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Challenges of river basin management: current status of, and prospects for, the River Danube from a river engineering perspective.

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Abstract

In the Danube River Basin multiple pressures affect the river system as a consequence of river engineering works, altering both the river hydrodynamics and morphodynamics. The main objective of this paper is to identify and detail the effects of hydropower development, flood protection and engineering works for navigation on the Danube and to examine specific impacts of these developments on sediment transport and river morphology. Whereas impoundments are characterised by deposition and an excess of sediment with remobilisation of fine sediments during severe floods, the remaining five free flowing sections of the Danube are experiencing river bed erosion of the order of several centimetres per year. Besides the effect of interruption of the sediment continuum, river bed degradation is caused by an increase in the sediment transport capacity following an increase in slope, a reduction of river bed width due to canalisation, prohibition of bank erosion by riprap or regressive erosion following base level lowering by flood protection measures and sediment dredging. As a consequence, the groundwater table is lowered, side arms are disconnected, instream structures are lost and habitat quality deteriorates affecting the ecological status of valuable wetland areas like National Park Donauauen downstream of Vienna. The lack of sediments, together with cutting off meanders and canalisation, leads also to erosion of the bed of main arms in the Danube Delta and coastal erosion. This paper details the causes and effects of river engineering measures and hydromorphological changes for the Upper, Middle, Lower Danube and the Danube Delta. It highlights the importance of adopting a basin-wide holistic approach to river management and demonstrates that past management in the basin has been characterised by a lack of integration. To-date insufficient attention has been paid to the wide-ranging impacts of river engineering works throughout the basin: from the basin headwaters to the Danube Delta, on the Black Sea coast. This highlights the importance of new initiatives that seek to advance knowledge exchange and knowledge transfer within the basin to reach the goal of integrated basin management.

Highlights:

- Hydropower, Navigation, Flood Protection resulted in a widely engineered Danube River
- River engineering affects significantly hydrodynamics and river morphodynamics (hydromorphology) of the Danube River
- Sediment surplus exists in impoundments and lack of sediments in free flowing sections
- River bed erosion causes technical and ecological deficits
- An improved river basin management needs an advanced knowledge exchange and transfer between environmental researchers, key stakeholders and managers

Keywords: Danube River, Hydromorphology, River Engineering, Sediment Transport, Hydropower, Navigation, Flood Risk Management, Ecology

1. Introduction

Globally rivers and their basins have been progressively impacted by human activity, as part of the wider modification of the global hydrological cycle through the Anthropocene (Vörösmarty et al., 2013). In many cases these impacts have been cumulative; associated with marked changes in river flow (Poff & Matthews, 2013), sediment (Syvitski et al., 2009), and nutrient flux (Seitzinger et al., 2006), and changes in the relationship between rivers and their basins. The latter include the loss of lateral connectivity (i.e. between river and floodplain, which negatively influences the exchange processes between various highly dynamic floodplains and the main channel; Allan, 2004, Wiens, 2002), longitudinal continuity (from the basin headwaters downstream) as well as the vertical connectivity (between channel and contiguous groundwater; Ward, 1989) through a combination of land use change and river and floodplain engineering works over past decades (time, as temporal scale; Ward, 1989). These changes have wider implications for basin hydrology, fluvial geomorphology and the conservation and management of freshwater biodiversity to the extent that it is now difficult to identify ‘pristine’ or ‘reference’ rivers against which the effects of anthropogenic change can be measured (Buise et al., 2003). Moreover, there are increasing problems in reconciling the conflicting demands placed upon river basins: in ensuring water security, providing flood protection, and enabling the development of hydropower whilst conserving associated ecosystem services, and minimizing the loss of biodiversity. Whilst these tensions are widely recognised (Vörösmarty et al., 2010) frequently the approaches to river and basin management have been reductionist in nature, given the need for river managers to adopt a pragmatic approach to advance the goal of sustainable river basin management (Newson & Large, 2006; Arthington et al., 2010).

The scale of the problems that arise in managing river basins is exemplified by the practical difficulties associated with maintaining, or improving, river hydromorphology. The latter is the product of the interaction between geomorphology and hydrology as they vary spatially and temporally through the basin (Vaughan et al., 2009; Habersack et al., 2013; Gurnell et al., 2015). As such hydromorphology integrates channel geomorphology with the flow regime and characterises the relationship between variations in river depth and width, and river morphology, at different levels: from river bed structure and substrate at individual reach scales, to the wider structure and form of the riparian zone as it varies through the basin. A major challenge, however, lies in identifying those processes that are responsible for changes in river hydrodynamics, as well as the morphodynamics, of a river, given possible confounding effects, such as pollution (Vaughan, et al., 2009), changes in river regime, and in patterns of water abstraction and use through the basin.

The problems are compounded by the extent to which these challenges are scale-dependent. Brierley et al. (2013) note the importance of placing the short-term (and local) problem of relating process-to-form at a particle, bedform and reach scale, in a wider context of the long-term complexities and uncertainties of basin-scale behaviour. This emphasis on landscape connectivity reinforces earlier work on the need to view streams within their basin context (Frissell et al., 1986), characterised by downstream changes in the predominance of individual process domains (Montgomery, 1999). Yet while natural or pristine rivers may self-regulate, being free to aggrade or degrade vertically, and/or to move laterally, most rivers are laterally confined to varying degrees, their flows regulated by impoundments and abstraction. This has implications for the degree to which managed rivers are able to continue to self-regulate and adjust to changing boundary conditions whilst also providing essential ecosystem services in the context of cumulative (and progressive) changes in their basins (Hauer et al., 2014; Gurnell et al., 2015; Blamauer et al., 2015). Such concerns are particularly important in ‘large river basins’ which can exhibit complex and dynamic interactions and occasional non-linear behaviour with varying resilience to external pressures, and are often characterised by high levels of uncertainty.

Within this wider context, a number of approaches have sought to advance the goal of integrated basin management by reconciling differing perspectives of river management (Hering et al., 2010). In Europe, the European Water Framework Directive 2000/60/EC (WFD) has been developed to form a new legal basis for water management. It offers a legal framework to protect and restore water bodies across Europe. It advocates water management within drainage basins, setting Member States specific deadlines to protect aquatic ecosystems and assuring the good ecological and chemical status of water bodies. The WFD specifically emphasises the importance of maintaining, or improving, the hydromorphology of a river, given its ecological significance and the degree to which the hydromorphology depends upon river process dynamics at different scales. However, this priority must be balanced against the importance of ensuring continued protection from flooding (covered by the Floods Directive 2007/60/EC); maintaining, or developing, navigation potential and allowing the sustainable development of hydropower. Clearly there are a number of contradictions here: notably in protecting the water environment whilst ensuring appropriate basin water use. These are acknowledged by the WFD, in advocating a focus on the drainage basin, and the problems are particularly significant for ‘large’ rivers and basins, and hence some water bodies can be designated ‘Heavily Modified Water Bodies’ (HMWB). While designation as a HMWB places constraints based on certain uses, still the principle of no-deterioration applies.

The Danube is the most international river basin globally, spanning 19 countries, and arguably it is one of the most complex basins in which the WFD and other EU directives have to be implemented. However, in 1994 the Danube River Protection Convention which established the International Commission for the Protection of the Danube River (ICPDR) was signed by 14 countries within the basin (each with >2,000 km² in the basin). The ICPDR provides the organisational structure that is a pre-requisite to resolving the conflicting pressures of protecting the water environment whilst enabling continued, sustainable, water use within the basin. Our aim in this paper is to build upon recent Danube basin overviews (e.g. Sommerwerk et al., 2009) to consider the scale of the challenges that confront river managers in the Danube Basin, and the need for a tool for knowledge exchange to advance sustainable river basin management. Thus, in this paper we explore current challenges in the integrated management of the Danube River Basin (DRB). We do this by describing and identifying: (1) pressures due to river engineering; (2) hydromorphological implications of engineering works; and (3) case studies of the current status of the Danube River. Whilst important in the context of the DRB itself, this work has wider implications for other transboundary rivers in Europe and globally. Moreover, while outside the scope of this paper, it is also important to acknowledge the impact of changes in the hydrology of the Danube River on coastal and marine systems downstream, as discussed elsewhere (e.g. ETC/ICM, 2012; ICPDR, 2004; Stanica et al., 2007; Vaughan et al., 2009).

2. The River Danube and the Danube River Basin

The Danube River Basin extends over 807,827 km^2 in Central and South-Eastern Europe. The Danube is 2,857 km long and flows in an easterly direction from the Black Forest Mountains to the Black Sea where its mean annual discharge is 6,486 m^3/s (~ 205 km^3/a) (Tockner et al., 2009; Kresser, 1973). As such, the river is the 21st largest river globally, and the second largest river in Europe (ICPDR, 2015). The 'natural' regime of the river varies seasonally and through the basin, reflecting the distribution of precipitation which varies from >3,000 mm annually in the West to <500 mm in the centre and east of the basin. The basin is spatially heterogeneous: one third of the basin is mountainous and the mean altitude of the basin is ~450 m asl, extending from Piz Bernina (4,052 m asl) in the West, and Peak Krivan (2,496 m asl) in the North to the Black Sea. Along its course, the Danube flows through a series of alternating basins and gorges: below the confluence of the Danube and the Morava, the river enters the Devin Gate, below which the Danube forms an internal delta as it starts to traverse the Pannonian Plain. Here the flow of the 'Middle' Danube is augmented by the Drava, the Tisza, and the Sava rivers: tributaries that rise in the Southern Alps, the Western Carpathians, and the Julian Alps respectively, highlighting the degree to which the Danube is dependent upon flow generated in alpine areas. Downstream the Danube flows through the 117 km long Iron Gate located in the Southern Carpathians. Below the Iron Gate, the 'Lower' Danube crosses the Romanian and Bulgarian lowlands before the river bifurcates into three channels as it flows through the Danube Delta and ultimately discharges into the Black Sea.

In this paper, in common with recent reviews of the DRB, we differentiate between four river sections of the Danube River that differ substantially in their character (Figure 1). Whereas the **Upper Danube,** with a length of 624 km, is characterised as a gravel bed river, downstream the Danube is a sand bed river. These changes are matched by the slope of the river which differs significantly through the basin: the mean slope of the upper reaches is 4 ‰, falling to 0.4 ‰ in the lower reaches. The **Middle Danube** (mean slope of about 0.1 ‰) is ~929 km long and surrounded by the Hungarian plain and ends in the incised Iron Gate Gorge which has a higher slope. The **Lower Danube** has a length of ~863 km and is characterised by a lower slope (0.05 to 0.01 ‰) with a substrate of fine material. Finally the **Danube Delta, Europe's largest deltaic wetland,** constitutes a separate river section; it is influenced significantly by changing sea levels, and is characterised by estuarine conditions.

