# Joint Danube Survey 3

icpdr iksd
International Commission for the Protection of the Danube River
Internationale Kommission zum Schutz der Donau

## Extended report on: Hydromorphology

Date: 21.10.2014

Ulrich Schwarz, Katarina Holubova, Radoslav Cuban, Peter Matok, Jan Busovsky

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# 1 Introduction

Considering the River basin analysis (2005) and first River Basin management plans (2009) across Europe hydromorphological alterations were recognised as significant water management issues which is also reflected in the updated River basin analysis (2013) and upcoming update of the Danube river basin district management plan (2015) elaborated under ICPDR coordination for the Danube. The most significant pressures were defined by longitudinal continuity interruptions (dams, weirs) and morphological alterations, lateral connectivity interruptions (loss of floodplains, bank reinforcements) and hydrological alterations. These alterations may cause the decline of species biodiversity, a reduced species abundance, altered population composition as well as the hindrance of species migration and the corresponding decline of naturally reproducing fish populations (in particular sturgeon species for the Danube river itself). Alterations of sediment quantity and composition as well as sediment accumulation and erosion upstream and downstream of dams have also to be considered.

The JDS 3 Hymo assessment (longitudinal survey) and detailed JDS site analysis serve as a Danube river wide investigation of hydromorphological conditions, an evaluation tool of the current hydromorphological conditions as well as the assessment of hydromorphological alterations based on the deviation from near to natural conditions which were defined by authors for JDS3 purposes. Further it delivers basic information/data for the development of restoration measures and increase knowledge of the hydromorphological conditions of the Danube. The hydromorphological assessments which were performed in the frame of JDS3 are based on a methodology which was elaborated for this purpose. The results provide information based on the applied methodology, which does not replace any national methodology in any Danube riparian country. The results can therefore by nature differ from assessments which were performed based on different national methodologies.

After the first overall hydromorphological assessment of the Danube during JDS 2 in 2007 (ICPDR 2008) a methodology which was oriented on the CEN standard (CEN "Water quality - Guidance standards on the assessment of hydromorphological features in rivers" (EN14614:2004 (CEN 2004) and CEN "Water quality – Guidance standard on determining the degree of modification of river hydromorphology" EN 15843:2010 (CEN 2010)) was further extended and applied during JDS 3 to 10 rkm segments. In addition a detailed in-situ measurement and sampling of hydromorphological parameters was possible for all of the 68 JDS 3 sites. The SOP (Standard Operational Procedure) for the hydromorphological analysis defines the two different approaches for the continuous longitudinal assessment and the detailed site survey. The first one will assess the hydromorphological situation along the whole Danube while the latter one provides substantial supporting data and information for the interpretation of biological results at a particular sampling site and allows the comparison and validation of the assessment by detailed field measurements by using a specific site assessment approach (CEN based national SK approach developed by VÚVH). To fulfil the main task the so called WFD 3Digit approach, a selection of relevant parameters applied for the near to natural[1] based assessment of the morphological, hydrological and continuity components required by WFD (Annex II and V) parameters of the continuous assessment were used during JDS 3.

The first time measured hydromorphological parameters for each site in detail raised the quality and reliability of hydromorphological assessment significantly and support directly the assessment of the

[1] for the entire document the near to natural conditions should be seen as those defined by authors for JDS3 purposes

biological elements for water bodies under the WFD. The strongest link is given to the physical habitat
description of fish, macrozoobenthos and macrophytes, by providing data on substrate composition, flow velocities, discharges and the width-depth variability of sites by detailed cross sections.

The JDS 3 hydromorphological survey delivers a sound based data set supporting the required hydromorphological risk assessment by the countries, underlined by in-situ measurements and provides for the first time detailed physical habitat data for 68 JDS sites allowing more specific analysis and correlation between Biological Quality Elements (BQE) and Hydromorphological Quality elements (namely for morphology and flow regime). The assessment was based on a concise methodology, applicable for the whole 2,400 rkm long Danube river stretch assessed during the survey and should supplement, but not substitute, the national hydromorphological assessments required by WFD.

During entire JDS 3 relatively steady low flow conditions prevailed in the Danube. Also not all of the methodological parameters could be measured in situ in all river sections due to different reasons.

# 2 Methods

The preparation, survey and elaboration of results were a process taking over two years and included a collection of a lot of background data and several working steps. Based on the experiences of JDS 2 the following working steps can be distinguished:

1. A various set of background maps and data was collected prior the survey and provided to the core team members such as current and older navigation maps or high resolution aerial images in form of so called “Fact sheets” for all JDS sites.
2. Method development (both for continuous assessment and site survey) and preparation of the survey equipment and operation.
3. Survey, site sampling (measurements and sediment samples), assessments and photo documentation
4. Databases, analysis with resulting graphs, maps and reports

To manage collection of all data during JDS 3 there were always two HYMO experts working on board of the ship and three experts involved in preparing the methods, data and evaluation of the results.
In general two major survey and assessment methodologies can be distinguished:

1. Continuous longitudinal hydromorphological assessment of 10 rkm segments (it is important to indicate that the CEN oriented method used in the JDS assessment are based on principle of “arithmetic mean” value both for WFD 3Digit and for the overall assessments).This approach was also applied for transboundary stretches where the arithmetic mean values integrate conditions from both banks and do not reflect the specific situation from each river bank.
2. Detailed site analysis by field work data, measurements, samples and assessment

For the continuous assessment all the data is qualitative and obtained by high resolution image analysis, maps and field observations, where ever possible during low water conditions.

## 2.1 Continuous longitudinal hydromorphological assessment of 10 rkm segments

The assessment is based on a 10rkm segmentation of the whole Danube from Kelheim to the delta (about 2,420 rkm) allowing assessment values for channel, left/right banks, left/right floodplain (forming the base dataset for the WFD 3Digit assessment) as well as the overall assessment.

The assessment of the hydromorphology is based on comparing the deviation from near to natural conditions which were defined by authors for JDS 3 purposes (see extended version on the attached CD) based on the given Danube typology developed in 2003 by Sommerhäuser et al. (see Table 1 below).While some parameters were derived from various historical sources (such as planform, floodplain extent, land use), other parameters are only defined as presence or absents (degree) of human alterations, namely the amount of artificial bank material.

## Table 1: The 10 River Section Types

| Section Type | Planform and slope | Substrates | Width-depth variability and erosion/deposition character | Floodplain |
|---|---|---|---|---|
| **Section Type 1: Upper course of the Danube (rkm 2786: confluence of Brigach and Breg – rkm 2581: Neu Ulm)** | Not part of JDS3 Hymo Assessment | | | |
| **Section Type 2: Western Alpine Foothills Danube (rkm 2581: Neu Ulm – rkm 2225: Passau) with a sub-section from Regensburg to Passau** | Prevailing anabranching character, smaller meandering sections in particular between Straubing and Vilshofen; the slope varies between 1.1 ‰ at Ulm and 0.3 ‰ at Regensburg. Gorge sections are Steppberg (km 2486 - 2478) and Weltenburger Enge (km 2422 - 2414). | The channel substrates are dominated in the upper course by cobbles, gravel or sand. Further downstream a mixture of gravel and sand is present. | High variability in main and side channels, most of the side channels are connected all over the year, rather high dynamic of banks and islands, highly developed riffle (ford)/pool sequences | Floodplain has 0.5-5 (locally up to 10 km) km hosting soft and hard woods as well as oxbows and meandering tributaries in the lowlands. |
| **Section Type 3: Eastern Alpine Foothills Danube (rkm 2225: Passau – rkm 2001: Krems)** | Characterised by narrow gorges (straight, even with several rapids over bedrock) and smaller floodplains such as Eferdinger Becken and Marchland with strongly anabranching types, slope is 0,43 ‰. | Bedrock and gravel is dominating, only in the rare widening (basins) finer material occurs. | Deeper channels in narrow sections and very high dynamic of gravel bars and therefore variability of various channels in widening and basins, strong deposition activity of alpine tributaries | Only very few widening (up to 8 km) predominated by pioneer stands and gravel habitats, only a very few old branches. |
| **Section Type 4: Lower Alpine Foothills Danube (rkm 2001: Krems – rkm 1807: Gönyü/Kližská Nemá)** | The alpine Danube enters the first large plains (Tullnerfeld, Wiener Becken) and later the small Hungarian Plain, leading to huge accumulation areas and partially braided but mostly strong anabranching and at this lower end even meandering types. Slope decreases significantly from | From gravel to sand, decrease of grain sizes towards the lower end, finer material on the margin of the floodplain. | Very high variability based on the frequently shifting system of the main channel or even several channels and extensive side-channel system. | The inland delta downstream of Bratislava (second sub-section) hosts the greatest variability of such transition zones from anabranching towards meandering characteristics offering perfect conditions for the whole range of floodplain habitats, including former branches/oxbows and |

| Section Type | Planform and slope | Substrates | Width-depth variability and erosion/deposition character | Floodplain |
|---|---|---|---|---|
| | 0.35 ‰ (sub-section from Krems to Devin) to 0.10 ‰. | | | variable meanders (width between 8 km in the AT part and up to 60 km in the inland delta). |
| **Section Type 5: Hungarian Danube Bend (rkm 1807: Gönyû/ Kližská Nemá – rkm 1497: Baja)** | Gorge and distinctive floodplain reach in SK and HU with mostly anabranching character, downstream of Budapest beginning of meandering, Slope varies between 0.17 ‰ and 0.07 ‰. | Still predominantly gravel but finer grain sizes and locally silty conditions in side-channels in the breakthrough also some smaller cobble. | Still high variability and dynamics in the different channels, strong island development. | Rich floodplain with a width of 5-10 km, huge island downstream of the Danube bend up to 25 km. |
| **Section Type 6: Pannonian Plain Danube (rkm 1497: Baja – rkm 1075 : Bazias)** | The upper part down to Drava confluence with strongly meandering character, further downstream truncated meanders alongside the southern loess steep banks , strong influence of increasing discharge by main tributaries; slope (0.07 ‰ to 0.04 ‰). | Prevailing sand with frequent fine and medium sized gravel, silt and clay are still rare but downstream of lowland river confluences of Tisa and Sava more frequent. | In the meander reaches typical point bar-steep bank sequences, more and more large sandy bottom dunes and fords in the main channel. | Huge floodplain up to 30 km in the upper part, originally half of Vojvodina was regularly flooded by Danube (and Tisa), strong oxbow development stages. |
| **Section Type 7: Iron Gate Danube (rkm 1075: Bazias – rkm 943: Turnu Severin)** | Several gorges and rapids, braided rocky channel at slope breaks (0.07 ‰ to 0.25 ‰, flow velocities up to 4m/s). | Large cobbles, boulders and bedrocks, but mostly all kind of gravel and finer materials in the slow flowing sections. A lot of woody debris draped. | Very high, locally strongly limited and shallow by rocky underground, but along short, small widening also deep pools and shallow banks. | Strongly limited to often some 100 m, several tributaries with rich alluvial wood fringes. |
| **Section Type 8: Western Pontic Danube (rkm 943: Turnu Severin – rkm 375.5: Chiciu/Silistra)** | Danube flows between a high bank southern bank and a terraced floodplain on its northern side and is characterised by various types predominantly anabranching, but also some truncated meandering characteristics | Fine gravel is frequent but sand is dominating in the lower part, gravel is prevailing downstream of Carpathian tributaries, in floodplain lakes finer materials can be find. | Rather high, depending on channel form (mono channel or strong anabranching sections). Building of natural bank levees, separating narrow tributary valleys and parts of the northern | Large floodplain lakes, developed by natural levee along Danube main bank and underground water from the terraced hinterland, but frequently flooded, high diversity of waterbodies in the up to 10 km width |

| Section Type | Planform and slope | Substrates | Width-depth variability and erosion/deposition character | Floodplain |
|---|---|---|---|---|
| | (limited by high bank). On its northern floodplain typical high dynamic floodplain lakes Slope remains at 0.04 ‰. | | floodplain with fine sediment deposition, but regular exchange during floods | floodplain. |
| **Section Type 9: Eastern Wallachian Danube (rkm 375.5: Chiciu/Silistra – rkm 100: Isaccea)** | Still anabranching character with many islands, bifurcation into two main branches, sections with meandering character Slope remains at 0.04 ‰. | Mostly sandy conditions with large underwater dunes, but locally gravel due to abrasion of limiting southern high bank conglomerate and rock. | Still high variability and mobility of the channels. Main channels become deeper. | Northwards huge floodplain with up to 40 km, in the south many smaller lakes in small tributary valleys (backwater by bank deposits of Danube main channel). |
| **Section Type 10: Danube Delta* (rkm 100: Isaccea – rkm 0 on Chilia arm, rkm 0 on Sulina arm and rkm 0 on Sf. Gheorghe arm)** | Meandering planform dominates, huge liman lakes on northern part, lagoons in the southern part. Slope 0.04 -0.001 ‰. | Only fine material, sand, silt and clay. | Not very high, in the main channels deep water at the entrance to the sea (marine influences, waves). In the delta front strong accumulation dynamics (delta expansion) | Huge floodplain 5,000 km² with large reed beds but also floodplain forests and sandy dunes. Large floodpain lakes with rich water plant communities. |

For the hydromorphological assessment the Danube was subdivided into 241 segments of 10 rkm length following the current navigation map plus 18 segments for the additional Delta branches (Chilia (11) and St. Gheorghe branches (7) beginning from branch separation). Only the very first segment at Kelheim has only about 5 rkm and at the dam of Straubing the rkm was changed decades ago switching now from 2,330 rkm at the hydropower dam to 2,322.2 rkm downstream, which means nearly 8 km are missing. Therefore the segment from 2,320-2,330 is missing and the neighbouring segment calls 2,310-2,330 to keep a consistent counting in the database. Altogether 1,554 (269 x 6) sub-segments were evaluated for right and left floodplain, right and left banks, channel as well as the overall assessment. Those segments where dams fall not close to its lower ends (buffer up to 3 km to further downstream segment) were assessed as whole as having the dam inside.

Assessment class boundaries:

Class 1 Reference conditions (blue) “Near-natural”

Class 2 (green) “Slightly modified”

Class 3 (yellow) “Moderately modified”

Class 4 (orange) “Extensively modified”

Class 5 (red) “Severely modified”

The following table 2 shows the parameter groups morphology, hydrology and river continuity. For hydrology and river continuity only one parameter was used for each of these two parameter groups. For morphology eight parameters were used (see table 2), calculating the arithmetic mean. Each morphological parameter got the assessment classes 1-5: 1 (near natural), 2 (slightly modified), 3 (moderately modified), 4 (extensively modified) and 5 (severely modified). The parameters for hydrology and river continuity got only values 1, 3 or 5.

## Table 2: Assessment scheme for WFD 3 digit continuous survey

| | **Parameter** | **Values/ descriptions** |
|---|---|---|
| **Morphology** | | |
| | Planform (based on deviation from near to natural conditions for section types) | 1 = 0 % to 5 % of reach length with changed planform.<br>2 = > 5 % to 15 % of reach length with changed planform.<br>3 = > 15 % to 35 % of reach length with changed planform.<br>4 = > 35 % to 75 % of reach length with changed planform.<br>5 = > 75 % of reach length with changed planform. |
| | Substrates (Natural substrate mix or character altered) (based on deviation from near to natural conditions for section types) | 1=Near-natural mix<br>3= Natural mix/character slightly to moderately altered<br>5=Natural mix/character greatly altered |
| | Erosion/deposition character (based on deviation from near to natural conditions for section types) | 1 = Erosion/deposition features reflect near-natural conditions.<br>3 = Erosion/deposition features reflect moderate departure from near-natural conditions (10 % to 50 % of the features expected are absent).<br>5 = Erosion/deposition features reflect great departure from near-natural conditions (≥ 50 % of the features expected are absent). |
| | Extent of reach affected by artificial bank material (% of bank length) | 1 = Banks affected by 0 % to 5 % hard, artificial materials.<br>2 = Banks affected by > 5 % to 15 % hard, artificial materials.<br>3 = Banks affected by > 15 % to 35 % hard, artificial materials.<br>4 = Banks affected by > 35 % to 75 % hard artificial materials.<br>5 = Banks affected by > 75 % hard artificial materials |
| | Land cover in riparian zone (top of banks and adjacent narrow strip) (% of bank length) | 1 = 0 % to 5 % non-natural land cover in riparian zone.<br>2 = > 5 % to 15 % non-natural land cover in riparian zone.<br>3 = > 15 % to 35 % non-natural land cover in riparian zone.<br>4 = > 35 % to 75 % non-natural land cover in riparian zone.<br>5 = > 75 % non-natural land cover in riparian zone. |
| | Land cover beyond the riparian zone (based on deviation from near to natural conditions for section types) | 1 = 0 % to 5 % non-natural land cover beyond the riparian zone.<br>2 = > 5 % to 15 % non-natural land cover beyond the riparian zone.<br>3 = > 15 % to 35 % non-natural land cover beyond the riparian zone.<br>4 = > 35 % to 75 % non-natural land cover beyond the riparian zone.<br>5 = > 75 % non-natural land cover beyond the riparian zone. |
| | Degree of lateral connectivity of river and floodplain (Extent of floodplain not allowed to flood regularly due to engineering-based on hydromorphological surveys.) (based on deviation from near to natural conditions for section types) | Is over-bank flooding likely to occur (or likely to have occurred historically) naturally in the reach?<br>Yes/No.<br>If No – N/A.<br>If Yes, score:<br>1 = 0 % to 5 % reach affected by floodbanks or other measures impeding flooding of floodplain (e.g. channel and bank regrading).<br>2 = > 5 % to 15 % as above. |

| | Parameter | Values/ descriptions |
|---|---|---|
| | | 3 = > 15 % to 35 % as above.<br>4 = > 35 % to 75 % as above.<br>5 = > 75 % as above. |
| | Degree of lateral movement of river channel (% of length where lateral movement is artificially constraint) | Is the river likely to move laterally within its floodplain in the absence of any man-made constraints?<br>Yes/No.<br>If No – N/A.<br>If Yes, score:<br>1 = 0 % to 5 % reach constrained.<br>2 = > 5 % to 15 % reach constrained.<br>3 = > 15 % to 35 % reach constrained.<br>4 = > 35 % to 75 % reach constrained.<br>5 = > 75 % reach constrained. |
| **Hydrology** | | |
| | Changes of flow conditions due to artificial in-channel structures within the reach (impoundments, density of groynes and reflectors) | 1= Flow character not or only slightly affected by structures<br>3= Flow character moderately altered<br>5= Flow character extensively altered |
| **River continuity** | | |
| | Reach-based and local impacts of sluices and weirs on river continuity with regard to biological and sediment continuity | 1 = No structures, or if present they have no effect (or very minor effect) on migration or on sediment transport.<br>3 = Structures present, but having only minor or moderate effects on migratory biota and sediment transport.<br>5 = Structures that in general are barriers to all species and to sediment. |

No residual water stretches where assessed (Bad Abbach, Szigetköz) with regard to parameter group hydrology. Hydropeaking and basin wide discharge regime couldn’t be systematically assessed due to insufficient data or below level of significance as set by the countries.

