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DEVELOPMENT OF SUSPENDED SEDIMENT MONITORING OF THE TISZA USING AN INDIRECT MEASUREMENT METHOD

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Abstract

The Tisza River experienced successive flood peaks between 1998 and 2010. The reasons of the increased flood height are various, one of them is overbank floodplain accumulation. The aim of the present study is to apply and test an alternative sediment measurement method to evaluate the sediment transport of the Tisza River, Hungary. The new method could help practitioners to better understand the fluvial processes. A significant problem with the current sediment measurement practice is that it does not consider or just to a limited extent, the hydrological conditions of a river. The data measured at the turbidity measuring station installed in the Middle Tisza at Szolnok are evaluated to determine whether or not this measurement procedure can be applied for the highly various sediment transport conditions of the Tisza. In measurement campaigns and based on continuous data from the turbidity measuring probe, a close relationship between near-bank turbidity and suspended sediment concentration was established. The suspended sediment concentrations calculated from the near-bank turbidity were compared with the results of suspended sediment yield from a few cross-section measurements. The results are encouraging; despite the limited number of measurements, the relationship between the parameters is close. In order to make the method more precise, additional series of measurements are needed, which also cover the high water range.

Keywords: Tisza, suspended sediment, sediment yield, turbidity measurement, turbidity probe

INTRODUCTION

The record floods at the turn of the 20th and 21st centuries drew the attention of specialists to the fact that significant changes had taken place in the flood conveyance capacity of the Tisza River, Hungary. The peak water levels of high floods successively exceeded the highest measured water levels. During the rising and falling limb the floods, continuous discharge and sediment measurements were carried out. The measurements provided an opportunity to examine the connection between discharge and stage. Based on the evaluation of the results, it was established (Kovács and Váriné Szöllősi, 2003) that the slope of the loop curves (Fig. 1) was constantly increasing, so the same discharge was conveyed by increasingly high water levels (Kiss et al., 2019). Based on previous studies, the factors affecting the increasing height of the flood waves are various, including the overbank accumulation of the floodplain, formation of natural levees and increasing density of riparian vegetation (Kiss and Fehérváry, 2023). These processes significantly limit the conveyance capacity of the floodplain; thus, the kinetic energy of the river decreases, and the transported suspended sediment is thereby deposited, accelerating the accumulation processes of riparian areas (Kiss and Sándor, 2009; Kiss et al., 2019).

The role of fluvial sediment transport monitoring has become more and more fundamental in water management, river engineering, thus multidisciplinary projects aimed to measure the sediment transport (Hauer et al., 2018). The Tisza transports large amount of suspended sediment; thus, the spatio-temporal description of its sediment transport is a fundamental research task.

The basics of sediment movement and transport processes in rivers have been investigated for a long time. However, today's technical level of measurement or other conversion methods require continuous research and development. Numerous studies and research results are already available (on the transport of sediment in the Hungarian section of the Danube, which are used for the application of modern measurement procedures (e.g., Danube Sediment, SEDDON projects) On the other hand, in the case of the Tisza, the sediment measurement were carried out just by water management directorates. In the water engineering literature, limited number of research has been done in the last 20-30 years on the modernization and development of the sediment transport of the Tisza River (Mohsen et al., 2021, 2022).

In current water management practice, sediment sampling is carried out according to a predetermined schedule. Besides these cases, data on fluvial sediment transport is collected on additional sampling campaigns during flood events. Based on these measured data, the discharge and sediment flow relationship could be established, but these curves can only partially describe the processes taking place in nature.

Bogárdi (1974) stated that in the case of the Tisza, suspended sediment transport is the most significant, while the amount of bedload is decreasing, especially

