W.H., Bernhardt, E.S. Elsevier B.V., Amsterdam, The Netherlands.
clast	A fragment of rock	https://www.merriam-webster.com/dictionary/clast

Term	Definition	Source
imposex	A disorder exhibited by many species of snails, where females develop imposed male sexual characteristics.	Bjerregaard, P., Andesen, C.B.I., Andersen, O., 2015. Ecotoxicology of Metals – Sources, Transport, and Effects on the Ecosystem. In: Handbook on the Toxicology of Metals, 4th edn., Nordberg, G.F., Fowler, B.A., Nordberg, M. (eds). Elsevier B.V., Amsterdam, The Netherlands.
intertidal	Of or denoting the area of a seashore which is covered at high tide and uncovered at low tide	Oxford Languages: https://languages.oup.com
longshore	Existing on, frequenting, or moving along the seashore., e.g. "longshore currents"	Oxford Languages: https://languages.oup.com
mitigation hierarchy	A hierarchical procedure in which mitigation actions are taken in the following order: (i) avoidance of impacts, (ii) reduction/minimisation of impacts, (iii) restoration/rehabilitation from impacts, (iv) offsetting of residual impacts.	Institute for European Environmental Policy, 2016. Supporting the Elaboration of the Impact Assessment for a Future EU Initiative on No Net Loss of Biodiversity and Ecosystem Services. Final Report, ENV.B."/SER/2014/0018. Institute for European Environmental Policy, London. https://ec.europa.eu/environment/nature/biodiversity/nnl/pdf/NNL_impact_assessment_support_study.pdf
multimodal	Of a frequency curve or distribution, having several modes or maxima.	Oxford Languages: https://languages.oup.com
natural water retention measures	Measures that aim to safeguard and enhance the water storage potential of landscape, soil, and aquifers, by restoring ecosystems, natural features and characteristics of water courses and using natural processes.	https://ec.europa.eu/environment/water/adaptation/ecosystemstorage.htm
nature-based solutions	Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions.	https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en

Term	Definition	Source
oxic	Of a process or environment, in which oxygen is involved or present.	Oxford Languages: https://languages.oup.com
progradation	Of shore or shoreline, the advance seawards due to the build up of sediment	https://www.collinsdictionary.com/dictionary/english/progradation
riparian	In law: relating to or situated on the banks of a river. In ecology: relating to wetlands adjacent to rivers and streams.	Oxford Languages: https://languages.oup.com
river basin, river catchment	The area of land from which all the water flows into a particular river	https://www.collinsdictionary.com/dictionary/english/river-basin
	An area of land that is drained by a river and its tributaries	https://wiki.reformrivers.eu/index.php/Catchment_delineation
river reach	A continuous extent of water, especially a stretch of river between two bends, or the part of a canal between locks.	Oxford Languages: https://languages.oup.com
saltation	The transport of hard particles over an uneven surface in a turbulent flow of air or water.	Oxford Languages: https://languages.oup.com
salting out	The phenomenon observed when the solubility of a nonelectrolyte (uncharged) compound in water decreases with an increase in the concentration of a salt.	Poole, C.F., 2020. Milestones in the Development of Liquid-Phase Extraction Techniques. In: Liquid-Phase Extraction, Poole C.F. (ed.). Elsevier B.V., Amsterdam, The Netherlands.
sediment cascade	A conceptual model in understanding the role of erosion and deposition in geomorphic systems. It depicts the sediment system as a network of sediment stores linked by a series of transfer processes.	Warburton, J., 20XX. Sediment Transport and Deposition. In: The SAGE Handbook of Geomorphology, Gregory, K.J., Goudie, A.S. (eds). SAGE Publications Ltd., London.
sediment connectivity	The connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape.	Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P. 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms, 40, 177–188.

Term	Definition	Source
sediment continuity	The physical transfer or exchange of sediment from one part of the fluvial system to another, representing the conservation of mass between sediment inputs, stores and outputs.	Joyce, H.M., Hardy, R.J., Warburton, J., Large, A.R.G., 2018. Sediment continuity through the upland sediment cascade: geomorphic response of an upland river to an extreme flood event. Geomorphology, 317, 45–61.
sediment continuum	The undisturbed process of sediment generation and movement within a river system.	
sediment deficit	The rate of sediment mass loss from a river catchment, a reach or other waterbody (e.g. lake, reservoir) within a catchment, or a coastal cell, where such loss is occurring	
sediment delivery	The transfer of sediment from terrestrial and riparian sources into a river channel	
sediment delivery ratio	The fraction of gross erosion that is expected to be delivered to the outlet of the drainage area considered.	Ferro, V., Minacapilli, M., Sediment delivery processes at basin scale. Hydrological Sciences Journal, 40, 703-717. https://doi.org/10.1080/02626669509491460
sediment dwelling	In the context of aquatic ecology, refers to organisms that live all or a majority of the aquatic part of their lifecycle within the bottom sediment. Also known as infaunal organisms.	
sediment dynamics	The motion of sediment particles during their formation, transport, and settling processes.	Zhang, W., 2014. Sediment Dynamics. In: Encyclopedia of Marine Geosciences , Harff, J., Meschede, M., Petersen, S., Thiede, J. (eds). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6644-0_175-1
sediment quantity	Refers generally to the amount of sediment within a river catchment or a reach or other waterbody (e.g. lake, reservoir) within a catchment	

Term	Definition	Source
sediment supply	The input of sediment to a river catchment, a reach or other waterbody (e.g. lake, reservoir) within a catchment, or a coastal cell, from external sources such as erosion/weathering and upstream/updrift transport	
sediment yield	The quantity of sediments which is transferred, in a given time interval, from eroding sources through the channel network to a basin outlet.	Ferro V, Minacapilli, M., Sediment delivery processes at basin scale, Hydrological Sciences Journal, 40:6, 703-717, DOI: 10.1080/02626669509491460
shoaling	In the context of coastal waters, the deformation of incident waves on the lower shoreface that starts when the water depth becomes less than about half of the wavelength, causing the waves to become steeper, increase in amplitude, and decrease in wavelength.	www.coastalwiki.org/wiki/Shoaling
sinuosity	The degree to which a river channel meanders back and forth across its floodplain	
soft engineering	The use of then natural environment to reduce erosion and flooding.	
SuDS	Sustainable Drainage Systems: drainage systems designed to mimic as far as possible natural runoff patterns and to cause minimal environmental degradation.	
supporting elements	Elements of water quality or hydromorphology that support the attainment of good chemical and/or ecological status under the WFD.	
swell wave	Surface gravity waves on the ocean that are not growing or being sustained any longer by the wind. Generated by the wind some distance away and now propagating freely across the ocean away from their area of generation, these waves can propagate in directions that differ from the direction of the wind.	https://graphical.weather.gov/definitions/defineSwell.html

Term	Definition	Source
tidal pumping	A type of water upwelling observed on the incoming tide in coastal and estuarine environments. Inflowing deep water encountering a shallow area is propelled upward into the surface layers.	http://courses.washington.edu/ocean101/Lex/Lecture20.pdf
upwelling	An instance or amount of water or other liquid rising up.	Oxford Languages: https://languages.oup.com
washload	Sediment with settling velocities so slow that it does not interact with the bed, such that it depends only on upstream supply.	Lamb, M.P., de Leeuw, J., Fischer, W.W., Moodie, A.J., Venditti, J.G., Nittrouer, J.A., Haught, D., Parker, G. ,2020. Mud in rivers transported as flocculated and suspended bed material. Nature Geoscience, 13, 566–570. https://doi.org/10.1038/s41561-020-0602-5

2