The overall CEN assessment (table 3) is based on individual parameters for channel, banks and floodplain and allows an assessment into five classes based on arithmetic mean values for each parameter group and the overall assessment. For channel, the parameter of “impacts of artificial in-channel structures” was assessed only in 1, 3 and 5.

Assessment class boundaries:

1,0 to 1,4= Class 1 Reference conditions (blue) “Near-natural”

1,5 to 2,4= Class 2 (green) “Slightly modified”

2,5 to 3,4= Class 3 (yellow) “Moderately modified”

3,5 to 4,4= Class 4 (orange) “Extensively modified”

4,5 to 5,0= Class 5 (red) “Severely modified”

## Table 3: Assessment scheme for the continuous survey

| | Parameter | Values/ descriptions |
|---|---|---|
| **Channel** | | |
| | Planform (based on deviation from near to natural conditions for section types) | 1 = 0 % to 5 % of reach length with changed planform.<br>2 = > 5 % to 15 % of reach length with changed planform.<br>3 = > 15 % to 35 % of reach length with changed planform.<br>4 = > 35 % to 75 % of reach length with changed planform.<br>5 = > 75 % of reach length with changed planform. |
| | Substrates (Natural substrate mix or character altered), (based on deviation from near to natural conditions for section types) | 1=Near-natural mix<br>3= Natural mix/character slightly to moderately altered<br>5=Natural mix/character greatly altered |
| | Erosion/deposition character (based on deviation from near to natural conditions for section types) | 1 = Erosion/deposition features reflect near-natural conditions.<br>3 = Erosion/deposition features reflect moderate departure from near-natural conditions (10 % to 50 % of the features expected are absent).<br>5 = Erosion/deposition features reflect great departure from near-natural conditions (≥ 50 % of the features expected are absent). |
| | Impacts of artificial in-channel structures within the reach (impoundments, groynes) (this single parameter was only assessed in 1, 3 and 5) | 1 = Flow character not, or only slightly, affected by structures within the reach.<br>3 = Flow character moderately altered.<br>5 = Flow character extensively altered. |
| | Reach-based and local impacts of sluices and weirs on ability of biota (e.g. migratory fish) to travel through reach, and sediment to be transported naturally | 1 = No structures, or if present they have no effect (or very minor effect) on migration or on sediment transport.<br>3 = Structures present, but having only minor or moderate effects on migratory biota and sediment transport.<br>5 = Structures that in general are barriers to all species and to sediment. |
| **Banks** | | |
| | Extent of reach affected by artificial bank material (% of bank length) | 1 = Banks affected by 0 % to 5 % hard, artificial materials.<br>2 = Banks affected by > 5 % to 15 % hard, artificial materials.<br>3 = Banks affected by > 15 % to 35 % hard, artificial materials.<br>4 = Banks affected by > 35 % to 75 % hard artificial materials.<br>5 = Banks affected by > 75 % hard artificial materials |
| | Land cover in riparian zone (% of bank length) | 1 = 0 % to 5 % non-natural land cover in riparian zone.<br>2 = > 5 % to 15 % non-natural land cover in riparian zone.<br>3 = > 15 % to 35 % non-natural land cover in riparian zone.<br>4 = > 35 % to 75 % non-natural land cover in riparian zone.<br>5 = > 75 % non-natural land cover in riparian zone. |
| **Floodplain** | | |
| | Land cover beyond the riparian zone | 1 = 0 % to 5 % non-natural land cover beyond the riparian zone.<br>2 = > 5 % to 15 % non-natural land cover beyond the riparian zone.<br>3 = > 15 % to 35 % non-natural land cover beyond the riparian zone.<br>4 = > 35 % to 75 % non-natural land cover beyond the riparian zone.<br>5 = > 75 % non-natural land cover beyond the riparian zone. |
| | Degree of lateral connectivity of river and floodplain (Extent of floodplain not allowed to flood regularly due to engineering-based on hydromorphological surveys.) (based on deviation from near to natural conditions for section types) | Is over-bank flooding likely to occur (or likely to have occurred historically) naturally in the reach?<br>Yes/No.<br>If No – N/A.<br>If Yes, score:<br>1 = 0 % to 5 % reach affected by floodbanks or other measures impeding flooding of floodplain (e.g. channel and bank regrading).<br>2 = > 5 % to 15 % as above.<br>3 = > 15 % to 35 % as above.<br>4 = > 35 % to 75 % as above.<br>5 = > 75 % as above. |
| | Degree of lateral movement of | Is the river likely to move laterally within its floodplain in the |

| | Parameter | Values/ descriptions |
|---|---|---|
| | river channel (% of length where lateral movement is artificially constraint) | absence of any man-made constraints?<br>Yes/No.<br>If No – N/A.<br>If Yes, score:<br>1 = 0 % to 5 % reach constrained.<br>2 = > 5 % to 15 % reach constrained.<br>3 = > 15 % to 35 % reach constrained.<br>4 = > 35 % to 75 % reach constrained.<br>5 = > 75 % reach constrained. |

The overall assessment was applied to maintain the continuity with JDS 2 assessments, while the 3-digit assessment was performed in order to address WFD requirements.

The results of the main assessment were visualised in form of a colour ribbon map and atlas showing the overall assessment as well as the individual assessments for channel, left/right banks and left/right floodplains and are available as digital annex on the supplementary CD attached to this report.

## 2.2 Methods of Site Survey - In situ Measurements

Hydrological, morphological and hydraulic parameters were selected to cover the main indicators of morphological alteration of the river channel in line with WFD (hydrology, continuity & morphology) considering time limit (4 hours/site) and technical equipment. The in-situ measurements included: discharge, velocity (flow pattern, surface velocity), cross sections, bed material sampling, suspended load sampling, water level fluctuation, and water level slope. Field measurements are accompanied by detailed visual observations, photos and sketches done for each survey site.

Purpose and methods of field measurements are described in Standard Operational Procedure (SOP, available for all core teams) but also briefly summarized in this report including modifications that had to be implemented due to specific site conditions. In-situ HYMO survey was prepared and performed by the team from VÚVH, Bratislava, Slovakia (4 experts – two of them always on board). Substantial part of the field survey at 67 sites of the Danube and main tributaries was done by two experts either from a small motor boat or from the river bank. Detailed site observation and documentation was done during the transport between sites.


Fig.1 Discharge & velocity measurements (ADCP)

Fig.2 Bed material sampling (bottom sampler)

**Flow velocity (v) and discharge (Q) measurements: ADCP** (Son Tek - River Surveyor, 0.7 m < H < 40 m) for 3D flow velocity measurements was used to provide spatial velocity distribution and cover the wide range of water depths and velocities in the Danube (Fig.1). ADCP measurements also provided data on river channel topography (cross sections). Measurements of surface velocity (SVR-Stalker, 0.2 m/s < v < 18 m/s) were performed mostly by the macrozoobenthos group. At the section between Kelheim (JDS2) and Budapest (JDS22) just one cross section was measured 5 times (two extreme values are excluded, resulting value is the average form remaining ones). Downstream of Budapest to Danube Delta five cross sections were measured once at the sections with constant discharge. This modification enabled to obtain more detailed topography data. Discharge & velocity were measured at 59 sites. The measurements from eight sites are missing due to weather conditions or too shallow water (tributaries). Accuracy of discharge measurement (ADCP) which is usually about 99% can be lower in case of strong impoundments (very slowly flowing water - velocity decrease bellow < 0.25 m/s, JDS43 rkm 1,073, JDS44 rkm 1,040, JDS45 rkm 956) due to specific flow conditions

**Sediment sampling and analysis:** bottom sampler - drag bucket type (Fig.2) was used to collect bed material samples. The sampler lowered to the river bottom was dragged along the bed to be filled with sediments. Minimum amount for each sample was about 20 kg. Collected sediments represent mixed composition of the river bed layer. Bed material was collected mostly in the middle part of the river channel on riffle sections. Only a few samples were taken on gravel bars. Each sample was documented by a photograph. Sampling of the tributary confluences was skipped due to time and space constrains. Four sites could not be sampled mostly due to armouring on the river bed or weather conditions. Samples were transported to Hydraulic laboratory (VÚVH) and dried out. Sediment calibre was estimated using sieving method. Grain size distribution curves were compiled for all sites.

**Suspended load sampling:** depth-integrating sampler was used for measurements of suspended sediment load. The bottle with one litre volume was continually filled with water and sediments while it was slowly sank to the river bottom and lifted back. Suspended sediment sampling was performed in one vertical approximately in the middle of the river channel. Suspended sediment concentration was evaluated for 65 samples at VÚVH laboratories.

**Water level slope:** local water level slope was measured at sampling sites using the methods of classical geodesy (total station Leica TS06). Measurements were done from the river banks within the distance up to 1,000 m on the sites of the Upper and Middle Danube. Weather conditions particularly strong wind producing high waves in combination with decreasing value of river bed slope negatively influenced these measurements on the Lower Danube and in the Danube Delta.

**Water level fluctuation** – pressure probe located in sufficient water depth close to the river bank was used to record water level fluctuation. Observation was usually done during the whole available time (max. 4 hours) at 62 sites (missing sites: JDS23 rkm 1,560, JDS48 rkm 837, JDS56 Russenski Lom river, JDS57 rkm 488, JDS58 Arges river – technical reasons). Changes of water level were automatically recorded for adjusted time interval. Data were stored in the logger and downloaded to the laptop after observation. Changes of water level provided information on steady or unsteady flow conditions during the survey - relevant to HYMO measurements. Due to a relatively short time the range of hydropeaking could not be identified (usually hydropeaking occurs during morning/afternoon for peak energy demand (higher energy prices) and the fluctuation takes several hours).

Based on field measurements main hydrological, morphological and hydraulic parameters were estimated: $Q_a$ - average discharge, $v_a$ - mean velocity (+ flow pattern), cross sections, $B_a$ - average channel width, $H_{max}$ - max. depth, A- area of cross sections, $D_{16}$, $D_{50}$, $D_{84}$ – characteristic grain size, $S_{wl}$ - local water level slope, $C_{ss}$ - suspended sediment concentration, $\Delta H_{max}$ - max. water level fluctuation. Field survey data including their evaluation are summarised in numerical (Hymo Summary Table - Annex 2.2.1) and graphical form (Hymo Survey Book - Annex 2.2.2) as a part of the Extended Report on the attached CD.

## Methods for HYMOQ site assesment

Methods of "physical habitat assessment" (hydromorphological quality elements - HYMOQE) are one of the most common methods within the EU countries to characterise the hydromorphological conditions. These methods include general description of the site, characterisation and a visual assessment of physical in-stream and riparian habitats. There is a tendency to define high status/near to natural conditions only on the basis of presence and abundance of morphological features neglecting the river processes that generate and maintain the morphological units and the temporal context within which processes operate and river channels are adjusted. Therefore these methods are not comprehensive enough to adequately identify causes of hydromorphological alteration. There is an increasing need to improve the characterisation and analysis of the hydromorphological conditions of water bodies (Rinaldi 2013). Methods which were used for hydromorphological site assessments in JDS 3 are linked with these recommendations.

Hydrological regime relates to discharge variations in time including changes in flow dynamics and connection to groundwater. Morphological conditions include the physical characteristics of the river, mainly the width/depth variation, bed structure and substrate, river banks and riparian zone (floodplain should be included as well). River continuity refers to ability of water, sediments, and migratory species to pass freely upstream/downstream along the river. It should be pointed out that "fish migration aids" has no effect on river morphology.

Hydromorphological assessment neglecting the understanding of the river behaviour and physical processes in the context of human interventions may not provide sustainable solutions in the management and restoration strategies (RBMP) particularly on large rivers. Method of "physical habitat assessment" can be improved by integration of key hydrological, morphological and hydraulic parameters (measurable/verifiable by monitoring), which reflect changes in the river processes thus can be used as indicators of hydromorphological alteration of the rivers. This approach was applied by VÚVH to develop the method for HYMOQ assessment (parameters partly harmonized by CEN standards) that was verified on many Slovak rivers within HYMO monitoring over a few years (as a part of ecological monitoring). As specific approach for site analysis only the main results of HYMOQ site assessment are briefly described in this report.

The HYMOQ assessment was done for JDS 3 sites within 10 km stretches, which are consistent with 10 km segments of continuous longitudinal survey. The specific HYMO information collected during the survey along these stretches (sketches, photos, description, etc.) including visual monitoring of upstream and downstream sections are considered as well. This approach enhances reliability of the assessment as physical conditions result from processes and causes that occur at a wider scale.

Results of hydromorphological survey accomplished with site observations, technical information (river regulation, in-stream structures, infrastructures, channel maintenance, etc.), actual maps and aerial photos create the necessary background for hydromorphological quality assessment (HYMOQ). Historical maps document the near to natural conditions just before systematic river regulation was done (near to natural conditions). These maps indicate a degree of current morphological alteration and delineate important framework for sustainable river restoration to achieve ecological targets of WFD. Therefore historical maps for entire Danube were used in HYMOQ site assessment (Schwarz 2013).

Eight indicators, which include several hydrological, morphological and hydraulic parameters are considered to estimate the final HYMOQ class: river planform, habitat diversity, flow regime & flow dynamics, sediment continuity (sediment, water, fish), local channel morphology, lateral connectivity, riparian zone and floodplain. Based on knowledge of hydromorphology, the main indicators are weighted as the impact of each differs. Final class is estimated as an average value ranging from class 1 to class 5 as follows:

| | | | | |
|---|---|---|---|---|
| near natural (1) | slightly modified (2) | moderately modified (3) | extensively modified (4) | severely modified (5) |

Scoring results which are summarized in protocols for each site (including each indicator and all measured/estimated parameters) clearly show the most important hydromorphological deficits that can be used as a basis for proposal of effective restoration measures. This makes the process of HYMOQ assessment as transparent as possible.

# 3 Results

## 3.1 Continuous longitudinal survey in 10 rkm segments

The results will be shown for each content/parameter group for the whole Danube and then for the Upper (rkm 2,415 – rkm 1,880 at AT-SK border), Middle (down to Iron Gate at rkm 1,880 - rkm 943) and Lower Danube (rkm 943 - rkm 0). In the Danube delta only the Sulina branch is included in the analysis. The hydromorphological atlas is supplemented in the CD annex and shows the full resolution of assessment in map form. One segment has 10 km length, which allows a fast readability of results (e.g. 21 segments are 210 km of the Danube).

### 3.1.1 Entire assessed Danube from rkm 2,415 – rkm 0

The WFD-3digit analysis for the entire Danube indicates the general alteration (prevailing classes 3-5), in particular the best documented parameter group „Morphology“, but also the „Hydrology“. The longitudinal continuity is interrupted by 18 dams (segments). For two with functionning fish passes and partial sediment feeding (Wien-Freudenau and Melk) the value is „3“ according to CEN standard.