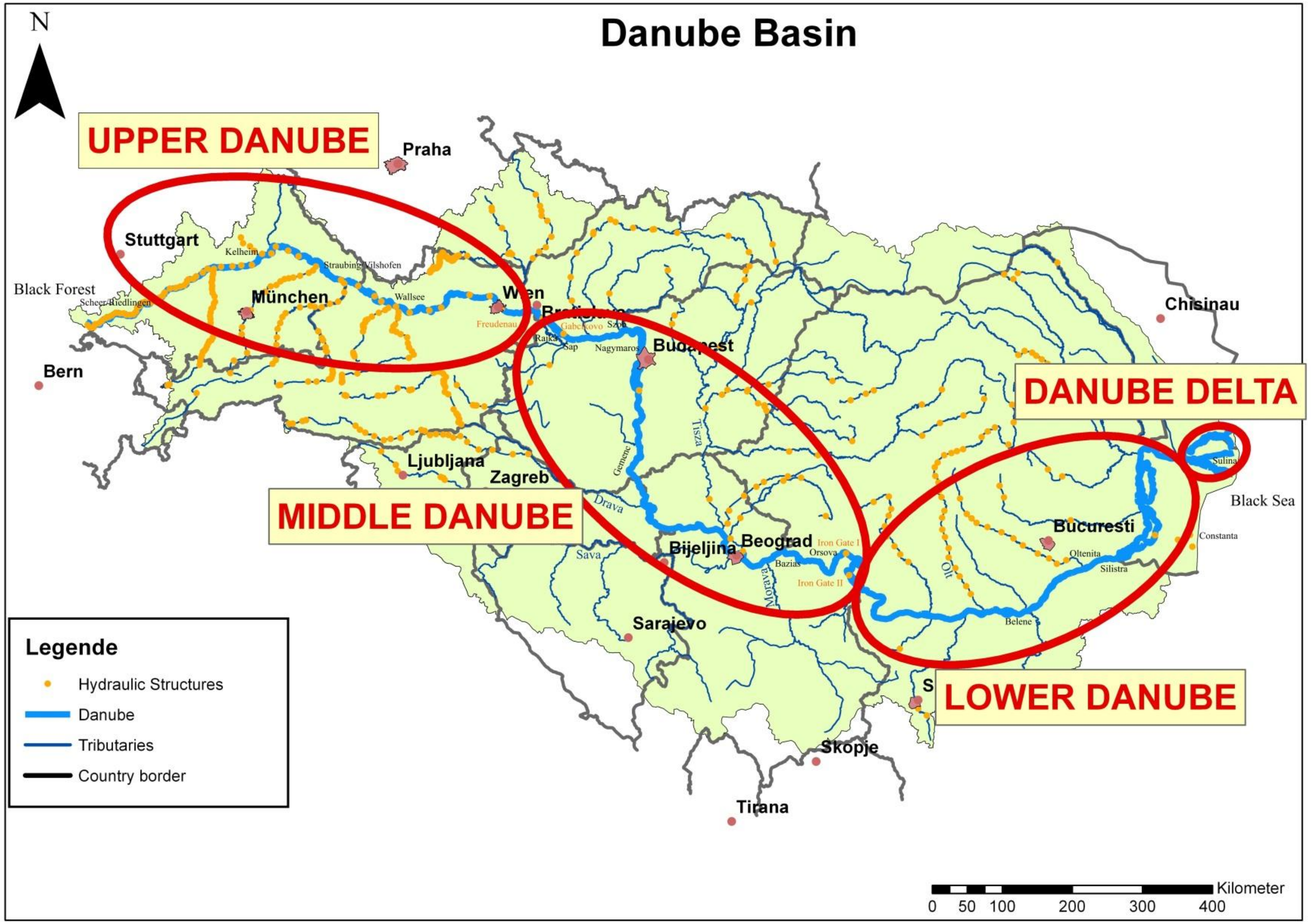

Figure 1: The Danube River Basin identifying four river sections: the Upper, Middle, and Lower Danube and the Danube Delta (base map: ICPDR)

3. River Engineering in the Danube River Basin

The River Danube and its tributaries have been progressively constrained for flood protection, navigation, and more recently for hydropower. The impacts of these developments on the river are compounded by point and diffuse pollution and the effects of land use change, such as agricultural intensification and forestry development. It has been estimated, for example, that when compared with the 19th Century, <19 % of the former floodplain remains in the entire basin: 7,845 km^2 of floodplain compared to 41,605 km^2 formerly (ICPDR, 2009). This reflects a combination of agricultural expansion, and increasing disconnection of river and floodplain due to engineering works along the river and floodplain.

3.1 Hydropower

At present, in most countries in the DRB (with the exception of Germany, Hungary and Moldavia) hydropower represents the most important component of renewable energy production, contributing > 45 % of the total (ICPDR 2013b). Looking at the Danube from a basin-wide perspective, hydropower plants are widely, but unevenly, distributed and have modified the river course and floodplain connectivity considerably (Figure 2). One consequence of this is that there are currently 78 barriers along the Danube and its principal tributaries, mainly situated at points of greatest change in slope (Figure 3). The largest hydropower scheme, at the Iron Gate, has been developed at a spot where there is a step change in altitude as a consequence of the geological development of the basin. The hydropower plants of Iron Gate I and II together have an installed capacity of ~2,840 MW, while situated progressively upstream are Gabčíkovo (720 MW) and Freudenau (172 MW). In Austria an additional chain of ten hydropower plants in the main stem of the river, has a total generating capacity of ~2,200 MW. The distribution of hydropower plants reflects hydrological and geomorphological differences in the DRB as well as the recent political and economical development of countries within the basin (Figure 2). Hydropower plants with >100 MW account for 50 % to > 80 % of total installed capacity in Austria, Bosnia-Herzegovina, Serbia, Slovakia, and Romania (ICPDR, 2013b). In contrast, plants with < 1 MW installed capacity only contribute a small share of the total installed hydropower capacity (<10 % for Austria, Germany, Croatia, Bosnia-Herzegovina, Moldavia, Romania, Serbia, Slovakia, and Ukraine).

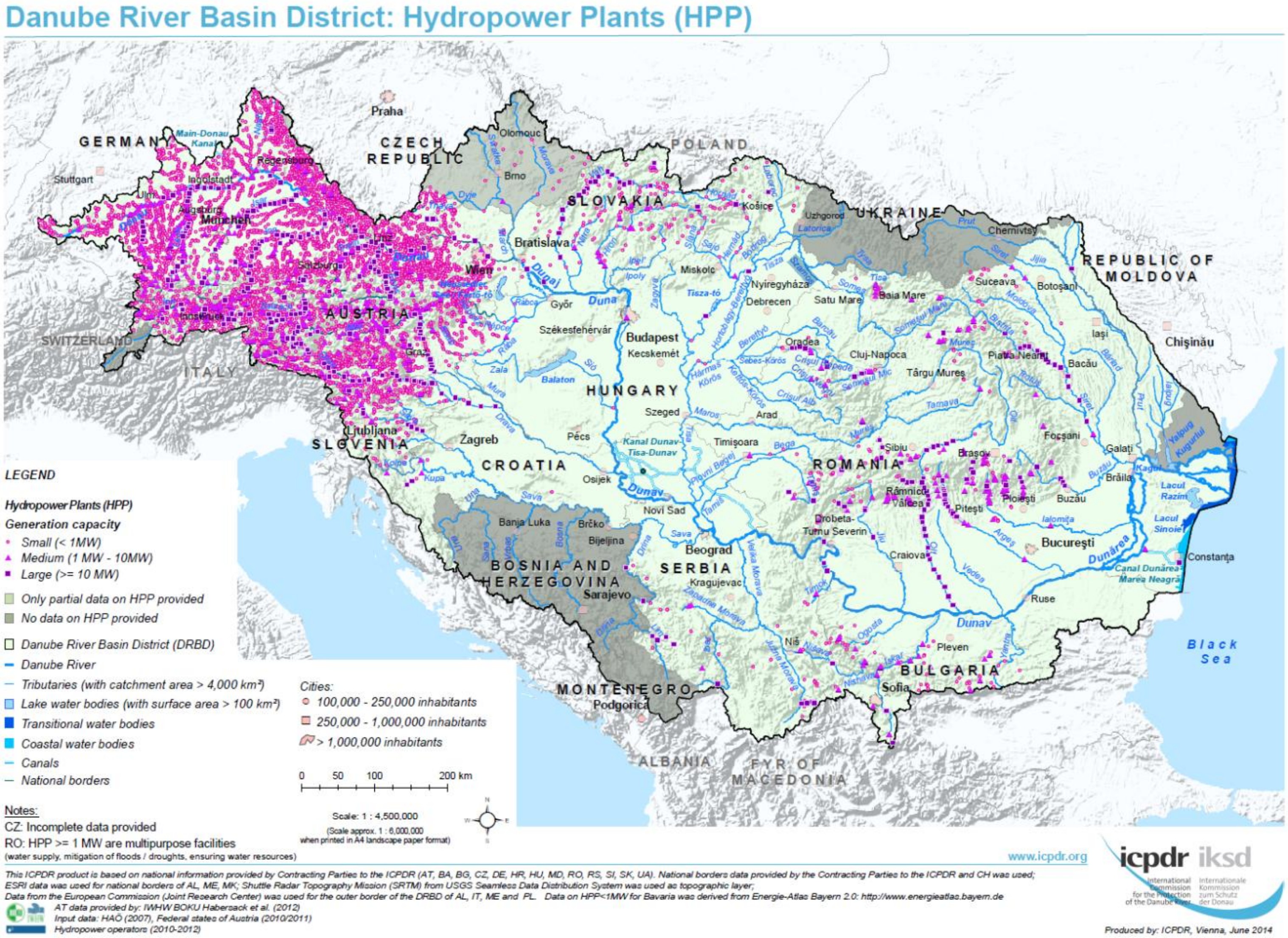

Figure 2: Distribution of hydropower plants in the Danube River Basin (ICPDR, 2013b)

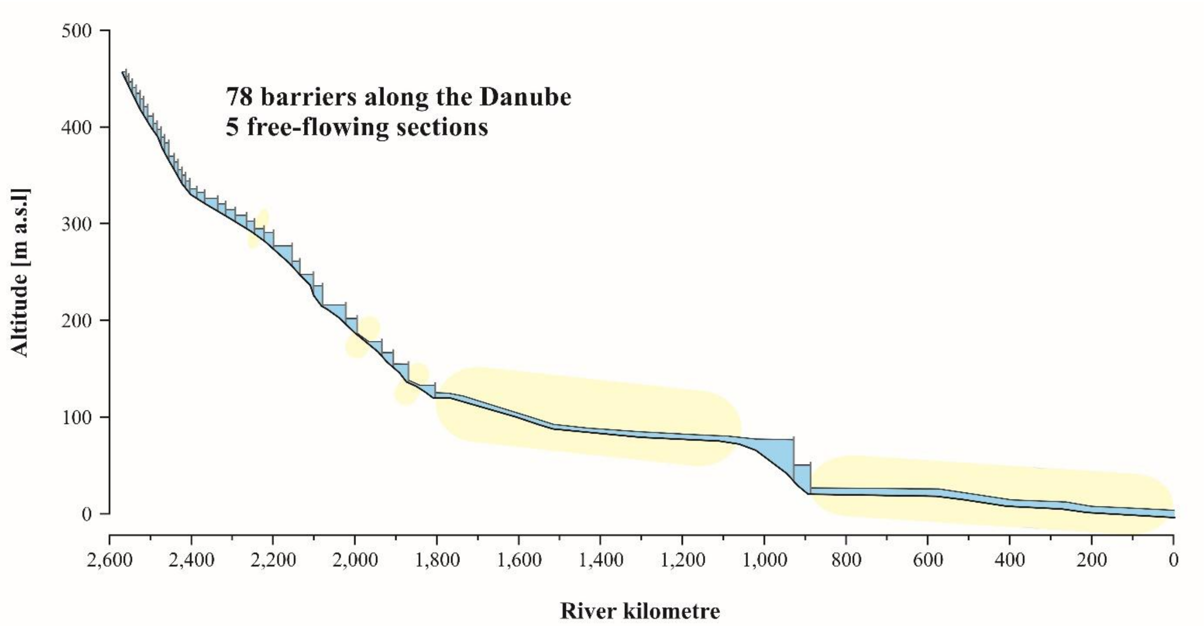

Figure 3: Longitudinal section of the Danube River, showing impoundments and free flowing sections (modified after Habersack et al., 2013)

An important consequence of the distribution of hydropower plants along the Danube is that the river is now split into many impounded reaches and only five free flowing river reaches remain. The longest free flowing reach extends from the mouth of the Danube in Romania to the Iron Gate hydropower plants. The second largest free flowing reach is situated mainly in the Hungarian Plain. In Austria two free flowing reaches remain: one of 48 km between Vienna and Bratislava and the second in the Wachau area. In Germany the last free flowing reach is found between Straubing and Vilshofen. These free flowing reaches also happen to be those reaches where navigation bottlenecks exist due to insufficient water depth (Habersack et al., 2013).