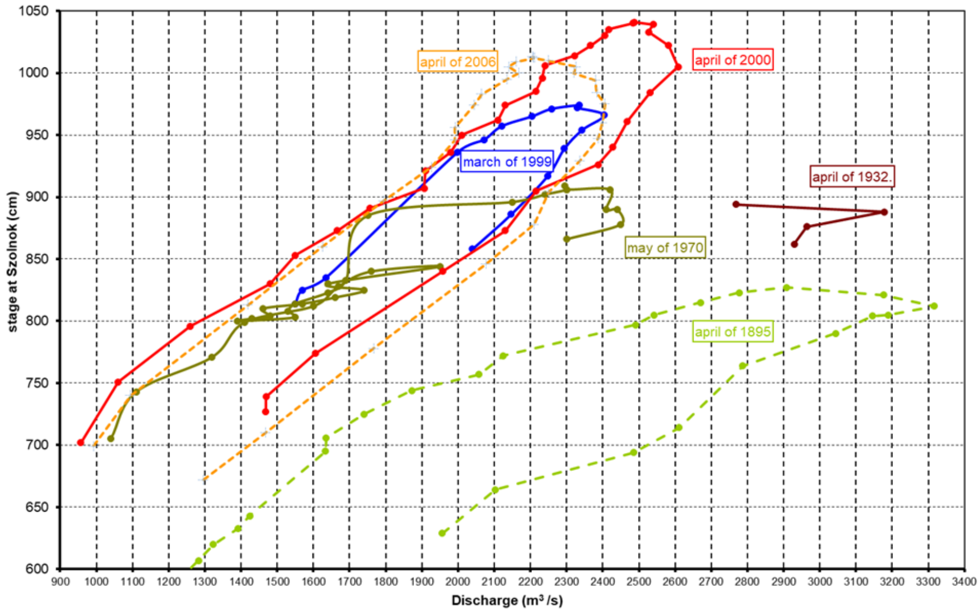

Fig.1 Water level – discharge loop-like curves at Szolnok gauging station (after Kovács and Váriné Szöllősi, 2003)

downstream of Záhony, Hungary. Regarding the suspended sediment concentration, the water of the Tisza has 3-5 times higher concentration than the Danube. Therefore, the aim of the present study is to present the calibration of a measurement procedure that also enables tracking of suspended sediment transport over time at the Szolnok gauging station of the Middle Tisza, Hungary.

STUDY AREA

A typical section of the Middle Tisza (section above the Zagyva confluence at Szolnok) was defined as the study area for the research (Fig. 2). The given cross-section was selected based on the results of numerous previous researches and publications: the geomorphological and floodplain accumulation processes in this section have a significant (typically negative) influence on floods. The section is characterized by a moderate slope (2-3 cm/km).

There is a gauging station in Szolnok (334.6 fluvial km; height: 78.78 m above Baltic Sea level), with a time series of water level for more than a hundred years, and with regular discharge and sediment measurements. Here, the flow velocity is 0.2-0.4 m/s at low water, 0.5-0.8 m/s at medium water, and 1.4-1.5 m/s in case of floods. The largest water level difference between the lowest and highest stages is 13.3 m (lowest stage: –291 cm; highest stage: 1041 cm). The lowest measured discharge is 68 m^3/s, while the highest is 2640 m^3/s; thus, there is an

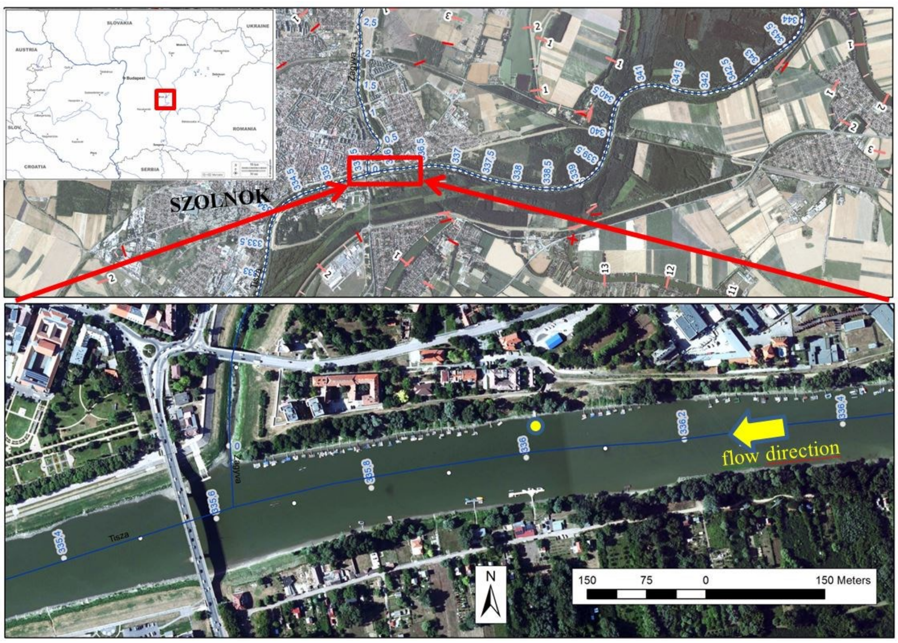

Fig.2 Studied section at Szolnok. The yellow dot represents the loction of the mounted turbidity probe (47.172710 N , 20.207566 E; Tisza River at ca. 336.0 fluvial km)

