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River Regulation and Sediment Transport

Introduction

Sediment monitoring on the river Danube started as early as the end of the 19th century, with scattered measurements carried out. Regular sediment sampling was developed in the first half of the 20th century all along the river, with different station density and monitoring frequencies in different countries. After the first few decades of regular sampling, the concept of (mainly industrial) development changed along the river and data needs changed as well, furthermore the complicated and inexact methods of sampling bed load on the alluvial reach of the river were not developed further.

River regulation works were started in the 19th century and are still going on along the Danube. The aim of the early activities was flood protection and to improve conditions for navigation. In the course of high-flow regulation, lowland areas along the river were protected from inundations. The first dikes had a local role, later they were followed by higher levees, stretching for a long distance along the river.

Both sediment transport processes and river regulation activities have been playing main roles in the morphological development of our rivers, and, as they are very much interconnected, we shall try to understand them in order to be able to draw consequences as regards to the flood conveyance capacity of our rivers.

Basics of sediment transport

The importance of the monitoring of sediment processes is unquestionable: sediment balance of regulated rivers suffered substantial alterations in the past century, affecting navigation, energy production, fish habitats and floodplain ecosystems alike; infiltration times to our drinking water wells have shortened, exposing them to an eventual pollution event and making them vulnerable; and sediment-attached contaminants accumulate in floodplains and reservoirs, threatening our healthy environment. The changes in flood characteristics and rating curves of our rivers are regularly being researched and described, involving state-of-the-art measurement methods, modelling tools and traditional statistics. Sediment processes, however, are much less known. Unlike the investigation of flow processes, sediment-related research is scarce, which is partly due to the outdated methodology and poor database background in the specific field.

Sediment-related data, information and analyses form an important and integral part of civil engineering in relation to rivers all over the world. In relation to the second largest river of Europe, the Danube, it is widely known in expert community and for

https://doi.org/10.36250/01052_07

long discussed at different expert forums that the sediment balance of the river Danube has changed drastically over the past century.

The most important parameters describing fluvial sediment transport are sediment load, Q_s, meaning the amount of sediment (volume or mass) passing through a given cross-section during a specified time; sediment yield, G_s, which is the mass of sediment passing by during a specified period of time; and, for suspended sediments, sediment concentration, cs, which is the ratio of the mass of sediment and the volume of the water in which it is contained.

The measurement of fluvial sediment is based on sampling procedures, as a result of which, based on protocols, sediment load and concentration can be calculated. Based on regular sediment measurement, it is essential to estimate the correlations between flow characteristics and sediment parameters, for different water regime conditions. The best way to achieve this is to draw up sediment rating curves.

The frequency of suspended sediment sampling is very low along the river, it is best organised in the upstream countries, where also on tributaries like the Drau/Drava monitoring stations are in operation. Sampling frequency of suspended load is 3 to 7 per year in Hungary, and even lower downstream.

Sediment management is a major challenge, as most methods developed until now are unsustainable, require continuous intervention and are also expensive. However, there is a new focus on the subject in the 21st century, which still lacks uniform methodological recommendations for measurements and analyses, and the number of engineers with sediment expertise and experience is alarmingly low. Data related to sediment quantity are unreliable and often contradictory. It is difficult to produce high quality long-term databases that could support and enable the mathematical calibration of sediment transport models. Furthermore, global changes in river basins due to climate change or changes in land use practices, as well as erosion conditions, make sediment monitoring and quantitative sediment management a very important task for the near future, especially under the recent impacted conditions and in light of the Water Framework Directive of the EU.

Definitions

Sediment in hydro-engineering constitutes of materials transported or deposited by the river (not including floating debris and organic matters).

Sediment transport is a term which collects processes connected to the erosion of the banks and the riverbed, the transport of sediments and the deposition.

Sediment can be characterised quantitatively and qualitatively. In river management, we focus mainly on the quantitative determination of the sediment. Thus, we can speak of sediment load, sediment yield, sediment concentration, etc.

Sediment load means the mass (or the volume) of the transported sediment in a time unit (second) in a given cross-section of a river:

$Q_s = m_s/t$ [g/s]

Sediment concentration means the ratio of the sediment load and the discharge in a given section:

$c_s = Q_s/Q$ [g/m^3]

Sediment transport is not a uniform phenomenon. The transportation of solid matters along the rivers is generally distinguished by the type of movement of the sediment particles, which can migrate to each other. Basically, there are three types of sediments to be distinguished.

Bed material is the material forming the riverbed (characteristically cobbles, gravels, sand, silt and clay). Bed material is not necessarily sediment, as on upper reaches of the rivers it can also be a solid rock which is naturally not transported.

Bed sediment (-load) consists of relatively coarser sediment particles moving on the top of the riverbed, relatively close to it, by jumping, rolling, sometimes rising and settling back down. It usually consists of relatively larger particles which often settle to the bed material and vice versa, bed material is sometimes mobilised and transported as bed load.

Bed load particles are not moving "individually", because they interact with each other to a large extent.

Suspended sediment (load) constitutes of relatively smaller size sediment particles, which are kept in suspension by the turbulent flow. Suspended sediment is moving with almost the same velocities as the water transporting them. Suspended sediment particles have almost no effect on each other.

Wash (or dissolved) load includes the sediment particles which are so small that they are continually kept in suspension by the flow. We sometimes distinguish this type in theory, but in practice it is very hard to separate these from suspended load particles, so when measured and/or calculated we consider these together with suspended load.

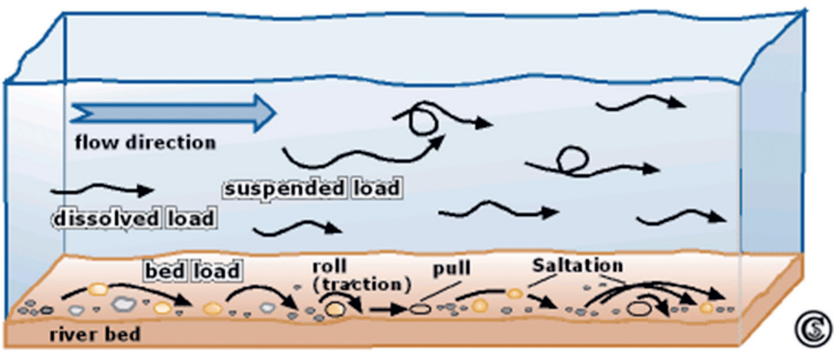

Figure 1. Types of sediment transport (Anette Stumptner after Christopherson 1994, 424[1])

[1] Online: www.geo.fu-berlin.de/en/v/iwm-network/learning_content/environmental-background/fluvial_processes/

According to the above, we can group sediments into the following types:
wash (or dissolved) load, Q_{sw}
suspended load, Q_{ss}
bed load, Q_{sb}
The total sediment load thus can be calculated by adding up the different types:
$Q_s = Q_{sb} + (Q_{sw} + Q_{ss}) \sim Q_{sb} + Q_{ss}$

Physical characteristics of the particulate matter, such as weight and size, determine when the grain is suspended and when it sinks to the bottom. During periods of high discharge, the turbulence can lift up larger grain sizes, which are then transported temporarily as suspended load. The threshold of the minimum grain size for suspension strongly correlates with the flow velocity and turbulence.