3.2 Flood Protection

With respect to flood protection, the upper reaches of the Danube, and large parts of the Middle Danube (principally in Hungary) are protected against floods with a recurrence interval of up to 1 in 100 years (Danube FloodRisk, 2013). This has reduced the length of the river and entailed widespread construction of levees and disconnection of the floodplain and river side-arms. Specifically as a result of measures for flood protection, the Danube has been shortened in length considerably (Bavarian Danube by 21 %; the Hungarian Danube by ~12 %; WWF, 2002), river width has decreased, and the resulting increase in shear stress has led to bed degradation. Currently, new flood management plans are being prepared for the Lower Danube. However, with respect to flood protection measures, the Lower Danube appears to be in a moderate state, as the river bed is not regulated, although flood levees/dikes (to protect against the 1 in 100 year flood) were constructed in Romania in the 1960s, inundation of the Danube Delta was possible (Habersack et al., 2010). While new management plans allow inundation of some areas of floodplain, the former flood protection scheme remains along a significant proportion of the river. The Flood Risk Management Plan for the DRB is based upon the EU Floods Directive and details appropriate objectives for flood risk management at the level of the international river basin district which covers the whole Danube basin (Figure 4, ICPDR, 2014).

Figure 4: Flood hazard and flooding scenarios in the Danube basin (ICPDR, 2014)

3.3 Navigation

The effects of flood protection and hydropower on the DRB are compounded by works to facilitate navigation and to connect Central Europe with the Black Sea region. There is a long history of navigation on the Danube: in 1845 construction of the ‘Ludwig-Main-Danube-Canal’ linked the basins of the Danube and Rhine and the European Commission for the Danube, established in 1856, coordinated engineering works to cut the Sulina arm of the Danube. Improvements in navigation from the Black Sea through the Danube Delta in the 19th Century enabled marine vessels to navigate ~120 km of the Lower Danube (Panin, 1998), and the introduction of steam navigation in 1830 led to increasing river canalisation and dredging, particularly in the lower reaches of the basin. Subsequently, from 1850 to 1900, implementation of ‘low water regulations’ for waterway transport led to increased erosion and sediment transport and ultimately to river bed incision. At present, the extent of navigation infrastructure generally decreases from the upper to the lower reaches of the Danube before becoming more numerous again in the Delta near the Black Sea (Habersack et al., 2013). Currently, the Danube is navigable for 2,414 km from Sulina in Romania to Kelheim in Germany. The annual transport in 2010 was 43×10^6 tons over a mean distance of ~600 km (via donau, 2013).

At present, there is a strong economic interest to increase navigation on the Danube, however, in a number of reaches the hydrological and hydro-morphological characteristics of the river significantly constrain the river’s navigation potential. For example, the EUSDR PA1A (2014; EU Strategy for the Danube Region; Improve mobility – Inland waterway) identifies critical locations through the basin which are a high priority for maintenance, including areas with lateral sedimentation and bars which extend over the entire width of the navigational channel (the bottlenecks are predominantly located within Natura 2000 areas). Consequently, a number of places have been highlighted where ongoing dredging, or other engineering measures, are required to release the pressures on navigation (EUSDR PA1A, 2014), but this would also have implications for the hydro- and morphodynamics and ecology of the river.

The hydrological and hydro-morphological characteristics of the Danube, in association with river engineering interventions, determine the nautical situation on the waterway (EUSDR PA1A, 2014). The nautical characteristics of various river reaches along the Danube, which are a boundary condition for navigation, are summarised in Table 1. Figure 5 depicts the maximum possible dimensions of vessels and convoys on the Danube waterway from Kelheim in Germany to the Black Sea related to waterway classes as defined by the UNECE (via donau, 2013).

Table 1: Nautical characteristics of the different Danube sections (Source: via donau, Danube Commission; Danube_FRMMP 2014)

	Upper Danube	Middle Danube	Lower Danube/ Danube Delta
Length of section	624 km	928.53 km	862.8 km
River - km	2,414.72 - 1,791.33	1,791.33 - 862.8	862.8 - 0,00
Mean gradient per km	ca. 37 cm	ca. 8 cm	ca. 4 cm
Height of fall	ca. 232 m	ca. 68 m	ca. 39 m
Upstream travel speed of vessels	9 -13 km h^{-1}	9 -13 km h^{-1}	11 - 15 km h^{-1}
Downstream travel speed of vessels	16 - 18 km h^{-1}	18 - 20 km h^{-1}	18 - 20 km h^{-1}

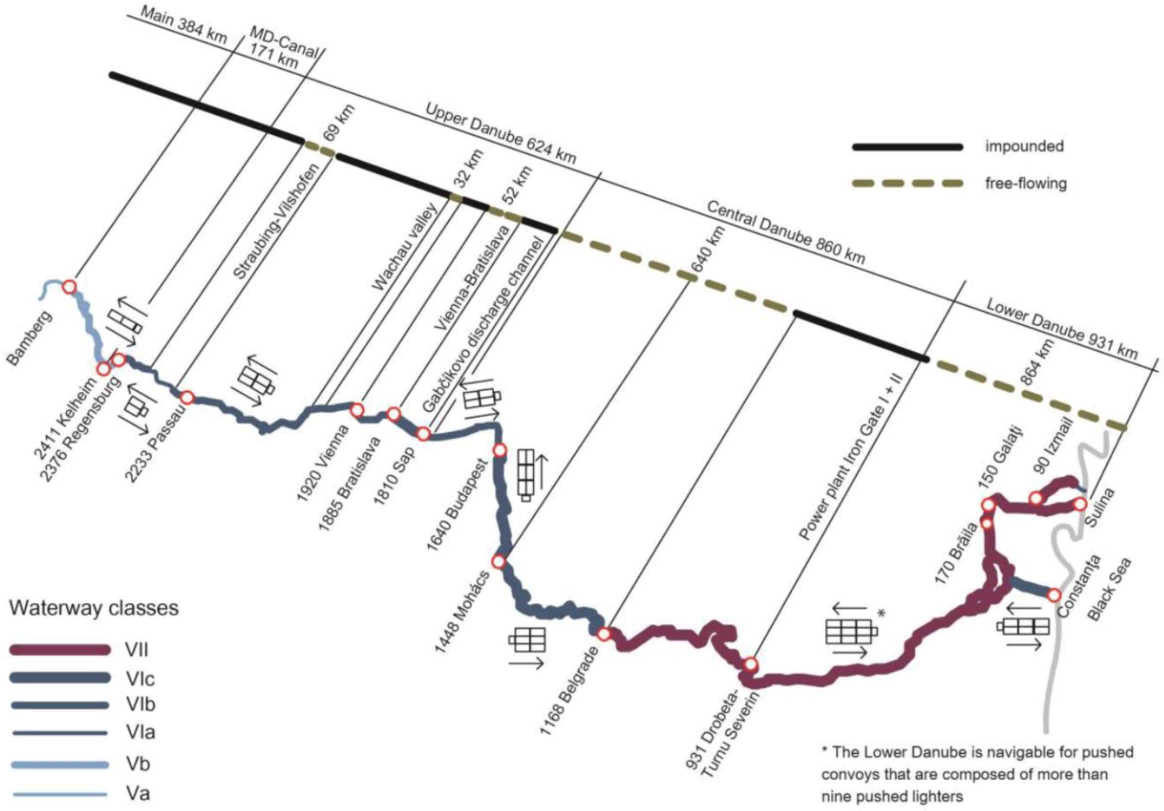

Figure 5: Maximum possible dimensions of convoys on the Danube waterway according to UNECE waterway classes; I 250–400 t; II 400–650 t; III 650–1,000 t; IV 1,000–1,500 t; Va 1,500–3,000 t; Vb 3,200–6,000 t; Via 3,200–6,000 t; VIb 6,400–12,000 t; VIc 9,600–18,000 t; VII 14,500–27,000 t (Source: via donau)

Notwithstanding the provisions of the ‘European Agreement on Main Inland Waterways of International Importance’ (AGN) and the ‘Recommendations on Minimum Requirements for Standard Fairway Parameters, Hydrotechnical and Other Improvements on the Danube’ published by the Danube Commission, the waterway management experts represented in the Network of Danube Waterway Administrations (NEWADA) recommended different minimum Levels of Service for the different phases in the waterway maintenance cycle. For example, the recommended minimum Level of Service related to fairway depth is defined as 2.50 m at Low Navigable Water Level (EUSDR PA1A, 2014). However, through the basin, a number of critical sectors for navigation have been identified on the Danube and its tributaries (EUSDR PA1A, 2014).

4. Impacts of engineering works on hydromorphological processes

It should be emphasised that most existing influences on river hydro- and morphodynamics are the result of multiple and often overlapping impacts, arising (in the DRB) from a combination of navigation, flood protection, and hydropower generation. The impacts of these are evident throughout the DRB and exhibit clear spatial trends: typically upper reaches are characterized by good water quality but with a highly regulated flow regime, whilst lower reaches generally have been modified less, but often the water quality is poor. Currently ~90 % of the reaches of the Upper Danube are impounded with implications for the river sections downstream. As noted above, one consequence is that only five significant free flowing sections of the Danube remain. Moreover, throughout the basin the Danube has been affected by (i) **hydrological and hydraulic changes**, such as increased and static water levels upstream of impoundments, while effects of river canalisation include accelerated flood wave passage, increased river bed slope, flow velocity, shear stress, loss of lateral hydrological connectivity and hence loss of floodplain storage, (ii) **changes in sediment transport**, such as interrupted bed load continuum, deposition of suspended sediment in impounded reaches, sediment deficit in free-flowing river sections, dredging (for navigation), river construction works, notably groins, leading to increased river bed erosion and sediment aggradation between groins (Technum et al., 2008), accelerated coastal erosion along the Black Sea coast in recent years, (iii) **modification of river morphology**, including a loss of longitudinal and lateral connectivity with changes in channel geometry, deterioration in river morphology at varying scales with a reduced river length and width, fixed river bed and banks, separation of side-arms and floodplains from the main channel, absence of lateral erosion and fine sediment aggradation in parts of the floodplain, (iv) **ecological and environmental degradation**, including reduced vertical connectivity to the groundwater, clogging of the hyporheic interstices leading to reduced oxygen availability in sediments, changes in macroinvertebrates and fish composition, loss of spawning grounds and zones for larval fish and degradation of riparian zones affecting algal communities, invertebrates and fish, loss of continuity for fish migration, significant loss of aquatic and semi-aquatic habitats along river margins (e.g. Petkovska & Urbanic, 2015).

These environmental implications are acknowledged explicitly when environmental objectives are prescribed for river management, although in practice, reaches where management is optimal are limited (e.g. to relatively short river sections East of Vienna). In the Middle Danube the impacts are more variable, ranging from moderate to considerable: the river has been reduced in length, there is increased river bed degradation, only limited lateral movement is possible and the side-arms and oxbows are aggrading. In contrast, environmental impacts on the Lower Danube are relatively small, including local bank instabilities (in the immediate vicinity of hydropower plants), wake and splash processes and locally increased turbidity due to dredging (navigation). Although lower reaches generally have been modified less, the Lower Danube is designated as a heavy modified water body (HMWB). However, since floodplains significantly contribute to floodrisk reduction (Hein et al., 2015), restoration / reconnection of inundation areas is an important goal for the Lower Danube.

In summary, environmental impacts are evident through the DRB, at a variety of levels, reflecting process interactions at different scales as detailed by ICPDR (2013a) who have identified:

First order impacts: those immediate abiotic effects that occur simultaneously with engineering work and which influence material and energy transfer immediately up- and downstream (including changes in flow, water quality and sediment load).