almost 40x difference between discharges. The suspended sediment monitoring station was placed on the floating platform located near to 336.0 fluvial km. Based on the data of Hydrographical Yearbooks (provided by KÖTIVIZIG) the annual average suspended sediment load (SSL) is about 11,530 tons/year (Fig. 3). The mean annual bedload transport is ca. less than 1% of the amount of suspended sediment.

MATERIAL AND METHODS

Methods for determining suspended sediment load can be divided into direct (e.g., along verticals, with a pump) and indirect methods (e.g., based on turbidity measurement or acoustic devices like ADCP backscatter, remote sensing). The description of the methods bellow is brief, and there is extensive literature on the subject.

The sample could be collected by a pump. In the Hungarian practice following the standard of ME-10-231-20:2009 (Measurement of suspended sediment in surface waters with a pump water sampler, *provided by KÖTIVIZIG*), the end of the pump's suction pipe is lowered into the pre-determined sampling depth and the required sample volume is taken. During sampling by a pump, it must be ensured that the flow velocity around the sampling tube is the same as the velocity of the water flowing into the tube due to pumping (isokinetic sampling condition).

Indirect methods, e.g., turbidity measurement can also determine the sediment concentration of rivers. (Boss et al., 2018) Turbidity expresses the reduced transparency of water, which is caused by the particles in the water scattering and absorbing light rays passing through the water. The turbidity meters used today are based on the laws of nephelometry. The size, colour, refractive index and shape of the particles influence the amount of scattering. During nephelometric measurements, the 90° scattering of light rays is measured in the visible or infrared range. Optical reflectance measurement (OBS-Optical backscatter sensors) instruments measure light rays scattered at 140-165° in the infrared range (Sutherland et al., 2000).

Thus, it can be concluded that direct methods require time and resources (sampling, laboratory and processing tasks). Indirect methods are based on using some physical relationship, and in all cases, calibration between the measured and sought physical variables is necessary. The calibration relationship requires large number of samplings; later on only expeditional control sampling and analysis is sufficient. Indirect methods do not only provide point-like information, but they can also be applied to a complete cross-section only after calibration. Their great advantage is that they provide many measurements/data, which can be transmitted to any location, and based on these data further analyses can be carried out without physical presence.

The basis of our method was already applied with satisfactory results at several locations on the Danube River, and it was adapted to the conditions of the Tisza. The studies produced in connection with the Danube Sediment project recommended a (so-called indirect) method for estimating the amount of suspended sediment based on turbidity measurements installed near to the river bank. The principle of the method is to measure the turbidity of the water with a continuously operating instrument and then to describe the relationship between the turbidity and sediment concentration with a calibration equation (Habersack et al., 2019) by taking point samples from a sufficient number of instruments located along the riverbank.

In Hungary, the researchers of the Budapest University of Technology and Economics have also successfully applied the method on the gravel-bed Danube reach between Sződliget and Ráckeve, where a relationship was established between the suspended sediment concentration registered near-bank and the sediment yield of the cross-section (Pomázi and Baranya, 2020). Vas and Tamás (2023) also reported on the applicability of the method (based on the data of the station installed in the lower section of the Danube in Hungary). During the evaluation of the results of a series of measurement campaigns entirely similar for the system built in the present study. During our measurements, we continuously checked the water samples with a portable, hand-held turbidity meter to check the accuracy of the