Transport is further characterised by grain sorting, dispersion and mixing processes. Most of the particles do not move exclusively on the top or the bottom but are continuously exchanged (large particles come in and displace smaller particles as the bottom layer is continuously rotating).

Therefore, it is important to know the particle or grain size distribution (PSD) of the sediment, which is the ratio of different particle sizes in a given sample or in a vertical/section.

Why sediments are moving

For a fluid to begin transporting sediment that is currently at rest, the bed shear stress exerted by the fluid must exceed the critical shear stress for the initiation of motion of grains at the bed.

$t_b > t_c$, or, dimensionless $t_b^* > t_c^*$

The critical shear stress is a function of the Reynolds number related to the particle

$t_b^* = f(Re_p^*)$

Particle Reynolds number

$Re_p = u_p D/n$,

where u_p is characteristic particle velocity, D is the grain diameter and n is the kinematic viscosity.

The specific particle Reynolds number is formed by replacing the velocity term in the Particle Reynolds number by the shear velocity

$u^* = SQRT(t_b/\square f)$
$Re_p^* = u^* D/n$

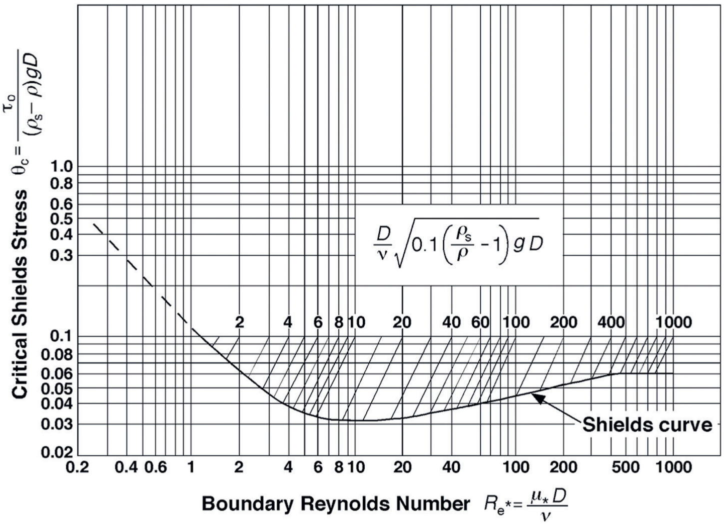

Figure 2. The Shields diagram (Shields, 1936) Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung Auf Die Geschiebebewegung, Zugl.: Berlin, TeH., Diss., 1936

The settling velocity

w_s

is a function of the particle Reynolds number. Generally, for small particles (laminar approximation), it can be calculated with Stokes's Law. Sometimes it is also called "terminal velocity" or "fall velocity". We can use it in PSD determination.

Stokes's Law

The force of viscosity on a small sphere moving through a viscous fluid is given by:

$F_d = 6phRv$,

where:
F_d is the frictional force (Stokes's drag) acting on the interface between the fluid and the particle
η is the dynamic viscosity
R is the radius of the spherical object
v is the flow velocity relative to the object
Fd [$N = kgms^{-2}$], η [$Pa = kgm^{-1}s^{-1}$], R [m] v [m/s]

Why to know sediment processes

There are several concerns related to sediments in aquatic systems. The problems related to high amounts e.g. include reduced capacity in reservoirs, and increased dredging requirements in shipping channels. Another concern with eroded sediments is that they can transport other pollutants into receiving waters. The plant nutrient phosphorus, for example, is most often transported from the fields where it was applied as fertilizer by chemically bonding to clay minerals. Many agricultural pesticides also bond to eroded clays and organic matter. Once these chemicals have entered the aquatic ecosystem, many processes occur that can result in the release of the pollutants from their sediment carriers.

Sediment size	Environmental issues	Associated engineering issues
Silts and clays	Erosion, especially loss of topsoil in agricultural areas; gullying	
	High sediment loads to reservoirs	Reservoir siltation
	Chemical transport of nutrients, metals, and chlorinated organic compounds	Drinking-water supply
	Accumulation of contaminants in organisms at the bottom of the food chain (particulate feeders)	
	Silting of fish spawning beds and disturbance of habitats (by erosion or siltation) for benthic organisms	
Sand	River bed and bank erosion	River channel deposition: navigation problems Instability of river cross-sections
	River bed and bank erosion	Sedimentation in reservoirs
	Habitat disturbance	
Gravel	Channel instability when dredged for aggregate	Instability of river channel leads to problems of navigation and flood-control
	Habitat disturbance	

Figure 3. Typical issues associated with sediment transport (compiled by the author)

The determination of sediment transport can be carried out in various ways. The most commonly used grouping of sediment determination is detailed here.

Data on riverine sediment transport rates can be derived typically from direct measurement techniques, but because these are very resource demanding, a common approach is to use transport equations, hydraulic models, transport curves or other estimating techniques instead. Yet, a reliable set of measured field data would still be required to calibrate these methods and to find the correlations which ensure their exactness.

Thus, the most reliable and useful fluvial–sediment–discharge data are derived from direct measurements of suspended sediment (along with water discharge) and/or bed load transport.

Sediment transport measurements

We generally need to measure sediment transport of streams in the field in order to quantify transport rates, which usually means separate measurements for suspended sediment load and bed load, based on which we can give the amount of total load. The results of the measurements can later be used in the calibration and/or verification of sediment transport rates derived from equations or hydraulic models in the calibration of sediment surrogate technologies.

During sediment measurements we obtain samples, which are also suitable for analyses of PSDs, concentrations of chemical constituents, and to quantify other selected characteristics of the entrained material.

Measurement technologies can be discrete or continuous.

The traditional type of sediment measurements are discrete measurements. Due to modern technologies, the measurement of time series, or continuous measurement is also possible, but in order to do this we use sediment surrogate measurements.

We have to mention though that suspended phase surrogate measurements tend to be spatially limited (i.e. not adaptable for bigger streams or long stretches), and although bed load surrogate technologies have been developed and field tested but none has yet been fully integrated into operational monitoring.

It is also very important that all the surrogate technologies require calibrations with data produced by reliable physical samplers and sampling methods. That is why direct field measurements still have an unquestionable importance in getting to know sediment-related phenomena.

Sediment sampling

Suspended load measurement

Direct measurement of SSL is possible either with a pump, or with a bottle. In general, we have to try to ensure that our sampling method is isokinetic.

In the following, the methods of sediment sampling in Hungary are described. However, we have to mention that in other countries sampling methods are not always comparable, and thus the data obtained from the different measurement methodologies must be very carefully used because of possible inhomogeneity issues.

When sampling suspended load in the whole cross-section, in Hungary it is usually three verticals and two samples per vertical. Before analyses, the samples taken from different depths are joined, thus the results in the grain size distribution give a vertical average only instead of a 2D distribution in the cross-section.

The most effective way of sampling suspended load is with a pump. An advantage is that it is not needed to regain the sampler onboard between the points. Thus, this method is the fastest, which is an issue, particularly at high velocities and when sampling is done in the navigation route. During sampling, it is very important to ensure that the sampling nozzle faces the flow, the pipe is not bent and to let enough time before taking samples to flush the pipe.

