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Sediment imbalances and flooding risk in European deltas and estuaries

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Abstract
Purpose We analysed the status of current water and sediment management practices in six deltas and estuaries, which were part of the European DELTANET, INTERREG-funded network.
Materials and methods These systems—the Danube, Ebro and Vistula deltas and the Elbe, Minho and Severn estuaries—represent different geographic regions of Europe. This enables comparison between the sites' approaches to common coastal issues, notably those associated with sediment budgets, contamination and flood risk. Based on documentary analysis, workshop events and expert discussion, we employ a simple classification scheme to distinguish between levels of risk from these aspects.
Results We suggest that flood risk is the most significant risk, followed by upstream sediment retention and sediment aggradation. Chemical contamination, though less severe, is not unimportant. Key management issues include a lack of environmental

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quality standards for sediment and suspended particulate matter, as well as the limited deployment of monitoring programmes, regular sediment sampling and associated chemical analyses.
Conclusions These include both general and specific recommendations. Within these, the limited scope of integrated plans that aim for sustainability of the respective systems is highlighted. It is suggested that these do not challenge traditional, classical engineering approaches sufficiently. Nor do they address the origin of many environmental problems, especially those which are closely linked to short-term political and economic priorities.

Keywords Deltas and estuaries · Flooding · Planning · Sediment management

1 General overview of European deltas and estuaries

Deltas and estuaries are of high ecological and economic value as a result of the services they provide. However, over the last two centuries, unregulated development, industry and tourism have destroyed many near-shore habitats and have deeply modified coastal land and seascapes across Europe (Reise 2005; Airoldi and Beck 2007). As a consequence, many European deltas and estuaries are amongst the most severely degraded temperate systems in the world (Lotze et al. 2006). These face increasing pressures from population growth (European Environmental Agency (EEA) 2005; 2006), as well as becoming progressively more vulnerable to flooding as a result of various natural and human-induced processes (Syvitski et al. 2009).

In Europe, fluvial sediment transfer from land to sea has decreased significantly over the last century (Poulos and Collins 2002) largely as a result of sediment retention associated with upstream reservoirs. The construction of infrastructure, including embankments, and navigation structures has resulted in many rivers becoming disconnected from their floodplains, to the detriment of habitats and species. Coastal structures also disrupt natural sediment fluxes, sometimes reducing marine sediment supply to deltas and estuaries. There are also concerns that these issues may be exacerbated as a result of global warming, given recent sea-level rise predictions. Moreover, many deltas and estuaries receive pollutants from upstream, causing additional stresses. Such substances may be absorbed by sediment and biota, and are both difficult and expensive to manage.

This paper provides an analysis and overview of the status and practice of water and sediment management in six European coastal deltas and estuaries. Coastal deltas are defined as low-lying landforms that occur at the mouths of rivers at locations where rivers deposit sediment as they flow into the sea. Estuaries are semi-enclosed coastal bodies of water which are freely connected to the open sea; in these, seawater is less saline than the open sea due to dilution from freshwater (Pritchard 1967). The six sites under review are part of the European delta network, DELTANET: Network of European Deltas (http://www.deltanet-project.eu) which was supported by INTERREG IV-C through the European Union's Regional Development Fund (2010–2013). Whilst the estuaries and deltas within the network have different sedimentary and fluvial regimes, they are sufficiently similar in terms of their physical processes and human issues to allow a comparison of management practice and to provide a useful overview for other similar systems. Although no primary research (i.e., new data) is presented, the paper and its associated analysis are based on a synthesis of technical and scientific (published and unpublished) documents. It also relies on a range of grey literature sources, including official reports and other documents related to the management and planning of these areas. Furthermore, the argument is supported by evidence and discussion gleaned from key DELTANET events (e.g., workshops and conferences), including discussions amongst experts.

2 The case studies

These represent different geographic regions of Europe (Fig. 1) and include the Danube (Romania) (Fig. 2), Ebro (Spain) (Fig. 3) and Vistula (Poland) (Fig. 4) deltas, and the Elbe (Germany) (Fig. 5), Minho (Spain) (Fig. 6) and Severn (UK) (Fig. 7) estuaries. The main features of each river and delta/estuary are summarised in Table 1. A brief description of each system is also provided in the Electronic supplementary material.

3 Analysis of the selected European deltas and estuaries

In this next section, the most common issues disrupting the equilibrium of the sites are examined. These focus on (1) sediment deficit and sediment aggradation, (2) sediment contamination and (3) flood risk.

3.1 Sediment deficit and sediment accretion

In the Lower Danube River (Table 2), the Iron Gate I and II reservoirs, and the large water management schemes along many of its tributaries, are major barriers to sediment transfer. So much so, that between 1970 and 1990 the total sediment load transferred downstream of reservoirs dropped from 67.5 to 7.3×10^6 t year^{-1} (Panin 1999; Tockner et al. 2009). This deficit has been exacerbated by dredging of the navigation canal and straightening of the river channel (International Commission for the Protection of the Danube River (ICPDR) 2009). In the Danube delta, the flow regime has also been modified (from about 160 m^3 s^{-1} in the nineteenth century to 620 m^3 s^{-1} in the period 1981–1990). Transport of fine sediments from drainage canals into the lake complexes has increased (International Commission for the Protection of the Danube River (ICPDR) 2009), leading to sedimentation of

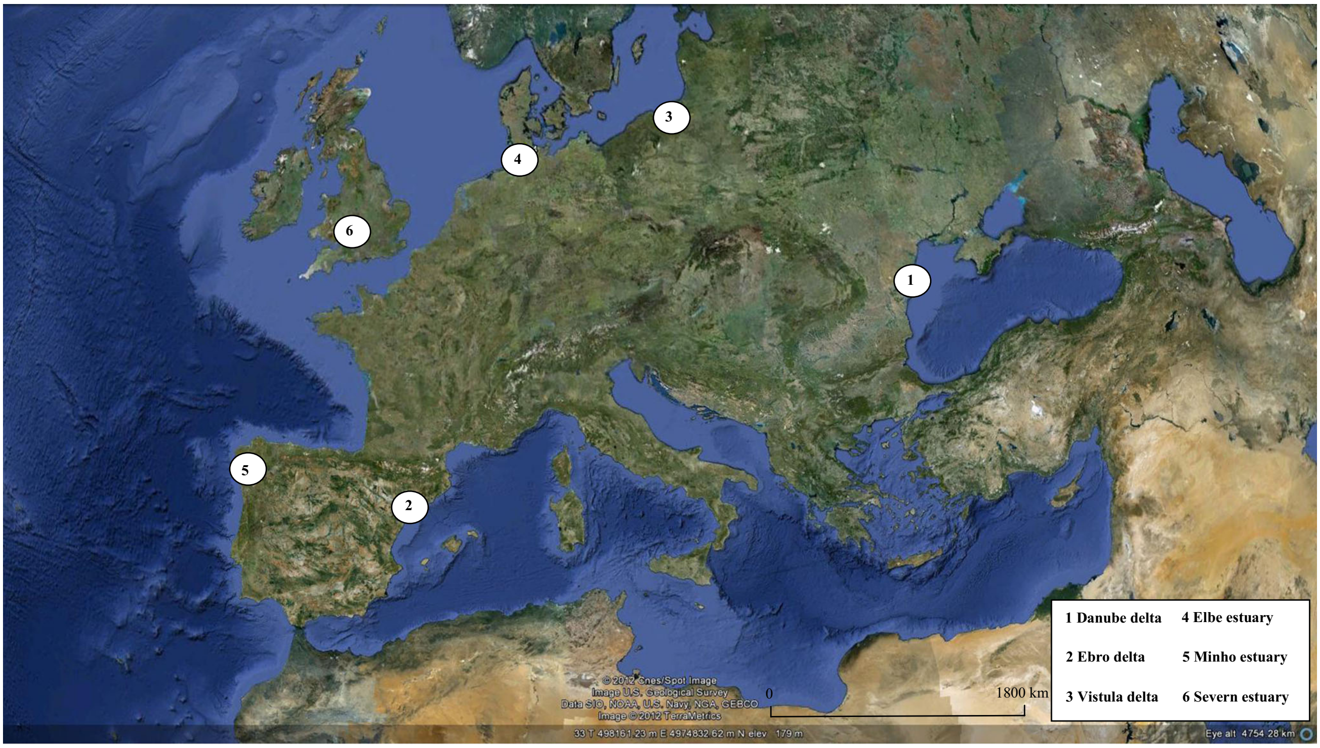

Fig. 1 Locations of the six delta and estuary regions in Europe. Source Google Earth 2012

the Inner Delta, particularly within the western-most lakes. Conversely, in other areas, the coast has retreated by between 20 and 30 m year^{-1} (Panin 1999). Further significant modifications include channel maintenance along the Sulina channel and at the river mouth (where a minimum water depth of 7.9 m is required for shipping; International Commission for the Protection of the Danube River (ICPDR) 2005), as well as the construction and extension of two parallel dikes which protect against siltation from the Stambulul Vechi branch (Robakiewicz 2010).