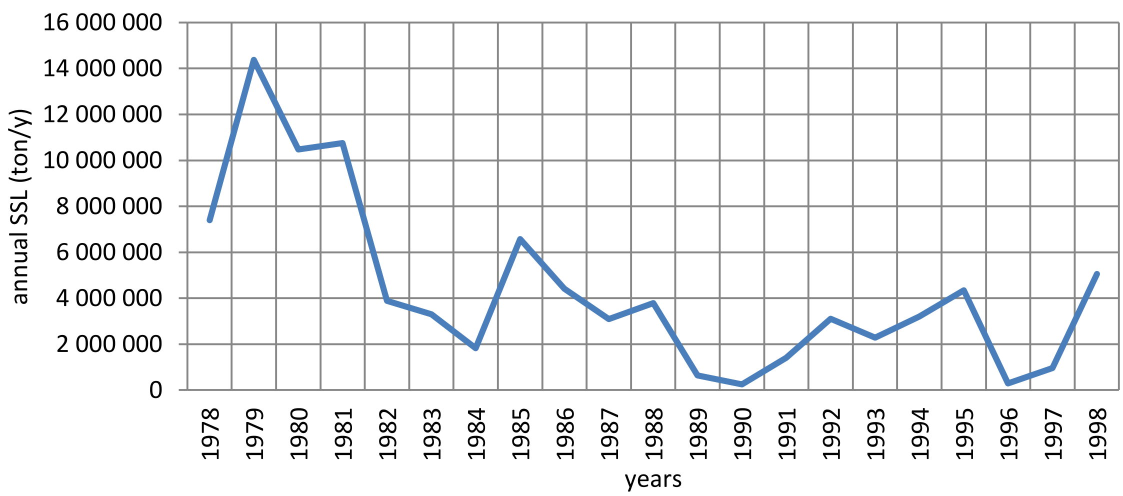

Fig.3 Variation of annual sediment load (SSL) at Szolnok guaging station

built-in turbidity measuring device. The details of control measurements are shown in the following table (Table 1).

Laboratory analyses

During the measurements, water sampling from the same depth of the water column near the turbidity probe is necessary to determine the sediment concentration of the Tisza. With the help of the Regional Laboratory of the Middle Tisza Region Water Directorate, the water samples were processed. First, the water samples were filtered with a vacuum filter unit, through a membrane filter with a 0.45 μm pore size, so that the suspended substances in the water remained on the surface of the filter paper. The individually numbered filter papers were dried in an oven at 105°C until their mass became constant. Then, their mass (m1) was weighed (on analytical scale, accuracy: ±0.1 mg). The volumes of the water samples were measured (Vm in ml), and then they were filtered through a membrane filter, then the filter papers were dried again until their weight became constant (at 105°C), and then their weight (m_2) was measured again. The suspended matter concentration (SSC) of a water sample was calculated using the following formula:

$$SSC\left({}^{mg}/_{l}\right) = \frac{m_{2-}m_1}{V_m}$$

Measurement of continuous turbidity data

The OTT HYDROLAB-7 type water quality probe was used (Fig. 4), which was centrally procured (2020) by the General Directorate of Water Management to measure turbidity. The instrument is suitable for measuring several parameters, e.g. turbidity (NTU- Nephelometric Turbidity Unit), chlorophyll content (chlorophyll-a; in mg/l) and temperature (°C). The built-in instrument can measure turbidity in the 0-3000 NTU range. The measurement was carried out based on the ISO 7027 standard, using infrared light with a wavelength of 880 nm. The sensor is sensitive to the formation of biofilm that settles and develops on its surface, so it is equipped with an automatic cleaning brush that ensures continuous cleaning. The measuring principle of the HL-7 probe and the hand-held turbidity meter (type: HACH2100Q) is different; while the former measures the reflection of infrared light according to the ISO 7027 standard, while the hand-held measuring device measures 90° dispersion according to the EPA180.1 standard. (HACH, 2021).

The measuring device was installed in the Szolnok section of the Tisza, on the downstream side of the floating platform located on the right bank of the river (ca. 336.0 fluvial km). The device consists of a protective and support structure, a data collection and control unit, and a solar panel that provides energy. Based on the instrument's configuration, it measures the parameters (turbidity, chlorophyll-a, temperature) in every 15 min, which were averaged to every hour. The data were transferred to the telemetry centre of the Middle Tisza Region Water Directorate (Fig. 5). The disadvantage of the method is that turbidity of water depends on the size, composition, color, and shape of the sediment particles. On the other hand, the accuracy can be greatly reduced by biofilm formation on the probe (see Fig. 4), so it is necessary to ensure continuous cleaning. Being an in direct method, calibration is required to convert turbidity into near-bank sediment concentration.