Sampling needs to be carried out in an isokinetic way as mentioned before, so with care to adjust the revolutions per minute value (RPM) or the discharge of the pump for the velocity through the nozzle V_{in} should not differ much from the velocity of the flow v at the given point:

$$0.8v \leq V_{in} \leq 1.5v$$

In case the velocities are outside this range, the RPM of the pump should be accordingly adjusted, or a tap should be installed at the end of the pipe to ensure that intake velocities match. In order to determine intake velocity, the discharge of the pump (qp) has to be divided by the cross-section area of the nozzle (fn):

$$V_{in} = qp / fn$$

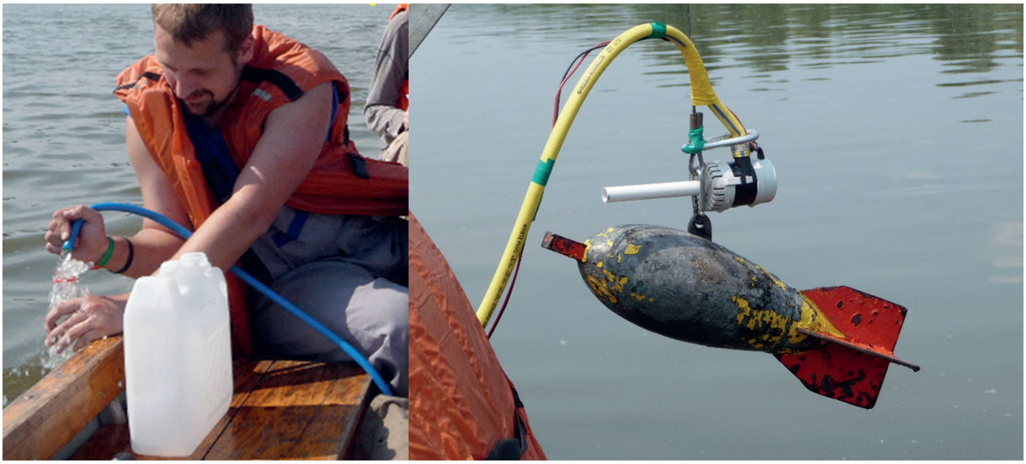

Figure 4. Sampling suspended load with a pump (photo taken by J. Sziebert)

In practice, we perform sampling with a constant pumping discharge, assigning a fixed intake velocity to different velocity ranges of the flow, keeping the hydraulic coefficient between the values 0.8 and 2.0. This ensures a maximum 20% difference in concentrations, which is acceptable.

Sampling with a wide range of different bottle samplers is also common worldwide. We mention here the two types of sampling bottles which are typically used in the Danube River Basin.

The first is the so-called Delft bottle sampler which was developed in the Netherlands. It operates on a flow-through principle. A reduction in flow velocity in the sample bottle between the nozzle and outlet results in collection of sand particles larger than about 0.1 mm for subsequent analysis.

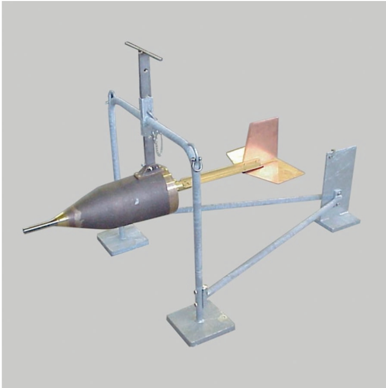

Figure 5. The Delft bottle[2]

The second typical bottle sampler is the fish-shaped isokinetic sampler developed by the USGS. It shall also be deployed in several verticals. The apparatus can be lowered to the desired measurement point by a winch. It contains a bottle that can be removed and transported to the laboratory for analyses.

Figure 6. The isokinetic bottle sampler[3]

Surrogate measurements for suspended load determination include light or sound or turbidity sensors of different types. In these types of measurements, the determination of the sediment load would in every case require a reliable calibration.

If we already have a large enough time series of sediment data, it would be possible to determine Qs in form of the correlation between suspended sediment transport and water discharge, that is usually called the sediment rating curve.

The sediment rating curve can be obtained as the function of the discharge:

$$Q_s = a\,Q^b$$

[2] Online: www.royaleijkelkamp.com/products/augers-samplers/sludge-sediment-samplers/suspended-sediment-sampler-sets/

[3] A Guide to the Proper Selection and Use of Federally Approved Sediment and Water-Quality Samplers, https://pubs.usgs.gov/of/2005/1087/pdf/OFR_2005-1087.pdf

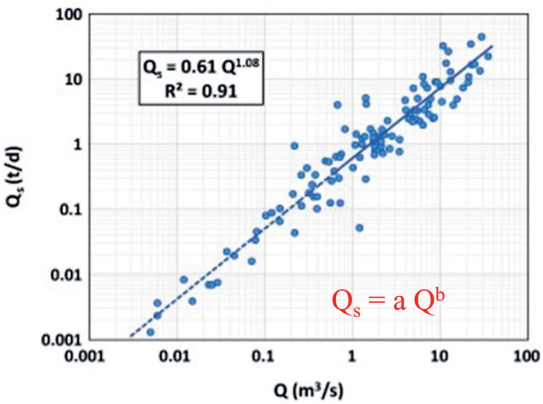

Figure 7. The sediment rating curve[4]

Based on the obtained sediment data for a certain cross-section, we shall draw up the sediment concentration distribution.

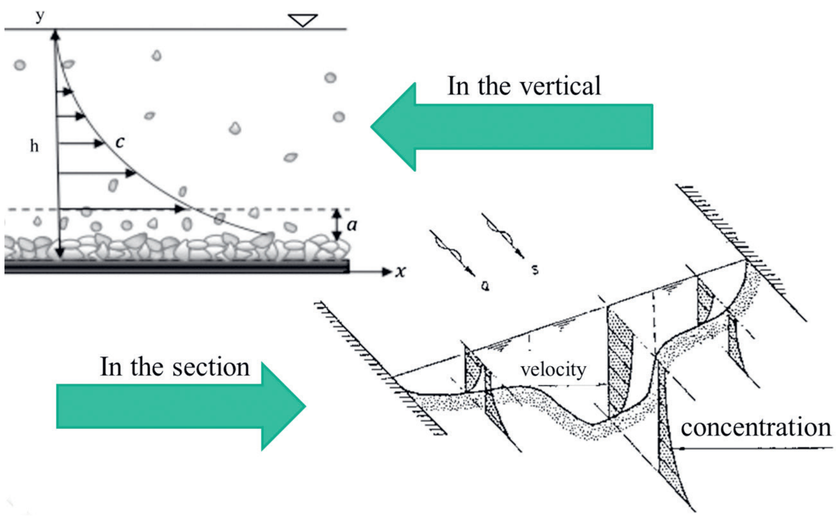

Figure 8. Typical sediment concentration distribution of a stream (compiled by the author based on [3])

4 Atieh, M, Mehltretter, SL, Gharabaghi, B, Rudra, R (2015): Integrative neural networks model for prediction of sediment rating curve parameters for ungauged basins,Journal of Hydrology, Volume 531, Part 3, pp 1095–1107, https://doi.org/10.1016/j.jhydrol.2015.11.008.

Bed load measurement

The sampler types which can be used to directly measure bed load can be:
- box or basket samplers
- pan or tray samplers
- pressure difference samplers
- trough or pit samplers

Direct sampling is difficult, as bed load transport is usually highly variable in space and time across the river, thus empirical equations based on sampling are questionable, and the results of empirically-based calculations or laboratory experiments are very difficult, or impossible to calibrate with field data.

