

Danube River Sediment Transport and Morphodynamics

Helmut Habersack, Elisabeth Jäger, and Christoph Hauer

Abstract Hydromorphological alterations of large rivers are evident and have to be related to multiple anthropogenic pressures. The presented results of an integrated study concerning the actual status of the hydromorphology of the Danube River Basin show that in particular, the sediment regime features a heavily disturbed system at various scales. Combined impacts of flood protection, navigation and hydropower measures applied over a long period of time have been identified based on the river-scaling concept (RSC) for being responsible for these specific alterations (lack of bed load and suspended load in the remaining free-flowing sections). Moreover, long sections of the Danube River have been narrowed, channelized, disconnected from floodplains and morphologically degraded over the last 200 years. This has caused increased bottom shear stresses, increased sediment transport capacities and in addition a lack of lateral self-forming processes and corresponding reduced morphodynamics in the non-impounded sections. As a consequence of both longitudinal and lateral disturbances of the sediment supply and additional impacts of the channelization, the remaining free-flowing sections are subject to various forms of river bed degradation. Such degradation or river bed incision leads to a loss of instream structures in general, with a disappearance of gravel bars at the Upper Danube, and changes of sandbars at the Lower Danube. Hence, for river systems and large river basins, it has to be stated that the preservation and restoration of morphodynamics is one of the most relevant issues for river engineering and ecology. This has to be considered especially for the implementation of legal directives and/or future river basin management plans.

H. Habersack (✉), E. Jäger, and C. Hauer
Christian Doppler Laboratory for Advanced Methods in River Monitoring, Modelling and Engineering, University of Natural Resources and Life Sciences, Muthgasse 107, 1190 Vienna, Austria
e-mail: helmut.habersack@boku.ac.at; elisabeth.jaeger@boku.ac.at;
christoph.hauer@boku.ac.at

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1 Introduction

Undisturbed hydromorphology in large river systems is rare and characterized by a dynamic equilibrium between hydraulic (e.g. flow dynamics) and morphological parameters (e.g. sediment supply [1]). Hence, anthropogenic influences have considerable effects on especially large river systems due to summarizing anthropogenic impacts of the entire (large) catchment areas, ending up in multiple and severe hydromorphological alterations. Therefore, not only for large rivers is the issue of hydromorphological alterations a potential area of conflict between environmental protection and other uses of the river, such as, e.g. inland navigation or flood protection. For that reason, hydromorphological alterations, as one of the main ecological pressures, have been identified as a significant issue for water management, especially according to the European Water Framework Directive (WFD). Since the implementation of the WFD in 2000, all European waters have to be managed by a river basin approach. Especially for large rivers, international commissions are responsible for, e.g. the protection of the Rhine and the Sava River Basins and moreover for coordinating national actions within this framework. For the Danube this responsibility and the accompanying requirements have been realized by the Danube countries and the International Commission for the Protection of the Danube River (ICPDR) through the so-called first Danube River Basin District Management Plan (DRBMP) in 2009. In this management plan, the central hydromorphological alterations at the Danube are listed, which, e.g. highlight the necessity to distinguish between the impacts and hydromorphological consequences of longitudinal and/or lateral interruption of the river and habitat continuity [2, 3]. Alterations of the Danube morphology which already started in the fifteenth century [1] are mainly related to the engineering approaches to create a single, straightened channel accompanied by changing the depth or width of the river. The consequently strongly affected ecological quality of the Danube, but also for other

larger river systems, is reflected in significant alterations of riverine habitats, subsequently leading to the decline of species biodiversity [4]. Especially the decline of species abundance, the altered population composition, the prevention of species migration routes for the aquatic/semiaquatic fauna and the corresponding decline in naturally reproducing fish populations (e.g. sturgeon) have to be mentioned [2]. In general, as key pressures for large river systems causing such a multitude of dramatic hydromorphological alterations navigation, flood protection and hydropower use have been identified in previous studies [1, 5–7]. Moreover, it is hypothesized that hydromorphological alterations of large rivers may be partially superimposed by other anthropogenic influences like urban settlements, agriculture or land use in general. Already discussed but not clearly figured out so far was the mentioned superimposition and interrelated processes of disturbed sediment regime and hydromorphology of the Danube and/or large rivers in general. It is partially evident and has already been analysed that anthropogenic interferences/barriers are frequently not only referred to a single pressure but contain multifunctional characteristics which, however, have not been identified for the entire Danube River Basin so far. Besides single aspects concerning the variety of anthropogenic pressures, a lack of integrative studies is evident for large river systems, dealing with multiple and/or superimposed pressures on sediment regime and the entire hydromorphological catchment-wide conditions.

Hence, the aim of the presented paper is to provide a scientific assessment based on the comprehensive description and analysis of anthropogenic pressures and impacts on Danube sediment regime and/or hydromorphology to address this lack of data. The assessment takes a case study approach to compile, evaluate and discuss historical as well as future impacts of the sediment regime and the morphological condition of this large European river. Besides the *DPSIR Framework* (*driving forces-pressures-state-impact-responses*), formulated by the European Environment Agency, the *river-scaling concept (RSC)* [8] was used to identify and evaluate the different sedimentological and/or morphological issues from small channel patterns up to the entire Danube River Basin. Moreover, the presented study should highlight a way of a systematic identification of hydromorphological alterations which could be applied to other large river basins as well. This book chapter is based on Habersack et al. [9].