In the Ebro River, total sediment transfer to the Mediterranean Sea dropped by over 99 % last century, from 30 to 0.1 × 10^{6} t year^{-1} in 2010 (Rovira and Ibáñez 2007) (Table 2). This reduction was caused by reservoir retention in the Mequinensa,

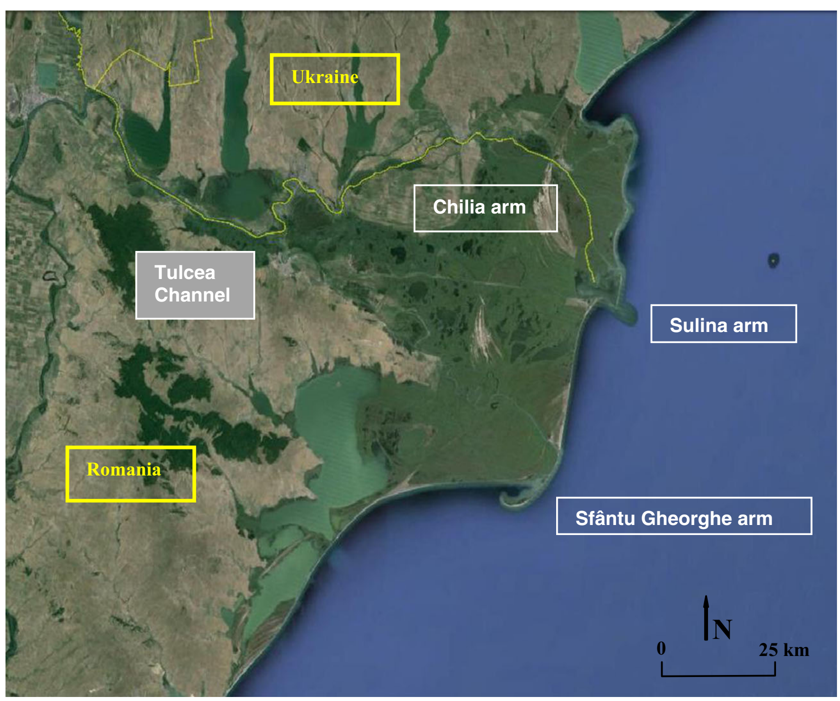

Fig. 2 Aerial view of the Danube delta. Source Google Earth 2012

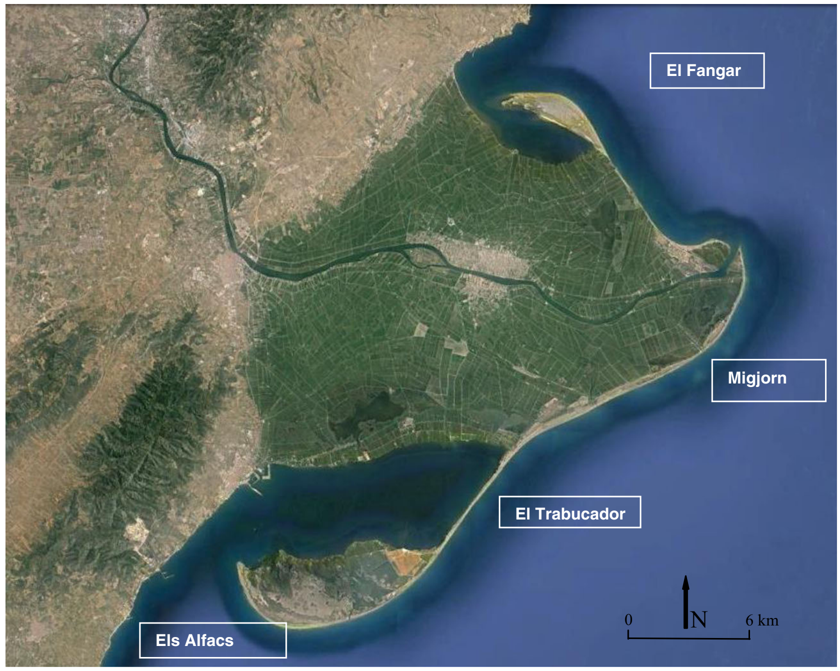

Fig. 3 Aerial view of the Ebro delta. Source Google Earth 2012

Riba-Roja and Flix reservoir complex, located 100 km upstream (Vericat and Batalla 2006). Sediment deficit has also been exacerbated by continuous dredging of the riverbed (2000 to 2004) and massive gravel mining operations along the Siurana River, the main downstream tributary (Batalla 2003). River regulation has also intensified these impacts. Furthermore, infrastructure construction within the delta (i.e., artificial levees, dikes, canals and roads) has led to a lateral disconnection between the river and the delta plain. This, in turn, has resulted in significant river bank erosion (SEO/BirdLife 1997).

In the Vistula River, the Wloclawek Reservoir has reduced suspended load from 2.3×10^6 t year^{-1} in 1970 to 1.6–0.5×10^6 t year^{-1} in recent years (Łajczak 1996; Lajczak et al. 2006). Furthermore, at least 2.1×10^6 m^3 sediment was mined from the Vistula main stem between 1955 and 1964, exhausting almost all the river's gravel resources as well as causing an incursion of salt water upstream (Lajczak et al. 2006).

In the Vistula Delta, similar modifications have occurred. In 1895, the construction of an artificial outlet (Table 2) resulted in 14 km of river shortening. Significant channelization also caused that the Nogat, Szkarpawa and Martwa Wisla arms become isolated from the main stem (Lajczak et al. 2006). As a consequence, a 'fan-delta' was formed in the near-shore zone of the Vistula river mouth and river-borne sediment contributed to coastal accretion (Pruszak et al. 2005).