The bed load of rivers is moving intermittently over the surface of the riverbed. As bed load samplers disturb the current, they have an effect on the transported bed load. When choosing the appropriate sampler, we have to minimalise disturbance. Sampling of the bed load usually happens with the Helley-Smith sampler (in fine sediment, e.g. sand) or the Károlyi sampler (in coarser sediment). Both samplers have different sizes and gaps for different river types, depending on the grain size and the mass flow of the sediment.

The samplers are lowered to the bottom of the river, and, depending on the sampling time (usually 10–15 minutes), based on the mass of the sample taken, bed load transport can be calculated:

$$q_b = \frac{G}{b \cdot T \cdot \rho_s},$$

where G is the dry mass of the sample
b is the width of the gap of the sampler
T is the sampling time and
ρ_s is the density of the bed load sample

In our experience, it is very useful to equip these samplers with an underwater camera, in order to be able to see the clogging of the sampler or anything blocking it; furthermore to determine the exact sampling time needed to collect a reasonable amount of sediment in the apparatus.

On the reaches where bed load is mainly sand, the Helley-Smith sampler is used, fitted with a camera. Depending on the expected coarseness of bed material, different size Helley-Smith samplers can be used. For example on the Drava River (right bank tributary to the Danube) for fine sand, a smaller sampler (length: 960 mm, height: 200 mm, wingspan: 400 mm, gap size: 152 × 152 mm, weight: 17 kg), and for coarse sand a bigger one (length: 1,550 mm, height: 240 mm, wingspan: 510 mm, gap size: 150 × 150 mm, weight: 35 kg).

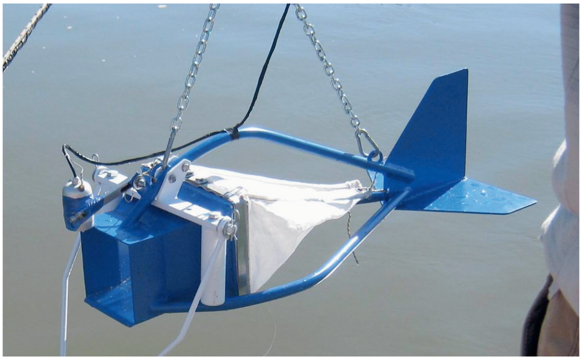

Figure 9. The Helley-Smith sampler with onboard camera mounted above the inlet (photo taken by the author)

Indirect bed load measurement is theoretically also possible, though not widely used yet. For this, we have to define the virtual velocity of the bed material, which is the total distance travelled (possibly incorporating multiple steps) by individual grains divided by the measurement interval.

The ability of the ADCP to determine virtual velocities of bed material sediments for potential bed load transport determination has been recognised for some time. A few investigators have made good progress in making measurements of virtual velocity using the ADCP.

Bed material measurement

The sampling of the bed material is usually achieved with a bucket sampler. Because armouring of the riverbed is to be expected on the river Drava, the edge of the sampler was sharpened to facilitate its penetration into the riverbed (length: 535 mm, diameter: 180 mm, weight: 9 kg).

Processing of the samples

The PSD of bed load and bed material have to be determined.

According to the traditional method, these are determined using Taylor sieves – separating fractions (0.063; 0.125; 0.25; 1.0; 2.0; 4.0; 8.0; 12.0; 16.0; 24.0; 32.0; 48.0; 63.0; 96.0; 125.0 mm); or by settling velocity method – separating fractions (> 0.10 mm; 0.05 – 0.10 mm; 0.02 – 0.05 mm; 0.01 – 0.02 mm; 0.005 – 0.01 mm; < 0.005 mm).

Drying of the samples is carried out at 105°C. After that, dry matter content measurement (analytical precision) is done. In a case when the ratio of fractions with diameters less than 0.15 (0.1) mm is higher than 10%, the hydrometry method must be used to establish the particle size distribution.

For suspended load, which is usually contained in about 5l water samples, the first important step is to measure the exact amount of the sample, to know from how much water we will measure sediment concentrations. The samples are then left to settle. When the sediment settles in the bottom of the containers, the excess water is carefully sucked from the containers and approximately 0.5l is left. The amount of clean water removed is precisely measured and recorded in the protocol. The samples are dried in an electronic oven for 24 hours at 105°C temperature. Then, we measure the weight of each sample and its dry matter content on a precision scale. Concentration is calculated as

$C_{ss} = \frac{m_d}{V_s}$, where

m_d is the dry matter weight and

V_s is the total volume of the sample.

In case of suspended load, when the grain size is too small for screening, the grain size determination is done with a special Atterberg-type settling device, which is operating on the principle of the Stokes equation. The main part of the settling velocity meter is a cylindrical glass tube with an inner diameter of 35–40 mm. There are six level markings on the tube. On the bottom of the tube, there is a stricture and a tap. It ends in a ca. 4 mm diameter rider. On the top of the tube, there is a funnel with a throttle. With the throttle open, the tube is filled up with distilled water, and the sample is also poured into the tube through it. There is a vent in the axis of the throttle, connected with a 0.1–0.2 mm diameter nozzle, to secure that outflow velocity does not exceed 0.2–1 cm s^{-1}. The tube has to be mounted on a stand with its axis vertical.

Before filling the samples in the tubes, we leave them dissolve in aqueous solution of sodium metasilicate to avoid coagulation. Then we fill the tubes with sodium metalsilicate solution and we pour the samples into it. The grain size fractions are < 0.10 mm; 0.10–0.05 mm; 0.05–0.02 mm; 0.02–0.01 mm; 0.01–0.005 mm and > 0.005 mm.

Figure 10. Atterberg-type settling device for PSD determination of fine sediments (photo taken by the author)

The particle size distribution (PSD) of the different samples can be drawn up as percentages from the data as a distribution curve. The results of sediment analyses are summarised by PSD curves. The measured precise weight of the fractions can be drawn up as percentages from the data as a distribution curve in e.g. MS Excel.

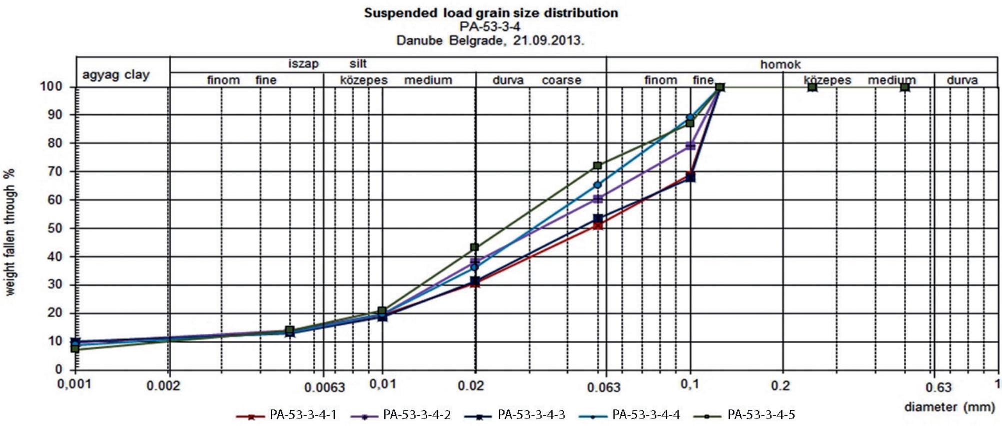

Figure 11. Typical PSD of the suspended load on the alluvial reach of the Danube River (compiled by the author)