2 The Danube River Basin

The Danube River Basin is located in Central and South-Eastern Europe. The main river is 2,857 km long with a catchment area of 801,463 km² [3] including all of Hungary; most parts of Romania, Austria, Slovenia, Croatia and Slovakia; and significant parts of Bulgaria, Germany, the Czech Republic, Moldova and Ukraine. Large territories of the former Federal Republic of Yugoslavia (today of Serbia and of Montenegro), of Bosnia and of Herzegovina and small parts of Italy, Switzerland, Albania and Poland are also included in the basin [10]. The Danube

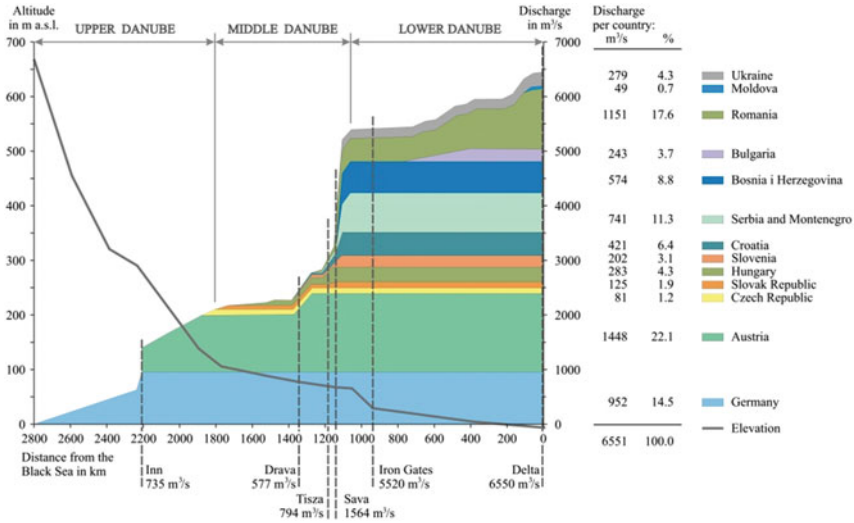


Fig. 1 Longitudinal profile of the Danube with river kilometres and the most important tributaries [11]

has a multiannual mean discharge of $6,500 \text{ m}^3 \text{ s}^{-1}$ into the Black Sea and is the 21st largest river of the world and, after the Volga River, the second largest river of Europe [10]. One third of the Danube River is mountainous, while the other 2/3 of the Danube passes hills and plains. The mean altitude of the Danube River Basin is only 475 m. Figure 1 shows the altitude, the discharge and the main tributaries of the three sub-catchments (sub-reaches) in a longitudinal profile of the Danube River. From the area of 10,508 million km^2 of total Europe, expanding between the western coast of Ireland and the Ural Mountains, the Danube catchment's share is 0.801 million km^2 (7.8%). About 783 million inhabitants are living on the continent, thereof more than 80 million people in the catchment of the Danube River. In the year 2013, 19 countries are sharing the catchment. Among them, there are 14 countries being the ICPDR Contracting Parties (with catchment areas $>2,000 \text{ km}^2$), the biggest shares of the catchment belonging to Romania (29.6%), Hungary (11.5%), Serbia (10.1%) and Austria (10.0%).

According to various authors, the entire Danube River can be divided into four sub-catchment areas, Upper, Middle and Lower Danube and Danube Delta, as shown in Fig. 1. The Upper Danube Basin (1) reaches from the sources in the Black Forest Mountains to the Gate of Devín (also called 'Pannonian Gate'), near Bratislava, where the foothills of the Alps, the Small Carpathians and the Leitha Mountains meet. The area covers in the north the Swabian and Franconian Alb, parts of the Oberpfälzer, the Bavarian and the Bohemian Forests, the Austrian Mühl- und Waldviertel and the Bohemian-Moravian Uplands. At the south of the Danube, the Swabian- Bavarian-Austrian Alpine foothills as well as large parts of the Alps up to the water divide in the crystalline Central Alps are situated [11]. The Middle Danube Basin (2) covers a large area reaching from the Gate of Devín to the

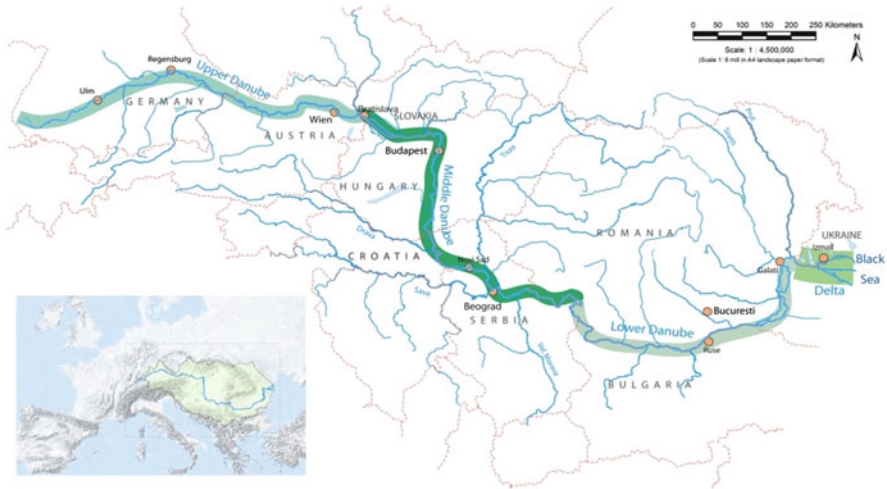


Fig. 2 Zoning of the Danube River into the Upper, Middle and Lower Danube and Danube Delta [15]

impressive gorges of the Danube at the Iron Gate (Iron Gate I and Iron Gate II), which divides the Southern Carpathian Mountains in the north and the Balkan Mountains in the south.

The Middle Danube Basin is confined by the Carpathians in the north and the east and by the Karnic Alps, the Karawankas, the Julian Alps and the Dinaric Mountains in the west and south. These mountains incorporate the Pannonian Plains and the Transylvanian Uplands [11]. The Lower Danube Basin (3) covers the Romanian-Bulgarian Danube sub-basin downstream of Cazane Gorge and the sub-basins of the Siret and Prut River. It is confined by the Carpathians in the north, by the Bessarabian Upland Plateau in the east and by the Dobrogea and Balkan Mountains in the south [11]. Finally the Danube Delta (4) has to be mentioned, which reaches from the confluence of the Prut River (Ukraine) to the mouth into the Black Sea (Ukraine) with an entire planimetric extent of 5,640 km² (Fig. 1), as the second largest river delta in Europe (Volga River = 23,000 km²) (Fig. 2).