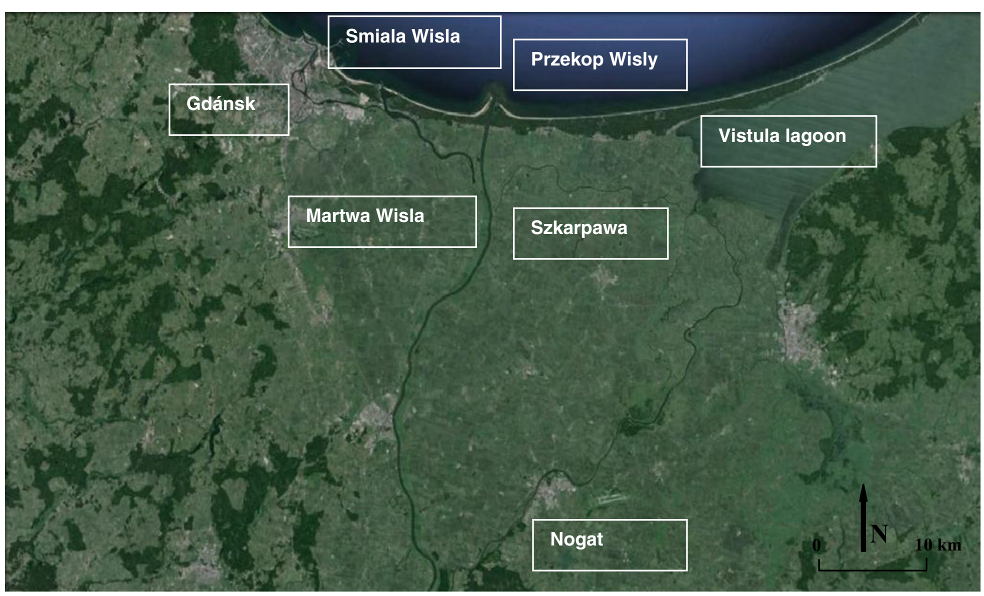

Fig. 4 Aerial view of the Vistula delta. Source Google Earth 2012

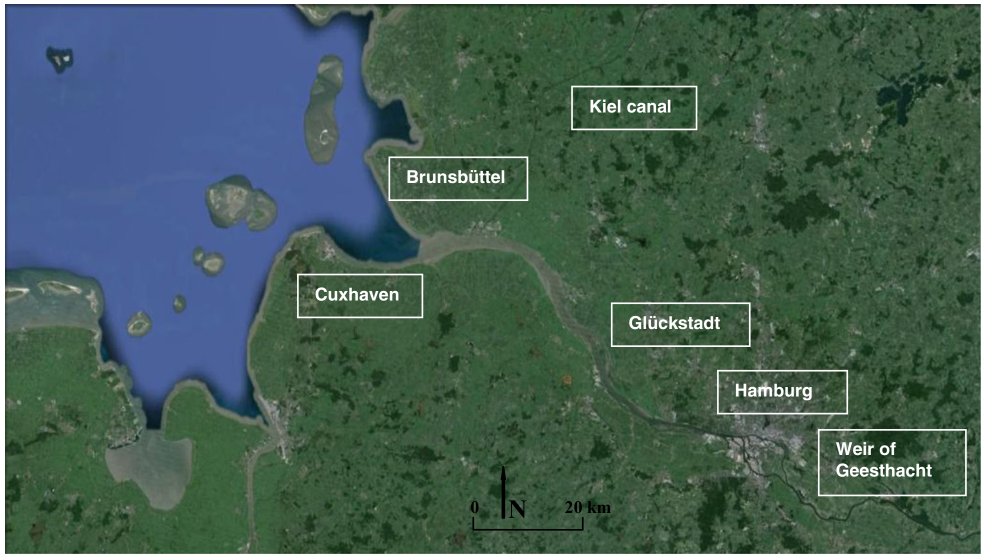

Fig. 5 Aerial view of the Elbe estuary. Source Google Earth 2012

During low-flow periods, notably in summer, sediment is deposited offshore. This forms shoals and small islands impeding navigation in the shallow waters (Grześ 1991). Strong marine waves and currents at other times of the year cause significant erosion of the delta fan, whilst the eroded material is transported eastwards causing accretion of the Vistula Spit and significant advance of the coastline (2 km since 1895) (Pruszak et al. 2005). Furthermore, to maintain the outlet of the artificial channel, continual lengthening of breakwaters is required (Majewski et al. 2003; Ostrowski et al. 2009); currently, the eastern breakwater is being extended by 200 m. In preparation of this, 180,000 m^3 of sediment has been dredged (April 2011) and monitoring systems have been installed at the river's mouth to inform future modifications of the breakwaters (Robakiewicz 2010). Additionally, there is a complex network of drainage ditches and channels associated with each polder in the delta plain and about 100 pumping stations continuously drain the area to maintain appropriate groundwater levels (Union of Vistula River Towns (UVRT) 2000). Associated concerns include the possible submergence of polders and significant flooding which could arise as a result of a levee breach (Kowalik 2008).

The Minho Estuary is mainly affected by sediment accumulation, caused largely by a combination of tidal effects, which transport material upstream, and the Frieira dam, located 80 km upstream (Table 2). In its natural state, sediment flow into the estuary was driven by periods of erosion and sedimentation; during high discharge flood events, fluvial processes governed

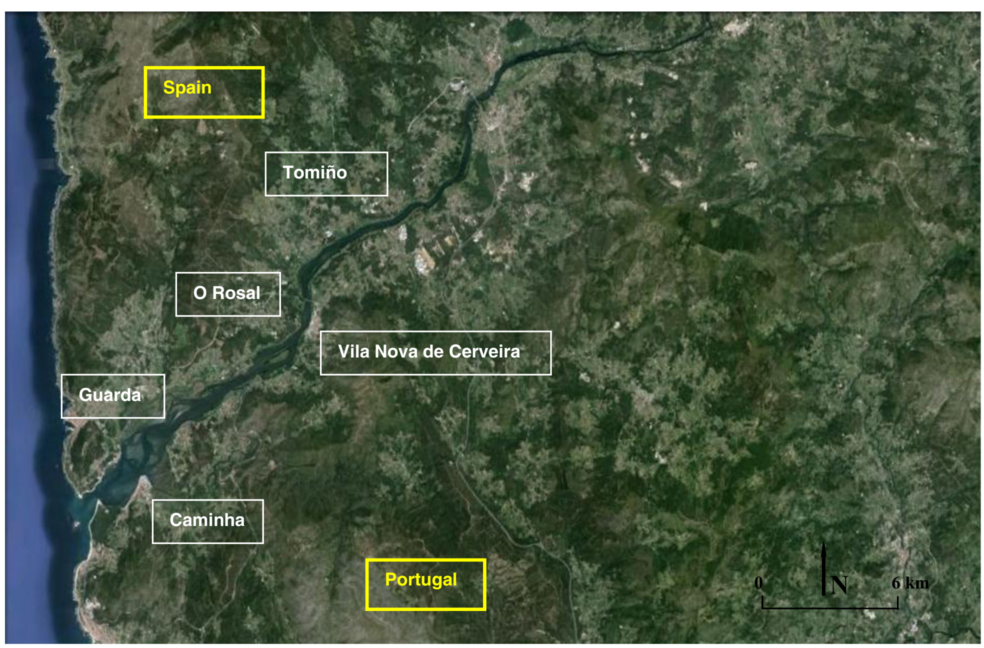

Fig. 6 Aerial view of the Minho estuary. Source Google Earth 2012

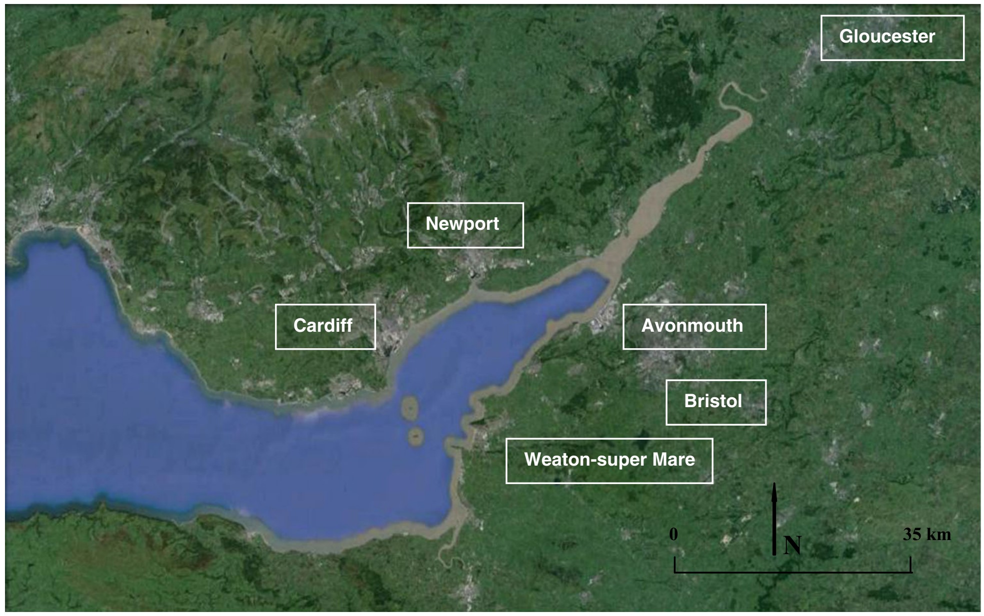

Fig. 7 Aerial view of the Severn estuary. Source Google Earth 2012

Table 1 Main features of the case studies

	Danube delta	Ebro delta	Vistula delta	Elbe estuary	Minho estuary	Severn estuary
River length	2,850 km	928 km	1,047 km	1,094 km	344 km	354 km
Drainage basin	801,463 km^2	85,530 km^2	194,424 km^2	148,268 km^2	17,757 km^2	11,266 km^2
Delta/Estuary area	5,800 km^2	330 km^2	2,320 km^2	431 Km^2	23 km^2	557 km^2
Estuary length	81 km	32 km	63 km	170 km	35 km	64 km
Dams in the river basin	700 (>60 along the main course of the Danube)	187	103	52	>40 (5 in the main course)	Check dams
Mean annual runoff at the river mouth	6,500 m^3/s	426 m^3/s	1,080 m^3/s	711 m^3/s	350 m^3/s	99.9 m^3/s
Main water uses	Drinking water Navigation Hydropower generation Industry Irrigation Disposal of municipal and industrial waste	Drinking water Hydropower generation Cooling nuclear power plants Irrigation Disposal of municipal and industrial waste	Drinking water Navigation Hydropower generation Industrial processes Irrigation Disposal of municipal and industrial waste	Navigation Drinking water Cooling nuclear power plants Industry Disposal of municipal and industrial waste	Fishing activity Hydropower generation Disposal of municipal waste	Drinking water Industrial processes Irrigation Navigation—for commercial and recreational use
Navigation	Yes (2,400 km)	Only small boats from Ascó to the river mouth (84 km)	Yes (941 km)	Yes (845 km)	Only the ferry (from Caminhas to Pasaxe) and sportive and recreational boats at the estuary (23 km)	Yes (290 km)
Embankments	Yes	Yes	Yes	Yes	Not important	Yes
Last Important Dams/ distance to the river mouth	Iron Gate I and II/ about 864 km.	Mequinensa-Riba-Roja-Flix system/ about 100 km.	Wloclawek/ about 266 km.	Geesthacht weir/ about 140 km.	Frieira/ about 80 km.	-

Table 2 Issues that are disrupting the equilibrium of the examined deltas and estuaries