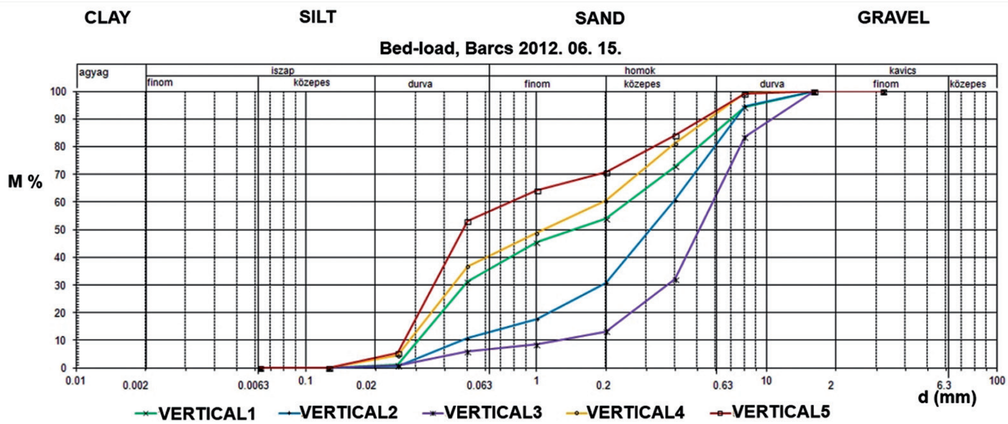

Figure 12. Typical PSD of the bed load on the middle reach of the Drava River (compiled by the author)

From the PSD we read the values of d_m, d_{eff}, d_g, d_{10} and d_{60} from the diagram and we calculate U unevenness factor ($U = d_{60}/d_{10}$), according to the Hungarian measurement standard.

Analyses based on sediment measurements

Concentrations of suspended load and grain size distribution curves of suspended sediment, bed load and bed material can be determined from each sample. Total yields can be also estimated if a simultaneous discharge measurement is available.

For a better description of sediment transport processes, we determine the correlation between discharge and suspended sediment concentration.

For the bed load and the suspended load, it is generally true for the whole Danube River (and its tributaries as well) that insufficient monitoring activities have been carried out, and long-term series are not available to assess the overall sediment balance on many rivers. Effects of important events or circumstances are often not captured. During floods, the amount of transported sediment can exceed the long-term average annual values. Also, the input of the sub-basins responsible for a flood in the main river strongly influences the concentration of the sediment load. Furthermore, in case of heavily eroded surface layers, it is possible that the river incises into softer sediment layers.

Data related to sediment quantity are unreliable and often contradictory. Even in countries where sediment sampling is well-organised and frequent, like Germany and Austria, it is difficult to produce high quality long-term databases that could support and enable the mathematical calibration of sediment transport models. Furthermore, global changes in river basins due to climate change or changes in land use practices, as well as erosion conditions, make sediment monitoring and quantitative sediment management a very important task for the near future, especially under the recent impacted conditions and in light of the WFD.

Basics of river regulation

River regulation (training or channelisation) includes those methods of engineering (resectioning, straightening, construction of levees, diversions, etc.) that modify existing river channels or create new channels, often changing the relationship between river channels and floodplains. Here we summarise these activities based on the Encyclopedia of Water Science [15].

Channelisation is carried out both on very large rivers and small streams; it is widespread in lowland rivers, but also many upland (mountain) rivers have experienced this type of human intervention. Human impact on rivers has a long history. Most alluvial rivers in Europe have been channelised during the last 2000 years and in the United States, the Federal Government has been regulating the rivers since the 1870s. Early regulation activities appeared in the Danube River Basin with the start of economic and industrial development; however, major interventions have been carried out in the 19th century.

Goals of river regulation

The most common purposes of river regulation are flood control, land drainage improvement, creation of new spaces for urbanisation or agriculture, maintenance or improvement of navigation and reduction of bank erosion.

However, along the Danube River itself, the most important goals tend to be the safe conveyance of floods and ice apart from the improvement of the navigation corridor.

Types of river regulation

Resectioning by widening and deepening

Widening and deepening increase the channel cross section; therefore, channel capacity to contain flows is increased and floodplain is inundated less frequently (flood control and agricultural purposes). In some cases this type of intervention is adopted to lower the water table for the improvement of agriculture. Channels are commonly designed with trapezoidal cross sections, but rectangular sections can be used where banks are stable (e.g. concrete banks) and triangular sections in small ditches.

Straightening

Straightening implies the cut of river bends (meander cutoff in case of a meandering river); it produces shortening of the river channel, increasing of the gradient and increasing of the flow velocity. The purpose is to reduce flood heights.

This type of activity was very commonly applied to many alluvial rivers worldwide, including the Danube River, over the 19th and the beginning of the 20th century.

Levees (or embankments)

The aim of levees is to increase channel capacity so that flood flows are confined and do not inundate the areas adjacent to the channels (floodplains), which would be inundated under normal conditions. Levees generally have a trapezoidal section and can be built close to channel banks (in this case levees must be quite high) or more far apart (for instance including the "shifting belt" or the "erodible corridor" of the river). This type of intervention, which is used both in rural and urban areas for flood control, requires extensive maintenance of the structure itself (geotechnical properties of materials may decay through time) as well as of the river channel.

It is very typical in the lowland part of the Danube River Basin. In Hungary alone, there are more than 4,000 kilometres of levees established, which is the second longest in Europe (after the Netherlands).

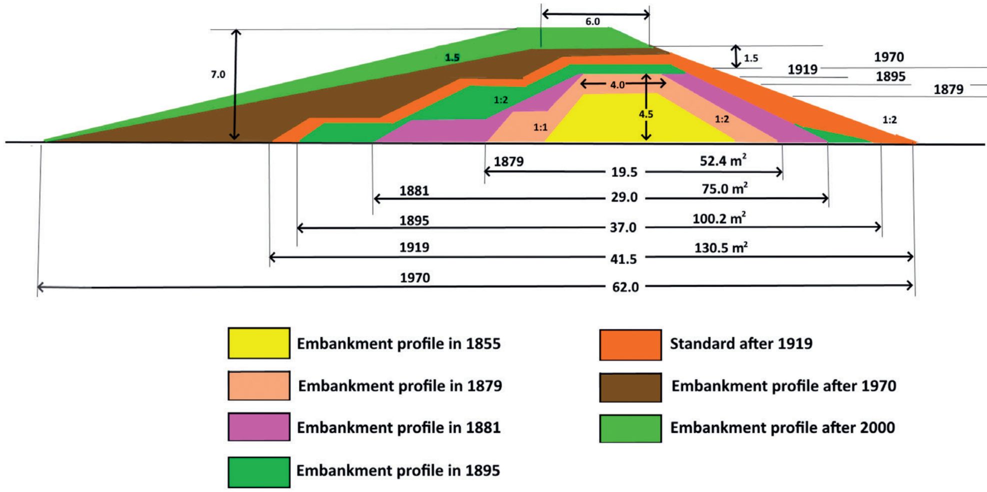

Figure 13. The changes in the Tisza river embankment as flood levels increased [11]

Flood walls and lined channels

This type of method is commonly used in urban areas where other kinds of channelisation are limited or where access for maintenance is restricted. Lined channels generally have a rectangular cross section with vertical sides made of concrete. This type of channelisation produces a remarkable decrease of channel roughness, an increase of flow velocity, and, consequently, a decrease of water level for a given discharge.