3 Methods

The driving forces in river morphology and the related instream habitats are strongly influenced by the unsteady transport of water and sediments on various scales in which the size of areas of interest and the upscaling and downscaling of possible driving forces are crucial. Thus, the applied method for characterizing anthropogenic pressures along the Danube was based on two main approaches allowing a detailed evaluation of especially the upscaling and downscaling of sedimentological and morphological issues. Both the so-called river-scaling

concept (*RSC*) [8] and the *DPSIR* Framework (driving forces–pressures–state–impact–responses), formulated by the European Environment Agency, were found to be valid to address the specific aims of the presented study. Especially the *RSC* has to be used as a basis for the assessment of the ecological integrity. Within the *RSC*, the following three scales are analysed in a hierarchical way: from large scale to small scale a differentiation between processes and the corresponding sedimentological/morphological condition of the entire Danube River Basin (catchment-wide scale), the Danube River reaches (reach/sectional scale) and the Danube River site-specific characteristics (local scale; e.g. river restoration East of Vienna). First of all, for all scales, the history and present status of hydromorphological alterations have been analysed and evaluated based on historical maps, published studies, governmental reports and engineering projects of the various Danube countries ($n = 14$). All alterations were discussed in order to identify historical as well as current pressures from diverse driving forces (e.g. inland navigation, flood protection) on hydromorphology especially along the Upper, Middle and Lower Danube.

In addition to the *RSC*, the *DPSIR Framework* has been implemented for a consistent structuring of the results. The European Environment Agency formulates the definition of *DPSIR* as ‘the causal framework for describing the interactions between society and the environment, dividing driving forces, pressures, states, impacts and responses’ (extension of the PSR model developed by OECD). The results of this paper refer predominantly to the components: driving forces, states and impacts on various scales. Moreover, due to the aims of the presented study, this paper should provide a scientific assessment based on the description and analysis of the anthropogenic impacts by addressing the main driving forces, and thereby all pressures and impacts on the hydromorphology of the Danube River have been listed. The entire assessment takes a catchment scale approach to compile, evaluate and discuss historical as well as future impacts from the main driving forces impacting the Danube’s sediment regime and/or hydromorphology for a future river basin management.

4 Results

The presentation of results is divided into two main chapters according to the aims of the presented study. First, the alterations and changes of sediment regime and sediment transport are described, which have to be seen as additional driving force on possible changes of Danube hydromorphology, which is presented under the second heading of results.

4.1 Status of the Sediment Regime

One of the basic problems concerning the entire Danube River Basin is a modified longitudinal and lateral sediment continuity and related regime. Especially during the last decades, the sediment regime of the Danube River has drastically been changed. Between 1950 and 1980, sixty-nine reservoirs, with an overall storage volume of about 7,300 million m³, were constructed in the Danube River Basin. In total 78 barriers exist along the Danube main stem, keeping only five free-flowing sections. Moreover, in addition to these numbers, the deficit of bed load in the Danube has been strongly affected by the decline of former bed load input from the main tributaries in the Basin, where more than 700 large hydropower plants/weirs have been constructed. Therefore, the bed load transport in and output from the upper reaches of the Danube dramatically declined after 1960 as shown in Fig. 3. Exemplarily, at the Upper Danube today, the bed load input from tributaries is reduced by about 90–95%. Comparing to the historical situation, significant reductions of bed load can be documented especially for the Austrian rivers Lech, Isar and Inn. For example, the bed load in the River Lech, formerly transporting 180,000 t year⁻¹, decreased at the confluence with the Danube to nearly no transport, whereas the bed load in the River Inn (main tributary for the Upper Danube) decreased from 540,000 to 180,000 t year⁻¹.

In contrast to the reduction of bed load transport of the tributaries and consequently the reduced input into the free-flowing sections of the Danube, there is a surplus of deposited sediments in impounded sections and reservoirs. The sediment trapping efficiency varies with time and depends on several factors, e.g. the size and shape of reservoirs, water depth and occasionally vegetation. Large reservoirs intercept more than 40% of the total water discharge, and thereof, 70% are subject

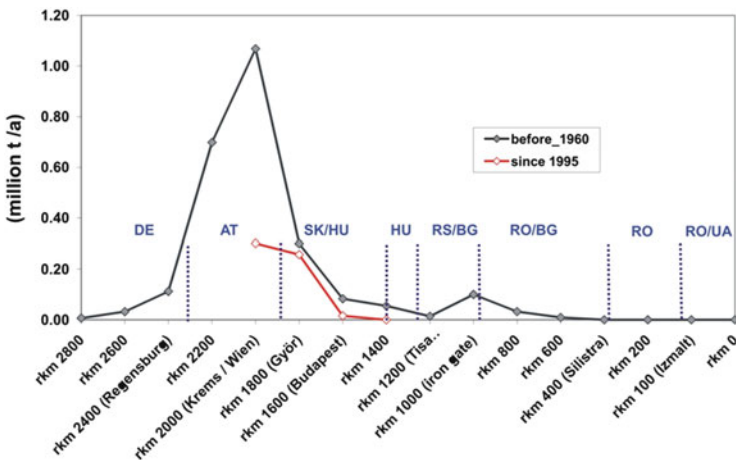


Fig. 3 Bed load transport (million t/a) within the Danube River ([12]; [13])

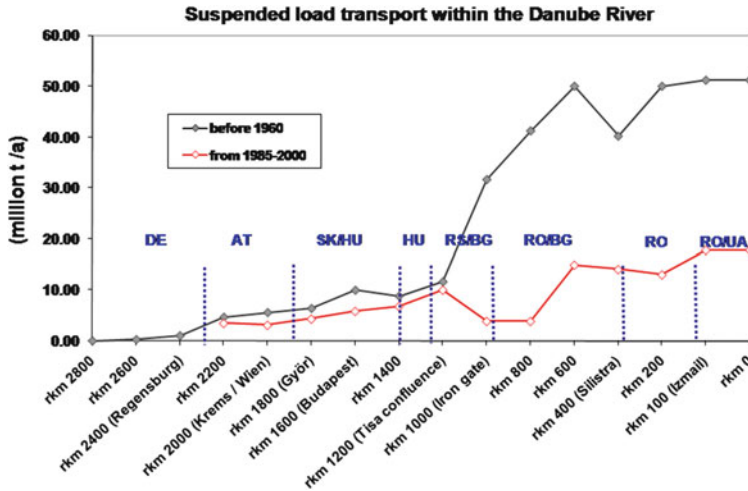


Fig. 4 Suspended load transport (million t/a) within the Danube River ([15])

to a sediment trapping efficiency of more than 50% of the entire Danube River Basin. In general, estimations indicate that about 25–30% of the sediment load to the coastal sea is trapped behind dams [14]. For the Upper Danube, the sediment trapping efficiency is about 17%. The most influencing constructions on the Lower Danube are the Iron Gate Complex, which comprises the largest dam system at the Danube. The Iron Gate dams and reservoirs influence the sediment transport significantly in two ways as they are, on the one hand, a trap for suspended sediments (Fig. 4) and, on the other hand, an important nutrient sink and deposition area of hazardous toxic matters for pollution [16].