Second order impacts: those changes that may occur over many years in channel and ecosystem structure as first order impacts are modified by local conditions (i.e. changes in channel and floodplain morphology, changes in plankton, macrophytes and periphyton).

Third order impacts: long-term biotic changes which are the integrated product of all first and second order changes. They include impacts on species in higher trophic levels or other food web interactions, and may occur over many years before a new 'ecological equilibrium' is achieved. However, in a dynamic river system those 3rd order impacts may be affected by (flood)-disturbances and change their development pattern.

4.1 Sediment regime and fluxes

The sediment regime of the Danube River has changed drastically over the last century. A total of 69 reservoirs were constructed in the DRB between 1950 and 1980, with a total volume of ~7.3×10^6 m^3. Reservoirs on the Danube itself account for ~50 % of this total, leading to a significant reduction in sediment transport (Dogterom, 2001). Changes in the sediment regime, particularly the balance between erosion and sedimentation have led to reservoir siltation upstream and river bed erosion in reaches downstream (Zinke, 1999). Thus dams impact the river hydrology and morphology downstream considerably, leading to a negative sediment balance and hence erosion (Dogterom, 2001; ICPDR, 2006) as the river bed degrades (i.e. is cut down, or deepened) until a new equilibrium between flow, sediment transport and river hydraulic parameters, is achieved. Decreased sediment supply from upstream areas of the DRB also impacts the Danube Delta coast, as noted above, with further implications for coastal morphology (Panin, 1998; Ungureanu & Stanica, 2000; Giosan et al., 2006; ICPDR, 2006; Stanica et al., 2007).

The effects of interacting processes on sediment transport through the DRB are evident when individual reaches are considered in detail. For example, as a result of bed load retention in impounded reaches upstream, almost no bed load enters the reach of the Danube below Vienna. This results in a bed load deficit and hence river bed incision: for example, Habersack et al. (2013) show that despite an artificial bed load supply downstream of the hydropower plant Freudenau in Vienna of up to 200,000 m^3 per year, river bed erosion of ~2 cm occurs annually. In addition, the combination of restricted lateral erosion and braiding restricts the lateral sediment input, whilst the river's sediment transport capacity is enhanced by the reduced channel width (Habersack, 2007). In contrast, the Lower Danube, is almost natural (or near-natural) as on the one hand lateral erosion provides an important sediment source, while on the other hand reduced bank stability and bank erosion processes contribute to an increased number of navigation bottlenecks (islands, fords).

In many reaches through the basin, sediment flux is significantly affected by dredging which in some cases has wider implications for the system. For example, dredging on the Danube near Budapest has led to the removal of 25×10^6 m^3 of sand and gravel with a reduced thickness of sand and gravel deposits. The latter were 4-7 m thick in the 1960s, but had fallen to 1-4 m by the 1990s. In this case, navigation was not the primary purpose of the dredging, although the subsequent channel incision of 1.6 m has been beneficial for navigation. The wider environmental impacts have included: the loss of filtering capacity of gravel beds, uneven river bed, depressions in bed filled with contaminated sediment (Lóczy, 2007). Similar effects have been noted elsewhere in the DRB, including on the Danube at Bratislava (50×10^6 m³ between 1976 and 1989 associated with a channel incision of 2 m over 30 years). In contrast, in the Lower Danube, where the navigation channel is affected by lateral erosion, additional river training works and dredging of shoals are required to maintain the minimum shipping depth (ICPDR, 2006). Here, dredging affects the vertical connectivity and directly influences benthic invertebrates in areas of gravel extraction. In addition, dredging activities can change the characteristics of a gravel-dominated river bed with potential implications for the sturgeon population, particularly for spawning (ICPDR, 2004).

4.2 Suspended sediment transport

Suspended sediment transport along the Danube has changed substantially in recent years, primarily due to the development of hydropower (Figure 6). Sediment trapping efficiency varies over time depending on factors including reservoir size and shape, depth, and basin vegetation. Large reservoirs have been estimated to intercept >40 % of the total river discharge, and have a sediment trapping efficiency of >50 % (Habersack et al., 2013). The trends in reservoir sediment storage in the Upper Danube are illustrated by data for the reservoir at Aschach in Austria in Figure 7. While the general trend is for the reservoir to silt up over time, during extreme events huge amounts of sediments are remobilised and transported downstream and up to 50 % of the annual suspended load originates from the reservoirs.

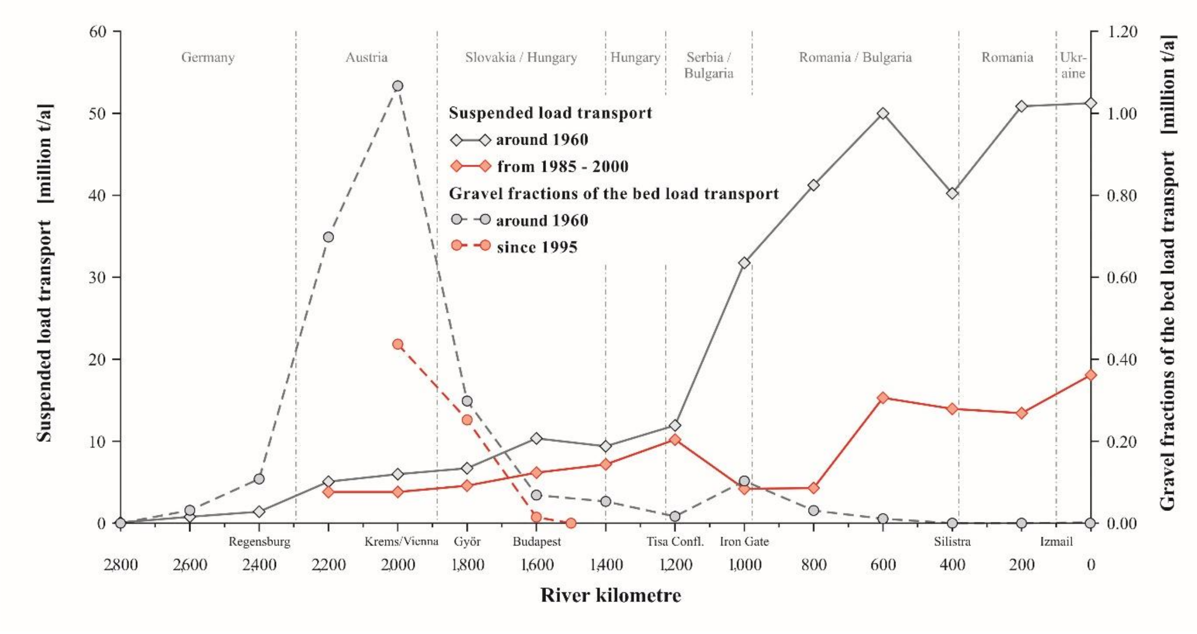

Figure 6: (a) Suspended load transport within the Danube River, (b) Gravel fractions of the bed load transport within the Danube River (modified after Habersack et al., 2013)

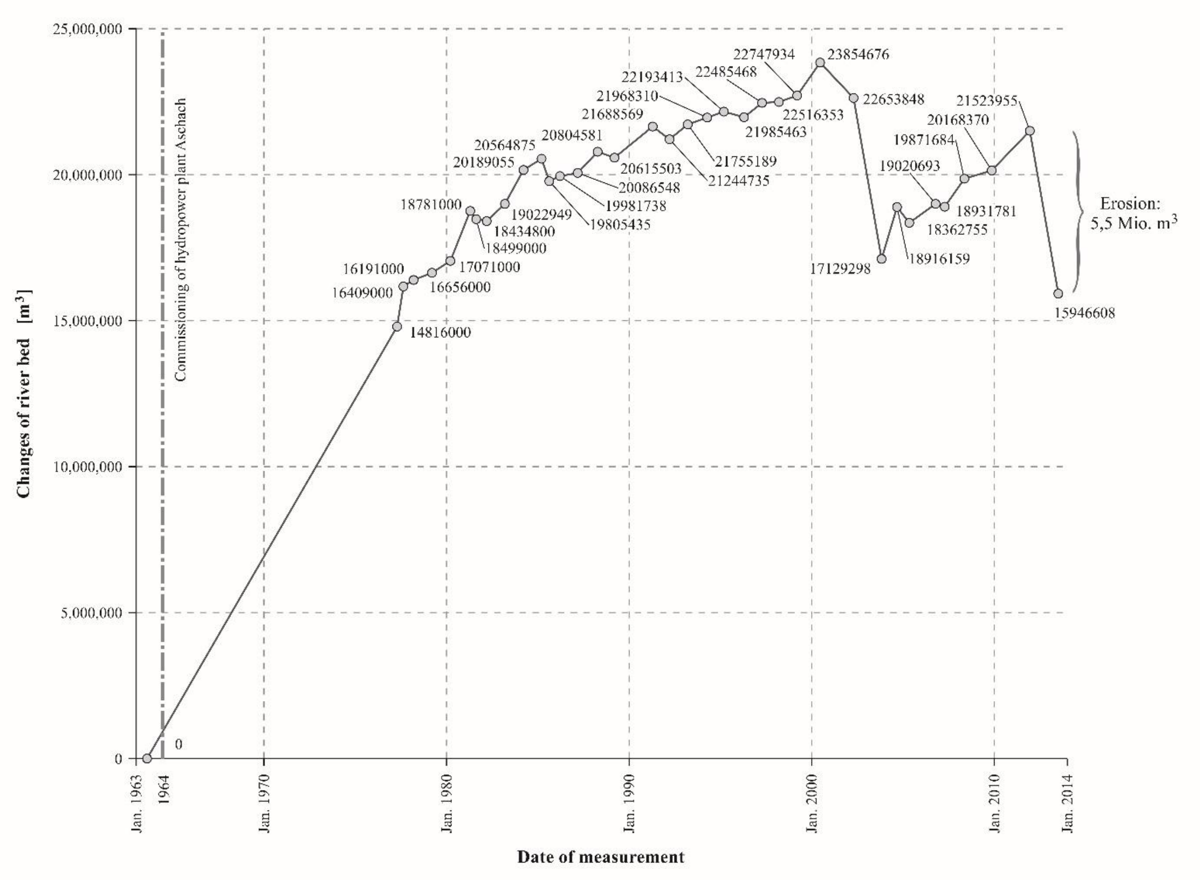

Figure 7: Sedimentation and remobilisation in the reservoir Aschach, Danube River (data base: Verbund)

ICPDR (2006) estimates that 25-30 % of the sediment load of the Danube that would formerly have been transported to the Danube Delta and the Black Sea is now trapped by dams on impounded river reaches. In the Lower Danube the suspended sediment load of the Romanian tributaries of the Danube is estimated to have fallen to 311 kg/s between 1985 and 2000 whilst between 1950 and 1971, sediment loads were estimated at 790.9 kg/s, and 876.4 kg/s between 1971 and 1984 (Figure 8; Bondar & Teodor, 2008).

Figure 8 summarises the mean annual suspended sediment load from 1955 until 1995 for four Bulgarian and Romanian stations. The intense decline of the suspended sediment transport is noticeable.