RESULTS

Accuracy check of the installed turbidity meter

Before analyzing the near-bank sediment samples and sediment concentration data, it is essential to check the accuracy of the turbidity data provided by the measuring probe. The previously mentioned manual, portable turbidity measuring device was used to achieve this. The water samples were taken directly from the water column next to the measuring probe. Then, the turbidity (of samples homogenized by shaking) was measured three times, and the arithmetic mean was taken. In the period

Table 1 Summary of control measurements data (The Turbidity is measured by portable tubidity meter)

Date	Turbidity [NTU]	Stage [cm]	Discharge [m^3/s]	Hydrological conditions	Depth of sampling [m]
24 May 2021	159	592	1246	rising	~1.2
25 May 2021	184	603	1250	rising	~1.2
26 May 2021	167	605	1219	stagnant	~1.2
27 May 2021	142	598	1156	falling	~1.2
01 June 2021	84	380	803	falling	~1.2
02 June 2021	86	333	750	falling	~1.2
03 June 2021	177	292	710	falling	~1.2
29 June 2021	22	-90	244	rising	~1.2
30 June 2021	26	-73	266	stagnant	~1.2
05 July 2021	27	-16	361	rising	~1.2
06 July 2021	41	71	462	rising	~1.2
07 July 2021	61	129	547	rising	~1.2
08 July 2021	44	127	484	falling	~1.2
15 July 2021	41	-41	330	falling	~1.2
16 July 2021	36	-36	319	stagnant	~1.2
17 July 2021	33	-34	295	falling	~1.2

after the installation of the measuring system, 38 control measurements were carried out, in 16 of these cases were used to calibrate the relationship between near-bank sediment concentration and turbidity. The comparison of the measurement results shows that the probe captures 70-90% of the data from the manual turbidity measurement.

On the one hand, the differences can arise from the measurement method between the two instruments or the measurement conditions, according to which the probe measures in situ, while manual turbidity measurement requires sampling. In addition, it is worth mentioning that the HL-7 probe is sensitive to biofouling formation (a significant biofilm formation occurred on the probe during the measurement period), which may also cause a difference. Close relationship can be established based on the comparative and control measurements and the obtained results are scattered around a straight line. The coefficient expressing the closeness of the relationship is R^2 =0.93, which statistically expresses a powerful relationship (Fig. 6). Vas and Tamás (2023) also established a similarly strong relationship based on the measurements. The data collected during the measurement period are presented in Figure 7, but it must be stated that the data represents mostly low flow conditions. From the analysis of the time series it can be deduced, that the turbidity and consequently the suspended sediment concentration along the near bank "peaks" on the rising limb of smaller flood-waves. In addition, there were cases when the water level was stagnant or falling, but the turbidity measuring probe measured a moderate increase in turbidity. We have not yet found a precise explanation for this, but it should be mentioned that due to the larger, more intense summer rainfalls, intensive run-off was observed from the banks, which can increase the turbidity of the water near the banklines. Investigating such "disturbing" effects requires additional measurements, because they do not influence the previously applied measurement practice. Much more detailed temporal resolution data is available, and their interpretation requires further tests and measurements.

Analysis and calibration of near-bank turbidity and sediment concentration data

In the following analysis phase, we looked for a connection between the turbidity data measured by the probe and the suspended sediment concentration data obtained from the point water samples. Since the installation of the instruments, in order to establish the correlation, a total of 16 water samples have been selected and their laboratory evaluation has been carried out. The suspended sediment concentration data (SSC) determined by the filtration (vacuum filter) method were compared with the turbidity data measured by the near-bank probe (corrected with the correction explained in the previous chapter). The calibration correlation of the improved near-bank turbidity and sediment concentration data obtained in this way gives reason for confidence. According to the results, the R^2 is 0.81, which assumes a reasonably close relationship between the two physical variables (Fig. 8).