Figure 14. Flood wall in Budapest, Hungary[5]

[5] Online: https://fromhungarywithlove.wordpress.com/2018/07/27/the-great-floods-of-danube-in-budapest/#jp-carousel-1737

Bank protection structures

The use of revetments is a technique adopted to prevent bank erosion. Different materials (concrete, gabions, synthetic materials, live or dead vegetation) are used for revetments.

Groynes

Groynes are structures built transverse to the river flow and extending from the banks into the channel. The aim of these structures which deflect the direction of the flow, is mainly to induce sediment deposition behind the structures and to protect the banks from erosion processes (groynes can be either impermeable or permeable).

Diversion channels

New channels can be constructed to divert flows out of the existing channel (e.g. the Danube River in Vienna). Diversion channels are usually aimed at flood control (for instance where the river channel cannot be resectioned or where levees cannot be built or built higher) and agriculture improvement.

Culverts

This type of channelisation has often been used for urban streams, but also for small rural/mountain streams. In the latter case large-diameter concrete pipes are used. Culverting of a stream is most likely the "hardest" type of channelisation since it implies the disappearance of the stream below ground surface for short or longer reaches.

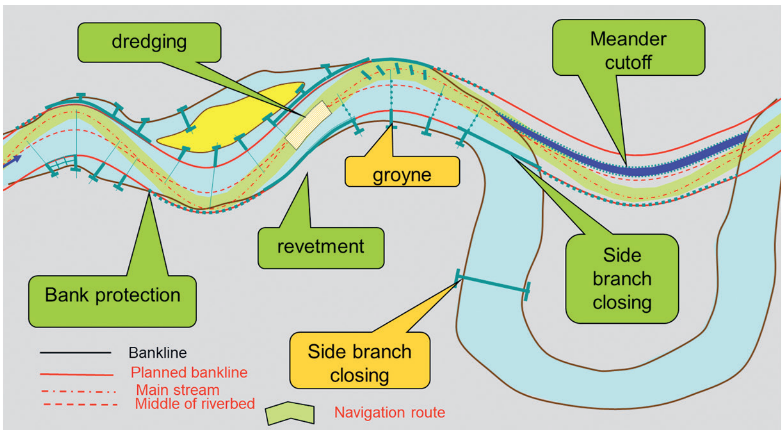

Figure 15. Summary of the most common river regulation structures for alluvial rivers (compiled by the author)

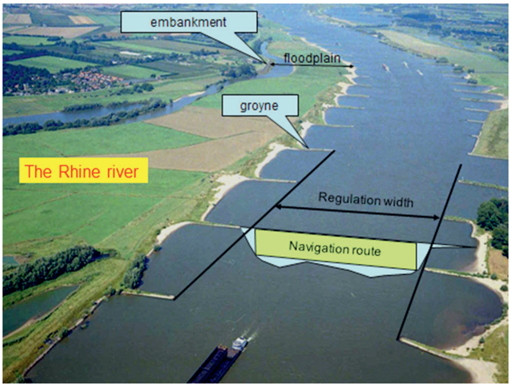

Figure 16. A typical channelised river (Rhine in the Netherlands)[6] *(compiled by the author)*

Consequences of river regulation and mitigation measures

It is widely known and for long discussed at different expert forums that the sediment balance of regulated rivers has changed drastically over the past century. The biggest problem for the experts along the Danube River to face with, which has to be addressed all along the river is sediment deficit.

Several studies have documented that channelisation may have different effects on channel morphology, riparian and floodplain ecology, human infrastructures, etc. Such effects regard not only the channelised reaches of a river but, quite often, also the upstream and downstream reaches (e.g. increased flood discharges in the downstream reaches). In some cases, the effects of channelisation have been really dramatic since early channelisation projects were designed with little or no consideration of sediment transport and river dynamics.

The effects of channelisation may be grouped into the following categories: river morphology and dynamics; hydrology; ecology; human structures and activities. Since in many situations channelisation is not the only human impact on rivers and their drainage basins, it is worth noting that most of these effects are often the results of a combination of such impacts (channelisation, dams, sediment mining, land use changes). We now go through these impacts referring to the Encyclopedia of Water Science, and, at the end we present the case study of the Danube River in Hungary.

River morphology and dynamics

River morphology and dynamics can be significantly affected by channelisation. Since the different types of channelisation imply changes in the morphological and hydraulic characteristics of a river (width, depth, slope, bed and banks roughness), morphological

[6] Photo: https://www.dutchwatersector.com/

adjustments are likely to take place to attain a new equilibrium condition. As regards bed-level adjustments, river incision, due to increased stream power, is a common phenomenon, but also bed aggradation is not infrequent. Other remarkable effects are those produced by the construction of levees (or by incision induced by other types of channelisation): such construction dramatically changes sediment fluxes, reducing sediment deposition in the floodplain.

Hydrology

Channelisation works affect river and floodplain hydrology. As for floods, channelisation generally produces higher velocity in the channelised reach (therefore lower water stage) but can induce increased flood discharges in the downstream reaches due to reduction (or elimination) of floodplain storage. Deepening of the channel or incision induced by channelisation may strongly affect relationships between the river and its floodplain. In the case of unconfined aquifer, the lowering of the water table is likely to occur, whereas in the case of confined aquifer an increase of stream flows may take place. In coastal reaches, changes of water table levels can produce soil salinisation due to variations in salt wedge position. In very low gradient rivers, overbank flows, which under natural conditions are due to backwater effects and are fundamental from an ecological point of view, can be significantly reduced or eliminated. In addition, there are several examples of the effects of channelisation on water quality.

Ecology

River channelisation frequently has serious effects on aquatic and riparian ecosystems, but may have far reaching effects extending into the floodplain. Both flora and fauna along the river are affected by changes induced by channelisation, such as morphological, sedimentological and hydrological change. Floodplain ecosystems may be affected since hydrological and sedimentary connectivity between the river and its floodplain may dramatically change. Wetland environments, which are often drained for agriculture, are frequently affected by channelisation.

The example of the Danube River in Hungary

The sediment regime of the Danube has been altered by two major types of human interventions: river regulation (meander cuts, building of groynes, dredging), and hydropower dam construction. Sediment deficit effects can be detected everywhere, but the most severe impact is affecting the free-flowing alluvial reaches downstream of impoundments. The gravel bed border section of the Danube between Slovakia and Hungary has experienced an extra large channel incision between 1965 and 1990 due to intensive sediment dredging for commercial purposes. The total volume of extraction was estimated about 64 million m^3. This could not have been supplemented even by the original bed load transport of the Danube (before barrage constructions). The reach downstream of Budapest was not so heavily affected by industrial dredging, because the demand for the finer (mostly sand) bed material was less than for gravel.

Several investigations of recent decades have revealed a significant lowering of the river bed along the alluvial reach of the river Danube. We are now assessing this phenomenon based on the published research [13].