	Danube delta	Ebro delta	Vistula delta	Elbe estuary	Minho estuary	Severn estuary
Issues	• Sediment retention into reservoirs • Retention of pollutants into the reservoirs • Dredging of the navigation canal • Straightening of the river channel • Artificial extension of the natural channel network • Transformation of wetlands in polders and fishponds • Floodplains cut off by embankments	• Sediment retention into reservoirs • Retention of pollutants into the reservoirs • Dredging of navigation channel • Suppression of large, short and irregular floods • Construction of artificial levees, dykes, canals and roads • Sediment input cut off to wetlands	• Sediment retention into reservoirs • Retention of pollutants into the reservoirs Dredging of navigation channel • River length shortening • River channelization and embankments • Isolation of river arms • Formation of ice jams and ice blocks collide • Exhaustion of almost the whole gravel resources • Strong marine dynamics • Creation of polders, dykes and artificial channels	• River regulation from reservoirs • River length shortening • Steepening of bed slope • Increase of flow velocity • Dredging of navigation channel and ports • Embankments, dykes and artificial levees • Floodplain cut off • Sediment contamination • High input of nutrients	• River regulation • Sediment retention into reservoirs • Dredging of navigation channel	• Construction of barrages • Changes in land uses • Coastal defences, embankments and dykes • Weirs • Dredging of navigation channels
Consequences	• Sediment deficit • Risk of contamination episodes • Sedimentation of the navigation channel • Bank erosion • Lateral disconnection between the river and the delta plain • Elimination of floods into the delta plain • Delta plain deposits degraded • Groundwater dynamics reduced • Silting of lake complexes, inner delta and some coastal areas • Coastal retreat in some other areas • Increased flooding risk • Constant dredging maintenance	• Sediment deficit • Incapacity of lamination of largest floods • Risk of contamination episodes • Lateral disconnection between the river and the delta plain • Progradation of the coast at certain parts and regression at others • Exacerbation of delta subsidence • Increased flooding risk	• Sediment deficit • Risk of contamination episodes • Sedimentation of the navigation channel • Lateral disconnection between river and delta plain • Creation of a fan-delta in front of the river mouth • River-borne sediment returned to shore • Damages to breakwaters and embankments • Coastal erosion • Accretion of Vistula spit • Continuous lengthening of groins at the river outlet • Continuous groundwater pumping	• Erosion of river channel • Dewatering and consolidation of certain floodplain areas • Increased flooding risk in polder areas • Increase of tidal amplitude • Risk of contamination episodes • Reinforcement of tidal pumping effect • Tendency towards sedimentation into the estuary • Widening of the funnel • Erosion into river mouth • Formation of algae blooms • Water oxygen consumption and depletion • Constant dredging maintenance	• Reinforcement of tidal pumping effect • Tendency towards sedimentation into the estuary • Erosion into river mouth • Water stirring	• Increased sedimentation into the estuary • Reduced bank stability • Reduced natural interaction between river and flood plain • Constant dredging maintenance • Increased flooding risk because artificial defences

Table 2 (continued)

	Danube delta	Ebro delta	Vistula delta	Elbe estuary	Minho estuary	Severn estuary
			• Increased flooding risk in polder areas • Constant dredging maintenance			

estuarine hydro-morphological dynamics, causing seaward migration of the salt wedge. At such times, the large volumes of sediments stored in the estuary or coming down the Minho River would be transferred seawards. Conversely, during low flows and storm surges, tidal processes dominated, causing tidal pumping to occur, by which large quantities of sand were transferred landward. Altogether the system was in balance, with equilibrium between sediment import and export. But, the subsequent construction of the Frieira Reservoir has changed this, reducing fluvial sediment and water inputs, whilst increasing associated erosion at the river's mouth (Oliveira et al. 1982; Dias 1990; Sousa et al. 2008). As a result, it has been estimated that 1,768,580 m^3 of sediment was lost from the estuary mouth between 1991 and 2004 (Dirección General de Costas (DGC) 2003). In contrast, the tidal pumping effect has intensified (Santos et al. 2006). Consequently, sand and fine sediment now accumulate in the estuary. This is a particular issue in the estuary's middle section, where the formation of low sand shoals, islands and deposits parallel to the coast block the river's mouth (Ferreira et al. 2003). In addition, significant infrastructure construction (associated with ports and other water-based activities) has resulted in high water turbulence in the estuary (Mil-Homens et al. 2010).

The sediment budget of tidal Elbe has been affected by the Geesthacht Weir, constructed in 1960 to aid inland navigation. This resulted in river regulation in the upper estuary and the significant modification of estuary dynamics, including tidal processes (Schuchardt et al. 1999a, b). In particular, the increased tidal amplitude has exacerbated sediment pumping from the North Sea. Currently, large amounts of sediment which are transported upstream towards the Port of Hamburg are a major challenge for navigation (Freitag et al. 2007). As a result, the annual volume of material dredged in the Hamburg area has increased considerably over the last 10 years. Before 2000, the quantity of dredged sediment had remained stable at about 2×10^6 m^3. Since then, dredging has increased. Indeed, in 2004, over 8×10^6 m^3 of sediment was dredged from the tidally influenced Hamburg area (Hamburg Port Authority (HPA) 2005). In complete contrast, there has been a significant reduction of sediment at the estuary mouth, caused partly by the shortening of the Elbe (by 115 km), required for navigation purposes. The bed gradient has also become steeper and flow velocity has increased. This has caused an increase in tidal energy and general erosion of the fluvial channel (Rolinski and Eichweber 2000). In contrast to these negative influences, most material generated from maintenance dredging within the port of Hamburg and its associated waterways is currently returned to the Elbe, minimizing the environmental effects of relocation (Rolinski and Eichweber 2000).

Man-made modifications in the Severn Estuary (Table 2) have significantly influenced the hydro-morphology of the estuary. These include a range of different land uses, flood protection strategies, navigational channels, ports and dredging; all of which have influenced sedimentation processes in the estuary (Severn Estuary Coastal Group (SECG) 2010). Recently, the construction of large structures, such as the Cardiff Bay barrage (completed in 1999), has altered sedimentation in select locations. In this case, increased sedimentation downstream and knock-on impacts for navigation dredging have occurred. Furthermore, flood defences around the estuary have reduced natural interactions with the floodplain, causing additional stresses on the system, including coastal squeeze. Dredging for aggregates (approximately 937,908 t landed in 2010; Severn Estuary Partnership (SEP) 2011) and navigation (for maintenance purposes) is undertaken at various sites within the estuary as well as at major, extensive relic sandbanks to the west (Green and Smith 2009). Between 1.5 and 2×10^6 m^3 of dredged material is removed annually (Department of Energy and Climate Change (DECC) 2010; Severn Estuary Partnership (SEP) 2011). Some local groups have expressed concern about the possible impacts of aggregate dredging on beach levels and erosion within the Bristol Channel. Nevertheless, sedimentological studies and formal investigations over many years have not revealed any detectable impacts on the sediment regime (Severn Estuary Partnership (SEP) 2001).

3.2 Sediment contamination

In the Danube River, most of the hazardous chemicals entering the river come from industrial activities, including mining, smelting and chemical processing (International Commission for the Protection of the Danube River (ICPDR) 2005). Agricultural practices have also given rise to diffuse pesticide inputs. Nevertheless, the Iron Gate I and II reservoirs act as important sinks for many pollutants (Milenkovic et al. 2005), resulting in relatively low concentrations of organochlorinated substances in sediment and suspended particulate matter downstream (International Commission for the Protection of the Danube River (ICPDR) 2009).

Similarly, sediment contamination is generally low downstream of reservoirs in the Ebro River as a result of sediment retention. It is estimated that the Flix reservoir alone retains approximately 1×10^{6} m^{3} of contaminated sediment from the large Ercross S.A. Chemical Complex (Carrasco et al. 2011). However, significant amounts of heavy metals and organo-chlorinated substances are re-suspended during flood events and accumulate in river biota (Cid et al. 2010).

The Wloclawek Reservoir along the Vistula River similarly 'protects' the lower reaches of the river from major pollution caused by extensive industrial activity in the river's upper reaches (Kentzer 2009). With some of the largest deposits of mineral resources in Europe located in the upper basin in Silesia, development, industrialisation and population growth over centuries has resulted in severe river pollution (Kajak 1993). As a result of associated pollution and habitat alteration, some species of commercially important migratory fish, including sturgeon and salmon, have disappeared from the river system (World Wide Fund for Nature 1986). Whilst about half of the agricultural land of the Baltic catchment is located in this region (HELCOM 1993), pollution risks are relatively low. These have also been reduced by recent changes in agricultural practice and the construction of numerous sewage treatment plants. There have been substantial decreases in pollution, particularly from organic substances (Buszewski et al. 2005). Nowadays, sediments in the mouth of the Vistula meet national Polish Standards and, therefore, can be disposed of at sea or used as building materials (Robakiewicz 2010).

In contrast, sediment contamination is a significant issue in the Elbe Estuary. Since the early 1980s, the river and its estuary have been recognised as amongst the most contaminated within Europe (Hellmann 1993; ATV – DVWK Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall. e.V. 2000; Netzband et al. 2002). The entire river basin, which includes extensive mining areas (such as the uranium mining area in the Ore mountains), is a large source of contamination. High-nutrient input from the catchment is also significant, inducing algal blooms and associated problems, including oxygen depletion, particularly during summer downstream of the city of Hamburg. Furthermore, these reduced oxygen levels impact on fish and other aquatic species (Kerner 2007).