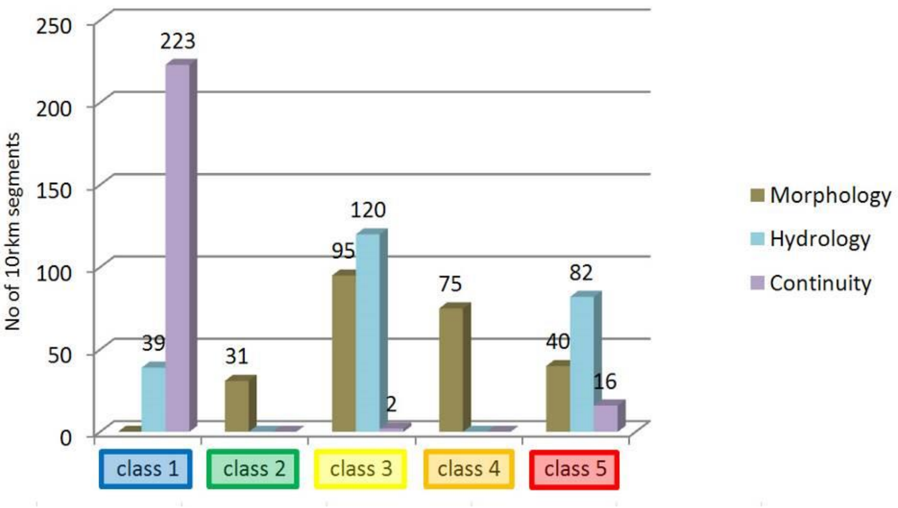


**Figure 3: WFD-3Digit assessment**[2]

**Next page Figure 4: Longitudinal visualisation of the WFD-3Digit assessment (for coloured assessment classes compare with previous chart)**

[2] For "Hydrology" and „Continuity" only the classes 1,3 and 5 were evaluated (same for Fig. 10, 12 and 14)


Morphology
Hydrology
Continuity
RKM_24102415
RKM_23802390
RKM_23502360
RKM_23102330
RKM_22802290
RKM_22502260
RKM_22202230
RKM_21902200
RKM_21602170
RKM_21302140
RKM_21002110
RKM_20702080
RKM_20402050
RKM_20102020
RKM_19801990
RKM_19501960
RKM_19201930
RKM_18901900
RKM_18601870
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RKM_18001810
RKM_17701780
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RKM_00600070
RKM_00300040
RKM_00000010
Dam chain in Bavaria
Free flowing Straubing-Vilshofen
Austrian dam chain
Wachau
Upstream Vienna dam chain
Gabcikovo dam (SK)
Danube bend (HU)
Gemenc
Croatian-Serbian reach
Beograd
Iron Gate I
Iron Gate II
Lower free flowing Danube
Galati
Sulina navigation channel

The longitudinal visualisation allows a comprehensive overview of impounded reaches with position of dams (middle and rigth coloumn) and the morphology on the left. The 10 rkm lables (text) can be not shown for each segment due to space reasons.

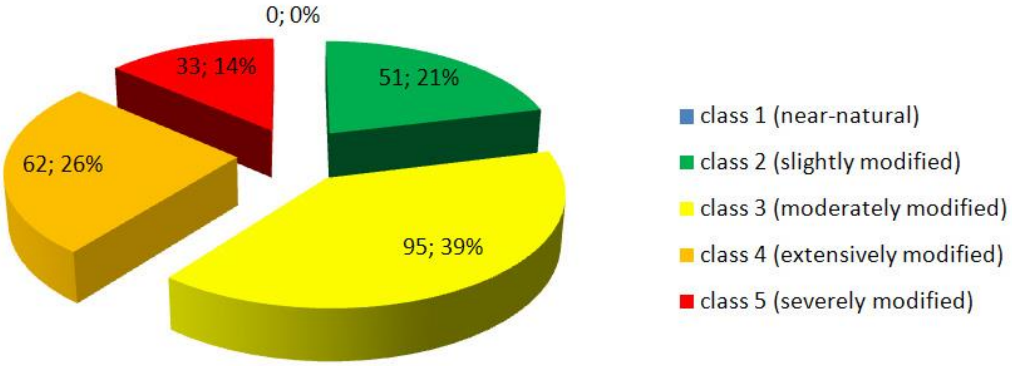


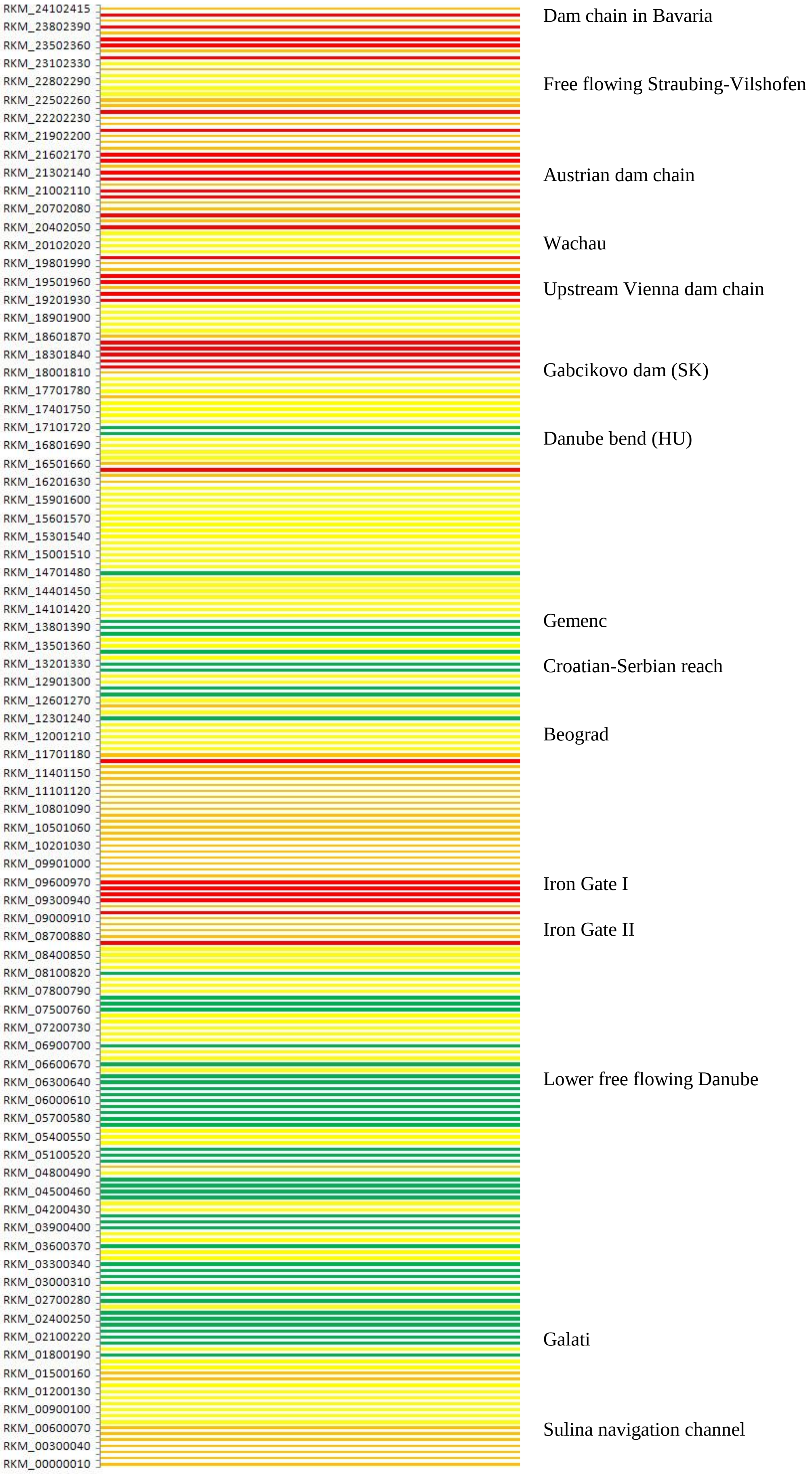

**Figure 5: CEN-Overall assessment (with colour and assessment schema)**

The class 2 (slightly modified) is represented by 21% of the analysed Danube reach (Fig. 5), followed by a significant portion of 39% in the "moderate" class (class 1 cannot be found at all). About 40% fall into the two worse classes 4 and 5. The overall picture is therefore split into a larger part with satisfactory conditions and a significant part of totally altered Danube reaches.

Figures 6 shows the whole longitudinal overview before comparing the three main sub-divisions of the Danube in detail and the single parameter groups in the next sub-chapters. The distribution of "good" and "poor" assessment in the upper and lower Danube is significant. The picture would be even more sharp taking the less modified two other delta branches (Chilia and St. Gheorghe) into consideration.

Regarding the direct comparison with JDS 2 results from 2007 it is not possible due to changed methodology. Aside of the spatial increas of assessment stretches (from 66 with an individual length of up to 120 km to 10 rkm segemnts) allowing now to assess all impoundments and regulation works in much more detail, the qualitative improvement by the assessment of 10 parameters per segment instead of one global assessment for JDS 2 lead to slightly shifitng assessments between neigbouting classes. However the overal picture having at least 60% in the classes two and three and up to 40% in four and five remains similar.

**Figure 6 (next page): Longitudinal visualisation of the CEN-Overall assessment (for coloured assessment classes compare with previous chart)**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Dam chain in Bavaria
Free flowing Straubing-Vilshofen
Austrian dam chain
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Gabcikovo dam (SK)
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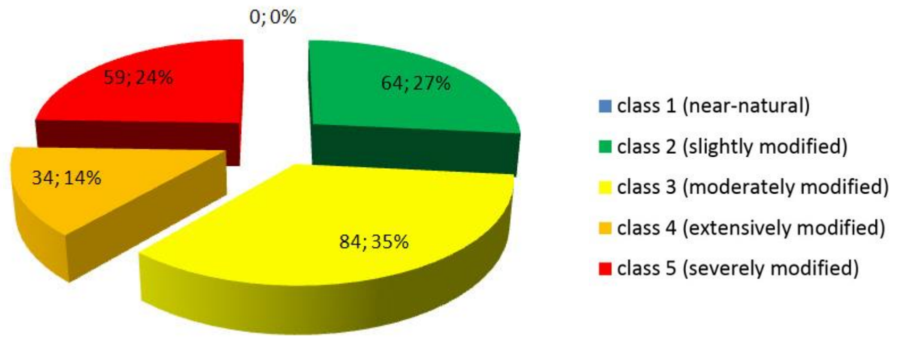
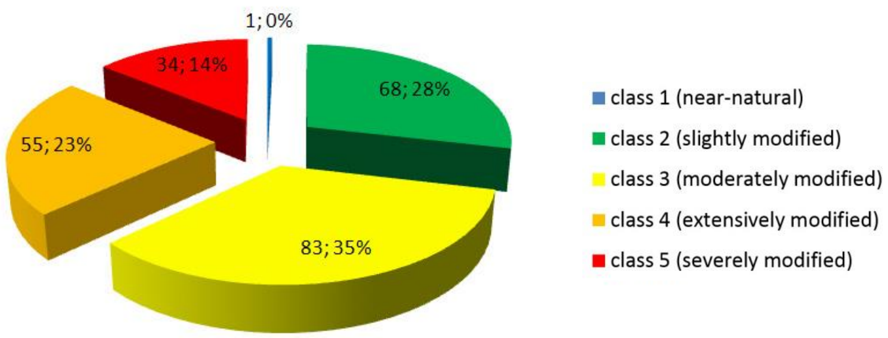
Iron Gate II
Lower free flowing Danube
Galati
Sulina navigation channel




## Figure 7: Assessment "channel"

The assessment of channel reflects very well the overall assessment. Significant amount of segments fall in the second and third class which is evident for the long free flowing stretches along the Middle (widely rectified channel, partially groynes) and in particular along the Lower Danube. About 590 km (out of 2,415 km) fall in the worst class (namely impoundments and severely altered stretches within dense settlements).




## Figure 8: Assessment "banks" (integrating left and right bank assessments)

Over one quarter of the surveyed banks fall into the classes 1-2 which is mainly due in the Lower Danube. However the transition zone from banks to floodplains is covered often by increasing poplar plantations and neophyte stands. Along the middle Danube in Hungary, Croatia and Serbia long bank sections are not continuously fortified by riprap whereas these fortified banks – belonging to the categories 4 and 5 - can be find along the Upper Danube (in addition to the higher degree of urbanisation and hydropower usage along Upper Danube, significant slope and flow velocities in free flowing reaches causing lateral erosion and channel shift which is critical for navigation).

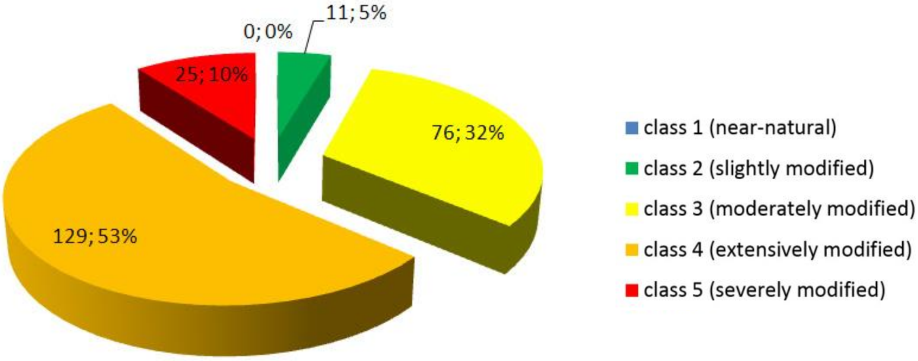
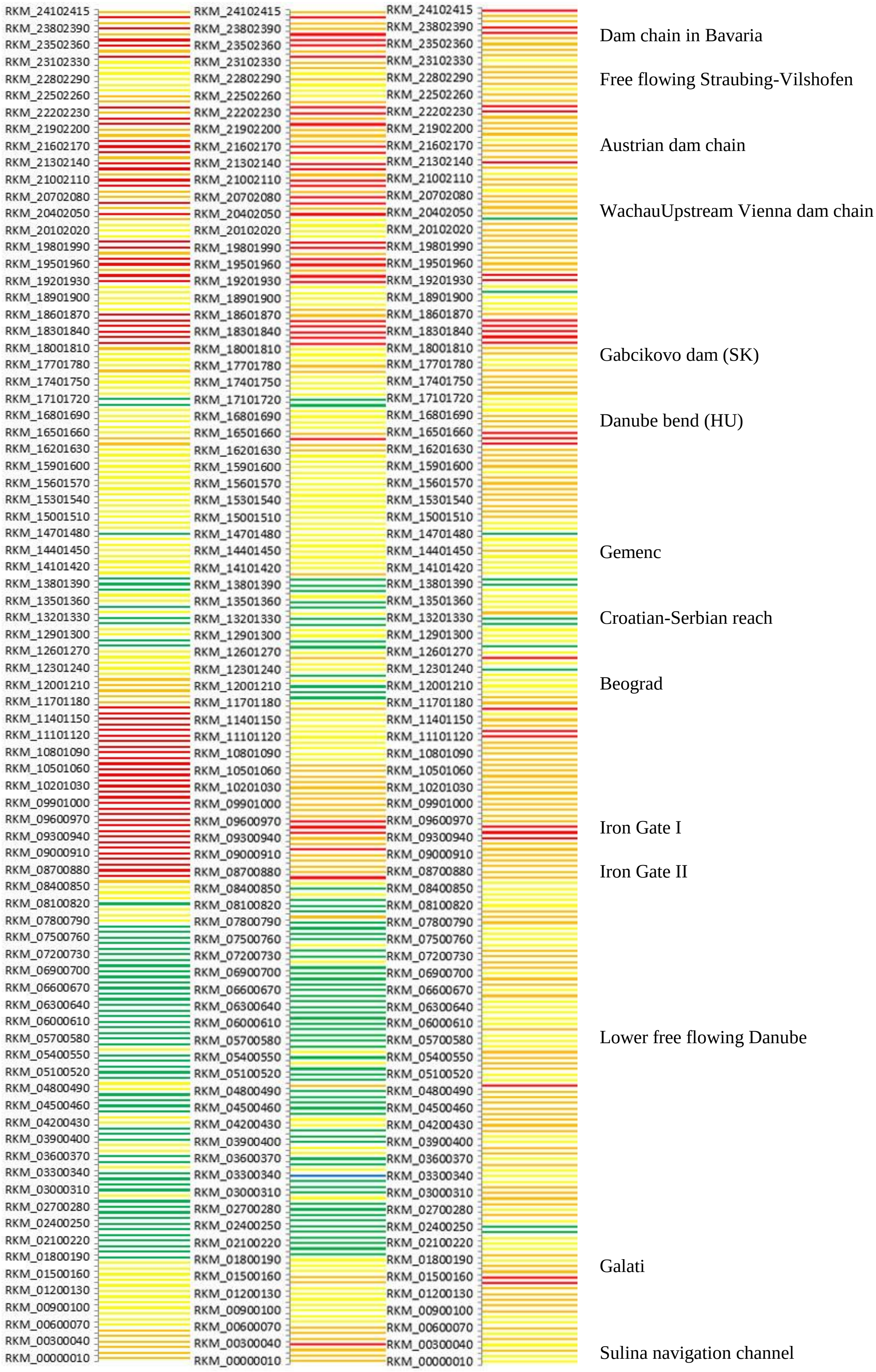



**Figure 9: Assessment "floodplains" (integrating left and right floodplain assessments)**

Only a very few stretches still host good conditions and stands of floodplains. The loss of floodplains can be assumed with at least 65-70 % for the entire river represented by class 4 and 5 but partially also by class 3. Still remaining floodplains suffer in many cases by long lasting processes of channel incision (hydrological disconnection) and fine sediment aggradation caused by dams. Furthermore, poplar plantations substitute in many cases the natural floodplain vegetation.