Fig.4 Applied HYDROLAB- HL 7 multiparameter probe without coverguard

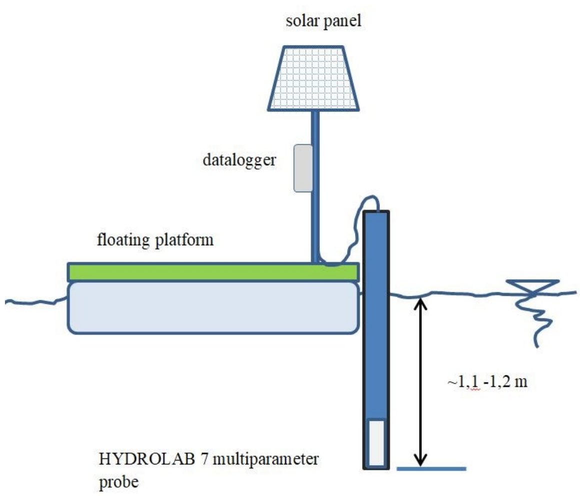

Fig.5 Design of an installed turbidity measuring probe

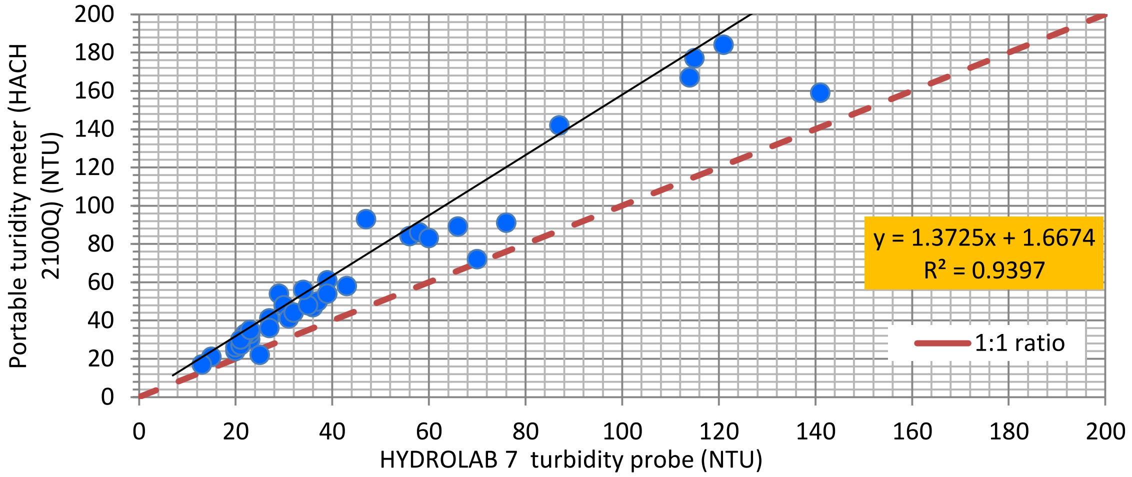

Fig.6 The relationship between the data of the HL 7 probe and portable hand-held turbidity meter (in NTU)