The deepening of the channel is a result of erosion processes that not only affect discrete sections but also long reaches of the river. This study is devoted to the Hungarian section of the Danube but, considering the reasons, it can be presumed that similar symptoms could be experienced in other parts of the Danube. Classifying the Hungarian Danube, it belongs mainly to the middle course, partly to the lower course with a lowland type. The river bed is alluvial. In accordance with the lowland character, the slope is mild (10–15 cm/km). The river bed is wide, with a typical width of 400–500 m. The average depth for the mean discharge is 5–6 m. A middle course type river usually has a balanced sediment transport and a balanced channel. The fact that this is not so nowadays for the Danube indicates that there were, or are, external effects disturbing the early balance.

Regular hydrological observations started in the second half of the 19th century in Hungary. It started first with observation of the water level at many stations along the Danube. Somewhat later, at the beginning of the 20th century, regular discharge measurements also began. Nowadays, there are water level records available for more than 100 years, and discharge records for 80–90 years for many stations on the Danube.

In the 1980s, a drying process of the floodplains on the lower Hungarian Danube reach became evident. The statistical analysis of the water levels took place, and showed that the riverbed of the Danube was lowering, the reason for which was thought to be the river regulation that took place in the 19th century. The maximum level decrease until 2005 is 216 cm, at the Dunaföldvár station (rkm 1,560).

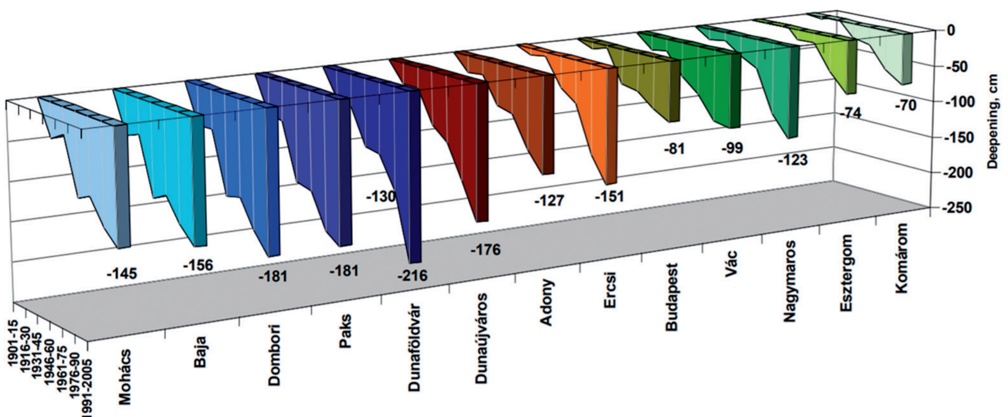

Figure 17. Lowering of the Danube stages along the Hungarian reach [2]

If we look at the dredging activities on the reach, it seems that apart from major river training works carried out all along the reach, dredging plays an important role in this extensive and fast deepening in that section.

Major hydraulic structures are built on the river on the reach in Germany and Austria, where slope permits for an effective exploitation of hydropower, furthermore there is one HPP in Slovakia (Gabcikovo) and two on the border of Serbia and Romania (Iron Gate I–II). The reservoirs of these HPPs are trapping a very large proportion of suspended sediment, apart from preventing the flow of bed load by blocking the river. On the Austrian reach, the "shallow" run of the river dams release much of the accumulated fine material during floods. Gabcikovo and in particular the Iron Gate dams, as are larger and partially deep impoundments, have much less potential for remobilisation (at least 35% of suspended load is trapped there). This phenomenon is not only a problem of the downstream reach – causing permanent erosion – but the accumulation in the reservoirs themselves pose a major daily challenge in the operation of HPPs. The observed steady deepening of the sand bed reach of the Hungarian Danube is rather due to this suspended sediment deficit than to the occasional dredging.

The morphological survey of the river bed (bathymetry) is a more direct and exact method to follow the changes of the bottom. However, adequate and sufficient results are available only from the latest decades, following the appearance of GPS, echograph and GIS applications. Nowadays, bathymetry is done every 5–6 years. Comparing the result of more surveys, done in different periods for the same spot, the changing of the river bed can be directly analysed. These comparing results of a typical section (near Dunaföldvár) are illustrated here.

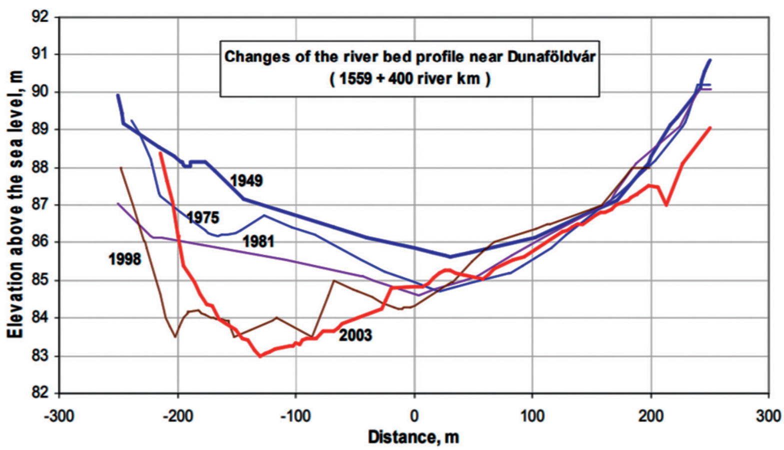

Figure 18. Changes in the Dunaföldvár section over time [2]

It is proven that the increased slope after the regulation (shortening of the river course) causes an increased sediment transport capacity and induces riverbed erosion.

Sediment transport capacity C (m^2 $time^{-1}$) can be calculated as the function of discharge and slope

$$C = \alpha \cdot Q_m \cdot \Lambda_n$$

where Λ is the slope gradient (∂z/∂x); m and n are constants giving an indication of the system. Sediment transport rate S (m^2 $time^{-1}$) is calculated based on the integrated continuity equation for sediment movement. The rate of sediment already in transport is S_0 (m^2 $time^{-1}$). If $S_0 < C$ there is erosion, while when $S_0 > C$ there is sedimentation. If S_0 decreases while the slope increases, erosion accelerates.

For a substantiated planning of sediment management measures, we need to know as much of the sediment transport of the river as possible. Not only the quantity, but the quality of sediment (grain size distribution) has to be examined, and it is vital that we have reliable field data.

Sediment management is a major challenge, as most methods developed until now are unsustainable, require continuous intervention and are expensive as well. Almost exclusively, artificial sediment supply is used as a compensation to the extensive sediment deficit problems along some European rivers. This is a symptomatic treatment, and we have to admit that it cannot be the long-term solution. It works for local–regional sections. No doubt, it should be reduced, maybe partially substitutes by granulometric improvements and by increased lateral erosion and channel shift on rivers with limited navigation usage and space such as the Drava.

Artificial supply of bed load, corresponding to the natural materials and grain sizes is carried out on the Rhine river since 1978, it amounts to approximately 2.1*105 m^3/y and costs around 8*106 EUR on an annual estimate. For case studies on waterways as shown, lateral erosion is almost no option, it works long term as long as there is good bed load supply feasible, granulometric improvements (size enlargement) is not yet proven in practice on the Danube, partly on the Elbe but only with shift of impact section.