**Figure 10 (next page): Longitudinal visualisation for channel, banks and floodplains (for coloured assessment classes compare with previous chart)**

Channel Banks Floodplains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RKM_20102020
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Dam chain in Bavaria
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Danube bend (HU)
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Croatian-Serbian reach
Beograd
Iron Gate I
Iron Gate II
Lower free flowing Danube
Galati
Sulina navigation channel

### 3.1.2 Upper Danube (rkm 2,415 – rkm 1,880)

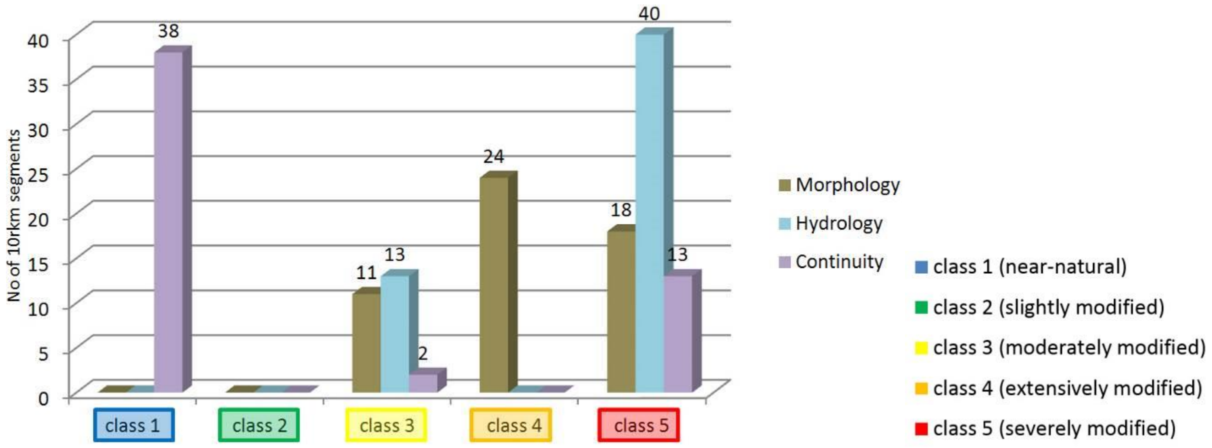



**Figure 11: WFD-3Digit assessment**[3]

The WFD-3digit analysis for the Upper Danube shows the rather high number of segments with continuum interruption (15 segments including two with fish passes). For "Morphology" class 4 and 5 prevail and the "Hydrology" clearly indicates the segments affected by impoundments and intensive river regulation works (Fig. 11).

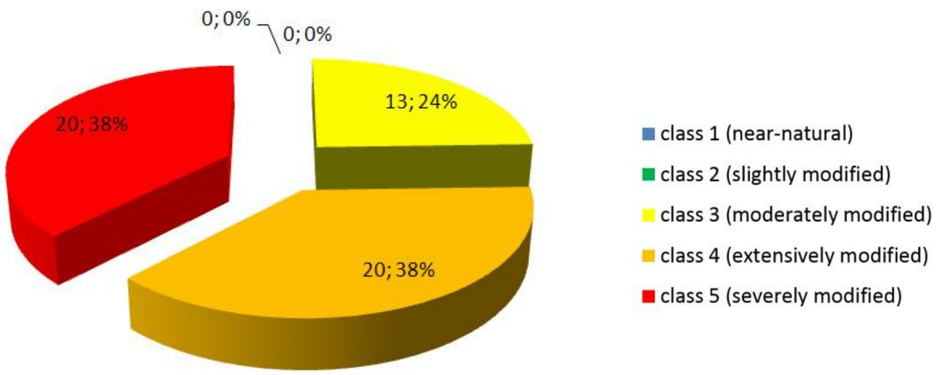



**Figure 12: CEN-Overall assessment**

Only the still free flowing reaches between Straubing-Vilsofen in Bavaria as well as Wachau and Vienna-Morava confluence fall into the „moderate" class (some segments come with an assessment value of 2.5 (arithmetic mean from individual parameter values) near to the second class). About one quarter is in class 3 „moderate" and the rest is intensively changed (Fig. 12).

[3]For "Hydrology" and „Continuity" only the classes 1, 3 and 5 were evaluated

Picture 1 (all pictures by Meter Matok, VUVH): Aside of the free-flowing section from Straubing to Vilshofen the Bavarian Danube is characterised by hydropower impoundments and navigation.

Picture 2: The Austrian Danube flows through several narrow valleys and floodplain sections. A typical picture shows an impoundment with variable bank material (rip-rap, natural rock and concrete).

Picture 3: In the Danube floodplain national park downstream of Vienna several banks were cleaned already from rip-rap, an ongoing restoration measure coordinated with navigation.

### 3.1.3 Middle Danube (rkm 1,890 – rkm 934)

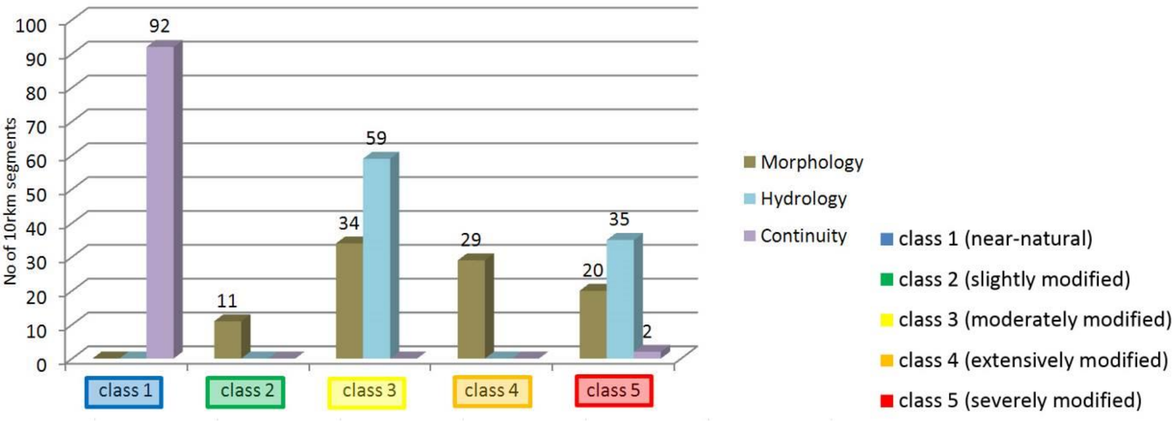



**Figure 13: WFD-3Digit assessment[4]**

The Middle Danube still hosts a couple of segments in the second class for "Morphology", but most of the segments fall into class 3 (Fig. 13). The significant number of segments for "Hydrology" in class 5 stands for the long impoundments of Gabčíkovo and in particular Iron Gate I dam. The river continuity is interrupted only in two segments (Gabčíkovo and Iron Gate I dams), but the effect of the two large dams comes along with long impoundments and sediment accumulation as well as deficits up and downstream of the dams.

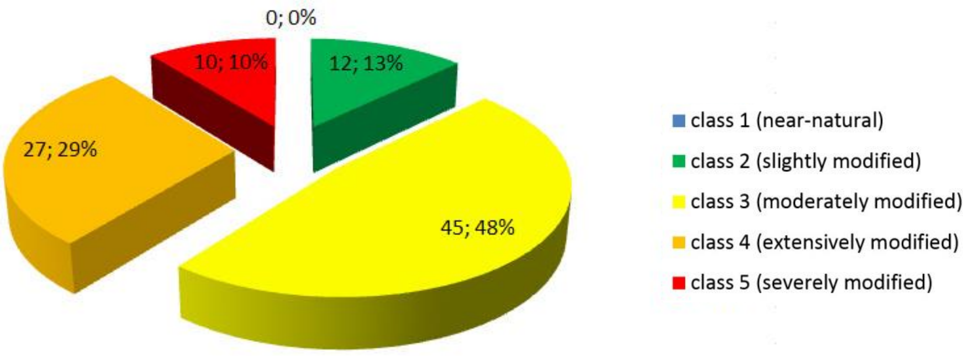



**Figure 14: CEN-Overall assessment**

At least 13% of the Middle Danube still has good hydromorphological conditions (Fig. 14), nearly the half falls in the moderate class. The rest can be found in the two reservoirs of Gabcikovo (not the Szigetköz fomer channel was assessed only the bypass canal) and Iron Gate as well as the city reaches of Budapest and Beograd.

[4]For "Hydrology" and „Continuity" only the classes 1, 3 and 5 were evaluated

Picture 4: The Danube bend upstream Budapest is still characterised by many near-natural banks and fine gravel bars.

Picture 5: Long stretches along the middle Danube are free flowing but were significantly rectified and banks frequently change from rip-rap near settlements and infrastructure to near natural banks and several groynes.

Picture 6: The Iron Gate I impoundment changed the river landscape significantly towards a lake looking ambient with reed along the shore and large water bodies.

### 3.1.4 Lower Danube (rkm 934 – 0 rkm)

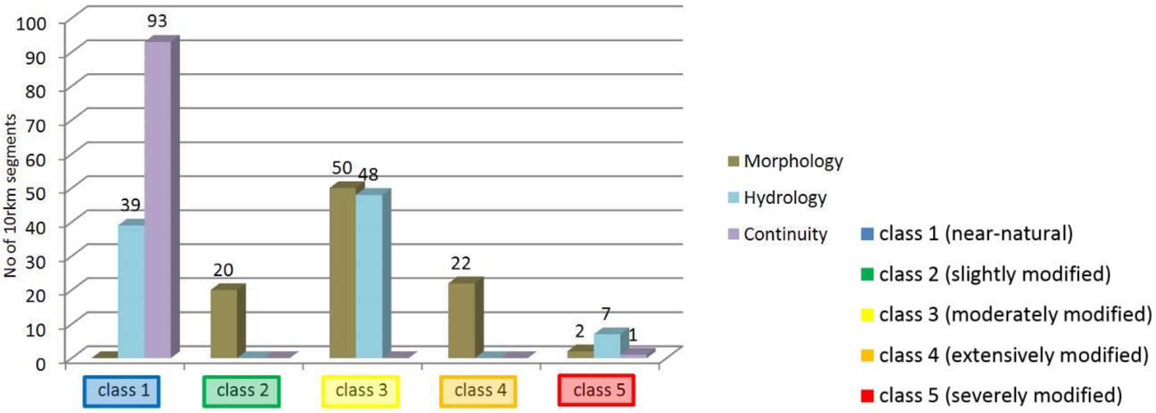



**Figure 15: WFD-3Digit assessment[5]**

Regarding the "Morphology" the Lower Danube still provides class 2 (slightly modified) stretches, but predominantly class 3 due to the limited lateral connectivity (floodplains). Class four and five fall mostly in the Iron Gate II reach. Regarding the continuity interruption only the Iron Gate falls in this reach, taking always into consideration that sediment and hydrological changes due to the two Iron

[5] For "Hydrology" and „Continuity" only the classes 1, 3 and 5 were evaluated

Gate dams (and various dams on the Lower Danube tributaries) affect the Lower Danube in generally. With about 860 km the Lower Danube represents the longest free flowing stretch of the Danube at all, represented by “Hydrology” in first and third class (Fig. 15).

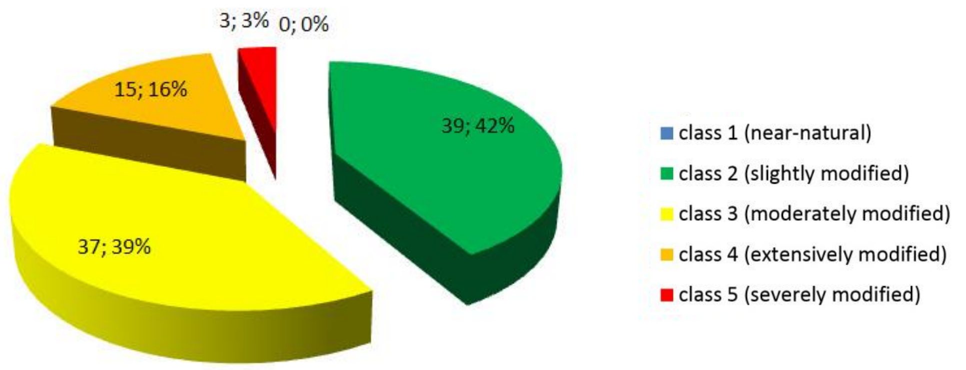



**Figure 16: CEN-Overall assessment**

Over 40% of the lower Danube stretch falls into the second class, which is remarkable in comparison with the upper Danube or e.g. Lower Rhine River. Moderate stretches fall into „town and harbour“ stretches and free flowing stretches with moderate regulation works and/or cut floodplains, the rest is in Iron Gate II reach and canalised Sulina channel in the delta. However, the entire lower Danube is inter alia influenced by the Iron Gate dams (similar as Middle Danube is inter alia influenced by major hydraulic structures from the Upper Danube) and along major tributaries (Fig. 16).

Picture 7: The lower Danube still hosts a lot of near natural banks, sand bars and islands.

Picture 8: Many eroded steep banks can be found, not only in front of natural islands or banks but also along poplar plantations.

Picture 9: Several fresh bank revetments to stop side erosion and lateral shift are under construction.

Picture 10: A non-typical picture for the Danube delta, a bank of the intensively used Sulina navigation branch.

## 3.2 Detailed JDS3 site analysis and assessment

Results provided by the detailed JDS site analysis and assessment consist of two substantial parts. The first part provides an overview of results and analyses of HYMO survey for the entire Danube. A more detailed interpretation is shown for the main morphological types defined on the Danube: Upper (rkm 2,412 – 1,880), Middle (rkm 1,880 - 943) and Lower Danube & Danube Delta (rkm 943 - 0). The second part of the results summarises the site assessment based on the results of hydromorphological survey using method VÚVH respecting WFD rules and CEN standards.

### 3.1.5 Results of hydromorphological survey - entire Danube

Relationship $Q_sD_{50} \sim QS$ represents proportionality between sediment discharge ($Q_s$), stream discharge (Q), particle size ($D_{50}$) and slope (S). A change in any of these variables sets up a series of mutual adjustments in the companion variables with a resulting direct change in the characteristics of the river (Lane, 1955). For example, changes in the bedload volume affect change in width, depth and river bed slope. Changes of the hydraulic and morphologic characteristics influence discharge capacity of the channel, which again affects river sediments. Except of sediment discharge the main variables controlling the river behaviour (Q, $S_{wl}$, $S_{bed}$, $D_{50}$) were measured or estimated during the HYMO survey. Interdependence of these variables (parameters) enables their exploitation as indicators sensitive to hydromorphological changes of the Danube river channel.

Variability of measured parameters clearly indicates the most significant changes in the river processes (erosion/deposition) that induce various degree of hydromorphological degradation along the Danube.

**Flow conditions** - interpreted by discharge, mean velocity and velocity pattern allow important insights to the hydrological and hydraulic situation during the survey. Unlike JDS2 when discharge downstream of Iron Gate significantly increased (data-gauging stations), relatively steady low flow conditions prevailed in the Danube during entire JDS3 (fig.17). There was only one major discharge increase that occurred at short section between Vienna and Bratislava. Low flow conditions enabled better site description of the river morphology (in-stream forms, river banks, riparian zone). With exception of impounded sections there is highly variable flow dynamics along the Danube (Fig.19).