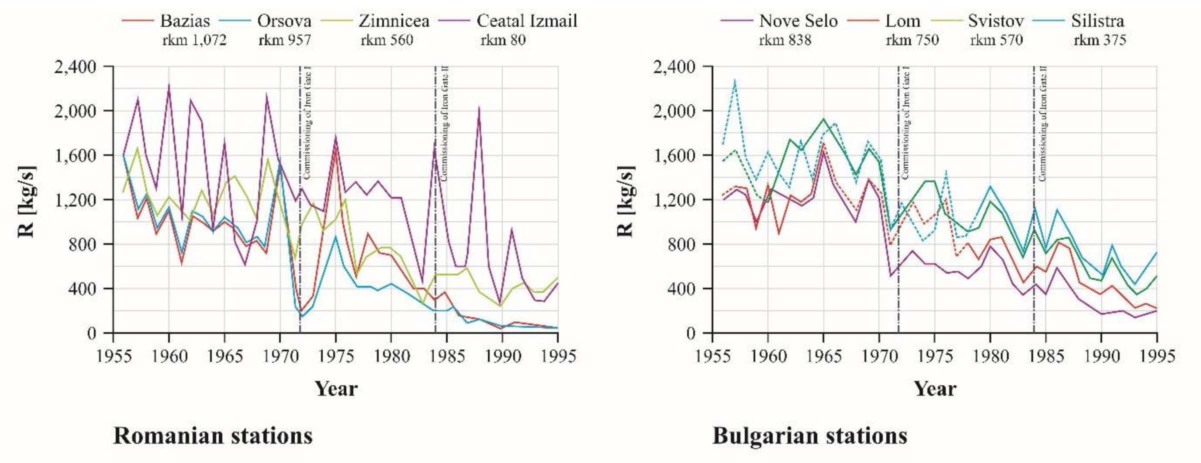

Figure 8: Mean annual suspended sediment load time series [kg/s] (Behr et al., 2003)

4.3 Bed load transport

Bed load transport from the upper part of the Danube practically stopped as shown in Figure 6 (Dogterom, 2001).

One of the most important regulating structures is the Iron Gate hydropower Complex. After completion of the Iron Gate dam in 1972, sediment retention by the Iron Gate I reservoir, is estimated to have totalled ~31 % of the total sediment input from upstream, and ~44 % of the suspended sediment. Considerable quantities of sediment have subsequently been retained: from 1972 to 1994 ~325 × 10^6 tons of sediment are estimated to have been retained by the Iron Gate dams. This equates to the deposition of up to 2.5 m of sediment in the Iron Gates I reservoir (between Bazias and Orsova) and up to 1 m in the Iron Gates II reservoir (Bondar & Teodor, 2008).

During floods a strong remobilisation of sediment from reservoirs occurs, whereas in the past the transport was distributed more evenly through the year during smaller floods (Nachtnebel et al., 2004). Moreover, at present sediment accumulates in impounded reaches above dams, due to the reduced flow velocity. In many cases, sediment extraction is required if a suitable river depth is to be maintained for navigation, and/or to restrict peak river levels to minimise the potential for flooding. More generally, flood protection works along the river (including river straightening, bank protection, levee construction) have led to river incision along individual reaches throughout the DRB, including along the Bavarian, Austrian and Hungarian Danube and in the Lower Danube (Keiter, 2007; Modev, 2008).

The process of river incision, or down-cutting, has had wider implications for the river morphology in some cases. For example, along the Upper Danube (in the Austrian section) about 2,000 islands existed prior to regulation works, but only a few now remain (Sommerwerk et al., 2009). In contrast, on the Lower Danube below the Iron Gates complex, the number of islands has increased by ~45 % from 1934 to 1992 on the section of the Danube at the border between Bulgaria and Romania (Bondar & Teodor, 2008). More generally, along the Lower Danube, lateral (side) erosion is still common as many of the banks and islands are unprotected (Bondar & Teodor, 2008). The lack of bank protection is the main cause for the formation of sand bars (Bondar, 2008), which are hydraulically and ecologically important.

In contrast, elsewhere in the DRB river engineering to improve navigation (and for flood control) has led to local increases in bed load transport. These conditions are enhanced given the substantial reduction in bed load input from the upper basin (ICPDR, 2007).

5. Current Status of the morphology of the Danube River

The impacts of river engineering on the morphology of the Danube are equally marked throughout the basin.

5.1 Upper Danube

In the Upper Danube, engineering works between Scheer and Riedlingen in Germany, including river straightening and bank protection, have led to significant erosion in the reach above Riedlingen, and deposition downstream. Currently, river reaches between Sigmaringen and Ulm are barely natural or even in an unnatural condition (Keiter, 2007). The Danube between Straubing and Vilshofen is also affected by river bed erosion with a short-term (~ period up to three years) mean erosion rate between Straubing and Reibersdorf of 0.02 to 0.03 m/year. In the absence of counter measures, these bed erosion rates are likely to continue for the next hundred years, by which time, erosion will have totalled ~1.5 m at the Isar estuary and ~1 m at Straubing (Hunziker – Zarn & Partner AG, 2001).

The immediate effects of river regulation are the loss of riverine inshore habitats which have a strong impact on riverine inshore characteristics and habitat value, reduced hydrological connectivity, a lower floodplain water table, reduced geomorphological diversity of floodplain processes and increased erosion of the channel bed (Schiemer et al., 1999; Hein et al., 2005). These impacts are seen in several reaches of the Upper Danube where the river length has been shortened to improve navigation. For example, on the Danube east of Wallsee, bed slope and flow velocity have increased significantly along the artificially straightened and narrow channel. The consequence has been regressive bed erosion in the main channel; the mobilised sediment has been difficult to control and has been deposited downstream (Hohensinner, 2008). Some of the incised reaches, with rocky beds have been similarly affected, in some cases the river cross-section has been modified by blasting, and the gorge morphology has changed. The process of river bed incision is illustrated by the behaviour of Danube River East of Vienna in Austria. Figure 9 summarises river bed erosion at two gauging stations (Donauconsult, 2006b): Fischamend (left) and Wildungsmauer (right). As a result of the low water conditions, the lack of bed load input (due to sediment retention upstream), backward erosion from Bratislava (where the river bed has been lowered for flood protection) river bed incision of 2 cm / year is occurring.

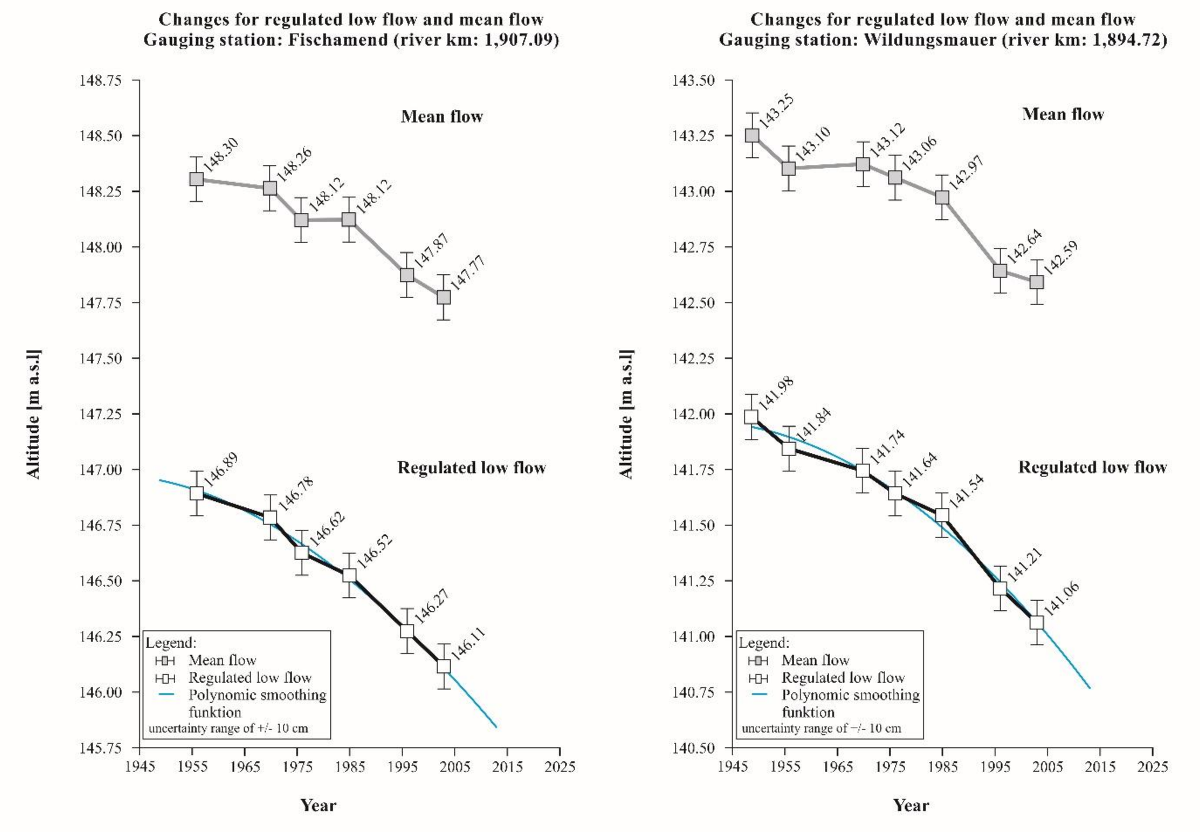

Figure 9: River bed erosion (2-3.5 cm year^{-1}) on the Austrian Danube at Fischamend (left) and Wildungsmauer (right) (Data source: KWD 'Kennzeichnende Wasserstände der Donau, WSD') from Donauconsult (2006b)

5.2 Middle Danube

The deficit in sediment supply in the Middle Danube, as a result of the chain of dams from the Alpine headwaters to Gabčíkovo and the changes in flow dynamics, has caused significant river bed degradation, particularly at the point where the tailrace canal joins the main Danube River. In the first years of Gabčíkovo operation (1992-1994) significant river bed erosion occurred (of ~4 m). Continued river bed erosion is occurring here with a negative impact on low flow water levels (Holubovà et al., 2004), which is incising down into the former main channel of the Danube. At present, the river transports 7 × 10^6 tons of sediment annually to the Gabčíkovo Barrage System and ~70 % of the sediment load is deposited in the reservoir. As a result, dredging is required to maintain the channel for navigation and the sediment load downstream has decreased significantly (Smith et al., 2002).

In Hungary the deepening of the channel (Figure 10) is a result of erosion that is not limited to individual points, but is occurring along long reaches of the river (Goda et al., 2007). The problems are compounded as bed load is deposited below reaches where the river bed is degraded presenting difficulties for navigation (Holubovà et al., 2004), which consequently requires dredging thereby exacerbating erosion along the Hungarian Danube (Goda et al., 2007). A similar trend is now seen along the 30 km reach of the Danube in the Gemenc region where river bed erosion has led to a fall in river levels over a large area (Guti, 2001).