Moreover, during the period 1972–1994, about 325 million t of sediments (10% of the entire reservoir) were retained by the Iron Gate dams, leading especially to a strong decline in suspended sediment transport along the downstream Lower Danube [14]. In addition, it has to be mentioned that also the temporal distribution of suspended load totally changed during the last decades as a consequence of the construction of reservoirs. Nowadays significant suspended transport occurs only at large flood events, in which most of the transported material is deposited along the floodplains during the falling limb. During these floodings, a strong remobilization of suspended sediments, however, occurs in the Danube reservoirs, whereas for the historical un-impounded Danube, the transport of suspended sediment was distributed over the entire year (e.g. during smaller floods). Especially upstream reaches of dams (impounded reaches) suffer from over proportional sediment surplus, as sediments accumulate due to lower flow velocities. These mostly coarser depositions often have to be extracted in order to maintain river depth for navigation as well as to limit the height of water level in case of floods [17]. Furthermore, the reduced bed slope and flow velocity and the related aggradation of sediments in the reservoirs affect natural gravel bed river habitats as they are covered with fine

sediments and clog the hyporheic interstices which moreover lead to a decrease in oxygen flow into the bed substrate [18]. These alterations in bed material composition may have effects on macroinvertebrates, fish fauna (e.g. spawning habitats) and aquatic flora [11]. In addition to storage in reservoirs, the sediment accumulation processes between river training measures, e.g. groins and chevrons (especially at the Lower Danube) constructed to improve navigation, modify the sediment transport in large river systems [19].

Moreover, as second crucial aspect in limiting sediment supply, the disturbances by the lateral interruption of sediment supply have to be mentioned. Habersack [20] stated that due to the prevention of side erosion and self-forming processes at the Upper Danube (e.g. by flood protection measures or for navigational purposes), the lateral connectivity in general, the sediment exchange between side arms and the main channel and thus the lateral exchange and input of sediments (bed load) have been reduced enormously, resulting in an additional deficit of sediments within the Danube River channel. In contrast, at the Lower Danube, it has to be noted that the lateral sediment (suspended sediment) input is more or less not impacted as the river is not embanked in most parts. The river banks in Romania are almost natural (near-natural); thus, side erosion plays an important role for the sediment regime and sediment transport, respectively. Nevertheless, at the Lower Danube where lateral river bed erosion may reduce the water depth due to larger cross sections and dislocate the navigation fairway in the Danube, additional river training works as well as dredging of fords are carried out to maintain the minimum fairway depth, thereby altering the sediment regime [14].

As the third crucial driving force influencing the sediment input along the Danube, land use has to be mentioned. In general, human-induced changes of the vegetation cover in river basins cause strong geomorphic response by disturbing sediment supply, transport and deposition regimes. As an example for the Upper Danube sub-basin (reach scale), changes in Austria's land cover (being of major significance for the whole basin) have been investigated in the period 1950–1995. The largest relative changes are for settlement areas which increased continuously by 109% between 1950 and 1995. Absolute changes are largest for woodlands with an increase of 4,004 km² and grassland with a decline of 4,187 km² [21]. From these data two options concerning changes in the sediment regime are possible: on the one hand, an increased input of fine sediments from adjacent areas into the Danube. Due to the intensification of agricultural production (enhanced soil erosion) and in areas of the Danube basin, where glaciers will retreat as a consequence of climate change, an increase of mainly fine sediments is predicted. But on the other hand, the input of sediments may also decrease as a consequence of reforestation.

Beside the longitudinal and lateral disruption of the sediment continuum, also the vertical dimension plays an important role for the sediment conditions at the Danube. Today, on the one hand, especially for the improvement of navigational conditions or flood protection (but formerly also for commercial purposes), the vertical sediment connectivity is disturbed due to regular (or even singular) dredging activities impacting/changing the bed composition. On the other hand, longitudinal impacts of dredging are evident by affecting the entire sediment regime,

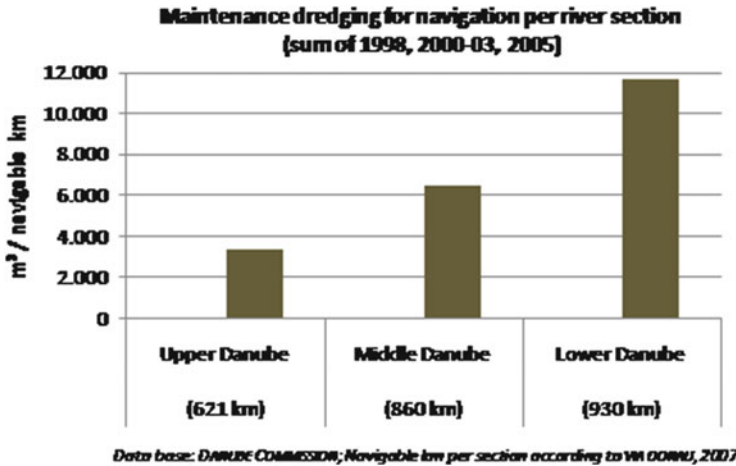


Fig. 5 Maintenance dredging for navigation per river section (sum of 1998, 2000–2003, 2005) ([15]; data base: Danube Commission; navigable km per section according to Via Donau [22])