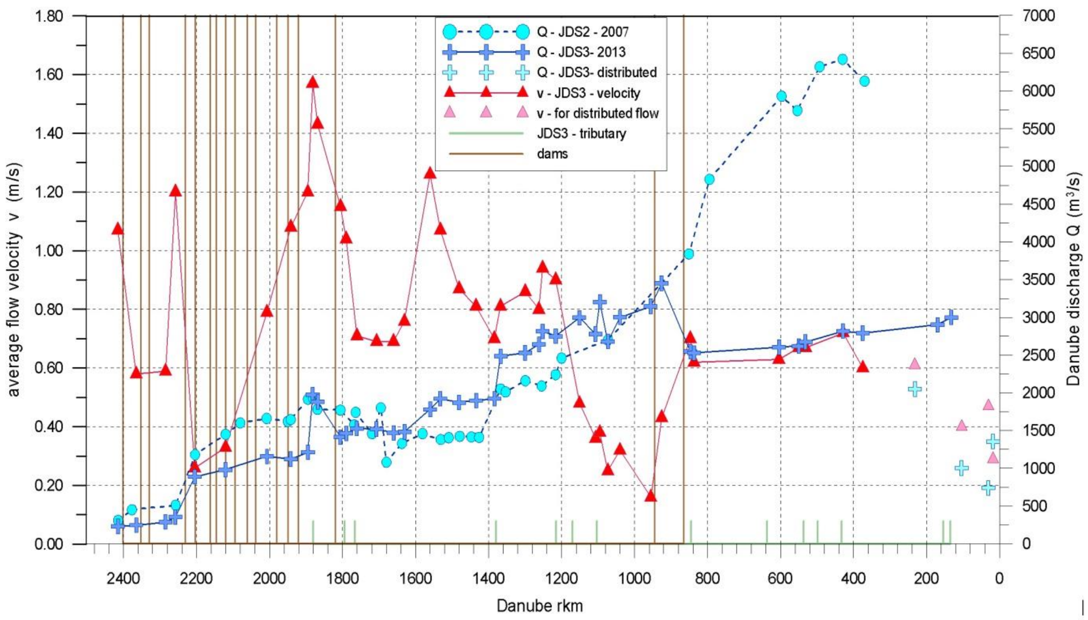



Fig.17: Flow conditions on JDS 3 and JDS 2

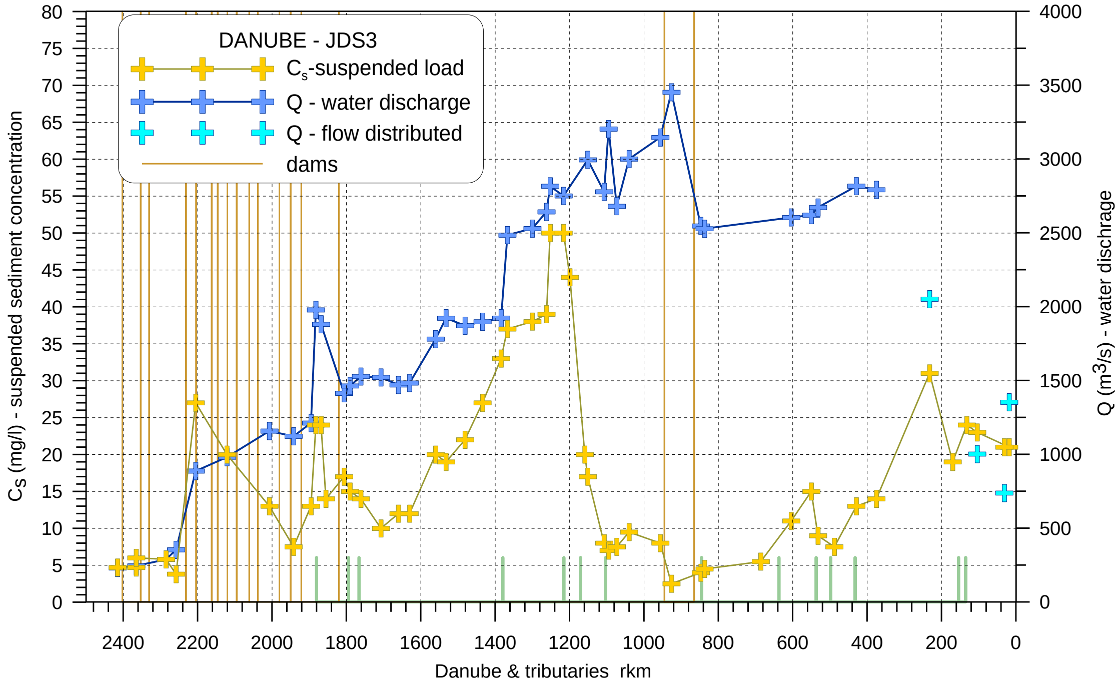


Fig.18: Suspended sediment concentrations & discharge

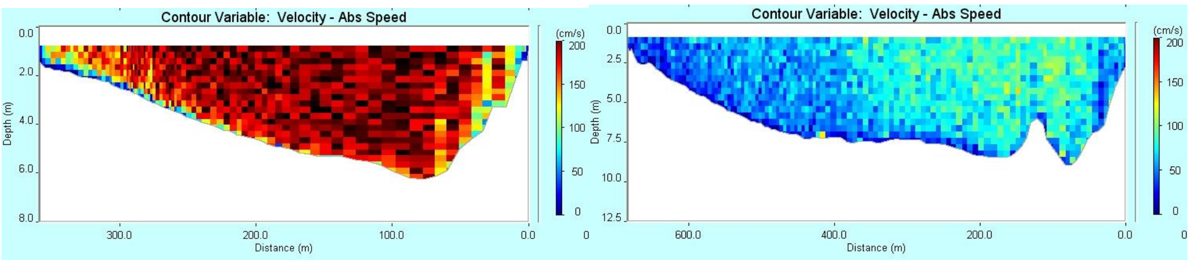



Fig.19: Flow pattern for the most dynamic flow (Upper Danube) and slowly flowing (Lower Danube)

Major changes of flow dynamics and sediment continuity along the Danube are caused by dams operated on the German – Austrian Danube (chain of dams), on the Slovak Danube (Gabčíkovo) and on the Serbian – Romanian Danube (Iron Gate). Danube dams create sections with flow deceleration (impoundment) or acceleration (just downstream of dams slope must be equalised if there is not immediately the backwater of next dam) where deposition/erosion prevail. These changes reflected in composition of the bed sediments (Fig.20), induce significant hydromorphological alteration at several longer stretches of the Danube. Changes of flow dynamics caused by groyne fields or other in-stream structures can have significant but mostly local effect on hydromorphology. There is an indication of flow regulation downstream of the Iron Gate where discharge decreased by 800 $m^3s^{-1}$. Flow regulation might cause certain effects on channel morphology downstream of the Iron Gate (discharge, sediments – see Fig. 17, 18).

**Sediment continuity** is documented by values of suspended sediment concentrations along entire Danube and tributaries (Fig.18) and implicitly by changes of flow dynamics and compositions of the bed sediments. Trapping effect of the Danube dams is documented by considerable decrease of suspended sediment concentration values along impounded sections. Disruption of sediment continuity generates not only deposition area upstream of the barrier but also lack of sediments in the downstream direction, usually related to erosion. Deficit of fine sediments downstream of the Iron Gate is obvious at long section of the Lower Danube & Delta (Fig.18). If fine sediment continuity (suspended load) is affected markedly then impact on coarser sediments (bedload) has to be even higher.

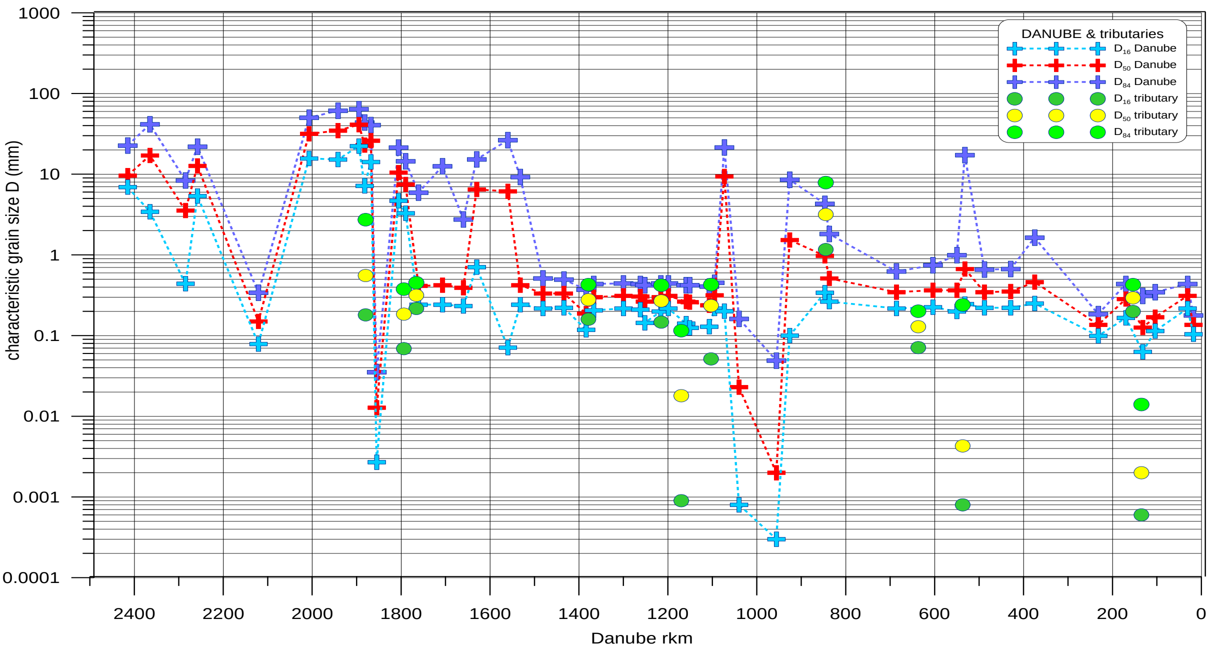


Fig.20: Downstream variation in bed material grain size on the entire Danube/tributaries

**Bed material** interpreted by grain size distribution curves represents an essential source of information to identify changes in channel morphology. Bed sediments vary in the downstream direction (Sternberg 1875), the coarse sediments of headwaters giving way to progressively finer alluvium as bas-level is approached (Ried et al. 1997). Composition of the river bed sediments, rate of downstream fining (Fig.20) and sediment sorting provide important knowledge on river processes (erosion/deposition) so they can be used as diagnostic tools mainly in case no bedload data are available.

Natural composition and downstream fining of bed sediments for corresponding channel type and geomorphological environment have been changed dramatically along entire Danube mostly due to disruption of sediment continuity and other human interventions (dams, dredging, in-stream structures, etc.). Extent of these changes is proved by high variability of bed sediment size ($D_{50}$, fig.20). Except for strong impoundments where fine sediments are deposited (sand, silt & clay) there are localities mostly downstream of dams with highly sorted coarse sediments (missing fine fractions) that imply either bed erosion or some degree of artificial bed stabilization.
Variation in bed material grain size shows even downstream coarsening instead of fining at Upper Danube (Fig.20). Better situation can be seen on the Middle and Lower Danube where composition of bed sediments is less altered and the downstream fining is already indicated. Nevertheless, the impact of two big dams (Gabčíkovo, Iron Gate) and other interventions is still evident. Results of regression analysis for downstream fining underpin these findings (coefficients of determination ($D_{50,}$ distance) for Upper Danube $r^2$ = 0,104 Middle Danube $r^2$ = 0,230 and Lower Danube $r^2$ = 0,473).

Values of mean sediment size ($D_{50}$) indicate slightly coarser bed sediments at Lower Danube (without Delta) compared with the Middle Danube. This can be caused by lack of finer sediments trapped in Iron Gate and also by coarser sediments coming from tributaries. Only one sample taken form tributary mouth does not allow more comprehensive view on the tributaries function in changes of the Danube river bed.

#### 3.1.5.1 Upper Danube (rkm 2,413 – rkm 1,880 )

Flow dynamics at the Upper Danube has been influenced by operation of the chain of hydropower plants (HPP) that creates cascade of more or less impounded sections (in case of low water impoundments are nearly continuous). Only two free flowing reaches in Wachau valley and downstream of Vienna still remain. Changes in flow dynamics can be seen on Fig.21. There are typical sections with slowing flow (just upstream of dams) or more dynamic flow (usually shorter section downstream of dams). More significant water level fluctuation ($\Delta h > 50$ cm) was not recorded on Upper Danube. The only increase in water discharge caused by more intensive precipitation occurred at short section downstream of Vienna.

Values of suspended sediment concentrations also show variability along impounded sections. (Fig.21). There are sites with evident decrease of values but also sites where suspended sediment concentration remains rather high (JDS6, JDS7) even if impounded (Fig.22). This indicates that suspended load can partly be transported through less impounded sections. Nevertheless, the chain of hydropower plants still creates a barrier for coarse sediment transport (bedload).

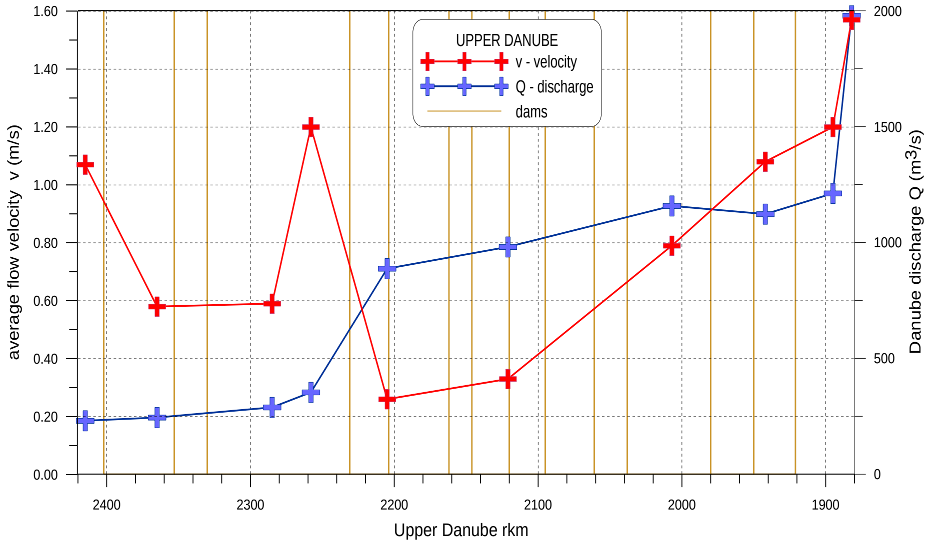



Fig.21: Mean velocity and discharge - Upper Danube

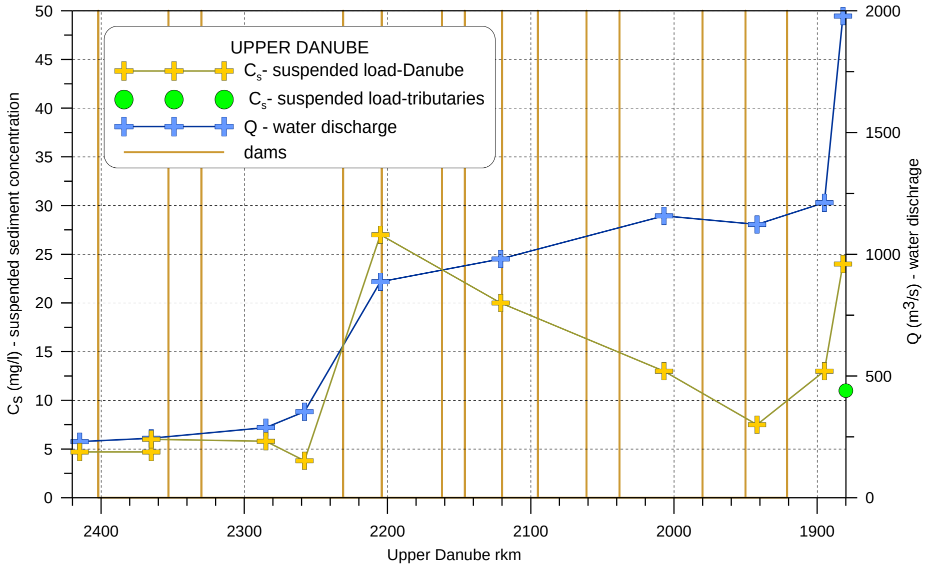
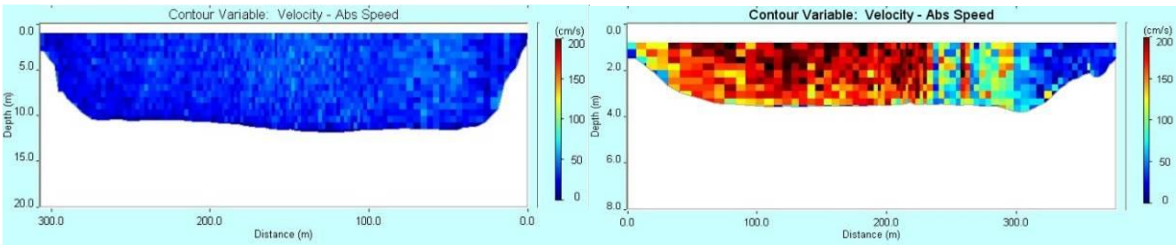



Fig.22: Suspended sediment concentrations and discharge




JDS 7-Abwiden (rkm 2121) - impoundment JDS 10 - Wildungsmauer (rkm 1895) – dstr. of HPP

Fig.23: Flow pattern for typical sites on the Upper Danube – just upstream and downstream of dam

Except for long impoundments the river bed consists of coarse and fine gravel with lower volume of cobbles. Characteristic composition of bed sediments and their variability can be seen on photos that document samples taken from the river bed at Upper Danube (Fig.24). Composition of the river considerably reflects flow conditions indicating river processes that prevail at particular site.

Difference between two samples (JDS4 rkm 2,285, JDS7 rkm 2,121) is induced by impoundment (JDS4 - coarser sediments: fine gravel, coarse & fine sand) or impoundment (JDS7 – coarse & fine sand, silt).

These differences between particular sites can be seen on grain size distribution curves (Fig.25). There are some other samples (e.g. JDS8 rkm 2,007, JDS11 rkm 1,882) taken from the river bed just downstream of dams which demonstrate high degree of sediment sorting. Bed material consists of coarse gravel and cobbles. Fractions of fine sediments are almost completely missing (Fig.24). This indicates either erosion of the river bed or some kind of river bed stabilization downstream of dams.

JDS2 Kelheim JDS4 - Deggendorf JDS7-Abwinden JDS8-Oberloiben JDS10 Wildungsmauer

Fig.24: Bed material samples - Upper Danube

Impact of tributaries on sediment composition cannot be analysed because no tributary was included in JDS 3 at this river section. Sediment continuity is highly altered at Upper Danube including two free flowing sections as due to lack of sediments from upper sections. This is proved by significant changes in river bed composition and also by high variability of sediment size along the river reach. Under these conditions downstream fining could not be identified - on the contrary, the coarsest sediments occurred at the lower edge of the river section (Fig.25, Fig.26).