The extensive intertidal areas of the Severn Estuary are characterised by fine-grained sediments, which act as sinks for various contaminants entering the system from a range of sources (Marine Biological Association (MBA) 2003). Heavy metals and other potential pollutants, including synthetic organic compounds enter the estuary through rivers, sewage effluents, industrial effluents, highway drainage and contaminated surface water runoff (Severn Estuary Partnership (SEP) 2001; Severn Estuary Coastal Group (SECG) 2010). Limited evidence suggests that heavy metal levels in sediments have declined since the 1970s (Apte et al. 1990). This has largely been a result of more stringent pollution control measures for industrial and municipal wastewater discharges (Ballinger and Stojanovic 2010; Severn Estuary Partnership (SEP) 2011). Indeed, it is envisaged that the Severn Estuary water bodies will meet the required standards of 'Good Environmental Status' under the Water Framework Directive by 2015. In addition, the highly dynamic nature of this hyper-tidal estuary, and associated constraints exerted by natural forcing, tend to restrict pollution impacts spatially (Owens 1984). This means that contamination is largely confined to industrial and urban areas, notably around Avonmouth, Cardiff and Newport.

In contrast to the other areas, the Vistula Delta and the Minho Estuary may be considered relatively unpolluted, the latter particularly so in terms of heavy metals (Mil-Homens et al. 2010). Contaminated soils, located in the Upper Sil system and Louro River, however, do contaminate groundwater, notably the alluvium of the Lower Minho (Confederación Hidrográfica del Minho-Sil (CHMS) 2010).

3.3 Flood risk

In the Danube Delta, significant activities affecting flood risk include the artificial extension of the natural channel network and the transformation of wetlands into huge agricultural polders and fishponds (Sommerwerk et al. 2010). During the nineteenth and twentieth century, 15,000 to 20,000 km^{2} of the floodplain became divorced from the main river as a consequence of embankment construction (International Commission for the Protection of the Danube River (ICPDR) 2009). As a consequence, floods were virtually eliminated from the delta plain, deposits became degraded, and the exchange of surface and groundwater was suppressed. Sediment input and organic accretion were also disrupted, diminishing the system's capacity to be able to compensate for delta subsidence (Panin 1999).

In the lower Ebro River, current reservoir management does not allow for large floods (i.e., 50 years return period). Thus, the entire delta remains at risk from flooding (Agència Catalana de l'Aigua (ACA) 2011). In addition, the cutting-off of fluvial sediment inputs to the deltaic wetlands and rice fields exacerbates the impacts associated with sea level rise and the natural subsidence of the delta (Ibáñez et al. 2010). As many eroding areas are important for humans and the biological system, this raises significant problems. Given that the development and morphology of the delta are now largely dominated by wave action (Rodriguez 2004), the capacity of the system to compensate for sea level rise and subsidence of the deltaic plain has been drastically reduced (Rovira and Ibáñez 2007).

The Vistula Delta has not been seriously inundated since the river was channelized and the artificial river outlet was constructed. Today, water flows freely to the sea so long as there is no blockage by transitory shoals and islands (Pruszak et al. 2005). However, during winter, the river can freeze over and ice jams then hamper water flow into the Baltic Sea, causing a significant rise in the river's water level. Ice blocks may also collide with sandbanks causing damage to breakwaters and embankments (Kowalik 2008). Areas most at risk from flooding include Żuławy, the Vistula valley and low-lying parts of Gdansk. A variety of factors trigger floods, including rainfall, snowmelt, ice jam and storms (Grześ 1991). Whilst some flood defences have improved, the risk of flooding has not diminished that significantly; most defences remain in need of major repair and improvement (Pomorskie Regional Board (PRB) 2007).

Engineering works along the Elbe River, designed for flood control, storm surges and navigability, have led to the dewatering and compaction of areas behind dikes. As a result, the river has been disconnected from its flood plain causing increased flood risk (Freitag et al. 2007). Furthermore, the stepwise deepening and canalisation of the outer and inner estuary has produced a marked increase in tidal amplitude (4 m at spring tide), placing the Elbe at the border between a mesotidal and macrotidal estuary (Schuchardt et al. 1999a, b).

Thousands of people around the Severn Estuary depend upon hard defences to protect coastal land and property from flooding and erosion (Environment Agency 1997). On low-lying shores, flood risk comes from both offshore and rivers, associated with either storm surges or surface runoff. Sea level rise is a concern especially given the size of potential areas influenced by tidal flooding, stretching 10 km inland (Severn Estuary Coastal Group (SECG) 2010) and increasing development on such land. Whilst flood defences are vital to maintain uses around the estuary, there is concern that these structures may inadvertently reduce natural interactions. There are also issues with respect to coastal squeeze, as coastal habitats become engulfed by rising sea levels (Frost 2008). Thus, sea level rise will cause marginal coastal habitats, such as salt marsh and shingle beaches, to become inundated or eroded at the seaward edge (Atkins 2009).

3.4 Classification of the issues

Each of the issues discussed in the previous sub-sections has been classified according to the risk it poses for each delta/estuary system (Tables 3 and 4). Based on a qualitative evaluation by DELTANET partners, the levels of risk associated with each type of risk have been assessed following the Van der Most (2009) classification:

- non-risk (0) if the risk is non-existent
- minor risk (1) if the risk is either unimportant, small in magnitude or well controlled
- moderate risk (2) if the risk is beginning to be relevant and require management and
- high risk (3) if the risk is not (yet) controlled and needs considerable management.

In terms of DELTANET, it should be noted that the classification of risk associated with sediment quality was based on both the size of affected area and the need for management (e.g., not controlled or start to be relevant). Levels of flood risk were determined from a socio-economical point of view, based on damage and casualties from such events.

The assessment was undertaken within a series of three workshops. The first workshop provided a general description each delta and estuary. The second workshop focused on the identification and analysis of the main problems associated with each study case based on a compilation of technical and scientific published and unpublished documents, as well as discussion with experts. The third workshop provided a qualitative evaluation of the issues, based on delegate views. All the workshops involved, amongst others, managers, scientists, technicians and politicians and so included a range of experts on relevant topics as well as those involved in the management of these systems. The outcome of this assessment is summarised in Table 3. It must be stressed that whilst the assessment is somewhat subjective, it provides a reasonable indication of the relative severity and significance of the risks for each area, enabling clear comparisons between the different case studies. It should be noted that the impact that has a difference of one point between levels of risk has not been considered on the final results. As well, the impact that has two different risks (e.g., sediment deficit and flood risk) with the same score has not been assessed. Finally, it should also be noted that the tables group the risks according to both case study types (deltas/estuaries) and according to issues.

Table 3 reveals flood risk to be the main issue for all regions, followed by sediment retention and sediment accretion. In contrast, chemical contamination is a minor but not unimportant factor. At the delta/estuary level, the systems most affected are the Danube, Ebro, Elbe and Vistula systems. In the Danube and Ebro deltas, sediment deficit and flood risk are key concerns whilst in the Elbe Estuary sediment accretion and contamination are the main issues. In the Vistula Delta and Severn Estuary, flooding is a major risk whilst in the Minho Estuary the main issue is sediment accretion. In contrast, sediment deficit is of minimal importance in the Severn Estuary due to the high levels of suspended sediment.

Analysis by delta/estuary types (Table 4) reveals that flood risk is a key issue for all systems. Deltas and estuaries do, however, show differing responses to river regulation. For the

Table 3 Classification of the analysed issues (sediment deficit, sediment aggradation, sediment contamination and flood risk) according to their role in each delta/estuary system

	Danube	Ebro	Vistula	Elbe	Minho	Severn
Sediment deficit	3	3	2	1	2	0
Sediment aggradation	2	1	2	3	3	2
Sediment contamination	1	2	1	3	1	1
Flood risk	3	3	3	2	1	3

No risk (0), low risk (1), moderate risk (2) and high risk (3). See text for details

deltas, water and sediment retention by reservoirs emerges as a principal issue. Resultant coastal subsidence and sea-level rise further expose the deltas to waves and tidal currents, resulting in a change from coastal accretion to erosion. Sediment accumulation at the river outlet is also often observed. In contrast, river regulation may enhance the tidal pumping effect in estuaries and lead to large quantities of sediment being transferred from offshore into the estuary system. This can produce sediment accretion in the middle sections as well as erosion in the lower reaches. As climate change accelerates, it is anticipated that increased water levels in some estuaries, such as the Elbe, will create a higher tidal range, which, in turn, will strengthen the tidal pumping effect (TIDE project 2009).

In other areas, sea level rise (SLR) and climate change are likely to cause major modifications to the delta and estuary systems. Many of the deltaic/coastal plains lie below sea level, making them particularly vulnerable. In the Vistula, where 30 % lies below sea level, drainage ditches and canals constantly transport water to pumping stations in order to maintain groundwater levels (Pomorskie Regional Board (PRB) 2007). As SLR continues, this region is likely to become more susceptible to serious flooding. In the Ebro Delta, it is estimated that SLR will be about 50 cm by the end of the century, resulting in approximately 45 % of the current deltaic area being drowned (Ibáñez et al. 1997). In the Danube, predicted SLR will result in the continued regression of beaches along the delta's coast, estimated at a rate of

Table 4 Classification of the analysed issues by deltas and estuaries

	Deltas	Estuaries
Sediment deficit	3	1
Sediment aggradation	2	3
Sediment contamination	1	2
Flood risk	3	2

No risk (0), low risk (1), moderate risk (2) and high risk (3). See text for details

between 3 and 5 m year^{-1}. A predicted SLR of 20–30 cm by 2020–2030 will also significantly affect water and sediment discharge at the seaward side of the delta (Panin 1999). At the same time, not only will low-lying areas be flooded but flood risk will be ever more likely across the entire delta (Panin 1999). Whilst there are concerns regarding the increased risk to humans of flooding associated with climate change, some of the greatest issues relate to predicted habitat loss and the associated implications of meeting the legal obligations of international legislation, notably the EC Habitats Directive (92/43/EEC). On the Severn Estuary, it is estimated that direct impacts of climate change could reduce the estuary's intertidal areas and salt-marshes by about 11 and 38 %, respectively, over the next 100 years (Severn Estuary Partnership (SEP) 2011). This will not only reduce the system's ability to withstand future storm events but will also have major nature conservation implications.