thereby leading to river bed incision. Sectional differences of dredging volumes along the Danube are exemplified by dredged volumes for navigational purpose (Fig. 5). In contrast to the past, along the Upper Danube, however, e.g. in Austria, a defined refilling of the dredged material is performed (if possible upstream of the dredging site), meaning that there is no extraction of sediments in total (no loss of sediments). According to the studied literature, there is no evidence that such refilling measures are performed, e.g. along the Lower Danube, as well. Based on the reports of the Danube Commission, the dredged volumes of especially fine material for the improvement of the fairway are much higher at the Lower Danube compared to upper reaches (considering the difference in the sectional river length and the grain size of the material), as shown in Fig. 5. Hence, in a summarized view of the river basin sediment regime, it has to be stated that the Danube River partially features a totally disturbed sediment system due to the combined impacts of the four driving forces influencing the Danube's sediment balance: flood protection, navigation (dredging), hydropower and land use.

4.2 Status of the Hydromorphology

Within this chapter the hydromorphological alterations and man-made changes are presented which are more or less enormous. In the course of several river training measures, beginning at the fifteenth century and performed along the whole reach in the upper reach in the nineteenth century, the Danube was shortened in length and width, which especially leads to increased shear stress resulting in bed degradation (erosion). On the one hand, due to channelization and bank protection measures, the

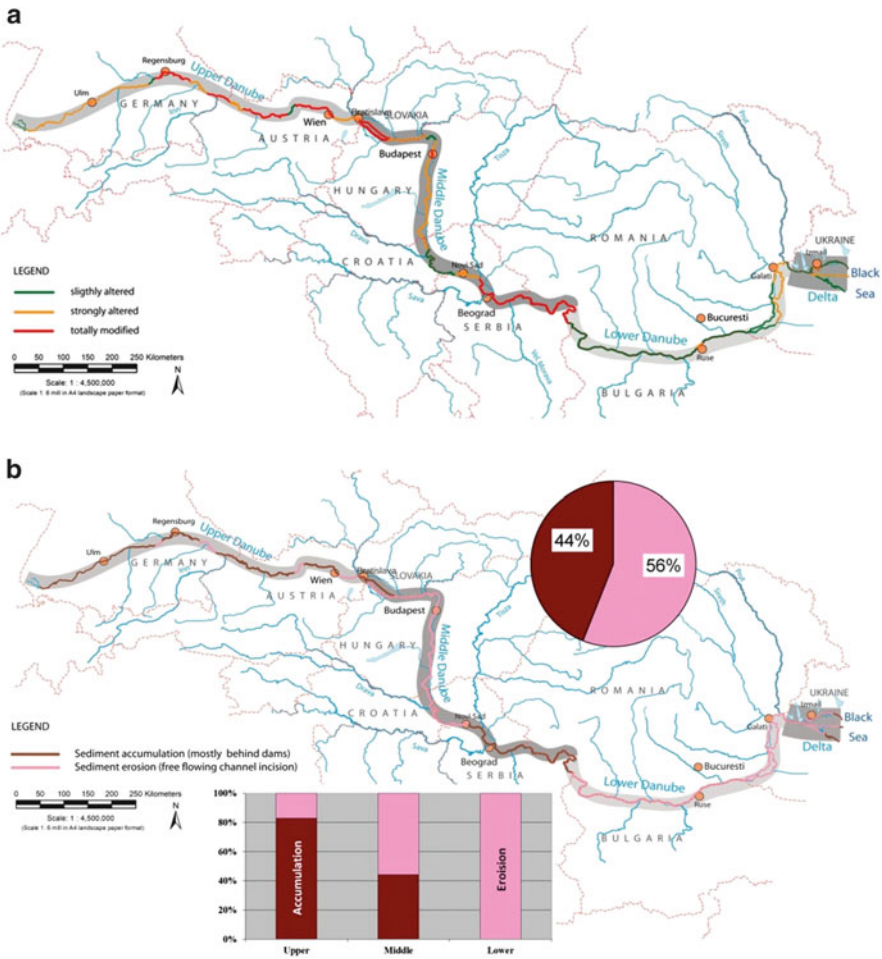


Fig. 6 (a) Degree of alteration of river morphology (channels and banks) (data base: Joint Danube Survey [2]), (b) erosion and accumulation reaches along the Danube River: maps (a) and (b) produced by Ulrich Schwarz

former morphodynamics and self-forming processes are prohibited with consequently significant ecological deficits [20]. On the other hand, deposition may occur due to side erosional processes, leading to wider river sections. This is enhancing island formation or increases at the Lower Danube, leading to bottlenecks for navigation. The current hydromorphological alterations of the channels and banks for the entire river basin are illustrated in Fig. 6. Moreover, it could be figured out that the hydromorphological conditions differ enormously between the upper and lower reaches of the Danube. The Upper Danube is mostly heavily impacted, while the Lower Danube predominantly still exhibits good

hydromorphological conditions. Summarizing Fig. 6, 1/3 of the entire Danube River shows good hydromorphological conditions, while 1/3 is strongly altered.

On the sectional scale due to meander cut-offs (e.g. the Hungarian Danube was shortened from 472 to 417 km) and/or stabilization of river banks as well as due to the disruption of river continuity (e.g. disconnection of side arms), the resulting singular uniform river bed resulted in significant hydrological and hydraulic long-term impacts ([23]). Exemplarily for the Upper Danube and parts of the Middle Danube, the reduced river length (e.g. Bavarian Danube 15%, Austrian Danube 15% and Hungarian Danube 18%; compare Table 3 [5]), decreased active channel width (e.g. in Austria from over 3 km to 300 m after the channelization) and increased bed slope and average flow velocity (flow time) consequently lead to lowered water levels (for the same discharge).