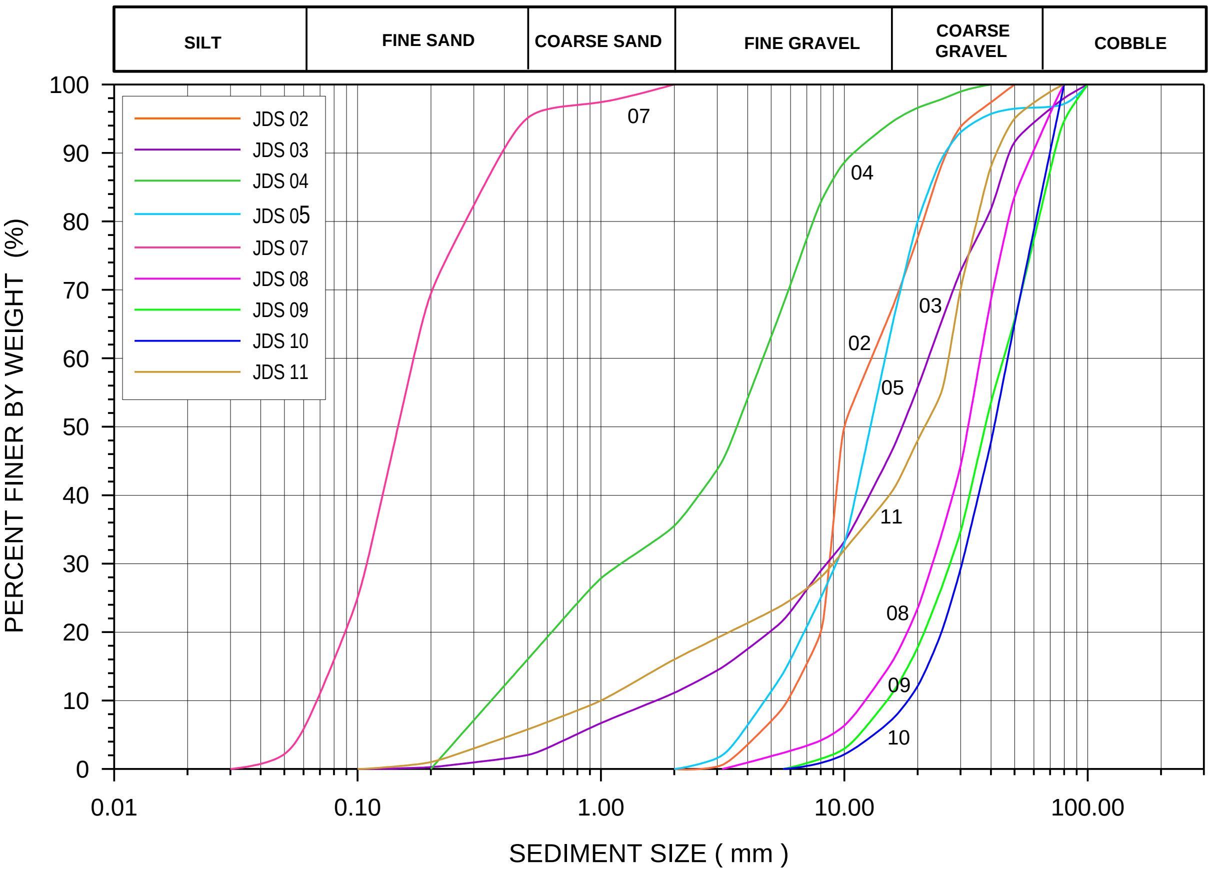


Fig.25: Grain size distribution curves- bed material

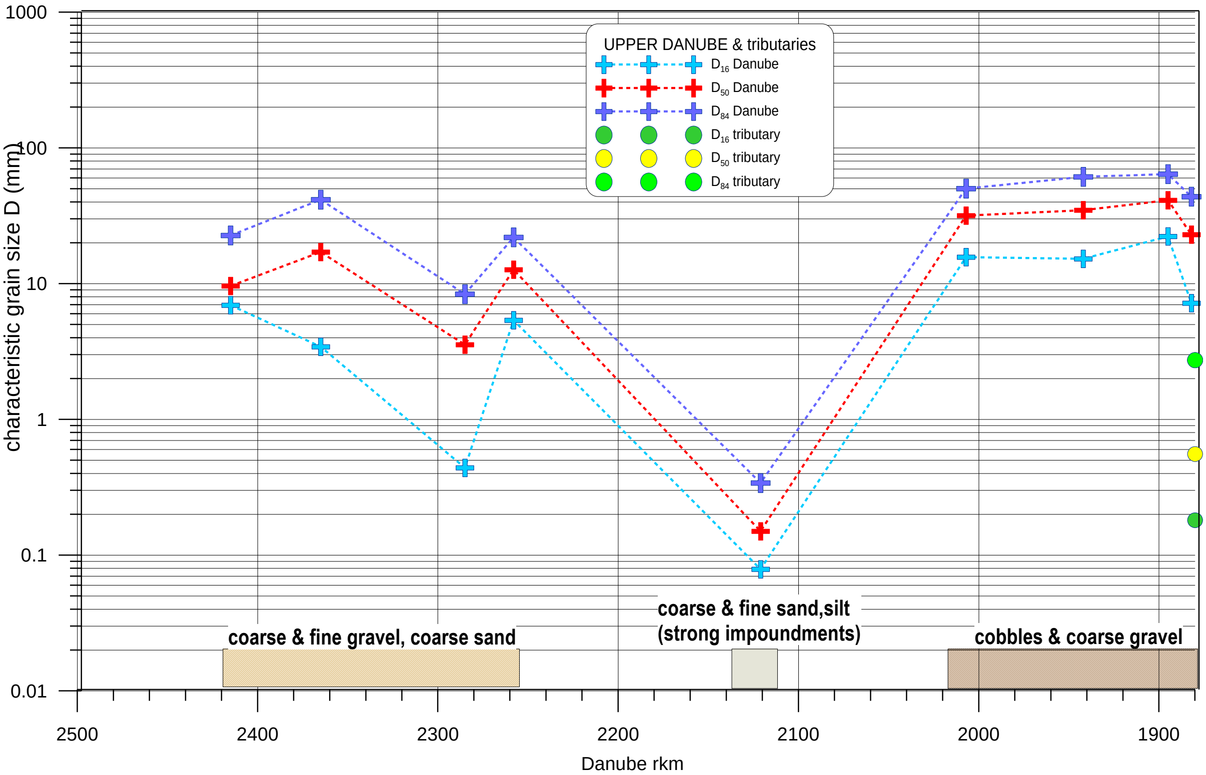



Fig.26: Downstream variation in grain size–Upper Danube

Changes in flow dynamics, sediment continuity and river morphology (regulated, uniform channel with stabilized river banks, in-channel structures e.g. groynes, deflective structures, etc.) induced high degree of hydromorphological alteration. That is the reason why the Danube sites are classified by 3, 4 and 5 in HMOQ site assessment for WFD. Nevertheless, there is still potential for improvement of the river hydromorphology as it can be seen upstream of Hainburg (area of the Danube National Park). This is the only green section (class 2) because of rather extensive ongoing restoration.

### 3.1.5.2 Middle Danube (rkm 1,880 – rkm 943 )

**Flow conditions** at the Middle Danube have been influenced by operation of two hydropower plants (HPPs) at both edges: Gabčíkovo at the beginning and the Iron Gate at lower end (Fig.27). Flow dynamics in the section between is mostly influenced longitudinally by in-stream structures (e.g. groynes) and laterally by side arms closure.  Effects of these interventions can be substantial but mostly local. Slowly flowing sections alternate more dynamic sections.

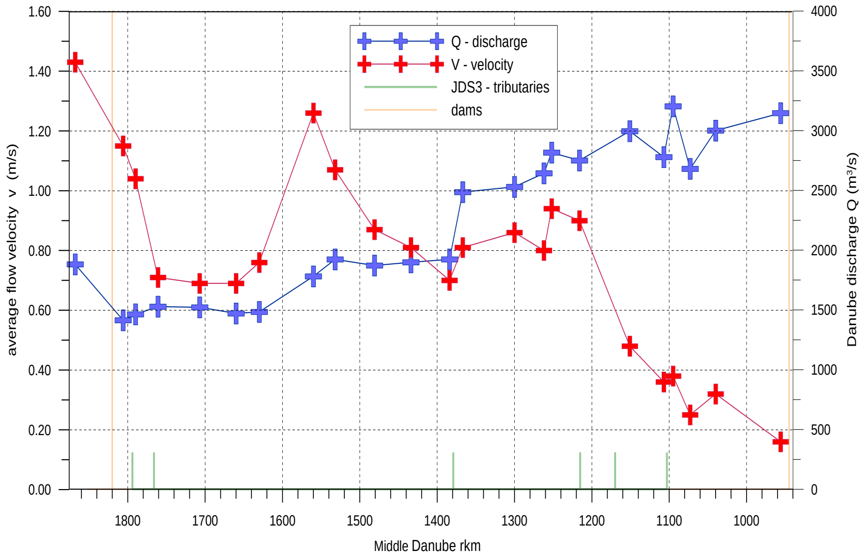



Fig.27: Mean velocity and discharge – Middle Danube

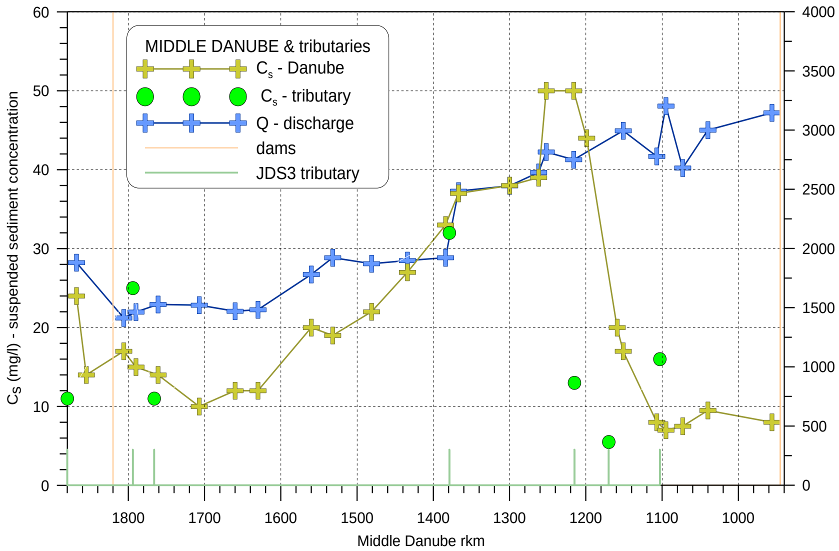
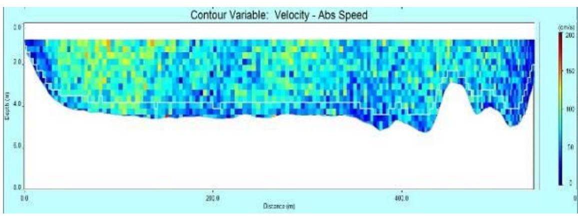
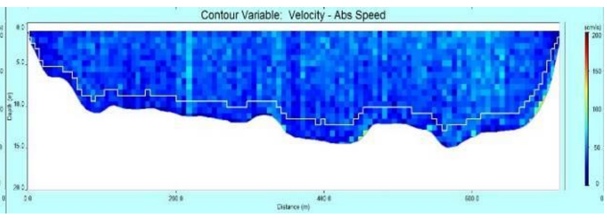



Fig.28: Suspended sediment concentrations & discharge

Gabcikovo HPP built on the bypass canal creates 40 km of abandoned channel of the Old Danube with strongly regulated flow but this part is not involved in JDS 3. Impoundment reaches nearly 50 km upstream inducing significant decrease of flow dynamics. The effect of flow regulation in the Danube downstream of Sap is small (Fig.27). Slight indication of hydropeaking was recorded during the survey (JDS15 rkm 1,806 12cm/4 hours) but it had no effect on the sections downstream (JDS17 rkm 1,790, JDS20 rkm 1,707). Results of max water level fluctuation for all sites can be found in the extended version of the report (CD).




JDS 20 – Szob (rkm 1707)




JDS 42 - Downstream Velika Morava (rkm 1095)

Fig.29: Flow pattern for selected impounded (Iron Gate) and free flowing (Szob) Middle Danube

The Iron Gate I as the largest dam on the Danube has considerable effect on flow dynamics creating impoundment of around 300 km upstream. This is documented by flow pattern (Fig.29) and mean velocity distributed along the river section (Fig.27). As the Middle Danube ends just in the locality of Iron Gate dam the impact on flow regulation is included in the next chapter – Lower Danube. The trapping effect of the Iron Gate reservoir causes considerable decrease of suspended sediment concentration downstream of km 1,180 (Fig.28) and it is linked to velocity decrease (Fig.27).

JDS14–Gabčíkovo r. JDS15-Medvedov JDS19– Iza/Szony JDS26 – Baja JDS45-Irongate r.

Fig.30: Bed material samples – Middle Danube

**Composition of the river bed** that reflects flow conditions clearly shows the impact of impoundment at both ends of the Middle Danube (Fig.30). Except for smaller amount of fine sand larger volume consists of silt and clay as can be seen on grain size distribution curves (Fig.30). Similar composition can be seen in the section of strong impoundment from the Iron Gate upstream to km 1,040 (JDS44). Coarse grains in sample JDS43 (Fig.31) belong to sediment transported from tributary Velika Morava. The river bed has a rather uniform character at the next relatively long section up to km 1,252 (JDS33). Bed sediments mostly consist of fine sand (well sorted) as a result of a less strong impoundment.

Gabcikovo creates sections with deposition upstream (40 km) and erosion downstream. Due to trapping effect of HPP there is a lack of sediments at the section downstream resulting in the river bed incision. Process of the bed erosion continues at certain section while transport capacity is not fully restored. Nevertheless sediments trapped in the both reservoirs (impoundments) create big deficit that is missing at the downstream sections.

Section of the Middle Danube outside of strong effect of both HPPs shows much more natural composition of the river bed material (Fig. 31). Bed sediments largely consist of coarse & fine gravel and coarse and fine sand. Downstream fining is indicated but influenced by high scatter due to impediments ($r^2$ = 0,230).

Composition and arrangement of the river bed (bed structure) at this less effected section are influenced by in-stream structures that concentrate the flow into navigable channel creating deeper parts with coarser (main channel) and shallow parts with finer sediments (deposits between groynes).

This effect is mostly local fixed directly to the place where structures are situated. The river bed dredging has more significant negative effect as it causes sediment deficit inducing river bed incision that can initiate downstream and upstream river bed degradation.