4 Management plans addressing sediment and flood risk

This section provides a short review of current water and sediment management plans and associated management practice in the DELTANET deltas and estuaries.

4.1 Sediment management

For the Danube Delta, sediment management is addressed within the Danube Basin District Management Plan (DRBM), prepared by the International Commission for the Protection of the Danube River (ICPDR). In relation to the delta's sediment balance, this plan recommends identification of possible climate change impacts, improvements to the channel (to ensure a sediment continuum), prevention of commercial extraction of sediments, and return of maintenance dredging to the river. Use of excess sediment from the Chilia and Sulina arms is also recommended for beach protection and nourishment (International Commission for the Protection of the Danube River (ICPDR) 2009).

In contrast, there is no sediment management plan for the entire Ebro River Basin and delta despite a significant sediment deficit and associated problems in and downstream of reservoirs (Rovira and Ibáñez 2007). Whilst sediment by-passing was successfully used to counter act such retention along the Noguera Ribagorçana and Ésera Rivers in the 1980s and 1990s (Avendaño and Cobo 1998), this practice was not continued even though it was demonstrated that the river recovered quickly from the environmental impacts of the by-passing operations

(Palau 2002). Agència Catalana de l'Aigua (ACA) has developed a sediment management plan ('SedMa Plan') for the Lower Ebro River (Agència Catalana de l'Aigua (ACA) 2007). This, however, is a non-statutory plan and, to date, the basin authority (CHE) has not considered its implementation. Currently, in the lower Ebro River, current sediment management practices mainly consist of channel navigation maintenance with dredged material being relocated in deeper parts of the riverbed or in the levees.

In the Vistula Delta, sediment management is included within the 'Programme for the Zulawy region till 2030 (first stage till 2015) - Complex flood protection' (Regional Water Management Board in Gdansk (RWMB) 2008). This includes measures to renovate both the eastern and western breakwaters at the river's mouth. As the sediment is unpolluted, excess sediment has also been used to build an artificial island (Regional Water Management Board in Gdansk (RWMB) 2008). Dredging is necessary to maintain the required navigable depth at the river mouth and other activities are required to maintain a sufficiently wide passage for the downstream flow of blocks of ice during spring (Robakiewicz 2010).

Given the cross-border nature of the Elbe River catchment, the International Commission for the Protection of the Elbe River (ICPER), established in 1990, has enabled the Czech Republic and Germany to work together to improve the river's water and sediment quality status. This has been accomplished through joint implementation of the EU Water Framework, Flood Protection and Accidental Water Pollution Directives, with noticeable results. In the Elbe, the Waterways and Shipping Administration (WSV) not only owns this federal waterway but is also responsible for its maintenance. In the State of Hamburg, which covers the river's lower reaches, however, management is delegated to the City of Hamburg, represented by Hamburg Port Authority (HPA). To preserve the Elbe's estuary habitat, protected under the Natura network, the federal states and the WSV have drawn up an integrated management plan, 'Integrated Management Plan Elbe estuary (Natura 2000)'. This attempts to integrate economic and ecological objectives through a set of proposed measures, taking into account the many uses of the waterway, including agriculture and recreation. As the plan is not legally binding, it relies on the voluntary commitment of stakeholders. To facilitate this, planning groups have been established to foster cooperation with stakeholders through regular meetings (TIDE project 2009).

To halt further degradation and promote sustainable development, HPA and WSA have developed a new approach. This aims to mitigate against the negative impacts of tidal energy, sediment transport and dredging, whilst affording benefits for the conservation of habitats, enhancement of biodiversity and other demands, including fisheries (TIDE project 2009). This approach aims to (1) establish new shallow water areas in the upper part of the estuary, (2) optimise sediment management and (3) dissipate incoming tidal energy by near-natural river engineering measures. To inform this approach, HPA established the international TIDE project to learn from other North Sea region estuaries. This has provided new insights and suggestions relating to estuary dynamics, mitigation measures and improved governance structures (TIDE project 2009).

Although there is no specific management plan for the Minho Estuary, the Minho-Sil Hydrographical Demarcation published a new 'Hydrological Plan' in December 2010. This, however, does not analyse or address any of the sedimentation problems or issues associated with maintenance dredging within the estuary.

Given the depth of the main navigation channel and the natural scour of tides in the Severn Estuary, it is only the approaches to ports which require regular dredging to maintain safe navigable depths (Severn Estuary Partnership (SEP) 2011). This is a highly regulated activity in order to minimise impacts from both the dredging process and the disposal of the dredged material. Aggregates from offshore sand banks within the estuary are of significant commercial interest; the sand is of high quality, with well-sorted grain sizes and hardly any wastage (Severn Estuary Partnership (SEP) 2011). As a result, the construction industry, particularly in south east Wales, is heavily reliant on these resources (Severn Estuary Partnership (SEP) 2011). The Crown Estate, which issues commercial licences for both prospecting and aggregate extraction, as well as the regulators—the Marine Management Organisation (England) and the Welsh Government (Wales)—oversee a highly structured planning and consenting process to ensure environmental impacts are minimised.

A general overview of plans for all the case studies shows that sediment management almost entirely focuses on dredging of port entrances and associated channels to maintain navigable fairways and port operations (Table 5). This review has shown that recent sediment management practice has started to consider possible beneficial uses of the dredged material. This has included the return of dredged material to river systems, minimizing relocation and dredging effects. In addition, some sediment is used for beach protection and nourishment and sometimes the construction of artificial islands or sand barrages in order to help dissipate tidal energy. Across all the sites, it should be noted that commercial extraction of aggregates is either forbidden or highly regulated.

The Minho Estuary and the Ebro Delta are two special cases. In the former, maintenance dredging ceased largely as a result of a sudden high rise in costs following the implementation of the Spanish Coastal Law, rather than as a consequence of any specific environmental impacts. In the 1990s, maintenance dredging and straightening of the channel were undertaken to improve navigation for vessels including Spanish and Portugese ferries. This caused significant environmental

Table 5 Existing management plans and present management practices

Delta region	Management plans	Current practices
Danube delta	• Danube River Basin District Management Plan • Danube Delta Regional Master Plan • Integrated Management Plan for the Reserve	• Dredging sediment into reservoirs • Dredging navigation canal and river mouth • Construction of parallel dykes in the Sulina arm • Material dug used for beach nourishment and protection
Ebro delta	• Hydrologic Plan of the Ebro River Basin • Ebro Delta Master Plan • Integral Plan for the Protection of the Ebro Delta	• Maintenance works of the navigational channel • Decontamination works into the Flix reservoir
Vistula delta	• Programme for the Zulawy region till 2030-Complex flood protection	• Sediment deposition monitoring • Dredging river mouth • Creation of artificial island • Ice clear works • Water pumping in polder areas
Elbe estuary	• TIDE project • Integrated Management Plan Elbe estuary (Natura 2000)	• Treatment of contaminated sediment (METHA-Plant) • Dredging port and waterways • Relocation of the sediment dredged in appropriated places • Treated sediment placed on special disposal sites
Minho estuary	• Hydrologic Plan of the Minho-Sil River Basin (Spanish part) • Hydrologic Plan of the Minho Basin (Portuguese part) • General Plan for flood protection	• Dredging navigation canal (stopped in 2007)
Severn estuary	• Flood Risk Management Strategy for the Severn estuary (to be approved) • Shoreline Management Plan Review (non statutory document)	• Dredging navigational channel and ports • Flood forecasting and warning systems

impacts to which there was considerable opposition from environmental groups and fishermen. At the time, such concerns were not heeded (Gallego 2005) and, although the dredging was expensive (about 2.3×10^6 € per year), selling the dredged sand partly compensated for the economic losses. In 2007, however, the Spanish Coastal Law forbade the sale of aggregates, leading to the cessation of these activities on purely economic grounds. In the Ebro Delta, there is no sediment management plan and currently port and navigation channel maintenance merely follow non-statutory, national guidance; 'Guidelines for the performance and disposal of dredging materials in Spanish ports' (Centro de Estudios y Experimentación de Obras Publicas (CEDEX) 1994). This establishes a classification for dredged sediment based on the natural characteristics (physical and chemical) and degree of contamination of the sediment.