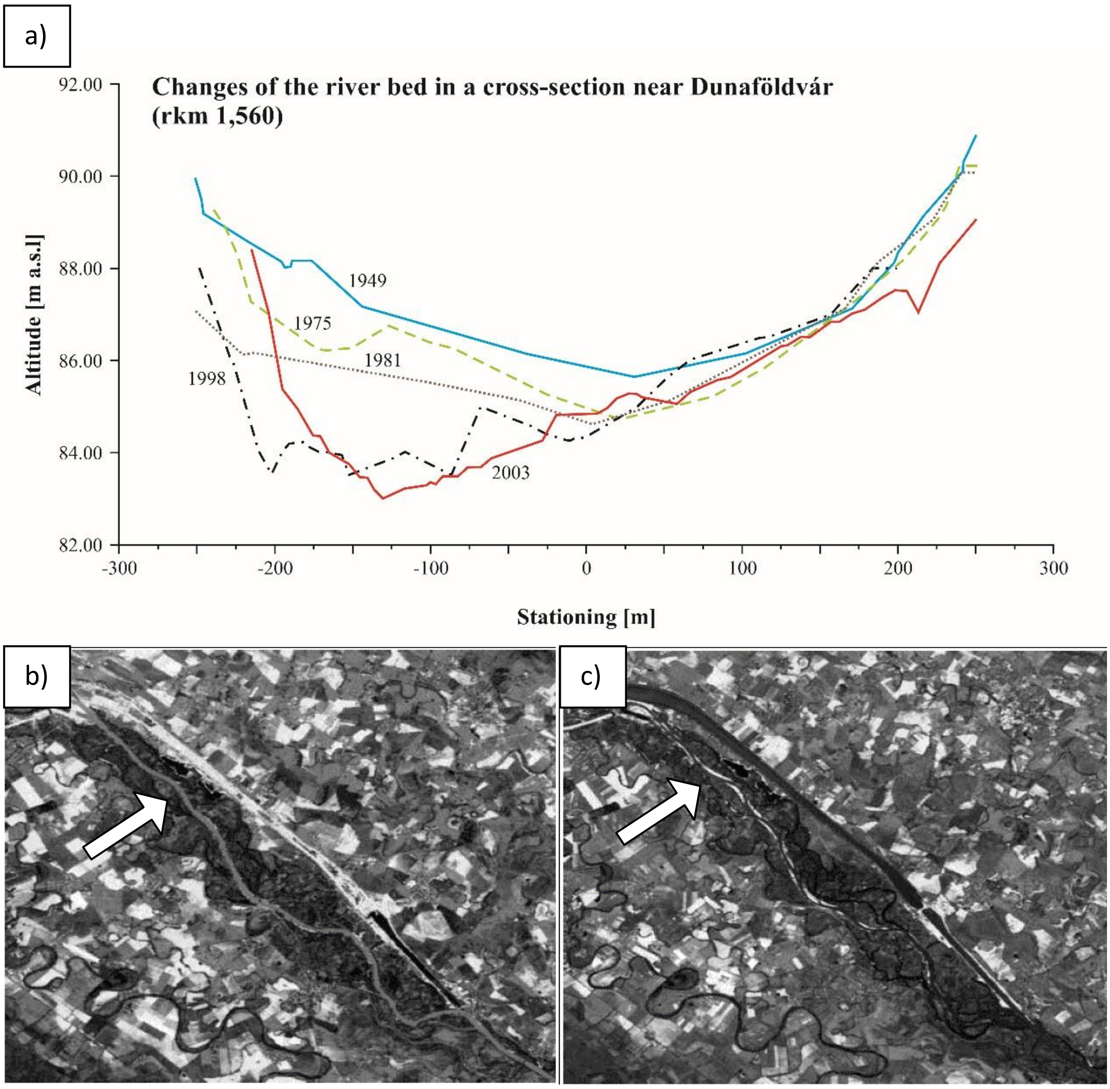

Figure 10: (a) Changes of the river bed near Dunaföldvár, Hungary (Goda et al., 2007); (b) Satellite image prior to diversion of the Danube (white arrow marks the ‘old’ Danube) (Smith et al., 2002); (c) Satellite image after diversion of the Danube (white arrow marks the ‘old’ Danube) (Smith et al., 2002)

More generally, former river engineering works to improve navigation along the Danube in Slovakia and Hungary, have limited lateral movement of the river, and contributed to morphological changes, specifically aggradation (to form shoals or fords), as well as degradation (bed erosion) and the separation of river side-arms has limited hydrological exchange between river and floodplain (Holubovà & Capekovà, 2005). Widespread meander cut-offs have led to a reduction in the length of the Hungarian Danube from 472 km to 417 km, changing river level and resulting in progressive siltation of many side-channels and oxbow lakes (ICPDR, 2004). The reduction in river length has increased bed slope which has increased river flow velocities and shear stress, resulting in further river bed degradation.

Dredging has a large impact on reaches throughout the Middle Danube and has contributed to a decrease in bed load transport downstream. This is largely due to dredging in Hungary and Slovakia from the 1960s to 1999, between Sap and Szob, primarily for construction (Rákóczi, 2000). There is a long history of commercial dredging in this area, which pre-dates the impoundment of the

Hungarian Danube, and was associated with significant river bed erosion, as for example, in the reach between Devín and Sap (Holubovà & Capekovà, 2005). Similarly, incision of 9 cm/year occurred over the period 1973-1985 near Bratislava, and 8.5 cm/year near Rajka (Rákóczi, 2000). Further downstream the incision rates are generally much smaller and vary according to the extent of local dredging. However, total incision over the period 1960-1987 has been estimated at ~ 1 m for the Danube at Szigetköz reach ~70 cm at Nagymaros, as a result of dredging.

The impacts of long-time dredging (which have led to sediment transport rates higher than the 'natural' rate) have also changed river flow characteristics contributing to a reduction in the floodplain water table (Rákóczi, 2000). For example, falling river levels in the main channel of the Danube between Devín and Sap (in Slovakia) have impacted water levels in the side channels and groundwater levels have also decreased due to commercial dredging (Holubovà & Capekovà, 2005). Since 1960 the water level associated with a discharge of 1,000 m^3 has decreased by 1-2 m between rkm 1,870 and rkm 1,840 and rkm 1,805 rkm 1,785 (rkm: river kilometre). This is due to river bed degradation as a result of extensive dredging along the Slovak-Hungarian Danube, with the volume of dredged material on some river reaches estimated at 1.5 to 2×10^6 m^3/year (Holcík, 2003).

Dredging also affects the timing and volume of water entering the side channels and floodplain of the Danube in Slovakia and Hungary. Parts of the Danube's inland delta between rkm 1,860 and rkm 1,840 are now flooded later than before, and with lower volumes of water. Moreover, in some years some of the side channels have completely dried up and this part of the floodplain is no longer inundated (Holcík, 2003).

5.3 Lower Danube

In the Lower Danube, most of the Romanian and Bulgarian tributaries of the Danube have low sediment loads due to the upstream dam construction which aggravates erosion rates. The river is relatively unstable as a result and there has been a reduction in floodplain area (~80 %) with general river engineering (Gutknecht et al., 2002; Schwarz et al., 2008). River bed erosion has resulted in low river levels which have affected the local groundwater table of the Lower Danube and floodplain wetlands (WWF, 2002). The Lower Danube has been extensively modified by active structures, such as flood protection dykes, and passive hydraulic constructions (e.g. for irrigation and drainage) which indirectly influence surface run-off parameters and river bank erosion (Modev, 2008). There has also been widespread floodplain loss: the braided sections of the Danube (up to Calarasi-Silistra at rkm 375) are characterized by shallow sections and islands. Given the loss of floodplain and its attendant capacity to retain floodwaters, the impact of floods within the areas protected by dikes is greater, and is compounded by the loss of habitat due to increased river bank erosion (WWF, 2002).

The Lower Danube River is strongly affected by lateral erosion: sand bars and islands are formed as a result of the natural regime of the river (Bondar, 2008). Lateral erosion is an important natural morphodynamic process that is limited elsewhere in the DBR due to bank protection. Lateral erosion has led to an increase in the number of islands in the Danube between Turnu Severin and Chiciu Calarasi from 93 in 1934 to 135 in 1992, with an increase in the total channel length from 283 km to >353 km over the same period as a result of river bank erosion (Bondar & Teodor, 2008). However, the lateral erosion has affected unregulated islands, some of which have been completely eroded whilst others are now protected. For example, the island of Belene in Bulgaria is affected by lateral erosion of 0.6 - 7 m/year and it has reduced in area from 3,940 ha in 1966 to 3,858 ha in 1980 (WWF, 2002).

The sediment deficit from upstream (caused by hydropower development) has led to river bed erosion along the Lower Danube. As a result, the river has increased in width and water levels have fallen, contributing to the instability of river banks and lateral erosion. These effects are compounded by erosion from ship waves which exacerbates river bank instability. However, at the same time annual dredging in Romania (Bulgaria) has varied from 4,943,000 (2,530,000) m^3 from 1961 to 1970, 2,311,300 (893,900) m^3 from 1971 to 1990 and 1,136,000 (452,000) m^3 from 1991 to 2005 (Modev, 2008). Recent dredging records from Romania for navigation (unpublished from the Danube Commission) are shown in Figure 11. Over the years shown, an estimated total of 8,820,812 m^3 of sediment was dredged by Romania, equal to a mean annual volume of 1,470,135 m^3.

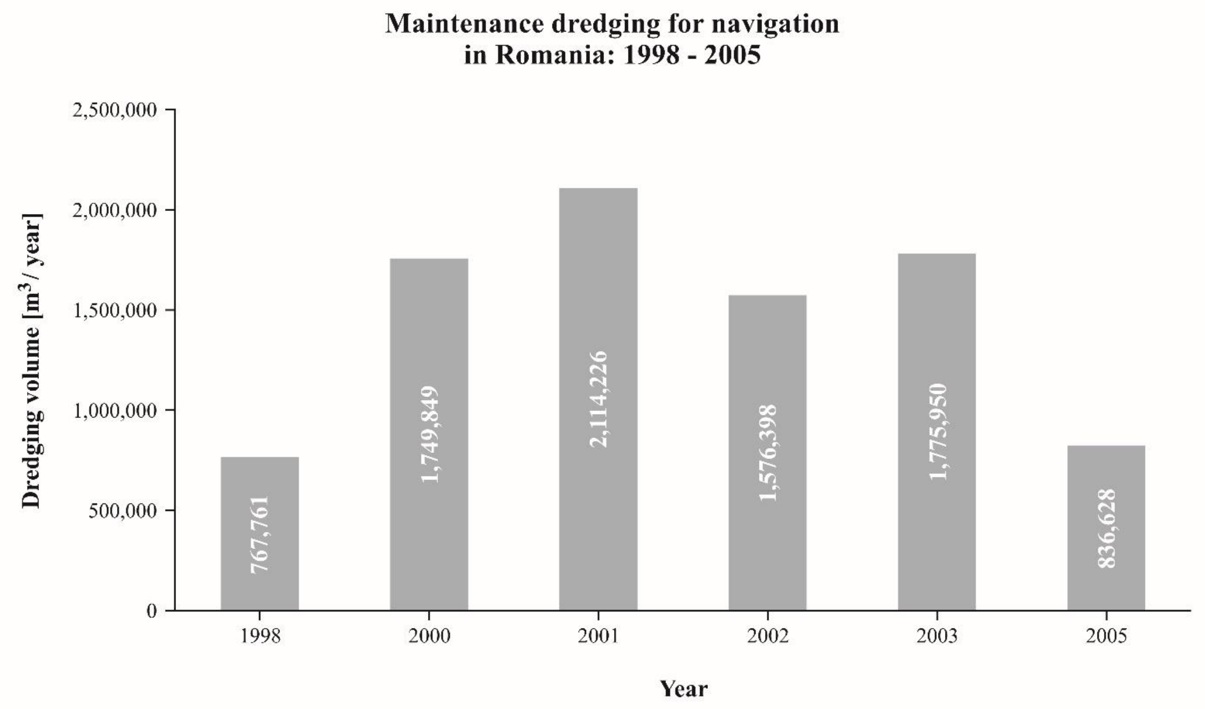

Figure 11: Dredged volumes for the maintenance of the fairway in Romania for several years (data base: Danube Commission)

At present there are only a few reaches of the Lower Danube where stable riverbed conditions are found (e.g. Turnu Magurele) where the river bed is confined by bedrock. With relatively few exceptions, most of the river reaches experience frequent morphological changes (Gutknecht et al., 2002) and according to Bondar & Teodor (2008) river bed erosion on the Danube River at Oltenita affects the entire river bed profile.

Turbidity levels also increase for up to 1 - 2 km downstream during dredging (Harris, 1999), and there are widespread effects on fish habitats and the benthic fauna. However, in many cases it is difficult to attribute these changes to specific causes: illustrated by the dramatic decline in the sturgeon population of the Lower Danube in the 20th Century. A contributing factor here has been the effects of dredging for industrial purposes near Calarasi (rkm 373) which destroyed spawning habitats for the sturgeon (Bacalbaşa-Dobrovici, 1997). Also important, though, are the effects of dams, pollution, overfishing, and the loss of wetlands along the Lower Danube which were formerly important spawning areas for many species.

5.4 Danube Delta

Several phases can be identified in the modification of the Danube Delta (Figure 12). They include alterations in channel hydro- and morphodynamics due to changes in the river regime as a result of upstream hydropower plants, excavation of new channels (such as the Sulina arm of the Danube in the 19th Century and the Saint George's arm in the 1980s) river constructions, navigation, and dredging. Other major impacts are due to changes in the Delta itself such as the extension of the natural channel network (described below) (WWF, 2002).