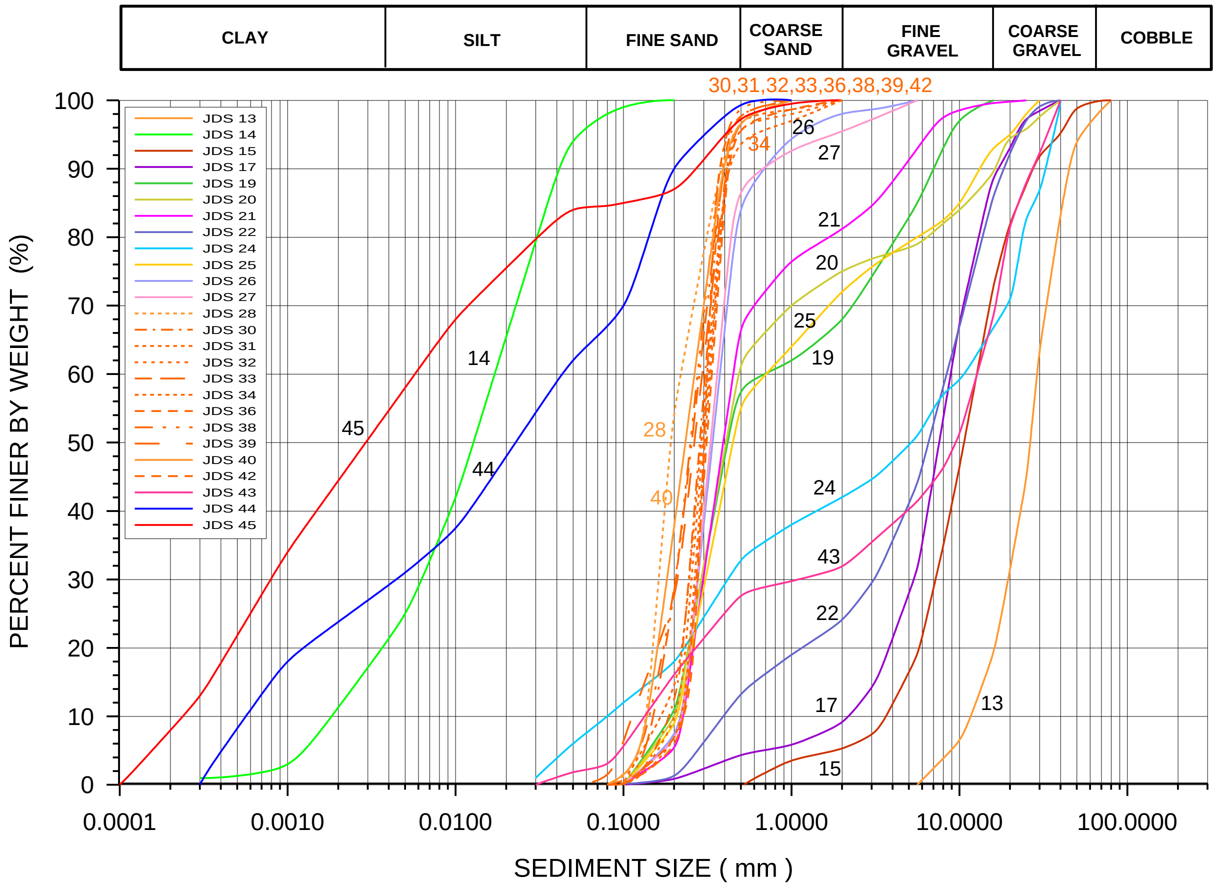



Fig.31: Grain size distribution curves-bed material

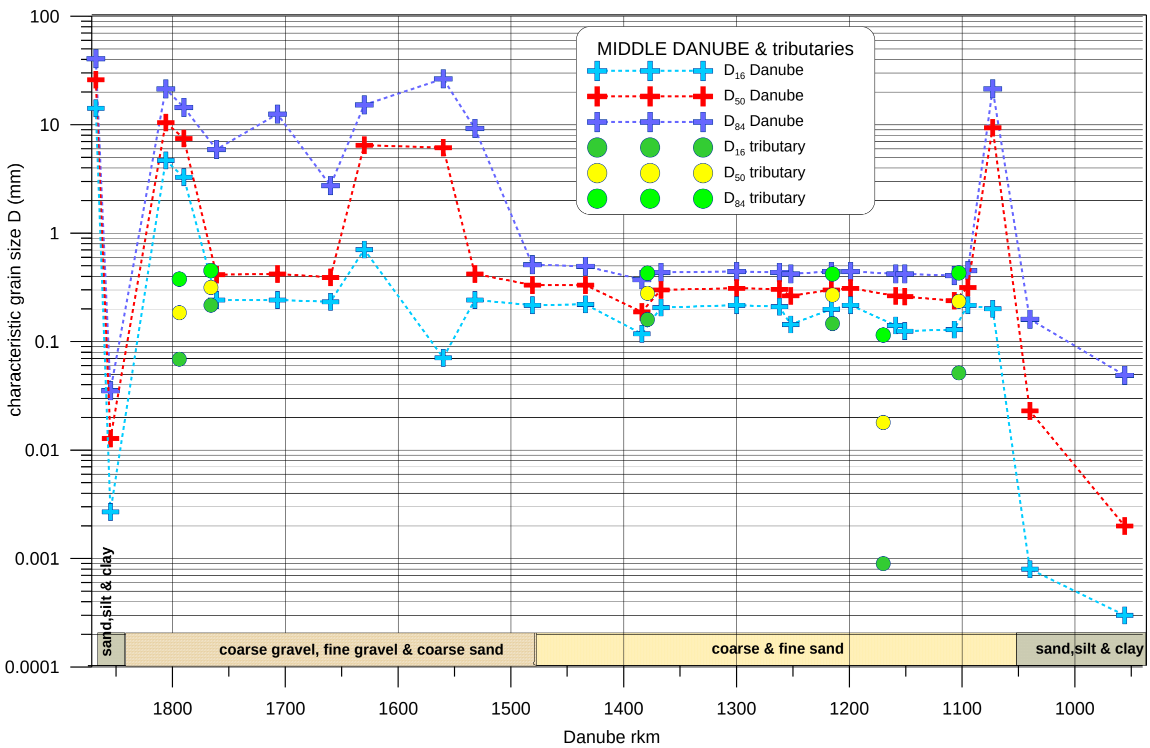



Fig.32: Downstream variation in grain size - Middle Danube

Hydromorphology of the Middle Danube is highly altered at sections of direct strong impact of both HPPs. At the section in between, there is mainly impact of river regulation (in-stream structures, dredging) but the character of the river indicates higher hydromorphological quality (e.g. higher channel variability B/H, in-stream habitats) compared with the upper sections. There are some parts with restored lateral connectivity (side arms, removal of bank stabilization, free banks). Except for strongly impacted sections which are classified by 4, 5 (extensively or severely modified), there are other sites classified mostly by 3 (moderately modified) and three sites by 2 (slightly modified). River section that is outside of strong effect of HPPs has relatively high potential for hydromorphological quality (HYMOQ) increase.

### 3.1.5.3 Lower Danube & Danube Delta (rkm 943 – rkm 0 )

**Flow conditions** at the Lower Danube can be influenced by flow regulation on the Iron Gate I HPP as it is indicated by discharge changes (Fig.17, Fig.33) and already commented in the chapter 3.1. However, without more complex data on flow regulation or water level fluctuation it cannot be confirmed. Flow regime in the Danube Delta is influenced by the Black Sea but it is a natural situation. Except for some extent of flow regulation that can possibly influence the river morphology, flow dynamics is affected locally by in-stream structures.

The river at this section is slowly flowing but there are still more dynamic and less dynamic sections . Maximum velocity is not higher than 0,7 m/s and in downstream direction decreases to 0,4 m/s (Fig.33). Flow conditions can be seen on the flow pattern (Fig. 33 and 35). Except of indicated discharge regulation downstream of Iron Gate hydrological conditions were changed very slightly along the Lower Danube (Fig.33).

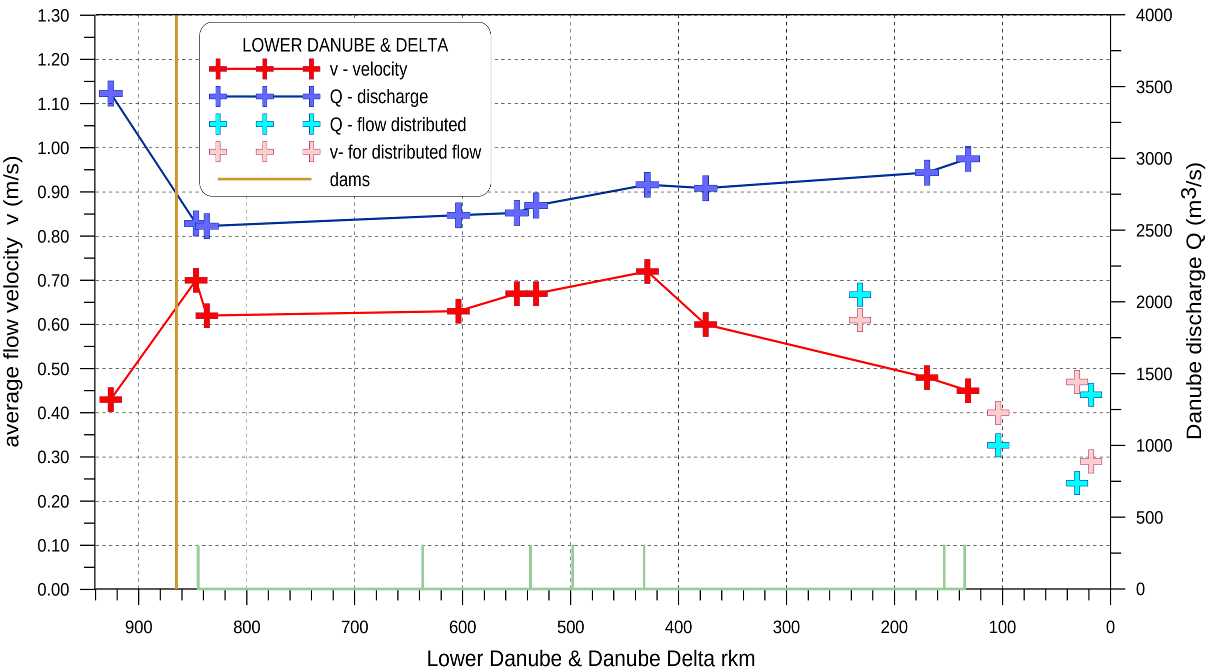



Fig.33: Mean velocity and discharge – Lower Danube

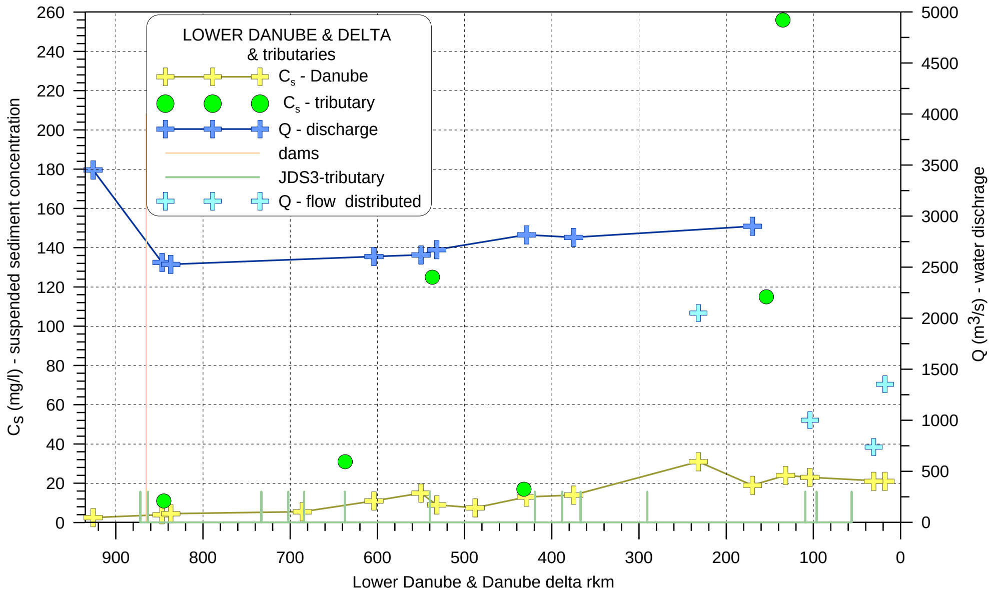
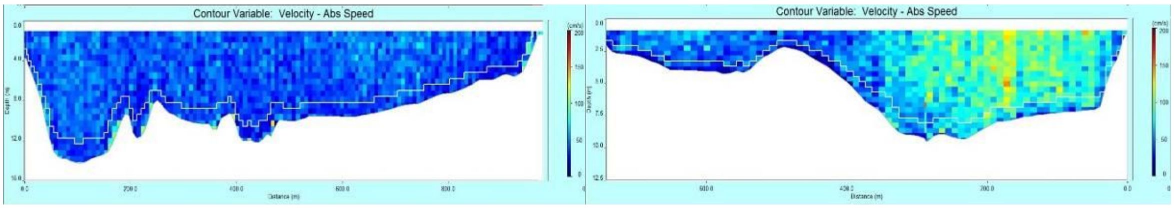



Fig.34: Suspended sediment concentrations & discharge




JDS46 – Vrbica/Simijan (rkm926 ) JDS55 – Downstream Jantra (rkm 532)

Fig.35: Flow pattern for selected impounded and free flowing Lower Danube

That was the reason why suspended sediment concentration increased on Jantra (125 mg/l) and Siret (154 mg/l). Extremely high value was measured on Prut (256 mg/l). Even though suspended load on these tributaries increased dramatically the effect on the Danube (fig.33) was rather low (Fig.17).

**Bed material** on the Lower Danube consists of coarser gravel, fine gravel and coarse sand. Coarser sediments occur at the section just downstream of Iron Gate II – JDS47 which is influenced by more dynamic conditions. Finer sediments - mostly fine and coarse sand, comprise the river bed in the Danube Delta (Fig.36).

JDS47 Rudujevac/Gruia JDS52-Downstr.Olt JDS52 - Oltenia JDS65- Reni JDS68-Sf.Gheorghe

Fig.36: Samples of bed material – Lower Danube& Danube Delta

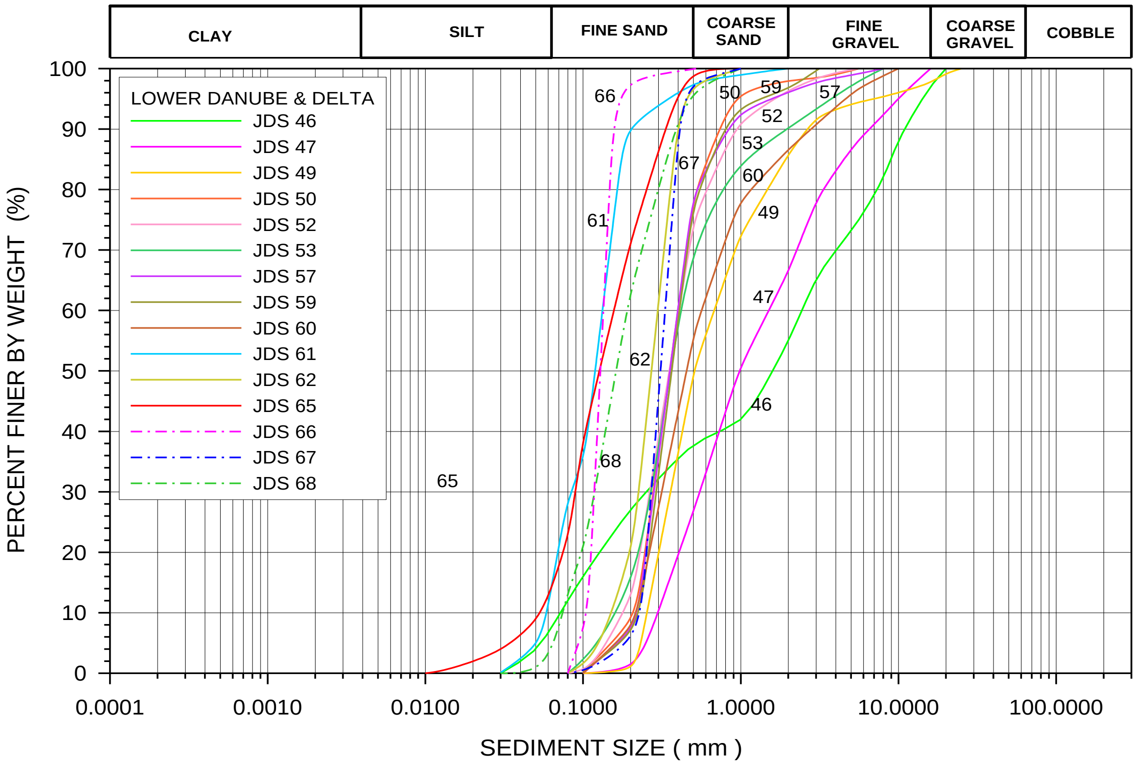



Fig.37: Grain size distribution curves - bed sediments

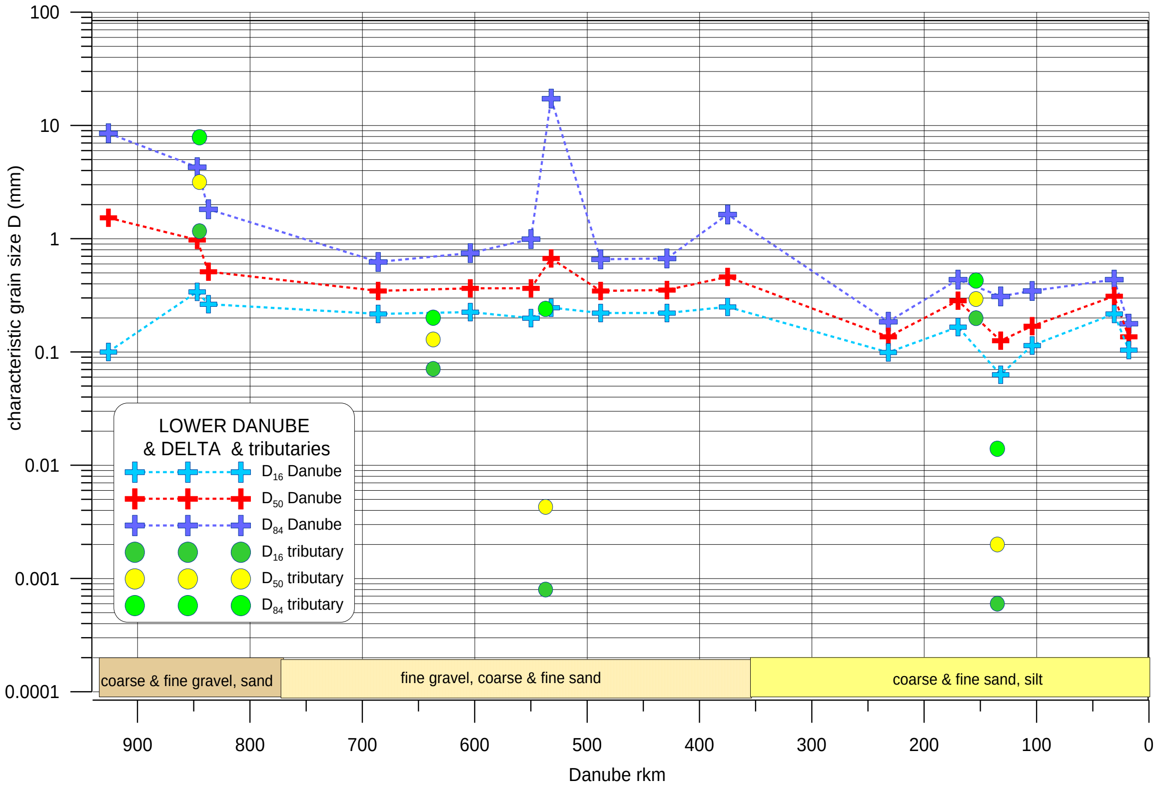



Fig.38: Downstream variation in grain size - bed sediments

Generally, proportion of smaller fractions nearly in all samples is very low and some fractions typical for river delta (silt and clay) are missing almost completely (Fig.37). This can be caused by the Iron Gate where large volumes of coarser and finer sediments are deposited. Significant deficit in sediment supply can be compensated by tributaries. Even though smaller fractions are mostly missing in the river bed. Downstream fining is identified with the highest value of coefficient of determination ($r^2$ = 0,367).