Especially on the sectional scale, the hydromorphological status of the Danube has to be linked to the already described disturbances in the sediment regime. Since the Danube River lost its longitudinal sediment continuum over the last decades and the lateral sediment continuum over the last hundreds of years, different erosion and accumulation reaches have been developed. Considering the entire Danube River Basin, the erosion and accumulation reaches are presented in Fig. 6b. The sum of accumulation reaches amounts to 44% of the entire Danube River, mostly appearing at the Upper Danube and less at the Middle Danube, while the erosion reaches amounts to 56%, e.g. representing the entire Lower Danube. These different sectional patterns in erosion and deposition have severe influence on local scale river morphology and the related instream habitat quality, which is exemplarily presented for the reaches with erosional trends based on the outcomes and ongoing research at the Danube East of Vienna (at the National park 'Donau-Auen').

Former river training measures (especially the regulations at the end of the nineteenth century), but also the retention of sediments due to dams and similar interferences in the Upper Danube catchment (e.g. torrent control), have forced erosion processes along the free-flowing sections (e.g. the reach East of Vienna), meaning a permanent decrease of load supply and consequently river bed degradation. The prevented side erosion and braiding restricts the lateral input of bed load to the regulated river bed itself, where the transport capacity is enhanced by the reduced channel width and slope increase. Moreover, the river banks of the Danube are continuously embanked (bank reinforcement by ripraps); thus, bed load uptake processes occur only in form of bed erosion (vertical erosion). The process of river bed incision is highlighted by an example of the Danube River East of Vienna in Austria at the gauging stations Fischamend (left) and Wildungsmauer (right) (Fig. 7a). Despite an artificial gravel supply of up to 200,000 m³ year⁻¹ downstream of the hydropower plant Freudenu, the river bed erodes by about 2 cm year⁻¹ along the Danube reach East of Vienna [24, 27]. The situation at some reaches along the Middle Danube is similar. For example, the erosion process at the Hungarian Danube at Dunaföldvár between 1949 and 2003 amounts to about 2.3 m (Fig. 7b).

The reach and local scale conditions at the Lower Danube, characterized as erosion reach (Fig. 6), are different in comparison to the upper reaches. The Lower

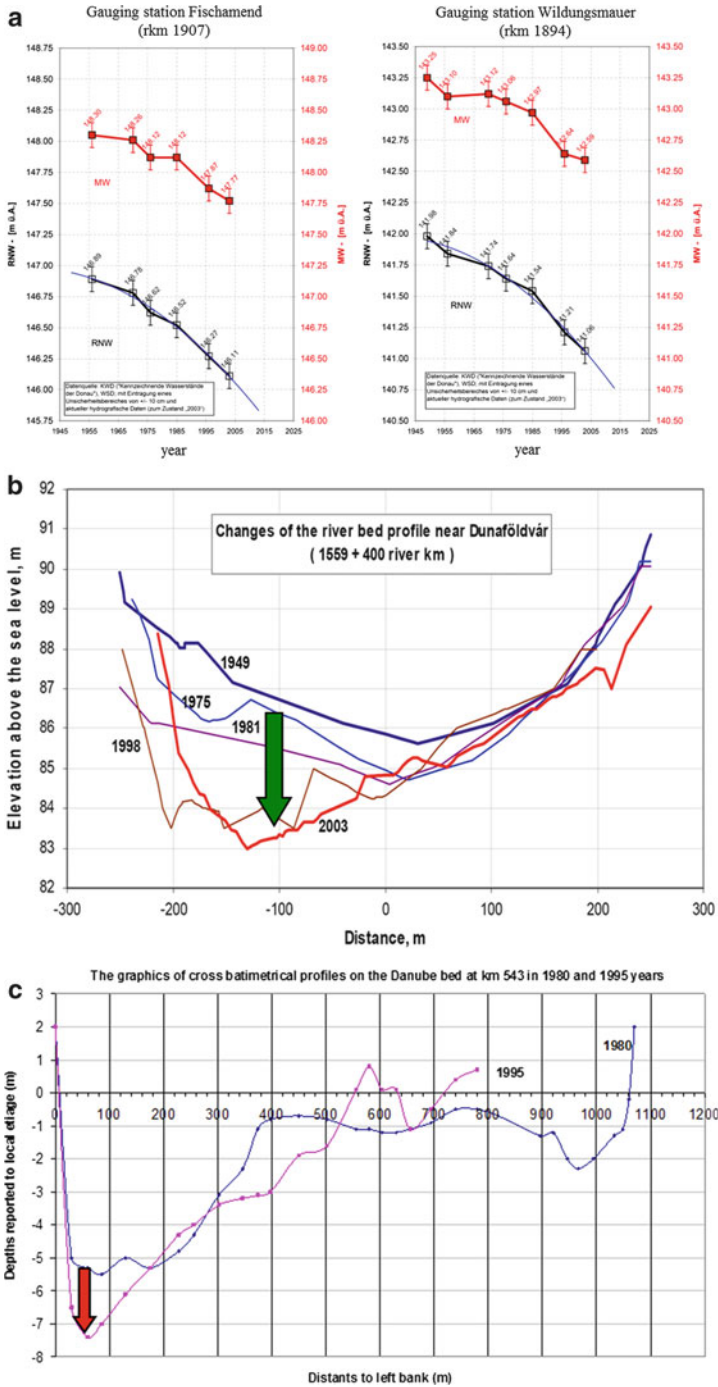


Fig. 7 (a) Erosion rate at the Danube East of Vienna at the gauging station Fischamend and Wildungsmauer [24], (b) erosion rate at the Hungarian Danube at Dunaföldvár [25], (c) river bed

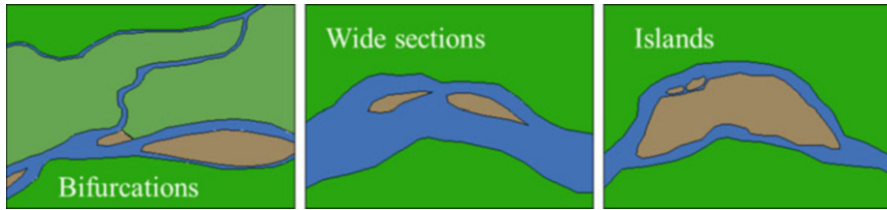


Fig. 8 Actual situation at the Lower Danube (*bottlenecks*)

Danube has to be described as a sandbed river with partially anastomosing morphology. Most of the river banks are still unprotected forming sandbars, which are ecologically very important. River bed incision is dominating. In calculating means, bed erosion has been determined which amounts to $1\text{--}3.5\text{ cm year}^{-1}$ between 1985 and 2005, highlighted, e.g. by a river transect at rkm 543 (Fig. 7c). The depths in the figure are corresponding to the low water level, compared to which the river bed incised in total by 2 m at that location. Similar is the situation between Corabia and Oltenita, which exhibited river bed incision along this section in the studied period between 1982 and 2000. At the present situation, mainly river bed erosion but also depositional processes (resulting in diverse morphological conditions, e.g. bifurcations, wide sections and islands) occur on the local scale of the Lower Danube together with the diverse demands of several stakeholders (e.g. navigation, ecology) which result in different bottlenecks (especially for navigation) (Fig. 8).