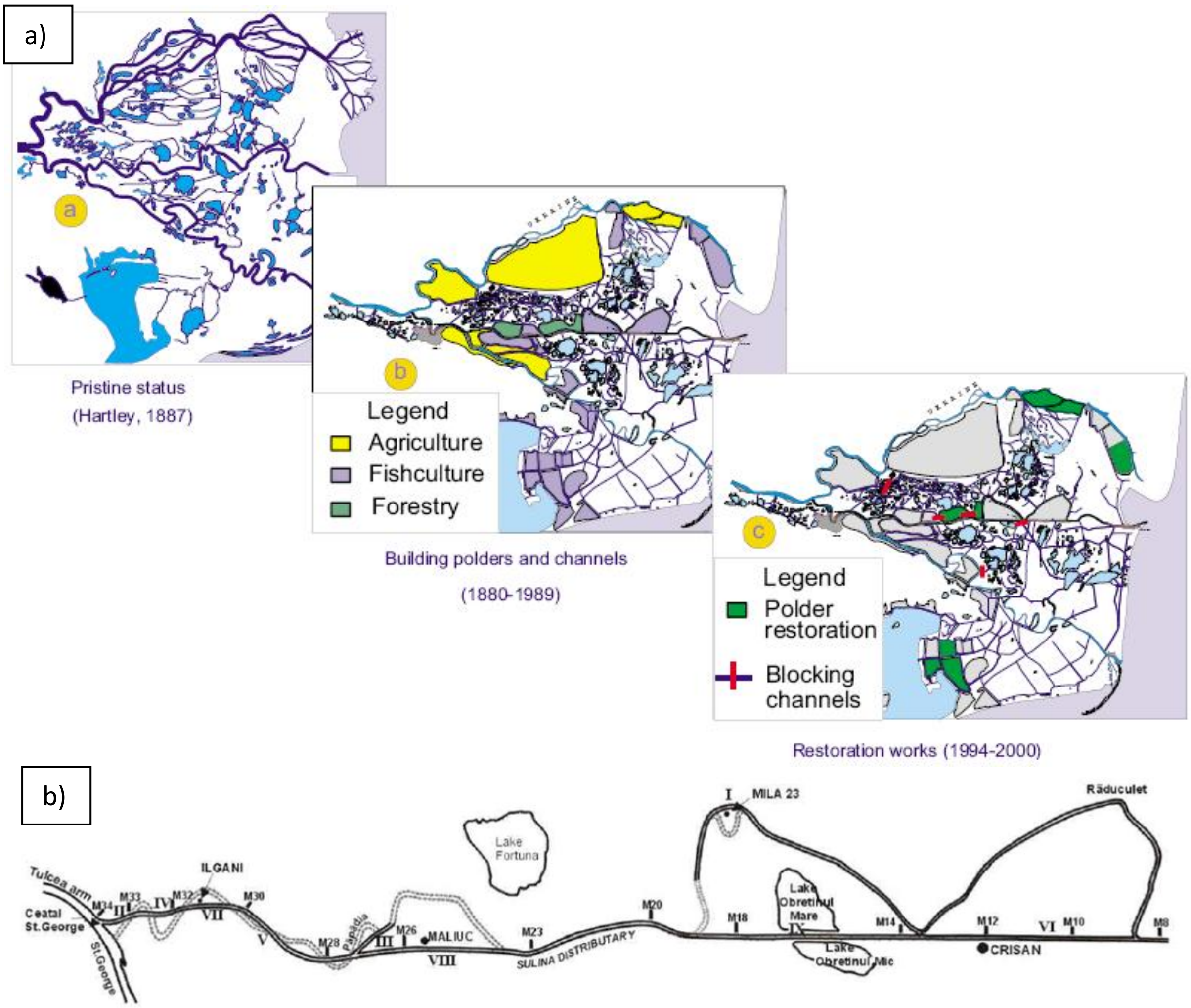

Figure 12: (a) Phases in the Danube Delta recent history (Staras, 2000), (b) Meander cut-off along the Sulina channel (Panin, 1998)

Extensive engineering works doubled the total channel length through the Delta from 1,743 to 3,496 km. Many channels now transport more fine sediment to the lakes of the Delta than previously, and the discharge through the lakes has increased from 167 m^3/s (prior to 1900) to 309 m^3/s (1921-1950), 358 m^3/s (1971-1980) and to 620 m^3/s (1980-1989) (Staras, 2000). Over this period there has been an increase in the discharge of the Sulina branch and a decreased discharge of the Chilia and

Saint George’s branches, although after the cutting-off of the natural meanders along the Saint George channel there has been a tendency for the discharge to increase.

After construction of the Iron Gate dams in 1972/1984 sediment input to the Delta fell by 30-40 %, leading to intense erosion of the deltaic littoral. At present, the sediment flux from the Danube to the Black Sea is ~25-35 × 10^6 t/year, of which 4-6 × 10^6 t/year is the sand fraction. This affects the rate of sedimentation on the inner shelf of the Black Sea south of Constanta and along the Bulgarian coast (Panin & Jipa, 2002).

At present, the level of the Black Sea is rising by ~3 mm annually (Panin, 1996, 1998; Stanica & Panin, 2009), and the discharge of the Chilia branch is falling, while the strongest rates of erosion of the waterway are observed in the Sulina branch, which has been straightened and the banks protected for navigation (Schwarz et al., 2008). The Sulina branch has been completely canalised since the beginning of the 20th Century and the channel length has been reduced from 85 to 62 km, following plans originally produced in the 19th Century Figure 12).

The 80 m wide navigation channel along the Sulina arm has to be permanently dredged to secure a depth of 7.3 m. Sulina, the middle branch, is viewed as ‘at risk’ due to the hydromorphological alterations (Schmutz, 2006). In addition, the St. George (Sfantu Gheorghe) branch is experiencing river bed erosion as a result of meander cut-offs in the 1980s which have reduced the channel length (by 50 km). Throughout the Delta, the river banks of the Danube are subject to erosion, and all three channels are widening at various rates with erosion of the river bed as a result of increased flow velocity because of the shortening of the channel by meander cut-offs.

Significant dredging continues in the Danube Delta. Many channels were dredged from the early 20th Century, and particularly between 1960 and 1990 to optimize water circulation for fish production. The total length of channels created artificially by dredging amounts to 1,700 km. Since the 1990s, the recovery of the Danube Delta floodplains is an ongoing process as a result of growing attention to the restoration of wetlands and natural habitats (ICPDR, 2006). However, significant parts of the floodplain (312 km² ≈ 10% of the Delta) have been embanked over the past 50 years (WWF, 2002; Coops et al., 2008) and > 100,000 ha of the Danube Delta are currently embanked. During 1994-2003 about 15% of the area with embankments have been reconnected (Staras, 2000; Schmutz, 2006).

In summary, over the last 50 years, the impacts of engineering work on the Delta have included (Margesson, 1997; Staras, 2000; Navodaru et al., 2002):

- decreased retention and purification capabilities of the deltaic wetlands due to dams and dikes and channel cut-offs, with a reduction of the natural area by 20 %;
- development of man-made polders surrounded by dikes;
- 25 % reduced retention capability; ~290,000 ha of floodplains have been lost in the lower Danube providing 4.3 km^3 less water storage;
- decreased flood peaks;
- silting-up and hydrological isolation of lakes (resulting in more pronounced eutrophic conditions; limnophilic sites have been decreased and habitats for rheophilic and indifferent fish species (concerning flow velocity) have been increased);
- accelerated coastal erosion of up to a maximum of 25 m / year);

- disturbed aquatic ecosystems, biodiversity (loss of species, losses of aquatic plants, changes in fish communities) and deterioration in habitats due to agriculture, fish farming, and aquaculture.

6. Discussion

Many of these impacts, summarised in Section 4 and Table 2, are cumulative and reflect a hierarchy of process-interactions throughout the basin. In this context, there is a new paradigm of ecosystem-based river management, but due to practical limitations on what can be achieved because of competing uses and interests it is difficult to manage rivers in developed basins, such as the DRB (Petts et al., 2006). In such basins, irrespective of the political context, there are significant questions of how it might be possible to reconcile various competing demands on the river system: complying with the WFD, whilst ensuring flood protection, enabling continued hydropower development and maintaining, or enhancing, the navigation potential of the waterway.

Table 2: Impacts of river engineering measures along the Danube River

	Upper Danube	Middle Danube	Lower Danube	Danube Delta
River Morphology and Ecology	Reduced river length in: * Baden-Württemberg by 73% * Bavaria by 15%, * Austria by 15%	Reduced river length in: * Hungary by about 18% (due to meander cut-offs) * Serbia by about 10%	Unstable river banks	Meander cut-offs: * Sulina: reduced by 23 km * Sfantu Gheorge: reduced by 50 km
	Reduced river bed width	River bed erosion along the Slovak and Hungarian Danube	Lateral erosion along unregulated banks of the Danube and its islands	Lateral erosion along all branches of the Danube due to dredging and ac-celerated wave erosion
	River bed degradation	River bed erosion of: * 8.5 cm / year at Rajka (1966 - 1985) * 1 m at Szigetköz (1960 - 1987) * 70 cm at Nagymaros (1960 - 1987)	River bed erosion	River bed erosion
	Reduction in floodplain geomorphological dynamics	Drying out of floodplains and forest areas (Gemenc)	River bed erosion and lateral erosion (down-stream of Iron Gate I and II)	Widening of branches: * Chilia branch by ~2 m/year * Sfantu Gheorghe by ~1.2 m/year
	Disconnection of floodplains	Disconnection of floodplains by narrow flood dikes (in Hungary south of Budapest)	Loss of 45 km^2 of floodplain wetlands	Increased coastal erosion up to 25 m/year
	Disconnection of tributaries for fish migration	Decreased retention capacity due to the loss of floodplains	Floodplain losses (~80 %): * 72,600 ha in Bulgaria * 426,000 ha in Romania	Loss of species, aquatic plants, natural spawning habitats
	Loss of riverine inshore habitats		Decrease in biodiversity	Changes in fish community
	Prevention of bank erosion		Wake and splash erosion	Morphological effects of regular dredging of the navigation channel on the Sulina branch and jetty
	Disconnection of side-arms			Floodplain disconnection (10 % were embanked in the last 50 years) and 25 % reduction in water retention capacity
				Silting up and separation of lakes
				Eutrophication
Sediment regime / transport	Sediment surplus in reservoirs (trapping efficiency: 17 %)	Silting-up of side-arms and oxbows	Increased turbidity due to dredging	Increased suspended sediment input in the Danube Delta lakes (but overall sediment load decreased by ~1/3)
	Reduction of bed load input from tributaries (minus 90-95 %)		Reduced lateral sediment input	
	Sediment deficit in free-flowing sections		Sediment deficit (due to sediment deposition in reservoirs upstream)	
			Reduced bed load transport	
			Deposition of suspended load at the impounded reaches	
			Reduced suspended sediment transport	
Hydrology / Hydraulics	Reduced hydrological connectivity	Lowered water levels	Decrease of river discharge (1840-2006)	
	Lower water levels due to reduced river length and channel width	Increase and/or acceleration of flood waves	Reduction in floodplain capacity for water ret-ention (from ~15.6 x 10^9 m^3 to 4.0 x 10^9 m^3)	

The consequences of river regulation and river engineering as demonstrated by the Danube are widespread and inter-related. They include significant change in material exchange, at different levels: from the basin headwaters to the alluvial reaches and delta downstream (there is an overwhelming need for an overall sediment budget as a basis for a basin-wide sediment management plan); lateral exchange between the river and floodplain; vertically: where alluvial groundwaters have been affected by changes in the river profile or gravel extraction; and over time. Whilst there is increasing recognition of the complexity of the river / environmental system, and the scale-dependence of key processes, considerable work is still required to translate this understanding into practical tools to advance management. This need is particularly critical for 'large river basins' given the degree to which they are hierarchically organised systems. In this respect, given the basin focus of the WFD, there is an opportunity to adopt a broader perspective, although many of the impacts of engineering work, such as the restructuring of the channel floodplain architecture, are particularly visible at the reach-scale.