4.2 Sediment contamination

In the Danube Delta, the Danube Basin District Management Plan (DRBM) provides a series of recommendations to address sediment contamination. These include the establishment of environmental quality standards for sediment and suspended particulate matter (SPM). Investigations into heavy metal contamination of sediments and SPM, focusing on fine suspended sediment and potential impact on aquatic communities, are also included (International Commission for the Protection of the Danube River (ICPDR) 2009). However, Romania does not presently apply sediment quality standards even though there is routine sediment sampling for many potential pollutants (RIZA International Water Assessment Centre 2001). For classification purposes Dutch, Belgian or Canadian standards are used (RIZA International Water Assessment Centre 2001). Overall, the Danube shows evidence of improving water quality and contains significant natural populations of flora and fauna, typical for such a large river (International Commission for the Protection of the Danube River (ICPDR) 2009). A number of important chemical and biological parameters have improved since 2001 (International Commission for the Protection of the Danube River (ICPDR) 2002). In addition, the first systematic survey of the river's hydromorphology has identified large areas in good natural condition. However, whilst nutrient loads into the basin have significantly decreased over the past two decades, they remain well above 1995 levels. There is also concern that future reduction of nutrient pollution may not occur because of increased diffuse agricultural pollution (International Commission for the Protection of the Danube River (ICPDR) 2002). Impacts from nutrients are already evident in the Black Sea as well as in many lakes and groundwater bodies throughout the basin (International Commission for the Protection of the Danube River (ICPDR) 2005).

For the lower Ebro River, the 'Integrated Plan for the Protection of the Ebro Delta (PIPDE)' focuses on the environmental restoration of the delta and proposes, amongst other things, the decontamination of the Flix reservoir through the removal of toxic sediment. As part of this, up to 1×10^6 m^3 of contaminated river sediment are to be dredged by 2015. Ecological dredging procedures will be deployed with the sludge being treated in nearby facilities. In addition, a fully equipped laboratory has been set up to monitor the different phases and to check on the effectiveness of the decontamination activities (ACUAMED 2011).

In the Elbe Estuary, contaminated sediment, treated in the large-scale METHA-plant (MEchanical Treatment and dewatering of HArbour sediments) (Netzband et al. 2002), is either sent to one of two disposal sites (Francop and Feldhole) or is used for other purposes. These include its use as (1) sealing material for disposal site construction or harbour backfilling, (2) construction material, (3) raw material or additive in industry, and in the field of the production of (4) ceramic products and (5) light-weight aggregates. Currently, the use of treated dredged material in dike construction is also being investigated (Detzner and Knies 2003).

There is no sediment contamination and monitoring programme specific to the Severn Estuary (Marine Biological Association (MBA) 2003) although previous surveys by the Environment Agency (in autumn/winter 2004) and the Marine Biological Association, particularly in the 1970s and 1980s, have provided an overview of contamination levels in the region. Currently, there are no environmental quality standards for sediments applicable in the UK, although certain EU Directives contain standstill provisions (i.e., concentrations in sediments should not increase) (Severn Estuary Partnership (SEP) 2011). In the absence of standards, interim guidelines adopted by Environment Canada (Canadian Council of Minister for the Environment (CCME) 1999) provide an indication of the risk to biota from sediment-associated contaminants and identify instances where efforts are needed to minimise inputs of substances (Marine Biological Association (MBA) 2003). Overall, there is a need to understand the system better, particularly metal release during sediment re-suspension events (Langston et al. 2010).

In both the Minho and Vistula estuaries, there is no sediment contamination since both, according to national standards, are considered unpolluted (Dmitruk et al. 2008; Reis et al. 2009). Nevertheless, Mil-Homens et al. (2010) suggest that regular sediment monitoring and associated chemical analysis should be undertaken in the former, particularly given increasing anthropogenic pressures. The authors also recommend ecotoxicity testing to assess potential adverse impacts on biological organisms.

In general, for all the estuaries and deltas, there is a lack of environmental quality standards for both sediments and SPM. Only in the Elbe River does contaminated sediment get treated for re-use. In addition, monitoring programmes, including regular sediment sampling and chemical analysis, are not widely established. There is also a need for a sediment inventory of metals at each site to account for metal release during sediment re-suspension events. Scientific investigations into pollution of fine suspended sediments are also required to study both their absorption capacity and their potential impact on aquatic communities.

4.3 Flood risk

In the Danube Delta, the 'Integrated Management Plan for the Danube Reserve' (1991) was devised to provide guidelines for key economic sectors (e.g., forestry, agriculture, fisheries, tourism) as well as suggesting practical conservation actions for individual agencies. Most projects within this plan ceased with Decree No. 103 (Official Publication of Romania 1990), 'Decree concerning the abolition of the reclamation works in the Danube Delta'. However, the Decree did allow the completion and maintenance of 'strictly necessary works,' including flood defences, limited river regulation and selected coastal protection works. Navigation management and bank protection of the Sulina Branch and maintenance of existing reclamation schemes were also permitted (Carauscu 1990; Official Publication of Romania 1990).

In 2006, the 'Danube Delta Regional Master Plan' was established to provide a holistic approach for the area. This considered relationships between socio-economic and natural aspects and involved a wide range of agencies and stakeholders. The plan defined a variety of management measures for specific locations, including development priorities, environmental measures and natural risk management tools. In addition, a strategic plan for the ecological rehabilitation of the delta (period 2005–2015) outlined further measures and actions to mitigate and minimise key problems. These included (1) renewal of the channel network to improve water circulation, (2) restoration and improvement of degraded areas and (3) restoration of selected agricultural zones and fishponds. Currently, there are several additional, on-going environmental restoration projects relating to the delta plain (International Commission for the Protection of the Danube River (ICPDR) 2009).

In the Ebro Delta, the organisation in charge of water management and planning for the whole river basin, Confederación Hidrográfica del Ebro (CHE), has recently developed a new water management plan (Plan Hidrológico de la Cuenca del Ebro; PHCE). Whilst this focuses on the development of hydraulic infrastructure and water quality control, it also complies with the requirements of the EU Water Framework Directive (WFD: 2000/60/EC), in that an environmental flow regime as well as a programme of measures to improve ecological quality have been outlined. However, the Spanish Government did not define the environmental flow regime until after the amount of water required to meet the socio-economic demands of the region had been determined. Since economic and social values prevail, the present operation of the Riba-Roja and Mequinensa dams takes little account of hydro-morphological and ecological needs. Instead, discharges, associated with hydropower production and water demand (notably from irrigation), remain the main drivers of the hydrology of the lower Ebro River (Ibáñez et al. 1996).

The Catalan Water Authority (ACA), which has some competences in the lower Ebro River and delta, has elaborated several proposals for the area's management. These include definition of a new environmental flow regime to comply with the WFD, measures to restore and improve the riverbed morphology, sediment management actions, measures to restore lateral and longitudinal river connectivity as well as other actions for preventing and controlling flood risk. As legal responsibility for water and sediment management remains with CHE, most proposals have not yet started. In addition, the Catalan Water Authority carried out a flood risk investigation of the lower Ebro River and its delta in 2009, the results of which have been included as an annex to the new water management plan for the Ebro basin (PHCE). This study identified potential flood areas associated with flood events of different magnitude and frequency (e.g., 10, 50, 100 and 500 years return period).

In the Vistula Delta, the Ministry of the Environment and the Regional Water Management Board in Gdansk (RZGW) has responsibilities for water management. This body formulated the 'Programme for the Zulawy region till 2030 (first stage till 2015) - Complex flood protection', previously mentioned. This programme aims to increase the effectiveness of the flood control and protection, and, thus, help achieve sustainable development of the delta. As a component of the Operational Program of Infrastructure and Environment (2009–2015), the main tasks will assist with the reconstruction and modernization of delta infrastructure. These include (1) renovation and lengthening of breakwaters at the river mouth, (2) modernization of about 400 km of flood protection dikes, (3) reconstruction of about 60 drainage pump stations and (4) reconstruction of about 260 km of the river bed and 600 km of drainage channels (Regional Water Management Board in Gdansk (RWMB) 2008).

The Minho River basin is managed by the Hydrographic Demarcation Miño-Sil (HDMS) and the Portuguese Administration of the Northern Hydrographic Region. The former is responsible for the Spanish area (95 % of the catchment) and the latter has responsibility for the Portuguese part. Each institution has developed its own management plan, to be approved in 2013. Nevertheless, HDMS still intends to produce a joint plan in collaboration with its Portuguese counterpart to help align policies and actions. Meanwhile, whilst HDMS has developed a management plan addressing flood prevention, this currently does not contain any specific actions related to the Minho Estuary.