As there are still conflicts of interests given along the unprotected banks and islands of the Lower Danube, the already mentioned process of lateral (local) erosion has to be addressed in detail. Exemplarily, within the reach between Turnu Severin and Chiciu Calarasi, the number of islands increased from 93 in the year 1934 (with a total length of 283 km) to 135 in the year 1992 (with a total length of over 353 km) as a result of successive river bank erosion (side erosional processes) as a consequence of river bed erosion [26]. As one of the reasons for the formation of sandbars and islands, the lack of sediment input from upstream has to be mentioned (causing incision and the related bank failure).

The alterations in river morphology and the sediment regime (longitudinal/lateral) and the consequent disturbances in river morphology may be further negatively enhanced due to extensive floodplain degradation in the river basin. Along the entire Danube River, land use modifications since the nineteenth century have led to partially drastic interventions into the river system and especially to the adjacent land (floodplains). The process of wetlands and floodplain forests destruction has accelerated over the last decades [16], as the building of flood protection dike and drainage canal systems allowed intensive, industrial development but also

Fig. 7 (continued) erosion at the Lower Danube at rkm 543 (between Zimnicea and Giurgiu) measured in 1980 and 1995 [26]

contributed to the overall loss of some 80% of the former Danube floodplains during the last 100 years [28]. About 80% of the original floodplain area in the Danube River Basin has been lost since the twentieth century (e.g. loss of floodplains in Hungary, 10,000 ha; in Slovakia, 4,000 ha; in Bulgaria, 72,600 ha; in Romania, 426,000 ha) leading to the loss of important functions for the entire river system (purification of water, flood storage, groundwater recharge). The total area of historical floodplain and wetlands along the Danube and some main tributaries was about 41,600 km²; the remaining floodplain wetlands amount only to 7,845 km², which results in a floodplain loss of more than 3/4 of the former dimension (only ~20% of the former floodplain area is remaining) [3, 28, 29]. Of course this reduction of floodplain width leads to an increase in bed shear stress of the main channel, thus increasing river bed erosion.

In summary, the formerly morphologically undisturbed Danube River system suffers on various scales from the combined impacts of several driving forces (predominantly flood protection, navigation as well as hydropower generation) which have been identified in the presented study. In order to support the conditions for navigation and for flood protection and hydropower generation purposes, most of the Danube has been constricted, channelized into one single channel and disrupted from the adjacent floodplain areas, leading to severe morphological degradation. Hence, the non-impounded sections feature conditions as increased shear stresses, sediment transport, reduced lateral sediment exchange and input and morphodynamics. Moreover, as a consequence of the sediment supply limitation and channelization, the free-flowing sections are subject to various forms of river bed degradation and loss of instream structures.

5 Discussion

Throughout the presented study, various anthropogenic pressures on Danube sediment regime and morphology have been identified and presented at different scales. As it could be clearly figured out, concerning the aims of the paper, the impacts are not always related to one trigger factor but have to be seen as a sum of multiple pressures on the river. In addition to sediment regime and hydromorphology, the role of hydropower plants (dams and weirs) in relation to a changed hydrology and hydraulics has also to be discussed [14]. Large hydropower plants alter the hydrology and hydraulic as they increase the water level upstream of the impoundments (e.g. Gabčíkovo – in Bratislava by about 2 m between 1992 and 1996) and lower flow velocities in hydropower reservoirs. In addition to that, the flood retention capacity has been reduced significantly (e.g. the retention capacity during floods at the Lower Danube reduced from 15.6×10^9 to 4.0×10^9 m³) resulting in increased flood wave velocities downstream (by approx. 12 h between 1950 and 2012 for the Upper Danube [30]) and with obviously negative consequences for flood protection. Moreover, the effects of intermittent hydropower

generation on river hydrology and hydraulics in the form of hydro-peaking may cause huge water level changes by releasing water by pulses several times per day [31].

Besides the already mentioned impacts from land use (e.g. decrease of floodplain areas and thereby impacting hydrological and hydraulic characteristics of the Danube), drainage and irrigation are also responsible for the change (drop) in water levels [11, 14] and have to be discussed and/or considered for future river basin management. Especially the changes in adjacent forest cover alter hydrological processes significantly. With regard to diffuse sources, the change from natural systems to agricultural land use heavily increases the nutrient emissions into the river system even if nutrient management is optimized for water protection [32]. An important issue concerning future land use change/management in the Danube River Basin is surface run-off in general, which goes hand in hand with soil erosion (less infiltration contributes to surface erosion). As the compaction of soil leads to higher surface run-off in general, soil cultivation/land management influences the intensity of surface run-off.

Moreover, additional increased impacts of climate change (global warming) are expected for the Danube hydrology affecting the entire river basin, increasing those pressures which are already given. The impacts on river hydrology resulting from climate change (e.g. the reduction of floods in springtime) are manifold. Strong regional differences have to be considered. Especially for alpine catchments (main tributaries of the Upper Danube), the effects especially in terms of snow accumulation and snow melt will be strong. There is the tendency of decreased snow accumulation and earlier snow smelt caused by higher air temperature and a higher rate in liquid precipitation. This will result in more run-off during winter and less in the summer period. In areas with lower altitude, the low flow periods will be strongly affected. Here a clear increase in days of low flow (e.g. dry periods) was recorded. Moreover, an overall trend to a seasonal change in flood appearance may be possible. The number of floods in summertime will decrease in which the amounts of the seasonal shift will vary from area to area.