Significantly, these concerns are not unique to the DRB and are apparent to varying degrees in other, international, large river basins. In the United States, the US Army Corps of Engineers, have the responsibility of ensuring the continuation of river navigation and providing an appropriate level of flood control. This is challenging at a variety of levels, given the difficulty in identifying appropriate management strategies within an artificially constrained river system. In such basins, it is very likely that river engineering, for whatever purpose, may lead to changes in fluvial form that have unintended consequences and which may subsequently require further engineering interventions to resolve (e.g. Hudson et al., 2008).

It is important here to look forward and reflect on future prospects for the management of large river basins such as the Danube. In a recent mapping exercise of literature on river research and river science, Vugteveen et al. (2014) suggest that there has been insufficient cross-disciplinary work in river science. The inference of this analysis was that the established 'ecosystem-based paradigm in river management' predominates in the literature, and that 'engineering research' is at present under-represented. Given the degree to which the DRB has been modified by river engineering, and engineering solutions are required to problems such as how to maintain a suitable depth of water for navigation, or how to model rates of sediment transport at the scale required in the DRB. In this respect, more fundamental research is needed to improve our understanding of system functioning and hydraulic engineering facilities in the DRB require substantial development if new tools are to be developed to model water and sediment fluxes through the basin at an appropriate scale. This requires refinement of existing physically-based models so that they can be applied at high discharges, as found in the DRB, to enable fundamental and applied research. An example of the approach required is the Danube River Research and Management DREAM project: this flagship project of the EU Danube Strategy aims to improve research infrastructure in theentire Danube basin. In addition to constructing two new laboratories in Romania and Austria, an upgrade of existing laboratories throughout the basin is proposed, as part of a network that spans the development (and application) of numerical models, field sites and a research vessel. DREAM seeks to foster improved cooperation between research organisations in the Danube basin as well as research groups based outside the region. Complex and in some cases conflicting problems in complex and large river basins, require a dedicated research infrastructure as envisaged in a second Flagship Research Infrastructure Project in the EUSDR: the International Centre of Advanced Studies on River-Sea Systems – DANUBIUS-RI. DANUBIUS-RI seeks to identify and implement solutions to reconcile conflicting human uses within the DBR and the Black Sea. These solutions require a holistic basin approach (from source to the sea) that spans the Danube – Black Sea system.

In addressing the engineering problems that arise in large river basins such as the Danube, a clearer scientific cross-disciplinary toolbox is needed that can enable basin managers to reconcile conflicting pressures in the river basin and draw upon the most appropriate knowledge to address emerging problems. Hillman (2009) suggests this should recognise three different (and complementary) knowledge sets: first, contextual or place dependent knowledge; second, technical / applied knowledge; third scientific knowledge. However, this by itself is insufficient to deliver a new paradigm in river management, and a vehicle for significantly enhanced communication, and Knowledge Transfer, is also required. The complexity of the DRB offers an ideal context in which to develop the methodology and support framework which is essential to advance the goal of sustainable river basin management. This is important for the DRB itself, but also for other transboundary rivers in Europe and elsewhere. The Danube is one of the most complicated basins in which the WFD has to be implemented. One consequence is that considerable practical and scientific knowledge has yet to be applied throughout the basin, and a number of significant research gaps remain. This requires innovative knowledge exchange and enhanced dialogue between stakeholders involved in river basin management and the scientific community. This is illustrated by Sommerwerk et al. (2010) who provide a relevant synopsis concerning the issues about stakeholder involvement in river basin management.

A relational diagram summarising the exchange required is illustrated in Figure 13. This represents a transferable methodology to facilitate knowledge exchange between environmental researchers and key stakeholders and managers. It acknowledges the importance of flood protection, hydropower, navigation and environmental restoration in the DRB, and envisages that scientific research in these areas will be captured, by a ’Knowledge Mining Engine’ and the results discussed by a ‘Knowledge Exchange Council’ in an attempt to reconcile competing demands between different stakeholder interests within the basin. In the Danube, an appropriate body to oversee this process already exists: the ICPDR, and the need for improved communication in this area is widely recognised. Petts et al. (2006), for example, highlighted the possible role of ‘third party intermediaries’ who understand the science (but do not do the science) and who can effectively translate the science into policy.

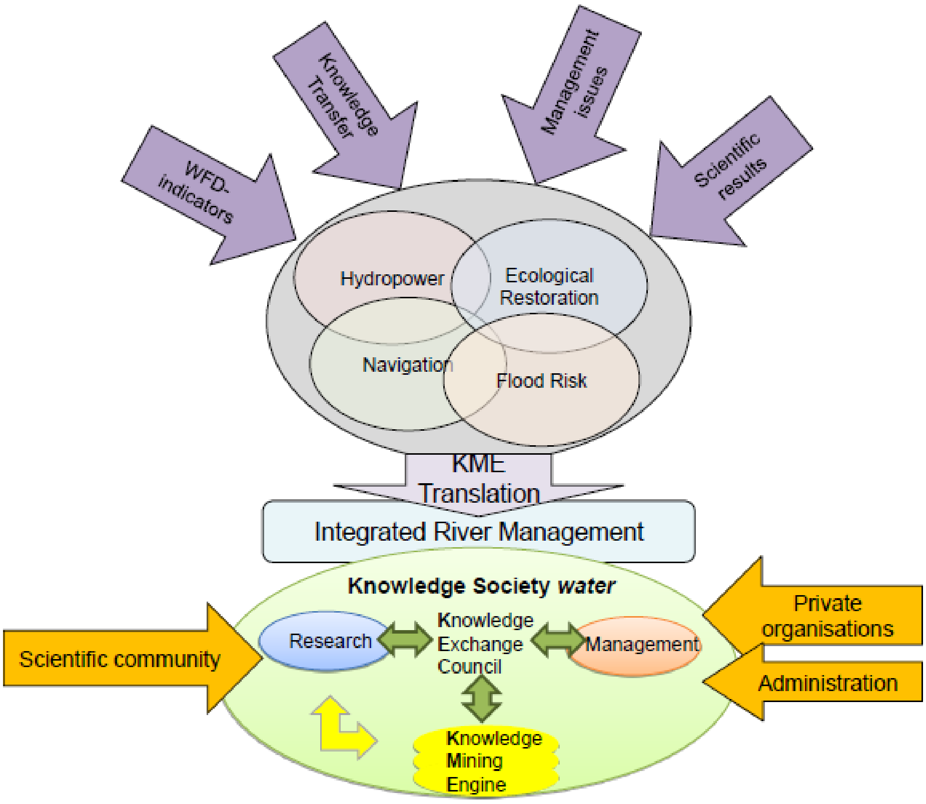

Figure 13: Danube River Basin Knowledge Translation and roles of Knowledge Exchange Council and Knowledge Mining Engine

Given the scale of the system, it is evident that particularly in the DRB, knowledge exchange (KE) is of utmost importance for improving river management at the whole basin scale, given the great variety of countries, approaches and engineering measures that have been practised throughout the basin, (in some cases without appreciation of their wider impact).

The disturbed sediment transport in particular, requires KE in research and management. Until now no Sediment Budget exists for the whole Danube River Basin, although this is needed to develop a Sediment Management Plan and reduce the gap between sediment surplus and deficit and improve morphodynamics. The lack of data on sediment balance is also the reason why the ICPDR were unable to decide if sediment management is a Significant Water Management Issue in the Danube River Basin District. Thus, considering future prospects one of the main challenges for an integral basin-wide river management plan will be the development of an overall sediment balance/budget for the DRB (which requires appropriate data collected by comparable methods at the respective national level) as well as additional investigations to identify the significance of sediment transport on the Danube basin-wide scale (ICPDR 2015).

Another crucial issue for Danube River Basin management in the future is the possible impact of climate change. The Danube River Basin shows great differences in climate conditions due to its large extent from west to east, and given its diverse relief. The western regions of the catchment are strongly influenced by the Atlantic climate with high precipitation, while eastern regions predominantly experience a Continental climate with lower precipitation and typical cold winters. In contrast, there is a mediterranean climate in the area of the Drava and Sava Rivers (UNDP/GEF, 2006). In addition to direct anthropogenic impacts on river discharge (e.g. hydrological engineering), climate change is responsible for the transformation of characteristically hydrological features. Climate models indicate a continuous increase in air temperature and a change in seasonal precipitation for middle Europe, even for Austria during the current century (Strauss et al., 2013) which leads to changes in snow accumulation, snow melt, and ultimately to river discharge (Holzmann et al., 2008). Climatic conditions have a distinct effect on river hydrology, thus both the extent and effects of climate change have to be taken into account when dealing with driving forces on the entire Danube River basin level. Forecast models considering climate change predict a decrease in snow accumulation and earlier snow melt leads to more run-off in winter and less during summer in alpine regions, an increase in low flow periods in areas at lower altitude, seasonal changes in flood appearance and a decrease of summer floods (Kundzewicz et al., 2005). An important influence will be the already measureable retreat of glaciers and reduction of permafrost areas. One of the consequences of this may be an increase in fine sediment supply which would affect the hydromorphology and sediment management in the whole Danube River Basin.

7. Conclusions

The Danube is an intensely engineered river in the context of the degree to which hydropower has been developed, in the use of the river for navigation and flood protection. To an extent that varies between the Upper, Middle and Lower Danube the length and width of the river has been reduced, the bed slope increased, the banks especially in the upper reaches were protected, and so no side (lateral) erosion is possible. Side arms and floodplains have been disconnected and dredging affects the sediment budget. One of the key drivers for changes in the river morphodynamics is the interruption of the sediment continuum by engineering structures like hydropower plants. This leads to a surplus of sediment in impounded reaches and a sediment deficit in the five remaining free flowing sections. Severe floods with open weirs cause remobilisation of sediments, as in 2013 when a 200 year flood triggered the flushing of over 4 million tonnes of fine material from the hydropower reservoir Aschach which was followed by sedimentation in areas inundated downstream. On the other side the river bed erodes in free flowing sections, e.g. 2 cm per year East of Vienna and up to 6 and more cm per year in the Lower Danube. In the Delta an erosion of the river bed in the three main channels can be observed and finally also coastal erosion at the Black Sea is increasing.

Consequently the ecological status of the Danube River is affected following the changes in hydromorphology, induced by engineering measures. In the Upper Danube river bed degradation may lead to a river bed ‘breakthrough’, where erosion of the gravel layer allows the Danube to incise downwards into the underlying finer marine deposits and form a canyon, as observed already at the Salzach River in the 1960s and during the 100 year flood of 2002. A lack of morphodynamics and instream structures, the disconnection of side arms and riprap are responsible for ecological deficits e.g. in key ecosystem functions, fish, macroinvertebrate fauna, birds and flora. Erosion occurs as well in the Middle and Lower Danube, where it is enhanced by the high sediment trapping efficiency of the Iron Gate I and II hydropower complex. Erosion of the Delta arms and the Black Sea coast as well affect the ecological status in these reaches. However, it is important to recognise that river restoration, based on improving self-forming processes, will also require a significant period of time.

Up to now no Sediment Budget exists for the whole Danube River Basin, which would be needed to develop a Sediment Management Plan as part of the River Basin Management plan. This necessitates a cooperation of all Danube countries and includes an intensified Knowledge Transfer and Exchange. Furthermore there is a need for new research infrastructure in the Danube basin, intended to be implemented by two EUSDR flagship projects (DREAM and DANUBIUS-RI).

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