Lower Danube and the Danube Delta have a better hydromorphological quality compared to upstream sections. The river is negatively influenced by regulated discharges and a significant lack of sediments downstream of Iron Gate dams as well as the disconnection of floodplains by the construction of dikes, mainly in the 1970ties. However, the river channel shows a significant morphologically variability (width/depth) with sand bars and islands providing a diversity of habitats. There are some localities more effected by regulation (mostly urban areas) but larger part of the Lower Danube including the Delta is classified by 3 (moderately modified) or 2 (slightly modified) - except for Sulina arm in the Delta (artificial, regulated arm).

### 3.1.6 Hydromorphological site assesment – JDS3 (VÚVH method)

Results of HYMOQ assessment indicate that the hydromorphological conditions of the Danube sites improve in the downstream direction. The highest degree of HYMO alteration has been assessed on the Upper Danube mostly due to the chain of HPPs and river regulation. Hydromorphology on the Middle Danube is still highly altered at long sections due to Gabcikovo and Iron Gate but in between the two huge dams the river channel indicates evident improvement towards moderate conditions. Although the Lower Danube and the Danube Delta is influenced by downstream effect of Iron Gate system (sediment regime) and also by other engineering measures the assessed HYMOQ quality is better compared with upper sections.

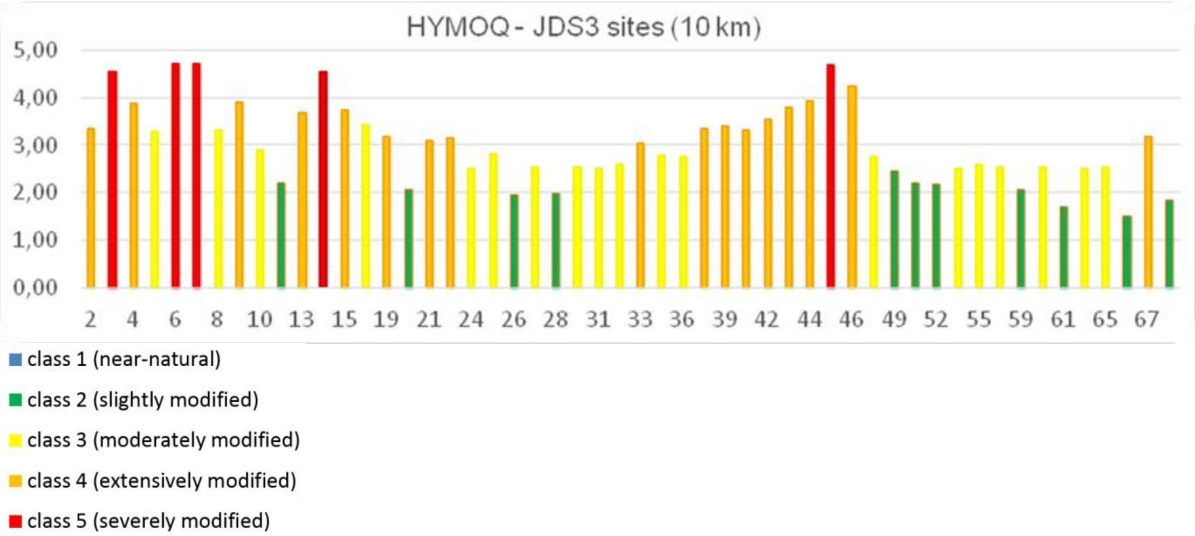



Fig. 39: Results of HYMOQ site assessment for the 68 JDS 3 sites

According to figure 39 (Lower Danube start with JDS site 46 in the Iron Gate II impoundment), 14 of the investigated sites belong to class 2 and 3 (each 7 sites), followed by two class 4 sites for Iron Gate II impoundment and Sulina branch in the delta.

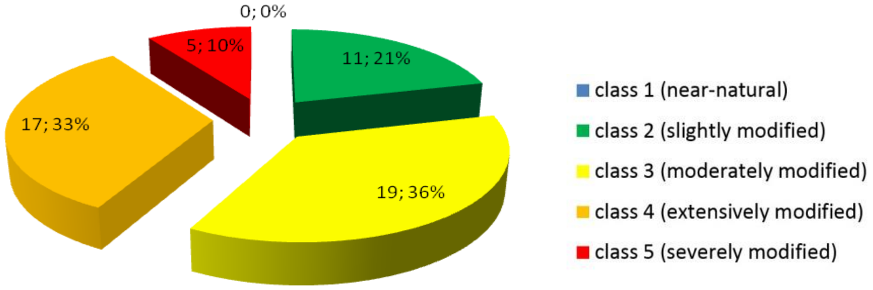



Fig.40: Proportionality of HYMOQ classes – JDS 3 sites (VÚVH site method)

The most sections on the entire Danube belong to class 3 (19 sites) so they are moderately modified (37%). 17 sections and second largest group are in class 4 - extensively modified (33%). 11 river sections are only slightly modified (11%) class 2 - reflecting the best HYMOQ assessed on the Danube. Last small group – 5 sites indicate the highest degree of HYMO modification with the worst quality – class 5 severely modified (10%).

## Table 4: Results of hydromorphological assessment using WFD-3digit method

| JDS3 site no. | Danube section rkm | HYMO class WFD (M, H,C)[6] | JDS3 site no. | Danube section rkm | HYMO class WFD (M, H,C) |
|---|---|---|---|---|---|
| 2 | 2415 - 2410 | 433 | 32 | 1270 - 1260 | 311 |
| 3 | 2360 - 2350 | 545 | 33 | 1260 - 1250 | 411 |
| 4 | 2290 - 2280 | 443 | 34 | 1220 - 1210 | 322 |
| 5 | 2260 - 2250 | 432 | 38 | 1200 - 1190 | 442 |
| 6 | 2210 - 2200 | 545 | 39 | 1160 - 1150 | 442 |
| 7 | 2130 - 2120 | 545 | 40 | 1150 - 1140 | 442 |
| 8 | 2010 - 2000 | 334 | 42 | 1110 - 1100 | 442 |
| 9 | 1950 - 1940 | 435 | 43 | 1100 - 1090 | 443 |
| 10 | 1900 - 1890 | 322 | 44 | 1080 - 1070 | 443 |
| 11 | 1890 - 1880 | 222 | 45 | 1050 - 1040 | 545 |
| 13 | 1870 - 1860 | 433 | 46 | 960 - 950 | 445 |
| 14 | 1860 - 1850 | 545 | 47 | 930 - 920 | 235 |
| 15 | 1810 - 1800 | 425 | 49 | 850 - 840 | 225 |
| 17 | 1790 - 1780 | 423 | 50 | 840 - 830 | 222 |
| 19 | 1770 - 1760 | 422 | 52 | 690 - 680 | 222 |
| 20 | 1710 - 1700 | 221 | 53 | 610 - 600 | 321 |
| 21 | 1660 - 1650 | 411 | 55 | 560 - 550 | 321 |
| 22 | 1640 - 1630 | 421 | 57 | 540 - 530 | 321 |
| 24 | 1570 - 1560 | 311 | 59 | 490 - 480 | 221 |
| 25 | 1540 - 1530 | 411 | 60 | 430 - 420 | 321 |
| 26 | 1490 - 1480 | 211 | 61 | 380 - 370 | 221 |
| 27 | 1440 - 1430 | 311 | 62 | 240 - 230 | 321 |
| 28 | 1390 - 1380 | 211 | 65 | 170 - 160 | 321 |
| 30 | 1370 - 1360 | 311 | 66 | 130 - 120 | 121 |
| 31 | 1300 - 1290 | 311 | 67 | 20 - 10 | 421 |
| | | | 68 | 60 - 50 | 221 |

Assessment of hydromorphological alteration according WFD requires evaluation of three categories: hydrology, morphology, continuity. Each category has to be evaluated separately and rated by quality classes ranged from one to five. As the final score consists of three digits this approach is often

[6] M-Morpholgy, H - Hydrology, C - Continuity

referred to as the “3Digit method”. This method of HYMO assessment was applied to data collected during JDS 3. The main HYMOQ indicators (VUVH method) are be linked to three categories required by WFD method: Hydrology, Morphology and continuity. Three digit results for each 10 km Danube section including JDS3 sites are included in tab.4 with graphical interpretation on fig.42.

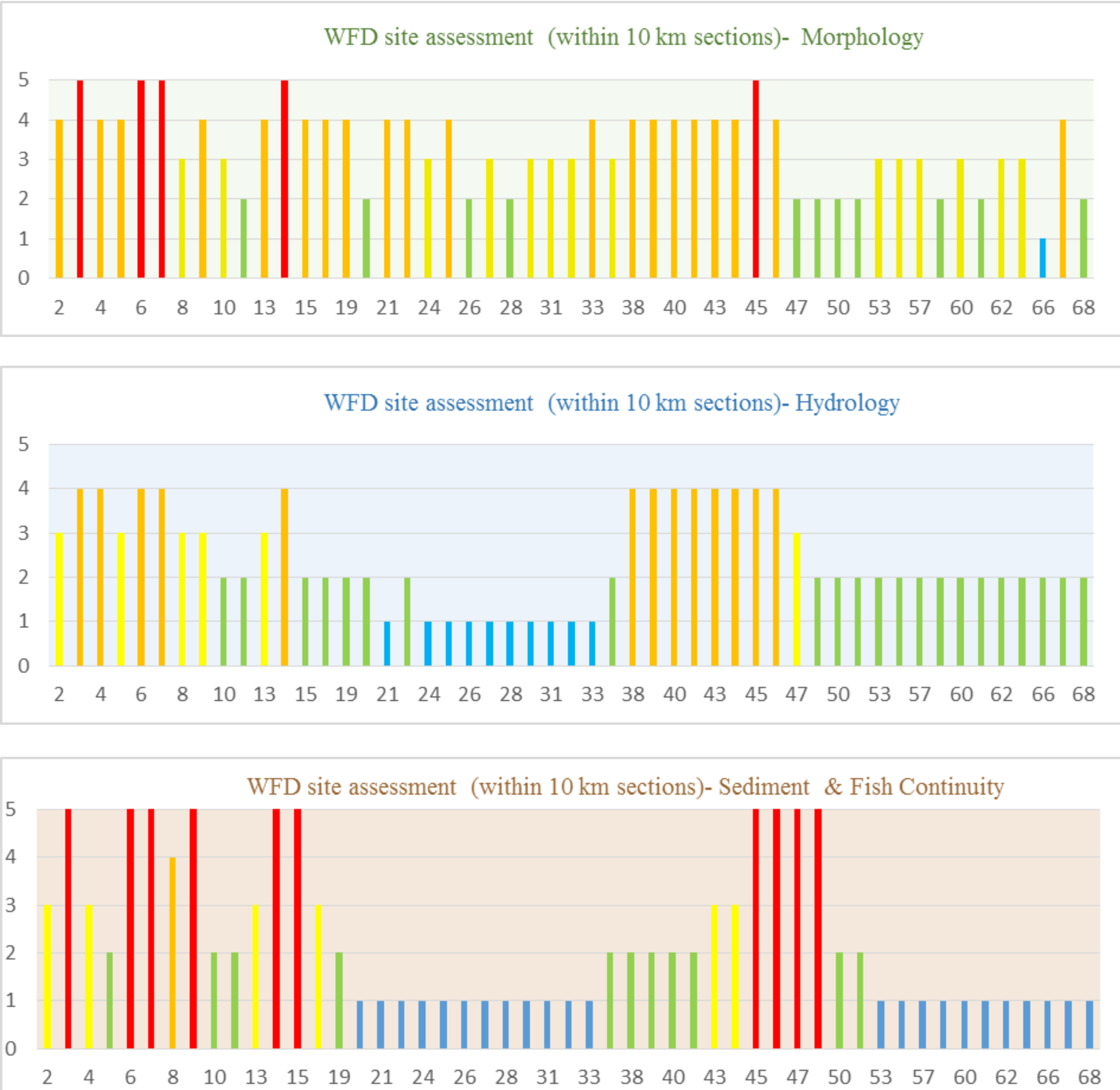



Fig. 42 Assessment of hydromorphological alteration using WFD method (hydrology, continuity and morphology) in combination with JDS3 data and VUVH method

Isolated assessment for hydrology, continuity and river morphology without consideration of their close interdependence can result in underestimation of their synergic effect. Rivers naturally adjust their shape and dimensions in response to the imposed discharge and sediment load. The habitats that are created are colonised by invertebrates, fish and flora, which are characteristic for particular river type. Any modification to the river pattern, flow dynamics and sediment transport through engineering works or river regulation can cause instability producing hydromorhological alteration (see chapter 3.1.5). Therefore channel processes interacted with flow conditions have to be analyzed in this complexity - particularly on large rivers.

Applied method for HYMOQ assessment (VUVH) based on results of in-situ hydromorphological measurements and additional important information combines improved “physical habitat assessment” (considering measured HYMO parameters) with process based approach respecting requirements of WFD and partly CEN standards (evaluated parameters). This approach could be the first step in progress from “descriptive methods” (e.g. WFD “three digit” method or those that integrate CEN standards but still remain strongly dependent on the personal expert knowledge and experiences) to more process based assessment.

# 4 Conclusions

## 4.1 General conclusions:

- Regarding the CEN WFD-3Digit assessment out of the 241 analysed 10 rkm segments 13% fall for morphology in class 2 (slightly modified), 39% in class 3 (moderately modified), 31% in class 4 (extensively modified) as well as 17% in class five (severely modified). For hydrology/flow regime and the continuity only the classes 1, 3 and 5 were assessed. For hydrology only 16% fall in the first class whereas class 3 with 50% and class 5 with 34% prevail. Regarding continuity, dams are located in 8% of segments (in total 18 dams, two dams with functioning fish passes and partial sediment management fall in class 3, the rest in class 5).
- The CEN overall hydromorphologcial analysis indicates that about 60% of the analysed Danube stretch falls below class 3 (21% in the second class „slightly modified" and 39% in the third class „moderately modified"), 40% fall in the two worse classes four (26%) and five (14%).
- Information on the hydromorphological conditions was significantly improved as in-situ measurements of hydrological, morphological and hydraulic characteristics were performed for the first time on the entire Danube and tributaries (JDS 3-sites).
- Results of hydromorphological survey are used to identify present hydromorphological conditions of the Danube. These can be used further for the WFD compliant assessment of the HYMO alterations with regard to hydrology, morphology and river continuity having no ambition to replace the national assessment method.
- Ecological groups provided feedback that the Hymo survey provided valuable information for the interpretation of the biological data.
- Results of in-situ measurements used for hydromorphological assessment improved characterisation and analyses of the hydromorphological conditions (including consideration on physical processes) of the Danube, creating a basis for more reliable considerations on sustainable restoration actions.
- The hydromorphological database creates an excellent basis for further hydromorphological analyses.
- The assessment of defined 10 rkm segments improve spatial and thematically resolution of the survey and assessment based on a common methodology. It can serve as solid base for the management requirements and monitoring over the next decades.
- The assessment results confirm the main findings of JDS 2 in 2007 (different situation along upper, middle and lower Danube), however the increased resolution allow a more precise assessment in particular of dams and their impacts but also regarding left/right banks.
- The importance and strong impact of existing dams in particularly regarding sediment balance up- and downstream, but also the hydrological changes (e.g. due to potential flow regulations) should be matter of further basin-wide investigations (sediment balance up- and in particular downstream of dams, detailed hydrological analysis downstream of dams).

## 4.2 Technical conclusions for next JDS:

- JDS sites should be selected in close cooperation and discussion of all participated working groups (including hydromorphology group) to find out the most representative river sections.
- There is an increasing need to improve "descriptive" method of hydromorphological assessments in particular for large rivers as it should by more "physical process" based. Further the linkage of

hymo parameters and biological response as well as monitoring efficiency should be improved. The first steps in this direction were already done by performing in-situ measurements on JDS 3.

- Based on field experience some technical improvements and optimization of hydrological and morphological measurements can be applied (in cooperation with other groups).
- To take fully into consideration the type-specific conditions according to WFD requirements.

## 4.3 Recommendations for measures:

- Taking into account the situation of the large European rivers which are severely altered to a large extent, it should be taken care that the remaining less altered water bodies along the Danube will be managed considering the environmental objectives.
- In addition to morphological restoration measures a management of the sediment balance is needed at Danube basin-wide scale.
- Prevention of fresh bank revetments and reinforcement to the absolute minimum.
- Continuation of restoration measures improving the hymo conditions to meet the good ecological status/potential along the entire Danube
- Restoration of floodplains should be a long-lasting goal for ecological and flood mitigation planning

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