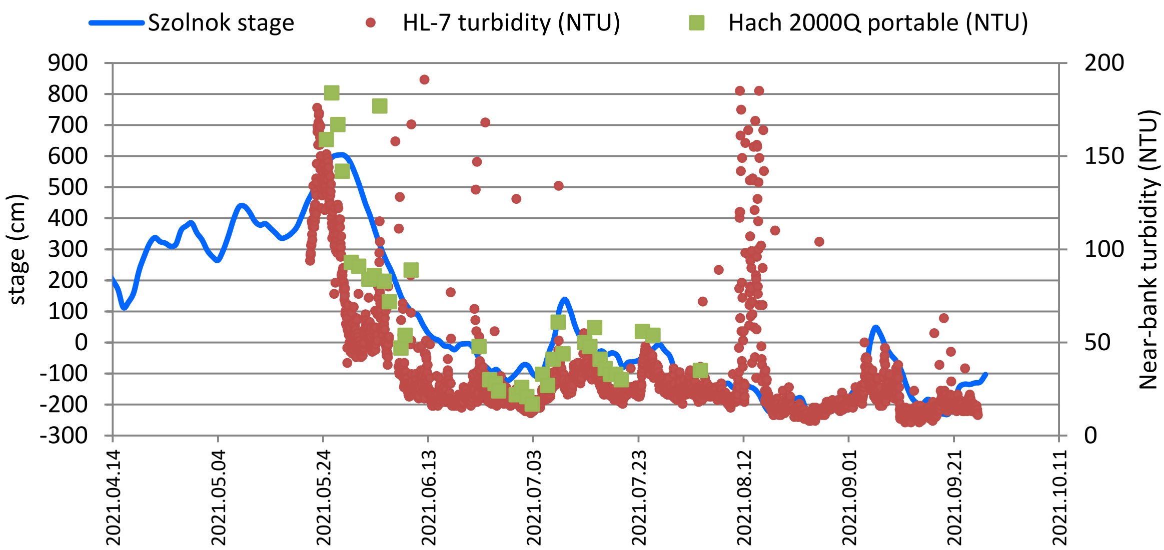

Fig.7 Near-bank turbidity (NTU) and stage (cm) time series at Szolnok

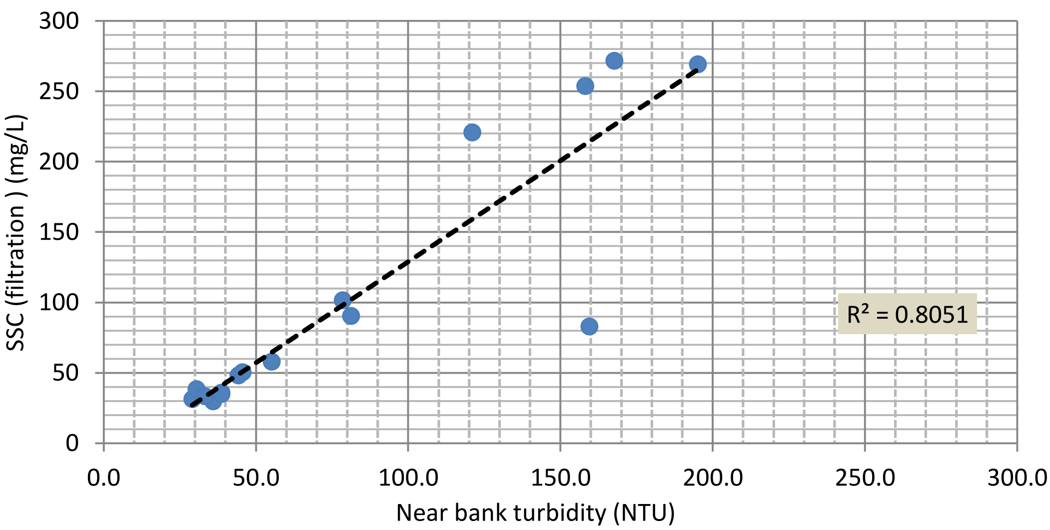

Fig.8 Correlation between the near-bank turbidity (NTU) and suspended sediment concentration (mg/l)

The results and the established relationship exceeded our expectations. However, it should be noted that the measurements reflect the results of a low (insufficient) number of samples from a statistical point of view, so further measurements are needed mostly in the mean and high flow conditions to refine the calibration. Nevertheless, the application of indirect methods on the scale of the Tisza River certainly seems effective and promising.

In the next step the relationships between the concentration data along the bank and the data along the profile and the concentration and sediment yield data were analysed. During measurement period the Middle Tisza District Water Directorate (KÖTIVIZIG) carried out measurements according to the annual measurement plan. The measurements were not taken directly near the installed probe, but approx. downstream of it by 600-650 m. The discharge measurement section located under the downtown bridge in Szolnok. In parallel with the discharge measurements, water samples were also taken from 5 verticals along the cross-section, which were analyzed with laboratory tests (Table 2).

The turbidity data registered at the measurement times were converted to near bank sediment concentrations (mg/l), then the relationship between the two variables was constructed based on the values of the cross sectional profile sediment yield (kg/s) obtained from the water samples taken during the annual measurements (Fig. 9). The correlation factor expressing the closeness of the relationship is 0.66, which is acceptable. Of course, the results of only 4 cross-sectional measurements are not sufficient to establish an acceptable quality connection, but nevertheless, we obtained results that exceeded our expectations. The measurements were made at low flow conditions in summer, so further measurements are needed in the broadest possible water regime to refine the calibration.

CONCLUSIONS

There is a well-established practice of measuring and calculating suspended sediment transport of rivers. In the case of the Danube, many research results have been published to describe the river's sediment transport using indirect methods. Concerning the Tisza River, sediment measurements are carried out mainly by the territorial water management directorates. New technologies and sediment monitoring systems have only been tested in a limited number so far. Knowing the amount of suspended sediment passing through a given section and describing its temporal and spatial variability can be important basic data for future developments and the monitoring of natural and anthropogenic effects on the life of the river.