The Environment Agency (EA) is developing a 'Flood Risk Management Strategy for the Severn' which aims to manage tidal flood risk in the region. The strategy also aims to define a 100-year plan of investment for flood defences by the EA and local authorities, to prioritise other flood risk management measures. It should also provide advice to help protect critical infrastructure, inform development control and flood warning investment. It will also facilitate more informed decision making about the creation of new compensatory inter-tidal habitats, needed because of habitat loss caused by rising sea level (Environment Agency 2011). The EA also produces flood warnings for both river and sea flooding to help emergency services, operating authorities and individuals to take measures to lessen the impact of flooding. A national Storm Tide Forecasting Service, operated by the Meteorological Office, informs this, together with meteorological forecasts and information from a network of tide level gauges. In addition, a comprehensive 'Shoreline Management Plan Review' (SMP2) process has been undertaken specifically for the Severn Estuary. This non-statutory plan advises on shoreline change and management over the next 100 years, but has yet to be signed-off by relevant Government departments. The SMP2 is important, guiding management of coastal flooding and erosion by local and national governments as well as other regulators and managers, including the EA and Natural Resources Wales (NRW). The draft SMP2 has also informed the development of the EAs flood risk plan, mentioned above.

Across all the areas studied, there are plans for flood protection, which recognise and address the expected effects of global warning. These are, however, all at different stages of development and implementation. They are also being designed and implemented with varying degrees of awareness. In general, there is increasing recognition that integrated plans may help achieve sustainability of these systems, enabling social and economic demands to become aligned with ecological and morphological needs. This has led to a range of new measures being put forward to minimise the effects of floods and sea level rise. These include, for example, the restoration of delta wetlands and river lateral connectivity, as well as the creation of specially designated flood areas to attenuate floods and store water. However, in some systems, large infrastructure projects are still being planned which are inconsistent with the integrated management plans or sustainable development. This includes the 170-km deep-water canal in the Danube Delta, to connect the Danube River to the Black Sea. Here, there are concerns that this may influence the drainage of the delta and its marshes as well as reduce water levels and quality (Duțu 2004; Staras 2005). There are similar fears over the potential environmental impacts of a planned new reservoir at Nieszawa, below the Włocławek dam on the Vistula River. This scheme, which does not appear economically justified, is unlikely to reduce flood risk and may even destroy some unique river habitats of international importance (Konečný and Słodczyk 2008). Not only does a Natura 2000 site extend across the entire area of the planned reservoir, but the dam's construction would also threaten three additional Natura 2000 sites. Konečný and Słodczyk (2008) suggest that the dam is politically driven. Certainly, there are other options, such as the decommissioning or modernization of the Włocławek dam, which may be preferable (Konečný and Słodczyk 2008), not only from an environmental but also from a social and economic perspective. This option is also seven times cheaper than a dam. The latter would also need at least 30 % co-financing by the State to become feasible for commercial investors (Kowalczewski 2001).

Since the nineteenth century, there have been many suggestions for creating a barrage across the Severn Estuary (and Bristol Channel). Most of these have focused on tidal power generation. However, to date, these have all been rejected by the British Government. The recent Severn Tidal Power Feasibility Study (2008–10) concluded there was no strategic or financial case for a barrage but noted that investigation of emerging technologies should be continued. Since then, a private consortium, Hafren Power, has developed a recent proposal for a barrage from Lavernock Point to Brean Down with external, private, overseas financial support (BBC News 2011). Nevertheless, a Government Select Committee rejected this proposal in 2013. Environmental impacts from such a scheme are wide and difficult to predict, particularly given the dynamic nature and complexity of the estuary. Impacts include reduction of the estuary's tidal range, as well as implications for the famous Severn bore and intertidal areas, and the feeding grounds of over-wintering wildfowl, designated under Natura 2000. Given the significant uncertainties and the wide range of users, all proposals to date have been highly contentious and have provoked significant debate (Ginige et al. 2011).

Across all the sites, major engineering/infrastructure projects are hindered not only by their huge costs but also by extensive social opposition, often related to the complexity and uncertainty of impacts. Not all the schemes seem to be designed with the principle of sustainable development in mind. As a result, it is suggested here that decisions related to such proposals—which involve complex trade-offs and multiple 'winners' and 'losers'—must be undertaken using objective and holistic environmental decision-making tools, such as Environmental Impact Assessment. Such tools, however, must be informed by best science and monitoring.

5 Towards integrated management of water and sediment

Over the last few decades, and especially following the implementation of the EU Water Framework Directive (WFD: 2000/60/EC), awareness of the problems of European rivers and deltas has increased. Gradually, this has been translated into the development and implementation of integrated management plans in an attempt to achieve the sustainability of these sensitive areas. However, the experiences of the DELTANET partners suggest that the implementation of key directives, notably the WFD and the Flood Directive (2007/60/EC), is being carried out to different levels and under contrasting philosophies. In the Elbe and Severn estuaries, directives appear to be well implemented within the context of a sustainable, holistic vision for the respective areas. In the case of the Elbe, the approach goes well beyond strict compliance as new tools, approaches and ideas are developed. In both cases, the application of directives has led to an increase in collaboration between agencies and stakeholders. In contrast, in the Minho and Ebro, directives are poorly implemented without a holistic vision, and with little collaboration between governmental agencies and stakeholders, with socio-economic interests prevailing over environmental needs. Finally, in the Vistula and the Danube, our results suggest that the implementation of EU directives is different again. Here, the directives seem to be viewed as an opportunity to promote sustainability. Alongside this, these regions have begun to realise that collaboration of governmental agencies and stakeholders is needed in order to achieve the equilibrium between socio-economic and environmental needs, a pre-requisite for sustainability.

Overall, there is still a need to improve water and sediment management of these systems further. In general, the management plans do not focus sufficiently on the 'origin' of problems, leading to impacts not being properly managed or mitigated. For instance, sediment management focuses on maintenance works and there are few specific sediment quality monitoring programmes. Consequently, new integrated approaches—identifying and dealing with the source of problems—need to be developed. These will have to challenge the economic, environmental and technically sustainability of traditional, classical engineering approaches and should include the development of new tools, methodologies and policies to stem further deterioration.

Accordingly, the DELTANET network has provided the following general recommendations, as well as more specific ones, addressing concerns related to sediment deficit and accretion, sediment contamination and flood risk.

5.1 General recommendations

- Authorities responsible for river basins extending across different administrative areas or states should urge the cooperation of relevant national and international agencies to come together to develop and implement appropriate management plans. At this scale, joint methods and strategies should be developed which link to the EU WFD as well as national and trans-boundary pilot projects.
- National and international networks should be created and consolidated to improve the effectiveness of regional development policies in delta and estuary regions. It is suggested that interregional cooperation, alongside the development of appropriate coordinated spatial planning measures, can be achieved by exchanging experiences through such networks. These, in turn, should help improve the effectiveness of policy instruments and aid the development of common governance methodologies and tools. Working together on common challenges should provide innovative insight into how differing demands in regional policy can be balanced and how improved policy instruments may be achieved.
- Increased awareness of the need for general and specific management plans to coordinate flood risk and sediment management actions is required. This is needed as sediment imbalance in many cases can lead to increased flood risk and coastal retreat as higher sea levels, increased subsidence and sediment retention disrupt the fragile equilibrium of the deltas and estuaries.

5.2 Specific recommendations: sediment deficit and accretion

- Restore the natural continuum of the fluvial system. It is suggested that this should be achieved by designing new water and sediment flow regimes from the reservoirs within the respective catchments. Revised reservoir management models should include periodic release of water and sediments from the reservoirs in order to maintain the ecological and physical character of the deltas and estuaries.
- Restore the natural flood regime of the rivers in deltas and estuaries through the elimination of embankments or artificial levees. This also includes the creation of designated flood retention areas at strategic locations along the rivers and across the delta plains. These will help to create new habitats as well as help to reduce flood events and flood risk. As well as improving the groundwater aquifer, they may also reduce the input of organic and inorganic nutrients. Additionally, they should promote vertical accretion of the delta plain, helping compensate for delta subsidence and sea level rise. As a consequence, this should arrest coastal retreat.
- Ensure strict regulation of the amounts of sediment that can be dredged from rivers, deltas and estuaries. Whilst regular maintenance dredging within active docks, berths and power station cooling water installations is necessary to ensure the continued viability of port operations, all dredging proposals should be the subject of independent, objective, site-specific environmental studies, based on best available science. There is also a need for these to be supported by appropriate monitoring regimes. These should help eliminate potentially significant negative sediment budget issues associated with over-dredging.

5.3 Specific recommendations: sediment contamination

- Reduce water and sediment contamination in rivers, deltas and estuaries through the development and adoption of general plans to minimise local and diffuse sources of pollution. The implementation of new technologies, the creation of sewage treatment plants and the enactment of more stringent legislation regarding the use of certain physicochemical substances in agriculture and industry are further actions to be considered.
- Implement monitoring programmes to improve the knowledge and understanding of the effectiveness of management policies. For instance, ecotoxicity tests could be used to assess potential adverse impacts of contamination on biota.

5.4 Specific recommendations: flood risk

- Employ new techniques in accordance with the integrated delta/estuary management approach. These could include restoration of delta/estuary wetlands, works increasing the river's lateral connectivity and the creation of specially designated flood areas.

– Avoid, wherever possible, the construction of new hydraulic infrastructure, particularly that which could unbalance the fragile equilibrium of these systems
– Reduce damage caused by floods by:

- not allowing future construction of houses and industries in present and future flood-prone areas
- adapting future developments to the risk of flooding and
- promoting appropriate land-use, agricultural and forestry practices.

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