For the prevention of further incision and in order to improve navigation a project is planned in Austria, east of Vienna. The granulometric improvement of the riverbed shall be carried out, in order to facilitate armouring, by artificially supplying coarse gravel 40 mm < d < 70 mm which will not start moving in the riverbed even in case of Q = 5,000 m^3/s, which has a return time of approximately 1 year. A relatively high amount of 3–4*105 m^3/s (2*106 m^3/y) sediment material has to be continuously fed in the river, in order to substitute sediments captured by several barrages upstream of the affected Danube section downstream Vienna.

Another measure in order to restore a part of the natural morphological processes is the removal of embankments from along the river (till now only behind point bars and transition bars only and with partial protection below the low water level). This kind of trials are currently going on along the Austrian reach of the Danube River, and short-term monitoring results show that no drawbacks from the viewpoint of navigation and flood safety are arising.

Often channelisation has induced severe effects on the environment (e.g. channel dynamics, groundwater resources, aquatic and riparian ecology, etc.) as well as on human structures (e.g. bridges, roads). For this reason, in some countries, especially in those strongly affected by channelisation, there have been some changes in the attitude about stream management through a more careful use of traditional methods, through the use of different approaches (in particular geomorphological and ecological ones) and the restoration (or rehabilitation) of existing channelised rivers.

As for floods, it should not be forgotten that channelisation itself induces an increase of human occupation and activities in floodplains and therefore an increase of flood risk.

Driven between the levees, floods are not able to spread – as they did in the natural, original state – and have a stronger effect on the bed forming processes.

During medium-flow regulation, strongly meandering bends were cut, the horizontal alignment of the river was fixed with bank protection structures and groynes, utilising also the energy of the flow to form the bed. The aim of this work was to speed up the travelling of floods and to help the movement of drifting ice. The improved shape of the channel was favourable for navigation as well because the narrowed river bed resulted in deeper water for longer duration. However, this transformation resulted in shortening of the river, increasing the slope and therefore increasing the sediment transportation capacity. Consequently, the original balance has been shifted towards sediment erosion. Narrowing of the river bed also increased flow velocities, involving the increase of the sediment transportation capacity again.

Low-flow regulation is an indispensable auxiliary element of medium-flow regulation. It concentrates on the stretches of the river where medium-flow regulation was not enough to develop the required profile, water is shallow and fords obstruct navigation. Additional regulation structures and direct dredging is applied on these stretches to get the required measures of the navigation profile. However, dredging helps the deepening processes, in more respects.

Deepening of the river bed has unfavourable effects on the natural environment, on navigation and also on operation of man-made structures in the river.

To improve the conditions of navigation is an important aim of river regulation work. Medium-flow regulation activities have been more or less finished by nowadays. Taking into consideration that the horizontal alignment of the Danube is practically stabilised – by cutting many bends, building bank protection structures and groynes – this work has been accomplished. However, the bed of the river is still continuously developing and forming. These changes are – at least partly – consequences of earlier interventions. The most frequent navigation obstructions are fords, shallows and contractions of the navigation channel during low water periods. Fords are continuously building and forming in the changing, unstable channel – calling for a permanent control of the responsible authorities. More studies, dealing with the analysis of low water periods and the efficiency of low water regulation prove that, despite of the extensive regulation dredging, the conditions of navigation did not improve.

The Gemenc Forest (part of the Danube–Drava National Park, Hungary) is one of the substantial floodplain forests of Europe. Gemenc is an irrecoverable natural value. The water demand of the forest and the wetlands is supplied by the Danube, partly by subsurface feeding, partly through the net of oxbows and channels, sometimes inundating the whole area during floods. Forestry experts observed certain drying processes of the forests in the second half of the 1980s. They noticed changes in the development of trees and also the replacement of autochthonous plant species. It was revealed by the detailed hydrological analysis of the water levels that the flood events reaching the oxbow lakes become rarer and their duration also decreased. Besides, the low water periods with longer duration are also unfavourable regarding the subsurface feeding. Some projects started after the investigations aiming at the improvement of water supply and water retention in the oxbow lakes; however, the effects of these interventions extend only to small areas and, regarding the whole of the forest, they cannot be appreciated as overall and accomplished solutions.

The Danube has an essential role in the agricultural water supply along the river. Large areas are supplied by artificial, gravitationally operated channels. When the water level is very low in the river, pumping is necessary to lift the water into the channels. In this system, developed primarily for gravitational operation, pumping entails a high economic burden. This problem appeared once or two times annually in the recent years.

The lowering of the river bed of the Danube is a complex problem as it has been outlined above. It has far-reaching effects which require complex solutions, taking into consideration not just economic but also ecological and social aspects, as well.

In recent years, there have been several studies dealing with the deepening of the river bed, the problems arising from this and the possible solutions. Even nowadays, there are several such projects underway searching for solutions. An essential question is whether traditional river regulation means are suitable to reach the above mentioned aims. Building barrages, that is to say the channelisation of the problematic sections of the Danube, could be an evident alternative for regulation structures and dredging. For this, as has already been mentioned, there are a number of examples on the Austrian and German stretch of the Danube.

Despite the problems, we have to state that knowledge of the sediment transport is essential to understand the morphological processes forming the river bed.

Consequently, the improvement of the methodology seems to be necessary both for the suspended and also for the bed load. Not just measuring techniques but also data processing methods should be improved. International cooperation would be highly desirable.

Concluding remarks

Today the goal of the sediment sampling is not only to describe sediment transport in the flow, but further to provide calibration and validation data for numeric modelling. Sediment measurements are different in the different countries in Europe. Methodologies and samplers vary, both for field and laboratory analyses. Even in Hungary, sampling and laboratory techniques have been modified several times in the past. Also, sediment sampling was never really systematic, and the sampling campaigns did not follow the hydrological processes. That is why sediment data can hardly be compared. The data series are inhomogeneous and cannot be statistically analysed. Sampling has to be carried out as to be able to obtain a true picture about the changes of sediment transport across the flow, along the flow and with respect to variability with depth. The sampling points have to be determined based on morphological and flow conditions. Discharge measurement has to be executed in parallel to sediment sampling. For a few years, water authorities in many countries have been using Acoustic Doppler Current Profilers (ADCP) for the measurement of the discharge. This opens up new possibilities for future analyses. Despite this fact, we still have to emphasise that the availability of hydromorphological data is extremely important for assessments under the Water Framework Directive, also to support ecological status evaluation. However, the lack of information on some large rivers is evident. The changes in the hydrological and sediment regime of river systems induced by hydromorphological alterations are not well understood, so in the near future there is an urgent need for a harmonised database. To this end, the first step is to intensify and reorganise hydromorphological monitoring, including sediment sampling and data management.

The hydrometry services of the different Danube countries do not have enough resources and they might also lack expert support. ICPDR expert groups are currently not dealing with sediment issues as a priority, though Monitoring and Assessment EG has produced an overview of the situation in the river basin, which more or less covers the subject of morphological monitoring as well.

The most urgent and highest importance action would be the introduction of a unified, regular, exact and thorough sediment monitoring system in the whole river basin.

When planning sediment management actions for the Hungarian reach, it is very important to take into account that the German and Austrian reaches are much more heavily regulated and flow conditions are much different, this way the environmental and nature protection aspect interventions can also differ a lot. Before applying the methods developed for the upstream reaches, there is a need to thoroughly investigate all potential impacts and effects from this point of view as well.

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