In this study, based on the recommendations of the DanubeSediment project, the aim was to develop and test suspended sediment monitoring of the Tisza using an optical turbidity meter. The system of tools forming the basis of the system was acquired by the National Directorate of Water, which was handed over to KÖTIVIZIG for testing. The study aimed to explore the potential of the instruments based on the measurement

Table 2 Details of discharge measurements in 2021, after the deployment of the turbidity probe

date	water level at Szolnok (cm)	discharge (m^3/s)	sediment yield (kg/s)
09. June. 2021	86	420	13.201
14. July. 2021	-34	318	13.110
11. Aug. 2021	-131	218	16.563
09. Aug. 2021	-42	296	9.761

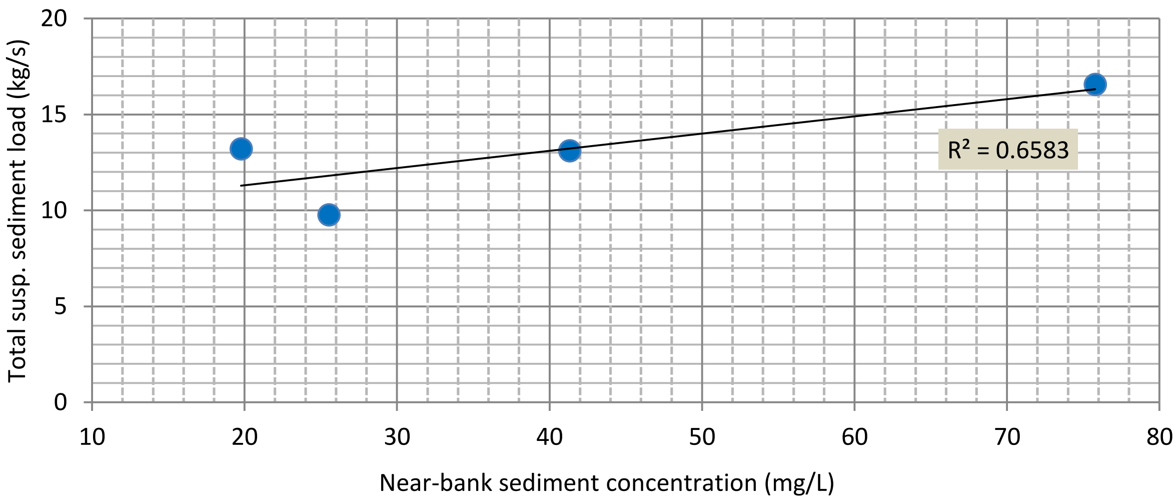

Fig.9 Suspended sediment yields (kg/s) as a function of near-bank suspended sediment concentration (mg/l)

methods and recommendations carried out and proposed on the Danube. The indirect measurement of the suspended sediment concentration by optical turbidity measurement is well discussed in the literature (Nagy, 2013; Kutai, 2014; Haimann et al., 2014; Boss et al., 2018; Habersack et al., 2019; Pomázi et al., 2020; Vas and Tamás, 2023). The greatest advantage of the measurement method is that compared to the traditional method, the temporal resolution of the measured data is orders of magnitude higher. We placed the monitoring station on a floating platform, continuously sending data to the telemetry centre in island-like operation. After starting the measurements, we also performed measurements with a manual turbidity meter in parallel to ensure the instrument's accuracy. We established a strong function relationship between the manual measurement and the turbidity data measured by the probe, which we could later use to improve/correct the registered turbidity data series.

The data measured by the probe cannot be used directly to calculate suspended sediment concentration; calibration is required. Currently, the results of the traditional vacuum filter method are considered as the starting point for the calibration. For the calibration measurements, we took water samples from the depth of the measuring probe, which were also analyzed with a manual turbidity meter. We have carried out a total of 16 calibration measurements so far, based on which we attempted to establish the calibration relationship. It was carried out with acceptable accuracy based on the existing data. We continued our investigations by analyzing the results of the measurements along the profile and the correlations based on turbidity measurements near the bankline, thus, it was possible to establish a sufficiently close relationship between the sediment yield flowing through the profile and the sediment concentration along the bankline, although based on only four measurements so far.

The results are promising, but the measurement campaign must be continued, and the functional relationships discovered so far need to be clarified by analyzing additional water samples. Thus, we plan to analyze water samples in the widest possible range of the hydrological regime. Of course, the new measuring technique based on optical turbidity measurement raises several new questions: Does the size and shape of the Tisza's sediment particles affect the measurement in the high-water range? How do algae growth and biofilm formation affect the measurement results?

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