The expected future costs of EU policies on climate change are enormous. Exemplarily, for the Upper Danube the estimated total damage of a 100-year flood is projected to rise by about 40% of the current damage estimate (corresponds to an increase of €18.5 billion) for the high emission scenario and about 19% for the low emission scenario (control period 1961–1990; future period 2071–2100). The number of people affected in the Upper Danube is estimated to increase by 242,000 (~11%) for the high emission scenario and 135,000 (~6%) for the low emission scenario [33]. Moreover, drought periods (e.g. in 2003), related to climate change, will have significant consequences on, e.g. hydro-generation, navigation as well as water quality (e.g. increased nutrient concentrations in the Danube Delta). The extreme drought in 2003 showed a significant reduction of hydro-energy production in the range of run-off-river power stations. In Austria, it was the least production since 1955 [34]. All these aspects of climate change have to be considered and discussed in addition to the alterations of sediment regime and hydromorphology according to the aims of the WFD for the necessary river basin management at the Danube.

For future mitigation, especially along the upper and middle reaches of the Danube, river restoration combined with the planned improvement of navigation should be implemented as an integrated aim. At the Lower Danube, however, preservation of already given morphodynamics and restoration of floodplains in combination with the improvement of navigation should be the target. Based on the findings of the presented study, ways for the preservation and/or restoration/improvement of the sediment continuum (i.e. sediment transport) along the entire Danube and its tributaries across hydropower plants and torrent control structures have to be discussed. Therefore, a catchment-wide sediment management concept should be developed under an integrated synopsis of bed morphological processes with the elaboration of measures (e.g. against river bed degradation and aggradation of reservoirs and of the inundation areas) that considers the improvement of the ecological status (EU legal requirements). Hence, the ongoing river bed degradation has to be stopped by, e.g. implementation of a sustainable stabilization of the mean bed level.

Referring to river restoration, the implementation of such measures has to be analysed and discussed according to the given river morphological processes by allowing side erosion as well as bed and side-arm development, which positively influence at the same time the heterogeneity in river morphology and the habitat diversity. Furthermore, the river morphology (type and processes) and sediment qualities (physical, chemical, biological) should be assessed prior to planning and executing any interventions. Based on the findings of the presented study (identification and listing of multiple alterations), the restoration of the longitudinal and lateral river continuum has to be seen as the basis for the sustainable improvement of the ecological status, especially at shorelines and side arms, by means of reconnection of the former side-arm system or at least connection during higher discharges, river bank restoration and the improvement of aquatic/semiaquatic habitat quantity and quality (pioneer and dynamic sites). Additionally, the remaining floodplains should be conserved and restored as natural landscapes and flood retention areas by initiating self-forming processes (morphodynamics).

The alterations described in this paper should be considered in all future projects and river basin management plans as there is the need for an integrated design of ecologically compatible measures for navigation, hydropower and flood protection (win-win situation) in order to equally regard hydraulic, morphological and ecological criteria. Moreover, the possible implementations of new measures need to have a repairing/restoring effect for hydromorphology. For example, navigation should be improved on the reach scale by developing ecologically compatible measures (preparation of an integrated design for regulation structures) adapted to the local situation (e.g. modification of existing groins where suitable, construction of new modified forms and lengths of groins with respect to distance relations, usage of innovative bed stabilization measures (e.g. granulometric bed improvement at the Upper Danube)).

Another essential point is the need for the application of an integrated planning approach and principles in order to improve the current situation from various perspectives. The establishment of interdisciplinary planning teams involving key

stakeholders, including Government bodies responsible for transport, water management and environment, waterway administrations, administrations of protected areas, local authorities, nongovernmental organizations, river-related stakeholders, scientific institutions and independent (international) experts is absolutely necessary. The interdisciplinary planning teams have to define joint planning objectives, set up transparent planning processes, avoid/minimize the impacts resulting from structural/hydraulic engineering interventions, consider climate change effects, monitor the effects of implemented measures and consult existing good practice measures to improve the purposes of diverse needs (e.g. navigation versus ecology). However, most of the identified alterations, the central statements or even recommendations derived in this paper are not only valid for the Danube River Basin but also for other large river basins as well. Thus, the scientific assessment on hydromorphological disturbances along the Danube should deliver a basis for discussion, information exchange and probably a method which can be applied for other (navigable) large rivers in Europe and beyond.

6 Conclusions

The results of this paper show that the Danube River partially features a totally disturbed system (e.g. sediment balance), due to the combined impacts of flood protection, navigation (dredging, channelization, erection of groins, cutting off side arms etc.) and hydropower. The sediment continuum has been decreased to a minimum (due to torrent control, hydropower etc.), leading to a lack of bed load and suspended load in the downstream free-flowing sections. For the improvement of inland navigation, flood protection and hydropower generation, the Danube River has over long distances been narrowed, channelized, disrupted from the floodplains and morphologically degraded, thus leading in the non-impounded sections to increased shear stresses, increased sediment transport, a lack of lateral sediment transport and reduced morphodynamics. As a consequence of the limited sediment supply and channelization in the entire catchment, the free-flowing sections are subject to different forms of river bed degradation on various river scales (reach and/or local scale). Results are a loss of instream structures, especially a disappearance of gravel bars, and changes of sandbars. With the lack of morphodynamics, spawning places are disappearing, leading to a worsening of the ecological status. One of the main conclusions is that hydromorphology is not only an ecological issue but also an essential aspect for future navigation, flood protection and hydropower generation. Moreover, hydromorphological processes differ between each river section along the Danube (Upper ↔ Middle ↔ Lower Danube). In addition, cumulative effects on hydromorphology are found not only in the downstream direction but also backwards (upstream). Although a number of mitigation schemes were initiated at the Danube, e.g. in Austria, Hungary and Romania, to avoid or reduce negative effects on river environments and the continuous loss of riverine landscapes, further actions will be necessary in the future to mitigate existing impacts and prevent future ones.

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